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DIGIMAN

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Digital Measurement Systems for Sensing and Monitoring Applications Manual

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1. METROLOGY AND MEASUREMENTS

Metrology is the field of knowledge related to measurements, encompassing all the theoretical and practical aspects of measurements, whatever their level of accuracy, the measured size, the manner and purpose of the measurement, as well as the field of science or technique in which they occur.

Measurement is the set of experimental operations performed to obtain quantitative information on certain properties of an object or phenomenon. The scientific reasoning carried out in an experiment in physics is based on a series of abstract notions of different species (geometric, mechanical, caloric, etc.) called entities. Each entity is characterized by quality and quantities:

- Quality represents the determination of objects and phenomena by establishing their essential and stable features and sides that make them to be the respective objects and phenomena; it determines the unity of the work. The quality of an entity cannot exist outside its quantitative aspect.
- Quantity characterizes objects and phenomena by the degree of development of their properties. Quantity is related to quality; changing one causes the other to change. The interdependence between them is expressed by the notion of measure, which is the boundary of the existence of the object indicating the extent to which the quantitative changes do not lead to qualitative changes.

The property of an object or phenomenon represents the external expression of quality in the relationship between it and other objects. Each entity has many independent properties: size, meaning, scalar or vector nature, colour, smell etc. From the metrological point of view, only the size of the entity is of interest. For this reason, instead of the word entity, it is commonly used the word size, considered a property of the entity. This substitution does not constitute an error as long as the nature of the entity is not sought. In order to simplify the expression, this substitution is accepted without losing, however, since it is the size of the entity, i.e. the size of the length, the size of the force and not the length, the force, etc. In order to make the comparison it is necessary to know the devices used and the operations performed, and the ratio "n" must be independent of the nature of the sizes. In a set of quantities A0, A1, ... An can be compared with each other at least two by two; they are said to be various quantities of a given size. Thus, the distance between two points, the height of a landmark against the ground, the length of a watercourse are quantities of the length size. So, one can reach sizes when considering quantities, which corresponds to the natural process of moving from concrete quantity to abstract (size).

Measurement process represents a certain property or characteristic of a material, phenomenon or process, which is defined and may vary quantitatively. Given that the size of the entity is its property, it can be considered under this name both the quality and quantity of the entity. In general, the amount used with the meaning and, consequently,

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the size of which has the property is essential to vary, increase or decrease, to be evaluated single quantity that is to be expressed numerically. Of all possible sizes, only those that can be expressed by an algebraic formula, that is, only physical quantities that are characteristic elements of physical states and can be evaluated by comparison, measurement or reference and expressed numerically. After their composition, the sizes can be classified into:

- extensive units that have the property of being able to be ordered and summed: the masses of two bodies can be both assembled and summed the new body having the total value of the two bodies.
- intensive units that are defined by ordinary properties, but not by addition: the temperatures of two distinct environments can be ordered by their value but cannot be summed.

Physical dimensions, by their character to be quantitatively evaluated, are a basic element of metrology. Thus, the following physical sizes can be identified:

- fundamental units, i.e. conventionally chosen independent or distinct sizes, by means of which other sizes can be defined
- derived units, that is, the quantities defined by the help of the fundamental quantities. Their definition is made by defining relationships.

From the point of view of mathematical expression, the units can be classified as follows:

- scalar if determined only by its numerical value and by the unit of measure in which this value is expressed;
- vector if it is described by its numerical value, a oriented support and the unit of measure in which this value is expressed;
- tensor if expressed by pictures of scalar values established in a certain geometrical space that changes with the change of the reference base.

In reality, the quantity is not constant over time. In metrology, it is considered that if the variations in its size is constant within a measurement time t_m is sufficiently small, typically much smaller than the uncertainty of measurement. The time, t_m, of measurement can vary from the order of the seconds to the order of the hours, depending on the complexity of the experiment, being specific to each application. Variable sizes can be of two types:

- stationary
- non-stationary

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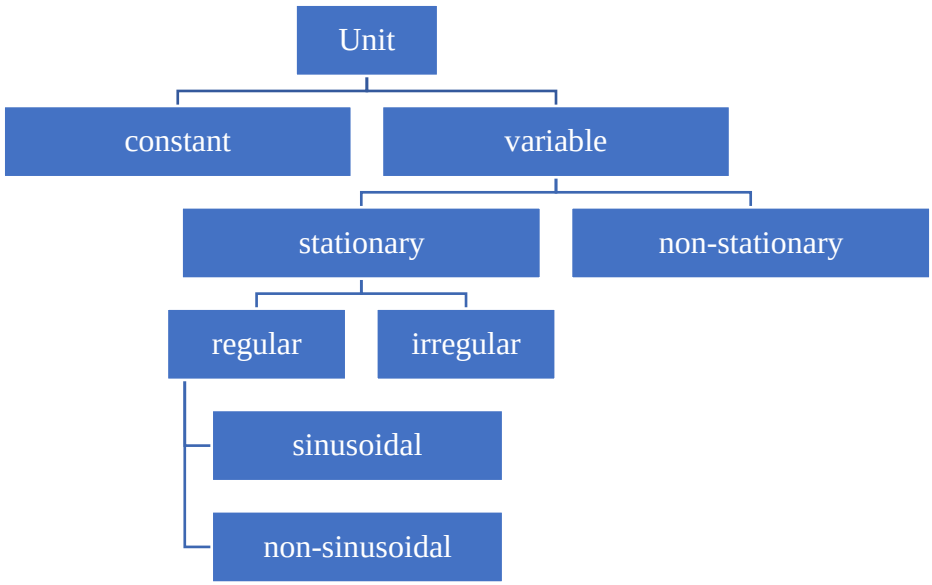


Figure 1: Units accepted by International System of Units

From measurement point of view, the stationary units can be measures as:

- certain instantaneous value
- overall instantaneous values in a certain window of time also called as signal curve
- a global parameter such as:
  - the effective value
  - the average value
  - average value of the module
  - the peak value
  - peak to peak value

For non-stationary quantities the following appreciations can be done:

- certain instantaneous value
- a string of discrete instantaneous values at different times
- the average value over a period of time
- the set of instant values for a given range

Of these, the mean value over a time interval, called mediation time, have particular importance when the variation in time of the measure is a disturbance. The set of discrete or continuous instantaneous values is measured by viewing or recording the evolution of the measurement. The problems imposed by the continuous development of science and its practical applications, have led to the need for well-established, precise units of

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measurement, which will ensure the creation of a system capable of expressing unitary the results of measurements. For each species, a unit of measure was adopted - an amount of the same species conventionally adopted as a unit with which to compare all species sizes, so that they can be easily defined, reproduced, preserved and accurately transmitted. Given the very large number of species of sizes, in accordance with the fundamental and derived sizes, two types of units of measure were adopted:

- fundamental units of measurement
- derived units of measurement: they are established using the definition equations forming the dimension equations by directly replacing the fundamental quantities with their units

The units of measurement of the derived sizes that are formed without the intervention of any numerical coefficient (coherence coefficient equal to 1) are called coherent. There are also units of measurement with a coherence coefficient different from 1 which can be found in systems other than SI, called non-coherent units. The rapid development of science and technology has questioned define countries and more precise measurement and a more and more sizes. In this way, it was size systems and then systems units, which are all all base units and derived units specific to a system sizes. A size system is consistent if all units of measurement corresponding to the derived sizes are coherent. It is obvious that if the size system is coherent, then the system of units of measurement is consistent. The derived dimensions without dimensions were named additional sizes until the recommendation of ICMW (International Committee of Measures and Weights) of 1980. The units of the fundamental sizes of the SI system have undergone various changes over time, in accordance with the evolution of the knowledge regarding them.

Measurement, in essence, is a complex information process that can be addressed to a subjective (non-instrumental) or objective (instrumental) domain and has become the main means by which the measurement information obtained by the management of various types of physical systems is obtained, technological, biological, sociological, military, etc., regardless of their structure or dimensions. Any measurement is based on a phenomenon, a legality or a physical effect. This scientific basis of measurement is generally referred to as the measurement principle. The measurement principles are studied in physics (theoretical aspects) and applied metrology (especially the application aspects). The set of theoretical relationships and experimental operations involved in measurement, viewed in general, characterizes the measurement method. The classification of the measurement methods can be done according to multiple criteria although the complex means of measurement usually combine the characteristics of several criteria, which makes it quite difficult to separate them into one of the categories.

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They can be organized as follows:

- According to the method of obtaining the value of the measure
  - The direct measurement method is the method by which the value of the measurement is obtained directly, without resorting to the measurement of other quantities related to it by definition relationships. It is considered a direct measurement method if other measurements are actually determined inside the measuring instrument, but these indicate the value of the measurement
  - The indirect measurement method by which the value of the measure is obtained according to other quantities actually measured, related to it by a physical relation. The indirect measurement method consists of one or more direct measurements, followed by calculations. The indirect measurement method can be regarded as a set of direct measurements
- Depending on the type of measurement
  - The measurement method by comparison, in which the value of the measurement is compared with the known value of the same size, reproduced by means of a size that intervenes in the measurement process. The comparative measurement method can be performed by:
    - simultaneous comparison: the measurement is compared directly with one or more sizes provided by a standard
    - successive comparison: the standard size does not participate in each measurement: it is used for the initial calibration of a device that thus keeps the measurement information and then transmits it to the measurement at each measurement.
  - Substitution method: in which the value of the measure object is replaced by a measure, such as the means of measuring the effects are the same
  - The method of measurement by coincidence when determining the value of the measure is based on observing the coincidence of some landmarks or signals
- By category of unit:
  - The method for measuring with contact where is necessary the contact between the measured object and an element of the instrument
  - Non-contact measurement method in which the contact between the object whose characteristics will be determined and elements of the measuring device is not necessary
  - Measurement at resonance: in which the relation between the compared quantities is obtained under the resonance conditions of an oscillating system

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- According to the measurement accuracy
  - Laboratory measurement methods in which measurement errors are determined and taken into account
  - Technical measurement methods that do not take into account the measurement errors, because the measuring instruments have known limit errors given by the precision classes
- After the measurement result playback mode
  - Analogue measurement methods - are characterized by the fact that any value of the input size in the measuring range continuously corresponds to a value in the output range
    - Numerical (digital) measurement methods - are characterized by the fact that in the measurement chain a conversion of the measurement signal takes place from analog to digital, p the signal processing in this case is done by counting, therefore, a value range of an input value is attached to a measured value in a certain encoded form

Particularizing those presented above, the measurement methods can be synthesized according to their applicability in the technical field. This summary of the measurement methods is presented in table below.

<table>
<tr><th colspan="5">Measurement methods</th><th>Examples</th></tr>
<tr><td rowspan="4">Direct measurement method</td><td rowspan="4">simultaneous comparison</td><td rowspan="3">1: 1</td><td colspan="2">direct</td><td>Measuring the length with a ruler
Comparison of voltage standards by opposition
Differential calorimeter</td></tr>
<tr><td rowspan="3">indirect</td><td>simple</td><td rowspan="3">Comparison of masses using a balance with equal arms
Comparison of resistors with a bridge with equal arms</td></tr>
<tr><td>by substitution</td></tr>
<tr><td>through permutation</td></tr>
<tr><td></td><td colspan="2">by addition</td><td>Comparison of masses by closed series method</td></tr>
</table>

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<table>
<tr><td rowspan="4"></td><td rowspan="2"></td><td rowspan="2">1: n</td><td></td><td>Comparison of electrical resistors by summation</td></tr>
<tr><td>by multiplication</td><td>Balance with unequal arms
DC compensator
Measuring bridge</td></tr>
<tr><td rowspan="3">successive comparison</td><td colspan="2">with mechanical memory</td><td>Pressure gauge with elastic element
Dynamometric balance
Electrical indicator instrument</td></tr>
<tr><td colspan="2">with electrical memory</td><td>Digital voltmeter
Electronic flow meter</td></tr>
<tr><td colspan="2">with other types of memory</td><td>Electrolytic emperor
Thermometer with liquid</td></tr>
<tr><td colspan="4">Method of indirect measurement</td><td>Pressure gauge with liquid column
Density measurement
Resistivity measurement</td></tr>
</table>

Figure 2: Clasification of measurement methods

In the simultaneous direct comparison, the measurement is compared with a standard of near or equal value, directly. It can be applied only to physical quantities that can take both possitive and negative values such as:

- Length
- Pressure
- Force

The simultaneous direct comparison cannot be applied to sizes that take only positive field values:

- Mass
- Electrical resistance

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The presence of the reference size given by the standard is indispensable in the measurement process. The simultaneous direct comparison is shown in figure below.

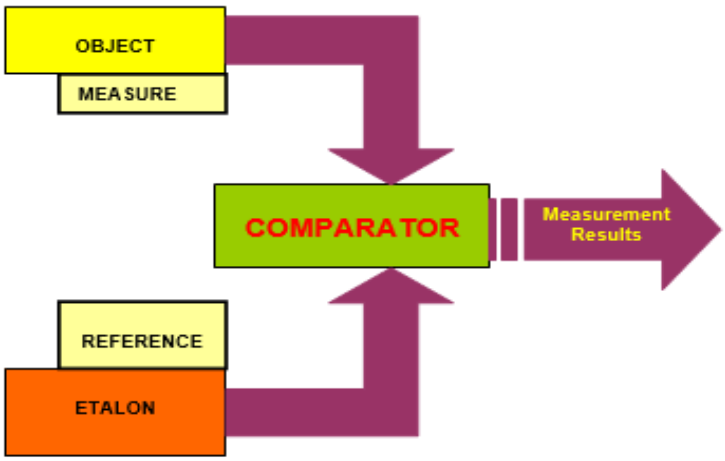


Figure 3: Simultaneous direct comparison

Simultaneous comparison methods can be:

- Differentials – the method is applied if the measurement is compared with a standard and the difference is measured according to equation

$$x = x_0 + d \tag{1.1}$$

where:

- x – the value of the measurement
- x_0 – the value of the standard
- d – the difference measured directly

If the difference d is sufficiently small relative to x_0, the error affecting d is negligible and the uncertainty of the result is practically equal to the uncertainty of x_0.

- Near to null – the method is applied as a particular case of the differential method in which it is intended that the difference between measurement and standard is zero, according to equation:

$$x = x_0 \tag{1.2}$$

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where:

- x – the value of the measurement
- x_0 – the value of the standard

Thus, the measuring device is used only as an indicator of zero and influences the measurement result even less. However, the result of the measurement by this method can be affected by errors due to the instability of the reference size or by the impossibility of varying it in sufficiently fine steps.

- By coincidence – the method by which the superposition of some benchmarks is sought

In comparison successive reference size is not directly involved in each measurement, it is used for the initial calibration of the device which stores memory information to the calibration information which received only once from the standard and to be drunk and lysed by the machine to each measurement according to figure presented below.

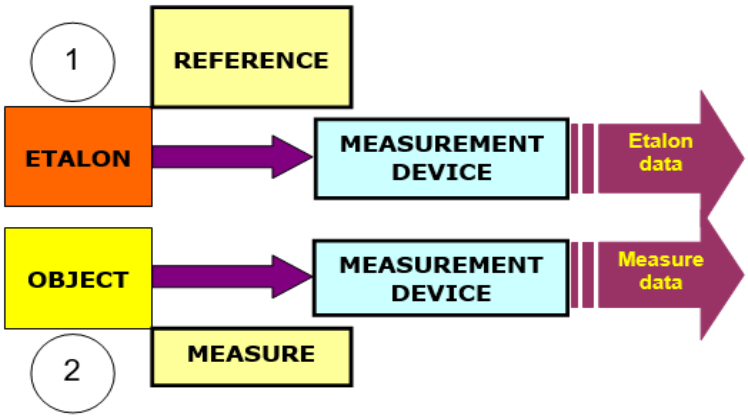


Figure 4: Successive comparison

The ones presented above are the reason why, periodically, according to the respective manufacturer's specifications and the national legislation, the devices are checked (the operation is called metrological maturity) to see if the stored calibration information has been altered and if so the device is recalibrated. The standard is a means of measurement intended to define, preserve or determine one or more known values of a size to serve as a reference in comparison with other means of measurement. The uniformity and compatibility of the measurements requires that these standards be properly categorized as follows:

- by definition – the standard must have the main units of measurement according

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to their definitions

- of transfer – the standard must provide the following aspects:
    - allows the correlation of the units of measurement derived from each other
    - to derive new units of measurement
    - to expand the field of multiples and sub-multiples of the basic units
    - to facilitate the transition from a static to a dynamic regime
- conservation – the standard must ensure that the units of measurement are kept constant over time

Means of measurement are technical assemblies used to obtain measurement information. They materialize, preserve and provide measurement information. The classification of the measuring means can usually be done according to multiple criteria, depending on the particular case in which they are classified:

- In terms of complexity, the main categories of measuring instruments are:
    - Measures
    - Measuring apparatus
    - Assemblies, installations and measuring systems
- From the point of view of the destination, the means of measurement fall into two categories:
    - Standard (standard means of measurement)
    - Means of measuring work
- After the position in a measuring device one can talk about:
    - Detector (sensitive element)
    - Adapter
    - Auxiliary element

The measure is the means of measurement that reproduces one or more values of a physical size. The measures are intended to preserve the units of measurement. Their main characteristic is the stability with which they retain their value over time or in the variation of disturbing factors. Generally, the measures can only be used to carry out measurements associated with devices, which are most often comparators, which compare the measurement with the reference size generated by the measurement. Except I make some measurements of length (rulers, roulettes, ribbons, etc.), of flat angle, of volume and others with which it can be measured and independently, the comparison being made visually. The measures can be:

- Single - value measures retain only one value of the measure
- The measures with multiple values are:
    - measures with discrete values e (several distinct values) achieved by combining several selectable or commutable measures with a suitable

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device
    - measures with continuous variable value (within a given range), usually provided with a graduated scale

It should be noted that in addition to simple construction measures, such as rails, weights, etc., there are measures with relatively complex construction, such as a resistor in decades. Their complex character, including even specific parts of measuring devices, does not change their quality of measurements. According to their destination, they are distinguished:

- measures standard - are used for calibration or verification of metrological measuring instruments, while working measures are used in current measurements
- working measures - are used in current measurements

Measured substances are measures that consist of substances (materials) having a certain physical property, high stability and a known value (liquids of known densities, pH buffer solutions, color samples, known electrolytic conductivity solutions.

2. SIGNALS, SENSORS AND TRANSDUCERS

2.1 Signals

By signal is meant a physical manifestation that can propagate through a given environment. In an evolving physical system, at least one main parameter is expressed which expresses the specific character of the system. A signal can be defined as an entity carrying information about the presence or evolution of a physical system. It can be regarded as a model of information. From this model, by studying its parameters as well as the prism of the knowledge that exists about it, the information can be obtained. The presence of this main parameter is established through the message provided by the system during its evolution. This is realized using a sensing device called sensor followed by a converter which transform the information provided by sensor. Thus, a signal can be obtained which can be sent through a transmission channel to the receiver. After that, all data can be used to evaluate and exploit the system.

An analog signal is a signal with continuous variation and a digital signal has a step by step variation. A good example, in terms of analog vs digital, is the functioning of the clocks: the analog clocks have indicators and therefore they do not have limited accuracy in terms of time measurement; on the other hand the digital clocks cannot indicate time gaps under their own capacity for displaying the time. In most of cases these resolutions can be quantified in seconds. Both categories of signals, analog and digital, can be applied in modern electronic systems.

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Regular signals

Regular signals are those signals that reproduce in identical form after a certain interval of time called period. They can be described in time domain as amplitude, frequency and phase functions. Any periodic signal can be described as a series of harmonics that is equivalent as in the following equation.

$$x(t) = A_0 + \sum_{n=1}^{\infty} A_n \cdot \cos(n \cdot \omega \cdot t + \varphi_n) \tag{2.1}$$

where it is known that:

$$\omega = 2 \cdot \pi \cdot f \tag{2.2}$$

By replacing into equation 2.2, it can be obtained:

$$x(t) = A_0 + \sum_{n=1}^{\infty} A_n \cdot \cos(2 \cdot \pi \cdot n \cdot f \cdot t + \varphi_n) \tag{2.3}$$

where can be found all three components presented above and a continuous component of the signal:

- A_0 – the continuous component of the periodic signal
- A_n – amplitude of **n**th regular signal
- f – fundamental signal
- nf – the nth harmonic of the regular signal
- φ_n – initial phase

Equation 2.4 highlights the fact that a periodic signal has a discrete frequency spectrum, consisting of spectral lines placed at multiple fundamental frequencies. Since time and frequency are two similar notions that represent the periodicity of a phenomenon, then signals can be represented by time or frequency. If one wants to represent the sinusoidal electrical voltage that varies after equation 2.4 , then the graph will look like the one in figure below.

$$u = U_m \cdot \sin(2 \cdot \pi \cdot f \cdot t) \tag{2.4}$$

where:

- u – sinusoidal electrical voltage
- U_m – the amplitude of the electrical voltage
- f – frequency of electrical voltage
- t – time

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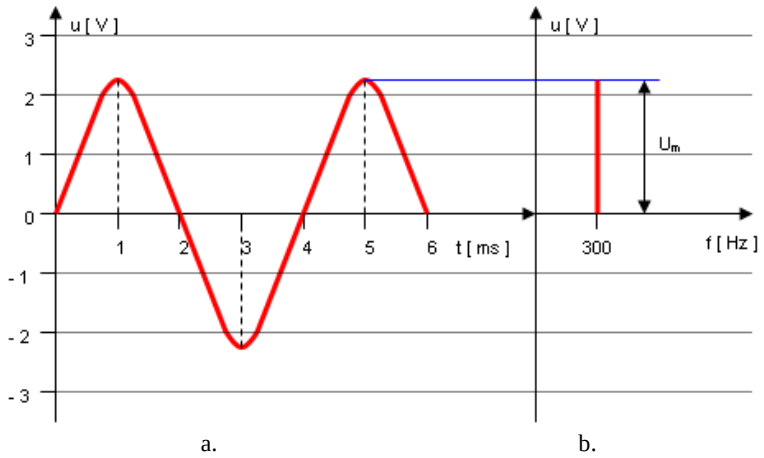


Figure 5: Representation of sinusoidal electrical voltage
a. time, b. frequency

For periodic signals the following parameters are characteristic:

- period T - represents the time interval between two reproductions in identical form
- frequency f - represents the number of periods in the unit of time
- the average value X_{med} - represents the continuous component of the signal and is defined by the equation 2.5, in which the time interval between t_1 and t_2 is considered equal to the period T:

$$X_{med} = \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} x(t) \cdot dt \tag{2.5}$$

- the average value of the module $|X|_{med}$ – defined by relation 1.6, in which the time interval between t_1 and t_2 is considered equal to the period T:

$$|X_{med}| = \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} |x(t)| \cdot dt \tag{2.6}$$

- maximum value X_{max}
- peak to peak value - represents the difference between the maximum value and the minimum value of the signal
- the effective value X_{ef} - defined by equation 2.7, in which the time interval

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between t_1 and t_2 is considered equal to the period T, and for known intermediate values, this is the radical of the sum of their squares:

$$X_{ef} = \sqrt{\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} x^2(t) \cdot dt} = \sqrt{\sum_i X_{ief}^2} \tag{2.7}$$

- the form factor k_f, defined by:

$$k_f = \frac{X_{ef}}{X_{med}} \tag{2.8}$$

- filling factor D, defined as ratio between pulse time and its period:

$$D = \frac{t_0}{T} \tag{2.9}$$

- ridge factor CF:

$$CF = \frac{X_{mas}}{X_{ef}} \tag{2.10}$$

Single signals

The single signals are those signals having a unique character that may be described in the time domain, the time function characterized by:

- moments when they cross through null value
- peak values
- signal duration
- energy

The single signals are used in the transmission of information, systems analysis, tests, etc. In the frequency domain, the analysis of the single signals is done similar to the method of analysis of the periodic signals, these being characterized by an infinite continuous spectrum of frequencies. Single and periodic signals are deterministic signals because they can be expressed by a law of known variation. The most used single signals are

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shown in the figures below:

- unit step signal

The mathematical function that represents the graph in Figure 6 can be written as in following equations:

- when t < 0:

$$f(t) = 0 \tag{2.11}$$

- when t > 0:

$$f(t) = 1 \tag{2.12}$$



Figure 6: Unit step signal

- ramp signal

The mathematical function that represents the graph in figure 1.3 can be written as in following equations:

- when t < 0:

$$f(t) = tg(\alpha) = 0 \tag{2.13}$$

- when t ≥ 0:

$$f(t) = tg(\alpha) = a \cdot t \tag{2.14}$$

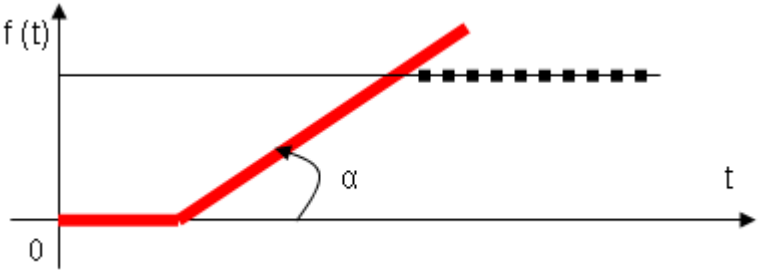


Figure 7: Ramp signal

- DIRAC pulse

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The mathematical function that represents the graph in Figure 7 can be written as in following equations:

- when $t < 0$:

$$f(t) = 0 \tag{2.15}$$

- when $0 \leq t \leq \Delta t$:

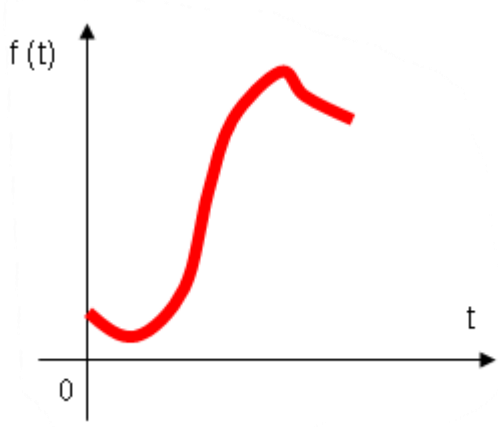
$$f(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \tag{2.16}$$

- when $t > 0$:

$$f(t) = 0 \tag{2.17}$$

Random signals

Random signals are those signals that have a random and unpredictable character over time, the instantaneous value of these signals is characterized by probability functions . These signals have a continuous spectrum in a given frequency band. Regardless of the type of signal, for the measurement process, the way of representing the signals in time is important, they can be:



a.

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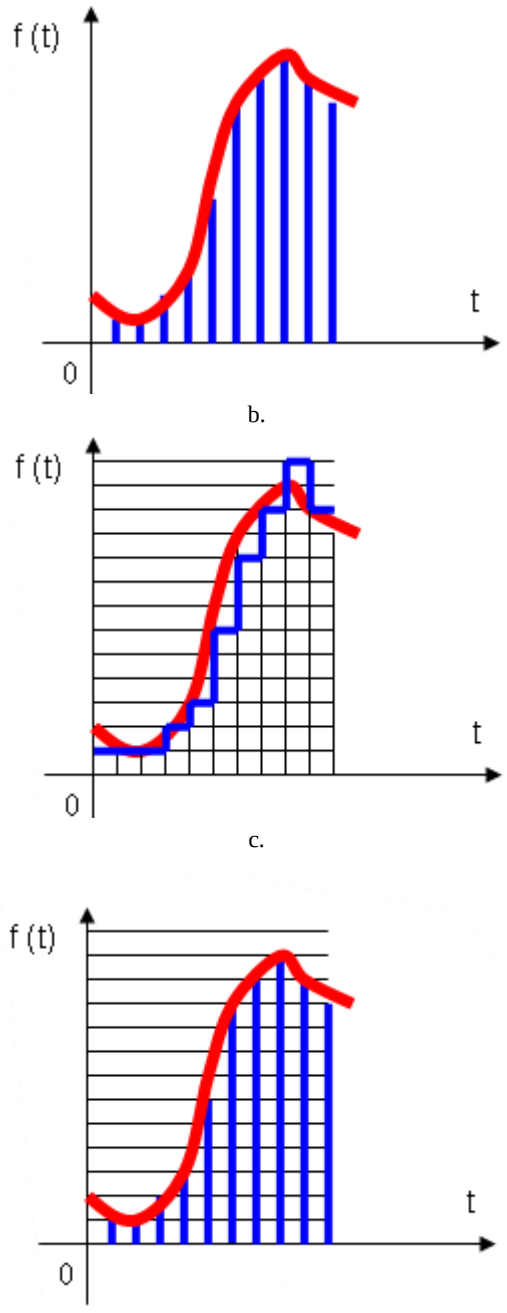


Figure 8:Variation of the signals in time
a. constant analog signal, b. discret variantion in time of analog signal, c. discret amplitude of constant analog signal, d. discret signal (amplitude and time)

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The disturbances are those parasitic signals that do not contain useful information and unwantedly overlap the useful signal. The signal processing is performed at the receiver level and has the purpose of recovering the useful signal. Obtained signal held by the system is considered as function of time, because the system evolution is a function of time. It should be noted that disturbances and noises are also phenomena that occur over time as useful signals, between useful signals and disturbances are not a difference of essence, but a subjective one from a human point of view. Unlike the useful signals, the disturbances are characterized by their unwanted appearance. Therefore, in the sphere of the signal notion, both the useful signal and the disturbances are included, their evolution over time being described by the signal function f (t). There are cases where the signal function can be expressed according to a different time- independent variable. These situations do not change the data processing procedure in principle, due to the presence of another variable than time. Usually, the disturbances are random, but they can also be deterministic signals. The distribution of disturbances can be made according to the frequency at which they appear as signals. The distribution of disturbances by frequency is shown in figure below.

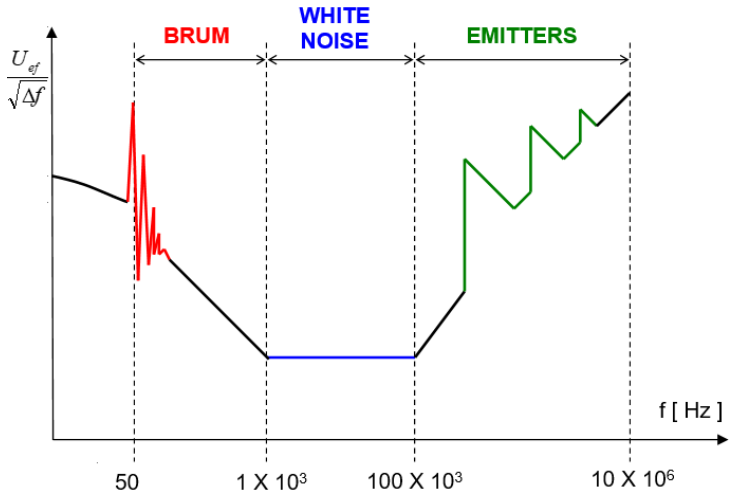


Figure 9: Distribution of disturbances in the frequency band

It can be seen from figure above that the disturbing signals can be classified according to three frequency ranges. Their classification according to the frequency range and the identification of the source that generates these disturbing signals, respectively the effects that are created with the generation of the disturbing signals over the useful signal, are presented in table below.

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Disturbing signal	Frequency range	Disturbing signal source	Effect obtained
atmospheric	0 - 50 Hz	Atmospheric electric discharges	Noise in the speakers
mechanic		Mechanical vibration	howling
Brum	50 - 10^3 Hz	Voltage induced by the electrical cables of the mains	Noise in loudspeakers
White Noise	10^3 - 10^5 Hz	Own noise of amplifiers, transistors, diodes, resistors	Internal noise
Emitters	above 10^5 Hz	Radio TV transmitters or other high frequency industrial components	Noticeable noise

Figure 10: Classification of disturbances

2.2 Sensors

The sensor represents a specific device that notifies data about the external state of a system. In order to achieve this goal, the sensor must react on the basis of a physical principle so that the modification of the reaction parameters of the sensor represents a measurable amount proportional to the information provided by the physical system. Figure below shows the interaction of the physical system sensor.

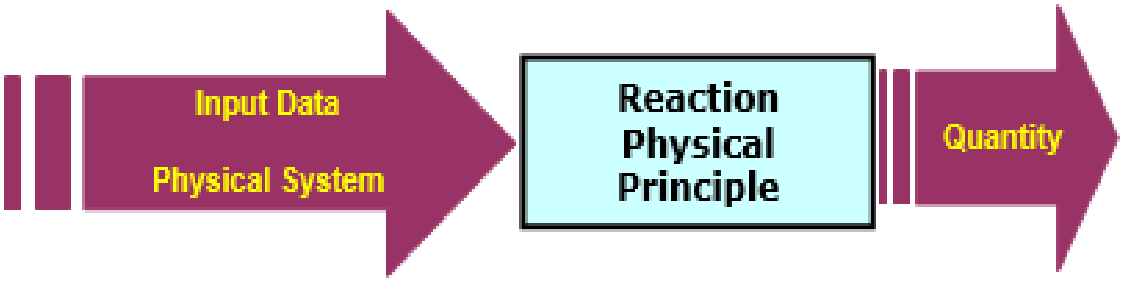


Figure 11: Interaction Sensor – Physical System

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The physical principles of reaction are those governed by the physical laws of the systems in which the actions are carried out. Some of them are presented below. They are focused on electric and magnetic laws that can be applied in sensing circuits in order to be able to monitor the temperature or to evaluate the evolution of the thermal fields.

Electrical Conduction (Ohm's law)

The electrical voltage at the terminals of a passive circuit (without energy sources) is equal to the product between the current intensity and the electrical resistance of the circuit.

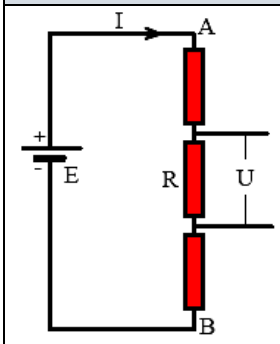
Principle	Equation
	$u_R = R \cdot i$
	Description
	U_R - the electrical voltage applied to the electrical resistance R - the electrical resistance of the circuit I - the intensity of the electric current in the circuit

Figure 12: Electrical Conduction Law

Lorentz Electromagnetic Force

Lorentz force, the force exerted on a charged particle *q* moving with velocity ***v*** through an electric ***E*** and magnetic field ***B***. The entire electromagnetic force ***F*** on the charged particle is called the Lorentz force. [1]

Principle	Equation
	$\vec{F} = q \cdot \vec{E} + q \cdot (\vec{v} \times \vec{B})$

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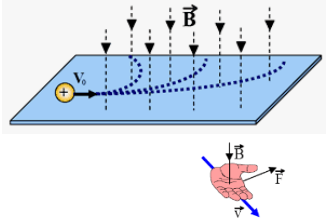
	**Description**
	q – charged particle E – electrical field B – magnetic field v – velocity of charged particle

Figure 13: Magnetic Law Circuit

Piezoelectric Effect

A crystal of a certain configuration of the crystalline lattice, will be electrically polarized in a certain direction if it is subjected to a mechanical stress after a given direction. The electrical charge that appears on the faces of the crystal by virtue of this phenomenon, is proportional to the mechanical effort exerted on it.

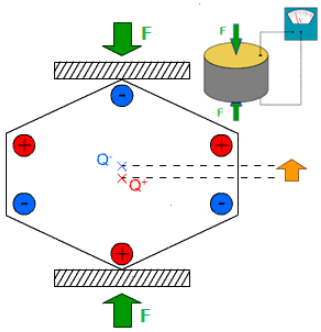
Principle	**Equation**
	$D = \varepsilon \cdot E$ $S = s \cdot T$ $\Rightarrow$ $\{S\} = [s^E]\{T\} + [d^t]\{E\}$ $\{D\} = [d]\{T\} + [\varepsilon^t]\{E\}$
	Description
	D – the electric density of the field ε – material electrical permittivity E – the intensity of the electric field S – constraint of the material s – compliance factor T – tension caused by constraint

Figure 14: Piezoelectric Effect

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Hall Effect

A semiconductor plate placed in a magnetic field B and traveled by current I allows a voltage signal to be drawn on its side faces.

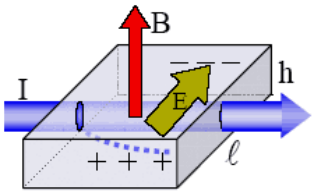
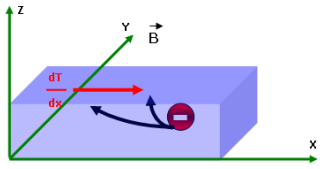
Principle	Equation
	$U = \frac{B \cdot I}{n \cdot q \cdot h}$
	Description
	U - Hall electromotive voltage B - induction of the magnetic field I - the intensity of the electric current n - number of pregnancy carriers q - the electric charge of the load h - thickness of the semiconductor plate

Figure 15: Hall Effect

Nerst Effect

A transverse thermal flux along the magnetic field lines leads to a potential difference.

Principle	Equation
	$\left\|N\right\| = \frac{\frac{E_Y}{B_Z}}{\frac{dT}{dx}}$
	Description

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	E_Y - electric field (Y-axis) B_Z - magnetic induction (Z-axis) $\frac{dT}{dx}$ - the temperature gradient

Figure 16: Nerst Effect

Pyroelectric Effect

The pyroelectric effect consists of the appearance of electrical charges and implicitly of a potential on the surface of anisotropic crystals whose spontaneous polarization depends on the temperature and is the inverse of the electrocaloric effect.

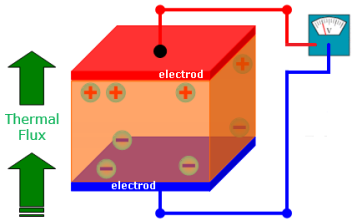
Principle	Equation
	$P_Q = \frac{dP_S}{dT}$ or $P_V = \frac{dE}{dT}$
	Description
	P_S - spontaneous polarization (spontaneous electrical charge) $P_{Q,\ V}$ - pyroelectric coefficient in current, respectively voltage E - the intensity of the electric field T - the considered time interval

Figure 17: Pyroelectric Effect

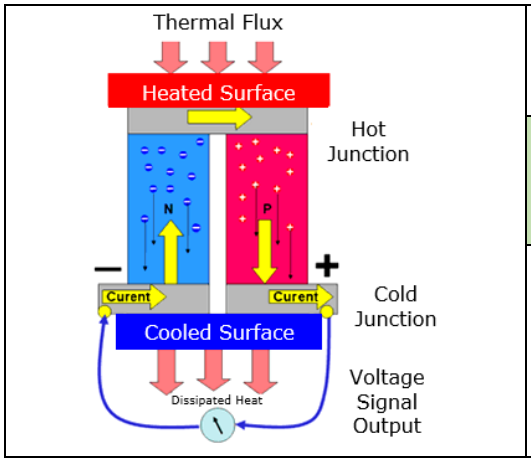
Seebeck Effect

If the temperature of the contact between two metals differs from that of the circuit, a thermoelectric electric voltage appears.

Principle	Equation

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$$V = \int_{T_1}^{T_2} [S_B(T) - S_A(T)]dT$$

Description

S_A, S_B - the Seebeck coefficient of material A and B

T_1, T_2 - temperature of the first and second junctions

Figure 18: Termoelectric Effect (Seebeck Effect)

Stefan-Boltzman law

The Stefan-Boltzman law of radiation states that as the temperature of a heat source is increased, the radiant output increases to the fourth power of its temperature. The conduction and convection components increase only in direct proportion with the temperature change. In other words, as the temperature of a heat source is increased, a much greater percentage of the total energy output is converted into radiant energy.

$$E = \sigma \cdot T^4 \tag{2.18}$$

Every object with a temperature above absolute zero emits infrared energy. This is because there exists in every object a measured amount of heat, so each object has the ability to radiate heat from itself. The object that radiates heat is called the emitting source, and the object to which it radiates heat, having a lesser amount of heat content, is called the target.

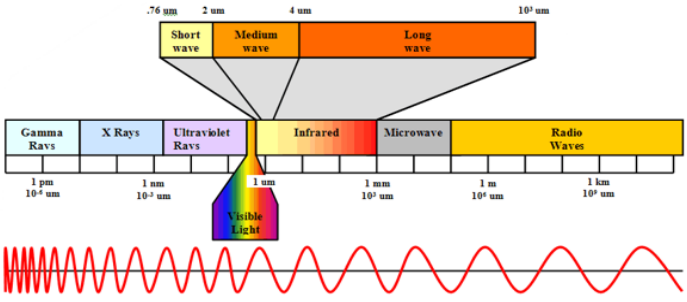


Figure 19: Electromagnetic spectrum [2, 3, 4]

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The radiation law by Planck shows the basic correlation for non-contact temperature measurements: It describes the spectral specific radiation Mλs of the black body into the half space depending on its temperature T and the wavelength λ. The infrared radiation covers a very limited part in the whole range of the electromagnetic spectrum: It starts at the visible range of about 0.78 µm and ends at wavelengths of approximately 1000 µm. Wavelengths ranging from 0.7 to 14 µm are important for infrared temperature measurement. Above these wavelengths the energy level is so low, that detectors are not sensitive enough to detect them [4].

2.3 Transducers

As stated in the previous subchapter for monitoring physical phenomena and measuring the physical quantities that characterize these phenomena, the development of detection and measurement systems based on known physical phenomena is required. In the following, we will present methods for detecting and measuring the physical quantities, respectively constructive solutions of the devices used in making these measurements. Signal transducers are components of the measurement chain that are usually part of a sensitive element assembly - the translator and have the role of converting an input size into another output size of a different nature for the purpose of carrying out the measurement process. It is shown in figure below the block diagram of an assembly element - transducer consisting of:

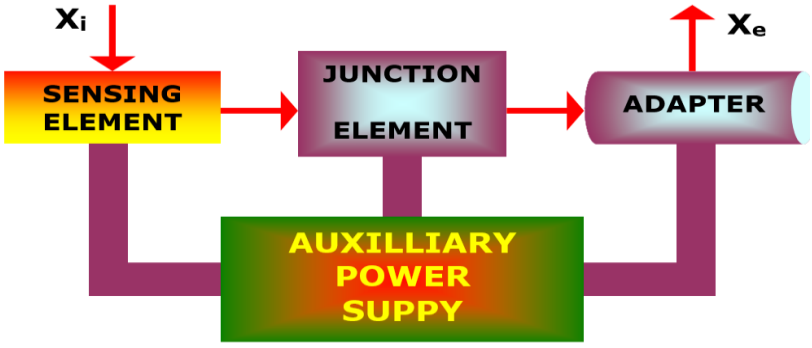


Figure 20: Block diagram for sensor-transducer system

The components of the sensor-transducer system are:

- sensing element - represents the element whose properties interact specifically with the quantity to be measured

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- adapter - represents the component that ensures the conversion of the signal provided by the sensing element into a directly usable quantity
- auxiliary power supply - it is the component that provides the energy input for the sensing elements
- junction element - represents the component that ensures the good correlation of the sensing element with the signal adapter

$$X_e = f(X_i) \tag{2.19}$$

where:

- X_i - the input data
- X_e - the output data

Starting from the equation presented above, we can establish some general characteristics of the transducers:

- input feature - represents the relationship between the input data that characterize the transducer's interaction with the object being measured
- output feature - represents the relationship between the output data of the transducer that characterizes the interaction with the coupled element at the output of the transducer
- transfer feature - represents the relationship between the input and output data of the transducer and characterizes the operation of the transducer itself

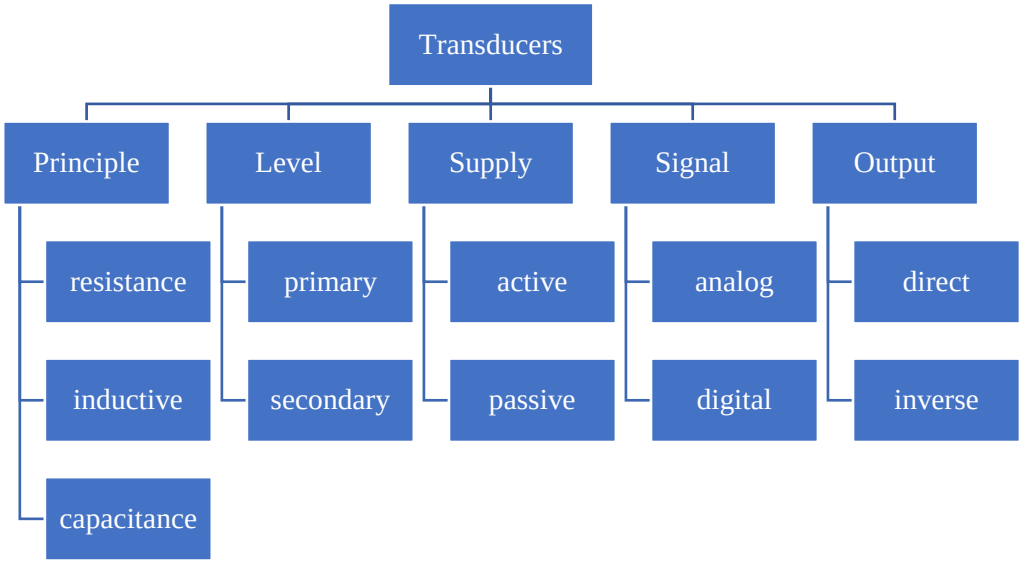


Figure 21: Classification of transducers

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The variety of transducer is very large because, on the one hand, there is a considerable number of objects to measure, and on the other hand, there is a variety of output data, which has led to the elaboration of classifications according to the following criteria:

- physical nature of the quantity measured
- the nature of the input and output data
- the shape of the output data

Principle

This type of classification indicates how the transducers convert the input quantity into resistance, inductance and capacitance.

Level

This type of classification indicates the stages for transduction process. The multiple transducing is required when the signal provided by inteaction object-sensor needs a second transformation in order to obtain an electrical output signal.

Supply

This type of classification indicates if the transducer needs an auxiliary power source for generating output quantity or they work based on self generating principle.

- Active transducers - are those which do not require any power source for their operation. They work on the energy conversion principle.
- Passive transducers - which require an external power source for their operation is called as a passive transducer. They produce an output signal in the form of some variation in resistance, capacitance or any other electrical parameter, which than has to be converted to an equivalent current or voltage signal.

Signal

This type of classification indicates the type of output quantity. They are classified in:

- Analog – the input quantity is converted into an analog output which is a function of time
- Digital – the input quanity is converted into electrical output which is in the form of pulses (1 or 0)

Output

This type of classification indicates what type of output is provided by transducer:

- Direct – converts non-electrical quantity into an electrical quantity
- Invers – converts electrical quantity into non-electrical quantity also called as actuators

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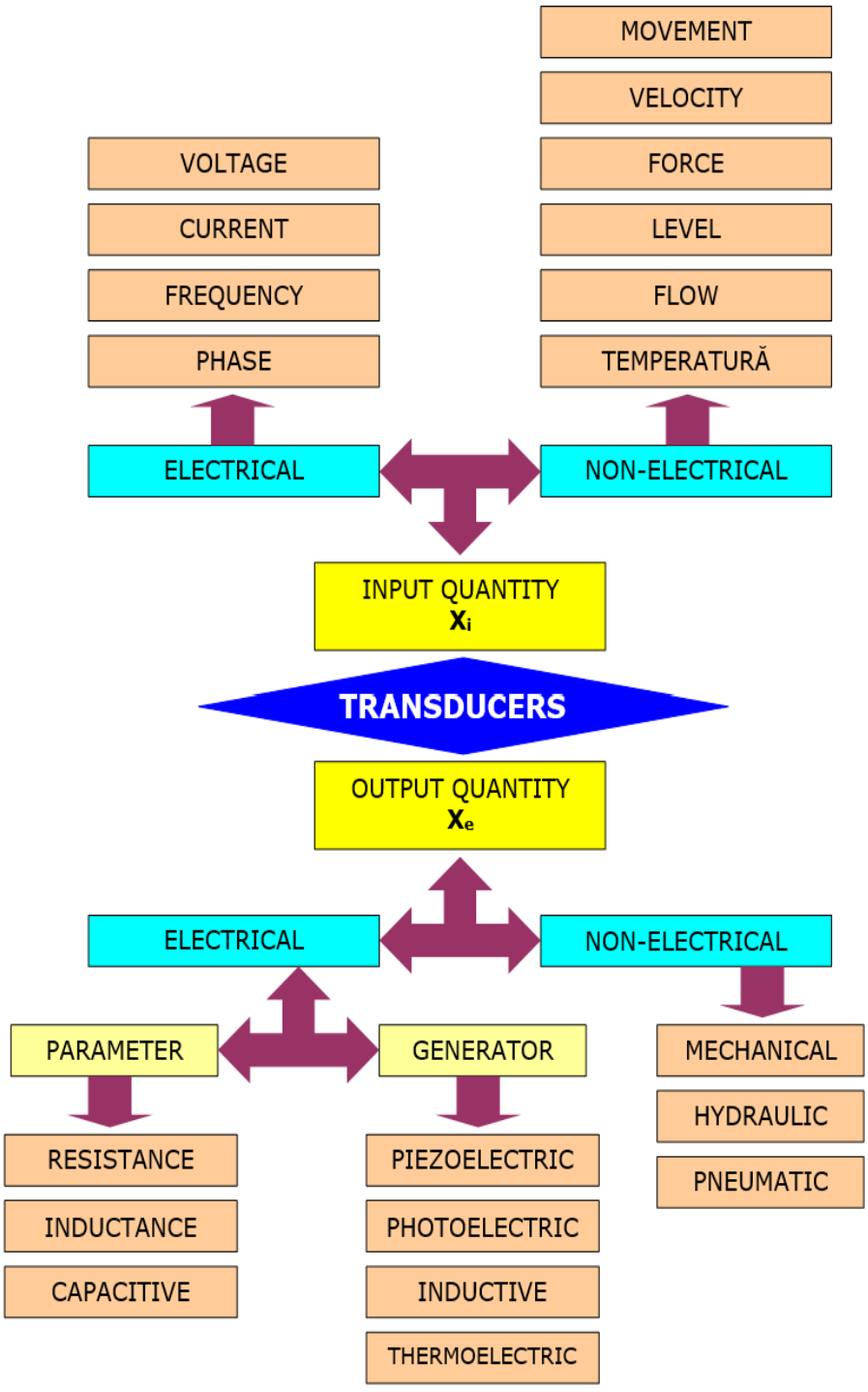


Figure 22: Classification of transducers

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3. DIGITAL MEASUREMENT IN SENSING APPLICATIONS

3.1 Basics structure of a digital measurement system

The basic structure of a digital measurement system (DMS) consists of transducers, instrumentation system and observer. The instrumentation system have the main goal to process the information gained from a measurement system without alterations of the data. The next step consists of transforming the information acquired in electrical signals which describe the evolution in time of the physical phenomena. The instrumentation systems are open and they are destined both to measurements and analysis of the quantities. [5]

DMS with serial/parallel communication

This category of digital measurement systems are one of oldest used in computational measurement. It uses the computer in the measurement process and the information is transmitted from the transducer to the computer using a serial communication protocol using the universal serial bus.

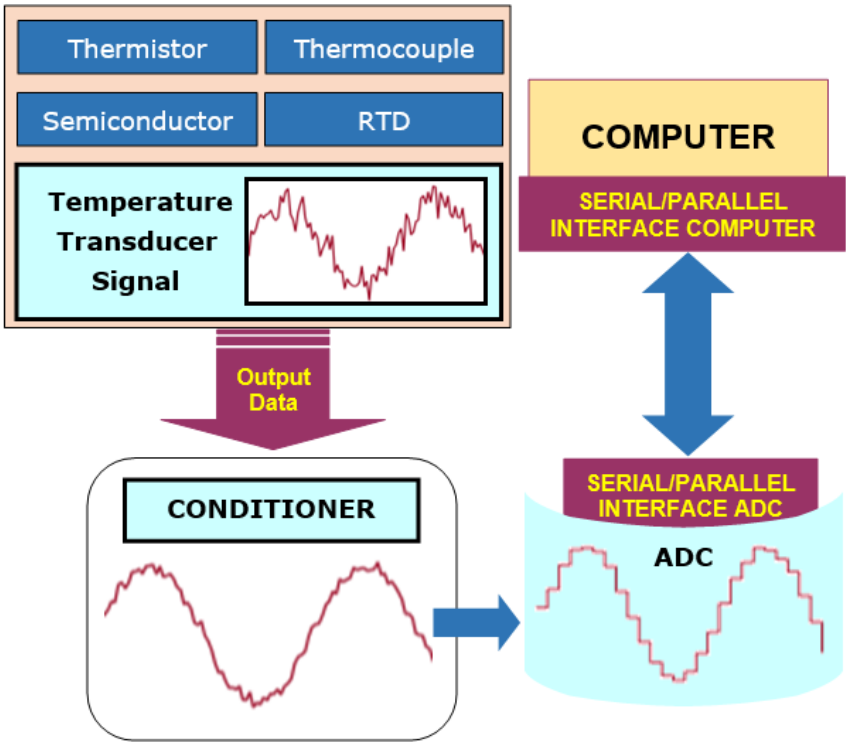


Figure 23: Block diagram of a DMS with serial communication

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This category of DMSs allow bidirectional communication between sensor-transducer block and computer. The computer can be used to transmit commands or to change different parameters such as emissivity in case of IR detectors. The main disadvantage at the begining of serial communication was the low speed of transmission and this can mean a reduced volume of data that is transmitted to and from computer. This category o measurement tools with parallel communication has a structure similar to serial communication but with different communication protocol. The high speed allowed by parallel interface will allow measuraments with high sampling rate.

DMS with data acquisition card

Data acquisition devices require specific electronic parts that are usually embedded into computers. These DMSs are identified by the data acquisition cards that converts directly the analog signals from transducers into digital signal. Therefore, these DMSs are more used în digital measurement application. The data acquisition cards work together with conditioners in order to establish certain intervals for analog signals. A schematic design of DMS with acquisition device is presented below.

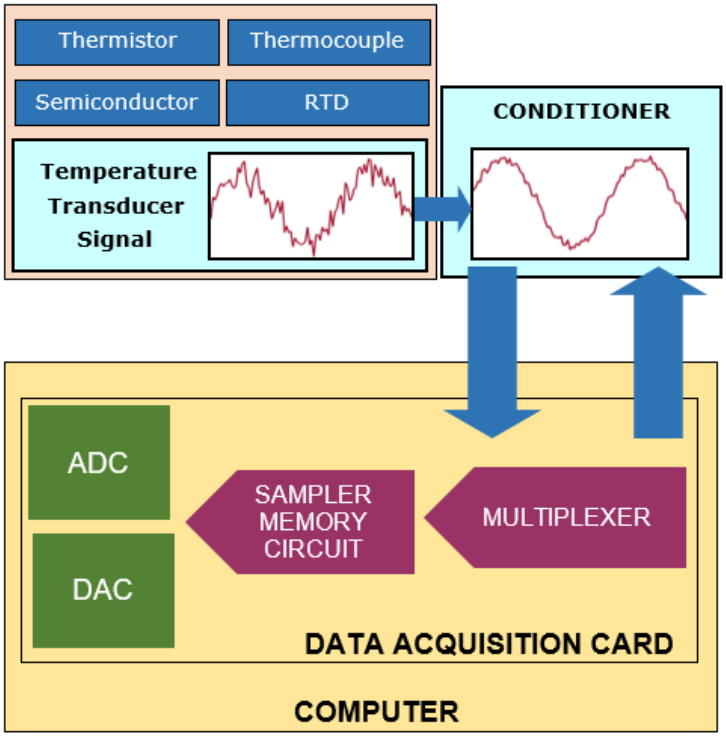


Figure 24: Block diagram of a DMS data acquisition card

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The conditioners represent the liason between signals provided by transducers and signals required by data acquisition cards. The communication between conditioners and data acquisition cards are bidirectional in order to allow to setup configuration of the conditioner. The signals transmitted between conditioner and data acquisition cards are both abalog and digital as follows:

- Analog signals are transmitted from conditioner to data acquisition card and contain the information provided by the transducers (sensor signal). These signals are used by ADC (analog to digital converter). However, some issues can occur if the distance between conditioner and data acquisition card is high or disturbant factors can influence the accuracy of the signal data. Therefore, is recommended to introduce additional devices (modulators or shields) in measurement chains.
- Digital signals are transmitted from computer through data acquisition card towards to conditioner in order to establish the current state. Using digital signals the process of measurement is more fast comparative with parallel communication system.

3.2 Signal conditioning

Most analog signals require some form of preparation before they can be digitized. Signal conditioning is the manipulation of a signal in a way that prepares it for the next stage of processing.

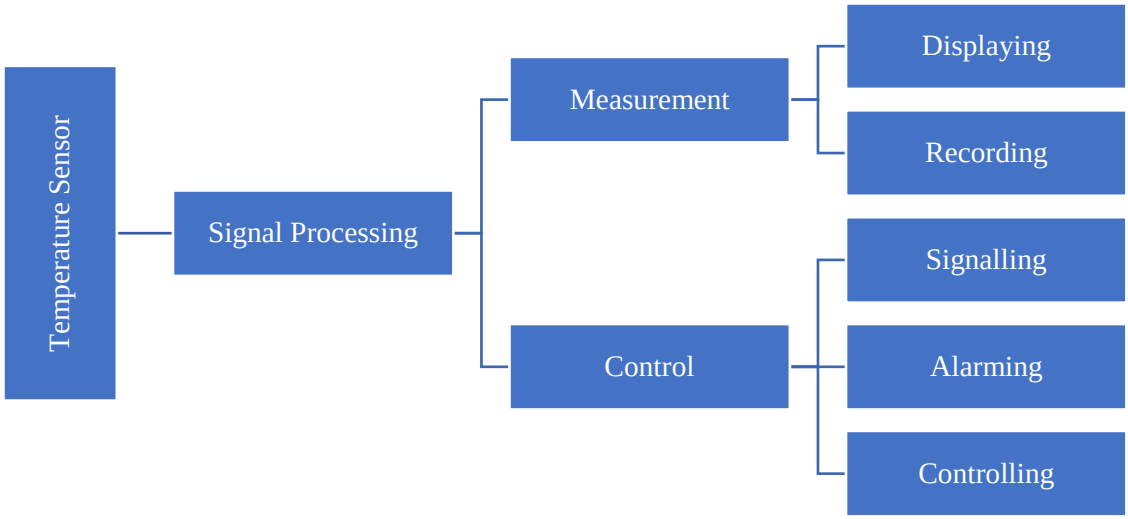


Figure 25: Signal processing from temperature sensor

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Many applications involve environmental or structural measurement, such as temperature and vibration, from sensors. These sensors, in turn, require signal conditioning before a data acquisition device can effectively and accurately measure the signal. For example, thermocouple signals have very small voltage levels that must be amplified before they can be digitized. Other sensors, such as resistance temperature detectors (RTDs), thermistors, strain gages, and accelerometers, require excitation to operate. All of these preparation technologies are forms of signal conditioning.
In case of temperature measurement, the signal is in themal energy domain and therefore it should be converted in electrical signal in order to fit to available modern instrumentation. Moreover, digital measurement cannot be aplied without an electrical signal. The electrical signal can be shaped or conditioned in order to fit to the measurement application. A basic diagram related to signal processing is presented above. Regarding the alteration suffered by the signal through its processing, there are considered three major groups that characterize the type of transformation.

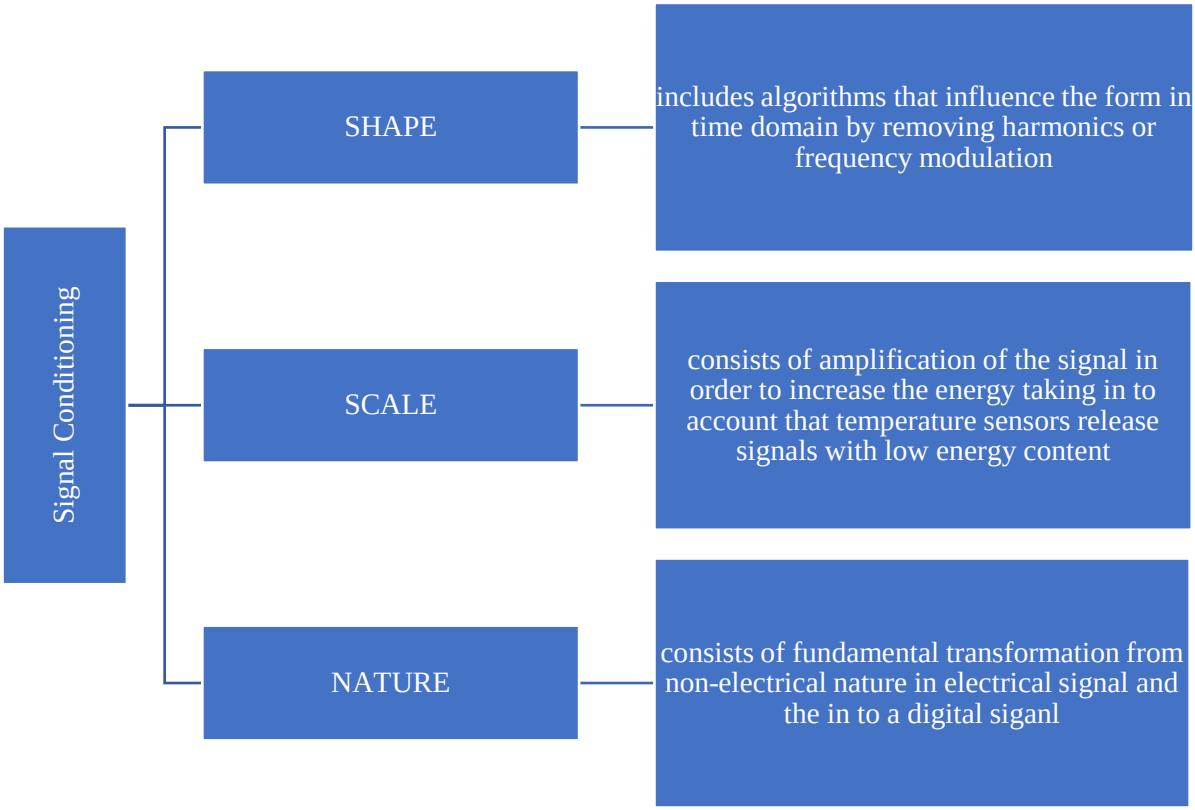


Figure 26: Conditioning of the initial signal

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The temperature sensors presented in this book provide analog electrical signals as follow of Seebeck effect. However, for digital measurement, the analog signal must be conditioned in a digital one that will be understand by microprocessor based systems. In case of temperature sensors that provide non-electrical signals when they interact with heated corps, the conditioner must transform the non-electrical signal in to electrical signal.

The conditioning of the signal shape means, in most of cases, the removing of the noise from initial signal provided by temperature sensors. The noise will affect, in a negative way, the process of measurement by reducing the accuracy of the measurement. This unwanted phenomena occurs mainly in industrial applications where electromagnetic fields can disturb the original signal.

The noise filters are usually realized on basis of low-pass RC filters where the bandwidth is determined by the frequency according to the equation presented below.

$$f_c = \frac{1}{2 \cdot \pi \cdot R \cdot C} \tag{2.20}$$

Passive and active noise filters have been presented in chapters above by providing wiring schemes and parts for electronic design. In this subchapter are presented and explained diagrams related to the input and output signal after the conditioning process. In terms of output signal from sensing element, two abnormalities can be identified:

- Non-linearity of the sensor
- Drift of the output temperature

Figure below shows a block diagram, a sensor, and how implementing a signal conditioner can compensate for temperature drift. The first block of the figure present the object targeted for temperature measurement, characterized by its own physical property noted with X. The second block presents the signal produced by sensing element (thermocouple, RTD, thermistor, etc.) noted with Y. The indication of the output temperature differs for different temperatures. That abnormality is called temperature drift and the process of conditioning is called compensation of the signal output. The graph from the second block shows the difference between real temperature ($T_{correct}$) and temperature values provided by sensing element (T_{sensor}).

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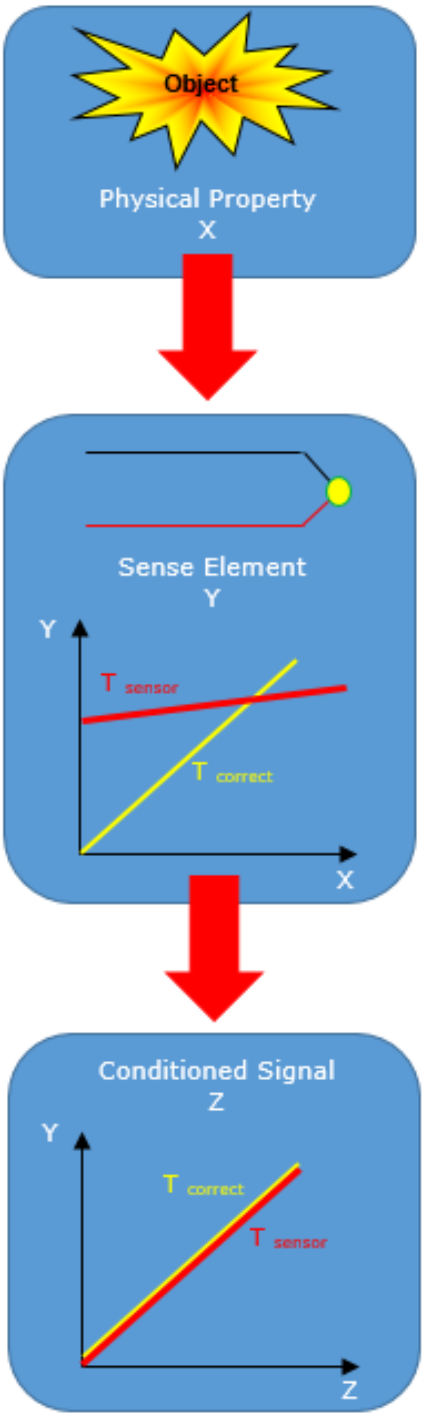


Figure 27: Conditioning of the initial signal for compensating the temperature drift

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To simplify the mathematical model, a linear variation is considered. Therefore, in modelation process the following equation can be used.

$$Y = [a_0 + a_1 \cdot (T_{sensor} - T_{20})] + [b_0 + b_1 \cdot (T_{sensor} - T_{20})] \cdot X \quad (2.21)$$

where:

- a_0 – sense element offset at room temperature, or the sense element output when the physical quantity being measured is at its minimum value and at room temperature.
- a_1 = sense element offset temperature drift coefficient, or the relative change in offset of sense element with a given change in temperature.
- b_0 = sense element span at room temperature, or the difference in the sense element outputs at maximum and minimum physical quantity being measured.
- b_1 = sense element span temperature drift coefficient, or the relative change in span of sense element with a given change in temperature.
- T_{sensor} – temperature provided by sensing element
- T_{20} – room temperature (considered to be 20^0 C)

The sense element ofset and span presents a first order temperature coefficient. Therefore, both wil change linearly with the temperature.

3.3 Signal multiplexing

Signal multiplexing is a process of combining more signals into one signal using a common medium.

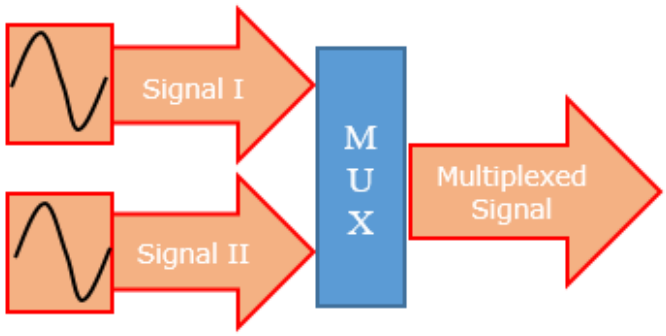


Figure 28: Multiplexing signals from different sources

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There are mainly two types of multiplexers, namely analog and digital. They are further divided into Frequency Division Multiplexing (FDM), Wavelength Division Multiplexing (WDM), and Time Division Multiplexing (TDM). The following figure gives a detailed idea about this classification [6].

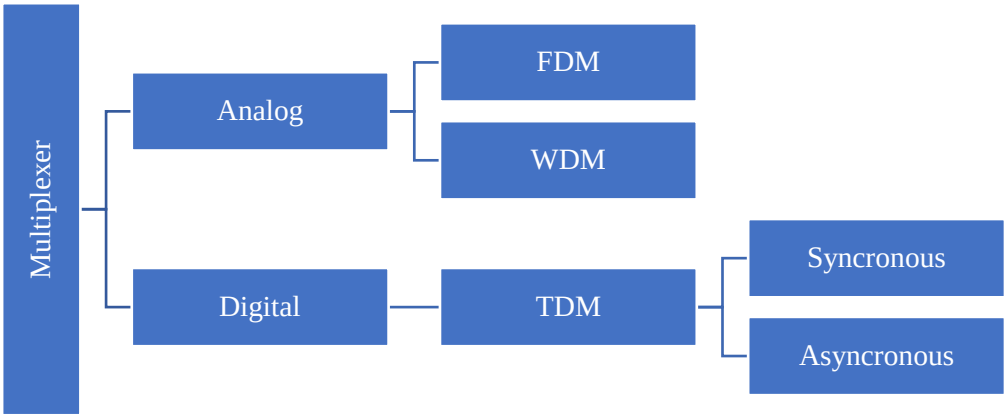


Figure 29: Type of multiplexers

Analog Multiplexing – Frequency Division Multiplexing (FDM)

In analog multiplexing, the most used technique is Frequency Division Multiplexing (FDM). This technique uses various frequencies to combine streams of data, for sending them on a communication medium, as a single signal. In FDM, the signals are electrical signals. One of the most common applications for FDM is traditional radio and television broadcasting from terrestrial, mobile or satellite stations, or cable television. Only one cable reaches a customer's residential area, but the service provider can send multiple television channels or signals simultaneously over that cable to all subscribers without interference. Receivers must tune to the appropriate frequency (channel) to access the desired signal [7].

Analog Multiplexing – Wavelength Division Multiplexing (WDM)

In fiber optic communications, the wavelength division multiplexing (WDM) is a technology which multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths (i.e., colors) of laser light. This technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity. The term WDM is commonly applied to an optical carrier, which is typically described by its wavelength, whereas frequency-division multiplexing typically applies

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to a radio carrier which is more often described by frequency. This is purely conventional because wavelength and frequency communicate the same information. Specifically, frequency (in Hertz, which is cycles per second) multiplied by wavelength (the physical length of one cycle) equals the velocity of the carrier wave. In vacuum, this is the velocity of light, usually denoted by the lower case letter, c. In glass fiber, it is substantially slower, usually about 0.7 times c. The data rate, which ideally might be at the carrier frequency, in practical systems is always a fraction of the carrier frequency [8, 9]. A simple circuit for multiplexing signals provided by thermocouples sensors is presented in figure below.

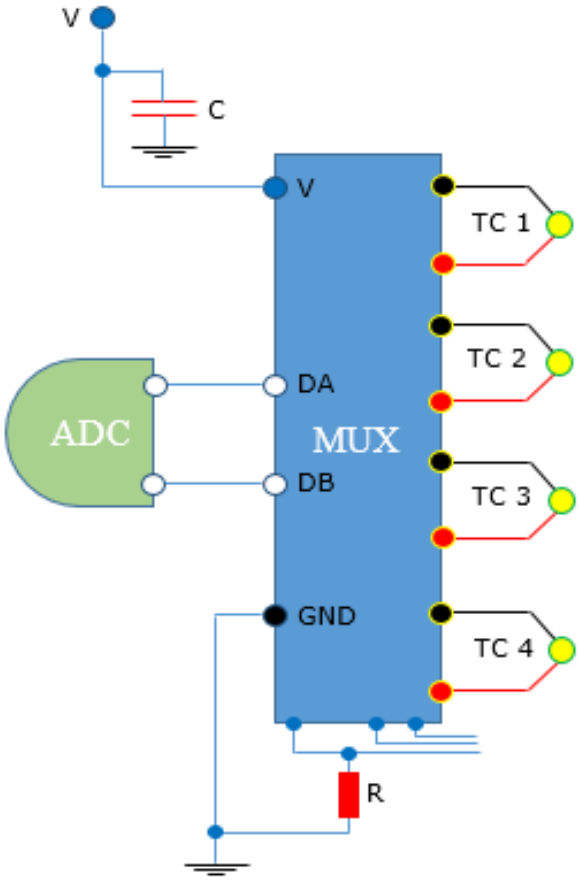


Figure 30: Example of analog multiplexer circuit

Digital Multiplexing – Time Division Multiplexing (TDM)

Time-division multiplexing (TDM) is a digital (or in rare cases, analog) technology which uses time, instead of space or frequency, to separate the different data streams.

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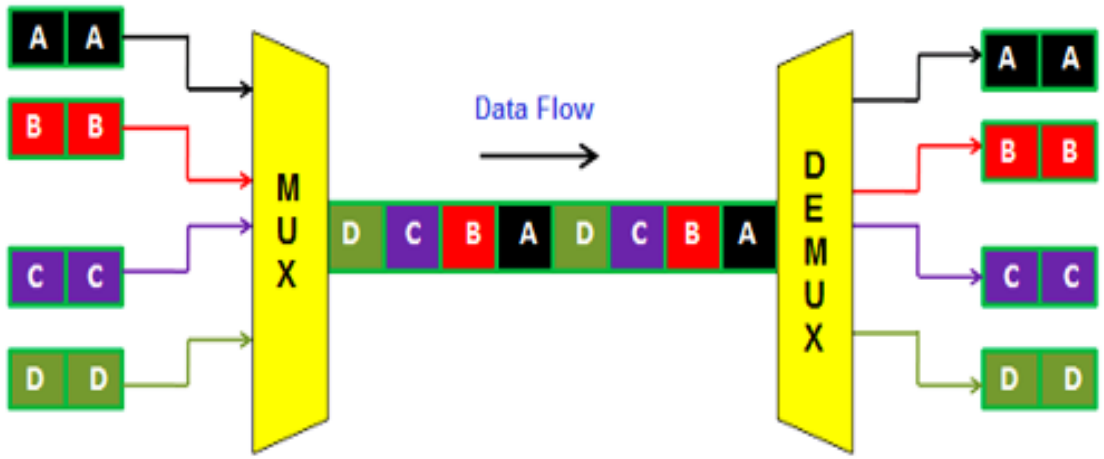


Figure 31: Example of analog multiplexer circuit

TDM involves sequencing groups of a few bits or bytes from each individual input stream, one after the other, and in such a way that they can be associated with the appropriate receiver. If done sufficiently quickly, the receiving devices will not detect that some of the circuit time was used to serve another logical communication path [10, 11].

3.4 Memory circuits

Memory circuits function by storing the voltage present on an input signal whenever they are triggered by a control signal, and they retain that stored voltage until the next assertion of the control (or trigger) signal. Between assertions of the control signal, the input signal is ignored and the output is driven to the most recently stored voltage. Since a memory circuit stores the input signal level at each assertion of the control input, the output will change immediately after the control signal is asserted (if the input value is opposite to what is stored), or it will remain constant. Two major families of memory circuits are in use today—dynamic memory and static memory. Dynamic memory cells use a minute capacitor to store a signal voltage, and they are used in the smallest and cheapest memory circuits. Since capacitor voltage decays over time, dynamic memory cells must be periodically refreshed or they will lose their stored value. Although this refresh requirement adds significant overhead, dynamic memory cells are very small, so they have become the most widely used of all memory circuits. Most static memory circuits

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store a logic values using two back-to-back inverters. Static memory devices do not need to be refreshed, and they can operate much faster than dynamic circuits. But since they require far greater chip area than dynamic memory cells, they are used only where they are most needed—in high speed memories, for example—or when only small amounts of memory are required.

A D-flip-flop (DFF) is one of the most fundamental memory devices. A DFF typically has three inputs: a data input that defines the next state; a timing control input that tells the flip-flop exactly when to “memorize” the data input; and a reset input that can cause the memory to be reset to '0' regardless of the other two inputs. The “D” in DFF arises from the name of the data input; thus, the flip-flop may also be called a data flip-flop. The timing control input, called “clock”, is used to coordinate when new data can be written into the memory element, and conversely, when data cannot be written. A clock signal is most typically a square wave that regularly repeats at some frequency. A DFF records (or registers) new data whenever an active clock edge occurs—the active edge can be either the rising edge or the falling edge. A rising-edge triggered (RET) DFF symbol uses a triangle to show that the flip-flop is edge-triggered; a falling-edge triggered (FET) DFF symbol uses the same triangle, but with a bubble on the outside of the bounding box (just like any other asserted-low input). The timing diagram below illustrates RET DFF behavior. Note that the Q output changes only on the active edge of the clock, and the reset signal forces the output to '0' regardless of the other inputs [12].

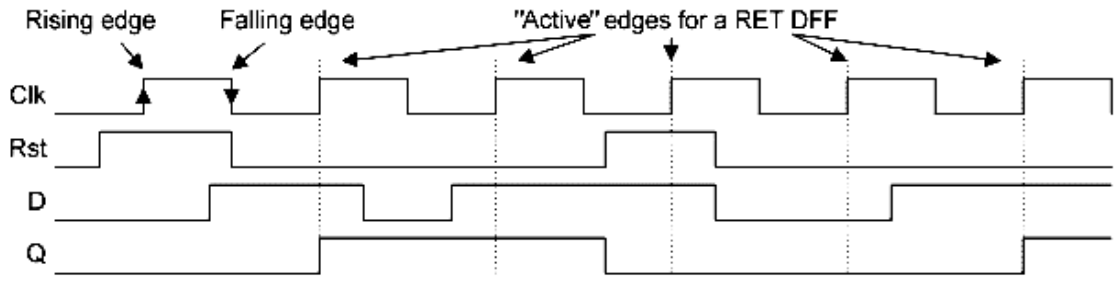


Figure 32: Timing diagram and DFF behavior

Registers represent one of the most important components of memory circuits. A register is a group of one or more D flip-flops that share a common clock signal, with each flip-flop having an individual input and output.

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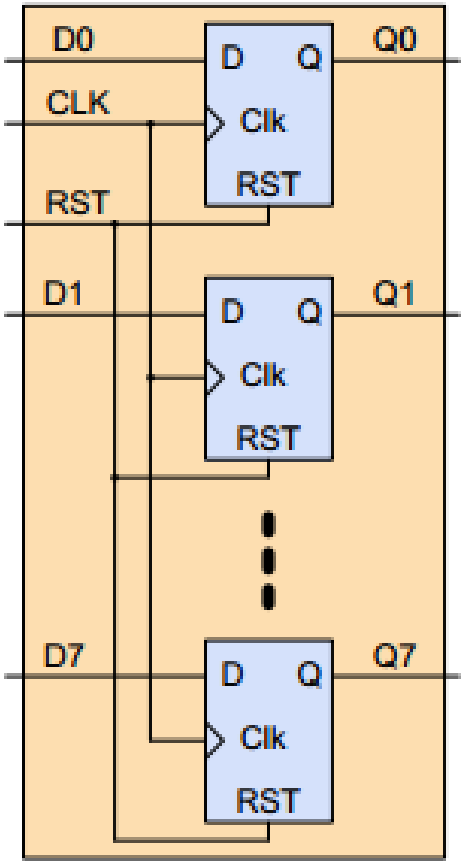


Figure 33: Example of register cicuit

Many other circuit topologies that exhibit memory are used in modern digital circuits. For example, the dynamic memory circuits used in computer memory arrays use a small capacitor to store digital signal levels. Fast SRAM structures (like those used in a computer's cache memory structure) use cross-coupled inverters to form a bistable cell. Cross-coupled inverters present a much smaller RAM cell, but they can only be programmed by “overdriving” the output of the feedback resistor using powerful write buffers. Non-volatile memory devices (such as the FLASH BIOS ROM in PCs) use floating gates to permanently store memory bits. Together, these “other” memory circuits make up the vast majority of memory devices in use today. The basic cell and flip-flop circuits shown here are conceptually simple, but they are not that common in modern digital design. These other memory circuits will be covered in more detail in later exercises.

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4. DIGITAL MEASUREMENT SYSTEMS FOR MONITORING APPLICATIONS

4.1 Sensing and controlling temperature in resistance heating

Sensing temperature in resistance heating is very important for controlling the processes. This paragraph deals with resistance heating in conventional ovens. Most of the newest ovens contains heating regulator taking into account that, for instance, during sintering processes, the temperature must follow a specific heating/cooling ramp. A common solution provided by Nabertherm is presented below.



Figure 34: Nabertherm conventional furnace up to 1500^0 C [13]

However, in this subchapter are presented two different aplications for sensing and controlling the heating process, in conventional oven without any available automation, using contact and non-contact sensors. These sensing applications can be used in laboratory conditions, but with minim adjustements can be applied in industrial processes. The applications are developed for heating processes in order to obtain composite nanostructured magnetic materials. The furnace used in sintering application was an old one without any automation for temperature monitoring. The sensing element were a S and B type thermocouples connected to a basic indicator device without any possibilities to record, analyse and save the data. The furnace is presented in the figure below.

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Main characteristics

Power Supply	400 V
Amps	60 A
	180 A
Voltage	12 V
	35 V
Control atmosphere	No
Sensing Element	Thermocouple type S, B
Maximum temperature	1500 ^{0}c
Ramp control	No

Figure 35: KU II conventional furnace up to 1500^{0} C

The thermocouple attached to the furnace was type B. The Type B thermocouple are suited for use at upto 1800 ^{0}C. These are used in extremely high temperature applications. Specialty of B Type thermocouple is that it has the highest temperature limit in all the other type of thermocouple. These thermocouple produce the same output at 0 ^{0}C and 42 ^{0}C, limiting their use below about 50°C. The emf function has a minimum around 21^{0}C, meaning that cold-junction compensation is easily performed, since the compensation voltage is essentially a constant for a reference at typical room temperatures.

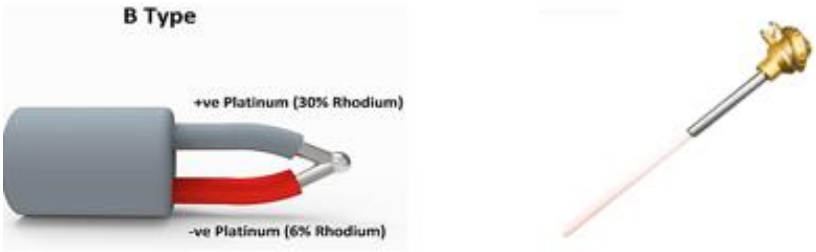


Figure 36: B-type thermocouple used in experimental programme [14]

Type B Thermocouple is composed of a positive leg which is 70% Platinum, 30% Rhodium and a negative leg which is 94% platinum, 6% Rhodium. However, the sensing system cannot provide useful information in digital format for further analysis.
The application proposed refers to resistance heating for synthesis and sintering the raw composite materials in order to obtain ceramic permanent magnets. For temperature monitoring (measurement, graphs and recording data) has been used a multichannel process regulator provided by Jumo [15]. JUMO IMAGO 500 is a process and program

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controller with up to eight controller channels or four program channels. The instrument is built to the format 144 mm × 130 mm for a standard 92 mm × 92 mm panel cut-out and a mounting depth of 170 mm. It has the following main characteristics:

- A maximum of eight analog inputs and 6 logic inputs are available
- A maximum six expansion slots for switched or analog outputs are available
- A setup program is available for comfortable configuration from a PC. Linearizations for the usual transmitter outputs are stored within the instrument, four customer-specific linearization tables can be programmed.
- A math and logic module can be used to adapt the instrument to a very wide range of control tasks.
- A serial interface RS422/485 or PROFIBUS-DP can be used to integrate the instrument into a data network.

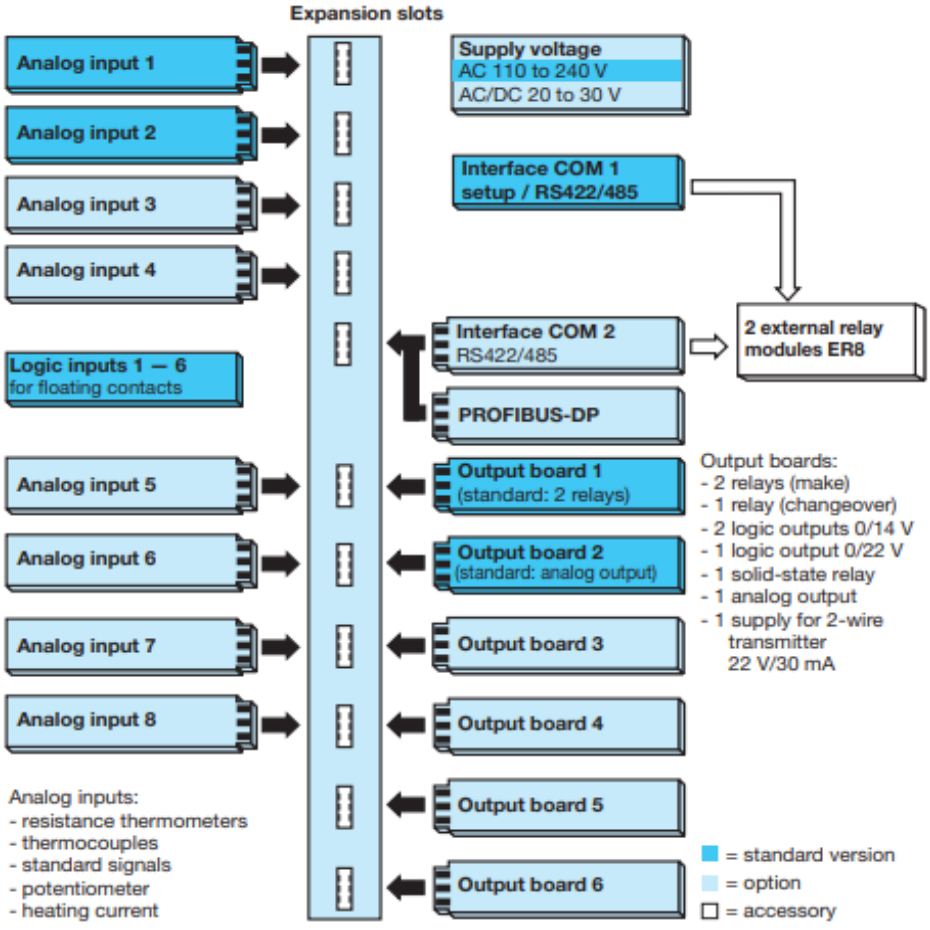


Figure 37: Expansion slots configuration on JUMO IMAGO 500 board [15]

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The connection diagram for the heating application, in terms of electrical isolation, provides various technical solution for sensing and controlling the heating process for KU II furnace. Since the instrument is short-circuit proof only to a limited extent, an external fusing and a switch-off facility must be provided. Depending on the supply voltage, the following values apply to the external fusing:

- AC/DC 20 to 53 V, 48 to 63 Hz – fuse 4 A slow
- AC 110 to 240 V +10/-15 %, 48 to 63 Hz – fuse 0,8 A slow

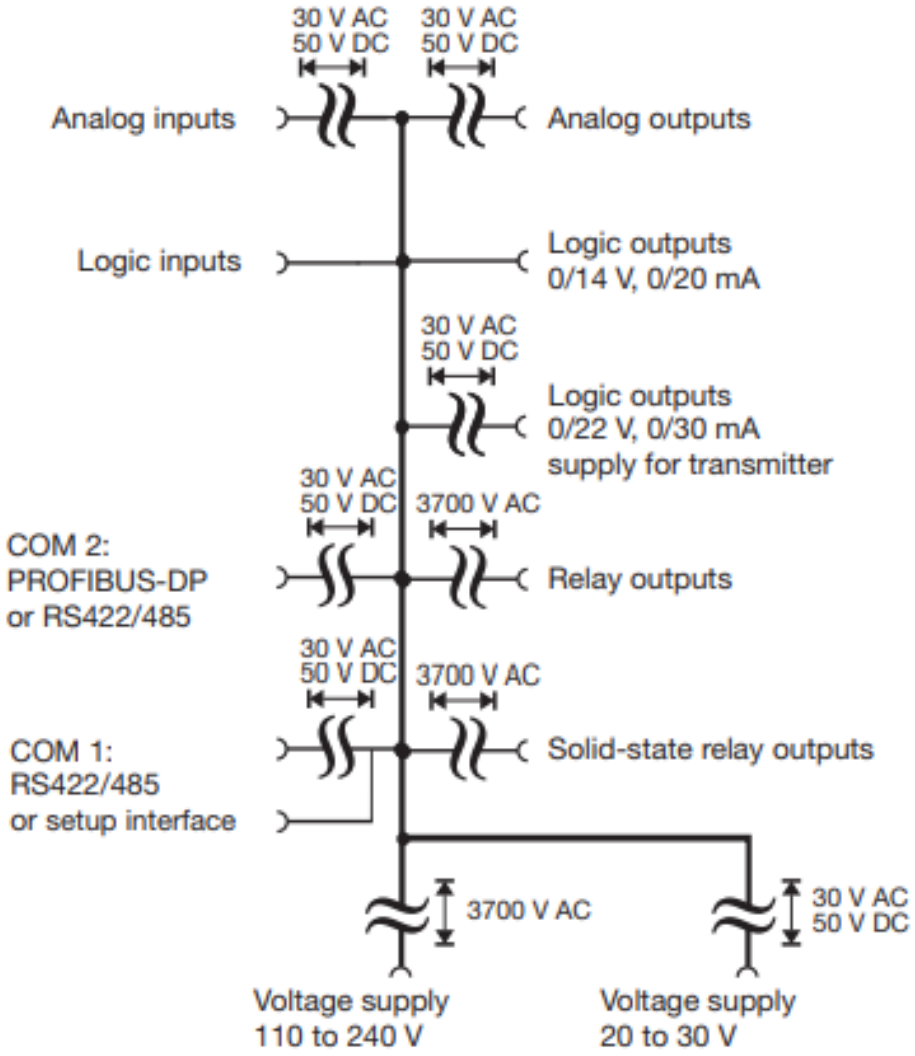


Figure 38: Electrical isolation diagram on JUMO IMAGO 500 board [15]

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Taking into account that the KU II furnace does not have automation, only manual switchers, the solution adopted for this application was to connect the output relays from IMAGO 500 to the voltage coil of the switchers. The base configuration of IMAGO 500 (according to figure above) presents two solid-state relays output that can be used for external commands. The electrical diagram developed for the resistance heating application using a KU II furnace is presented in figure below.

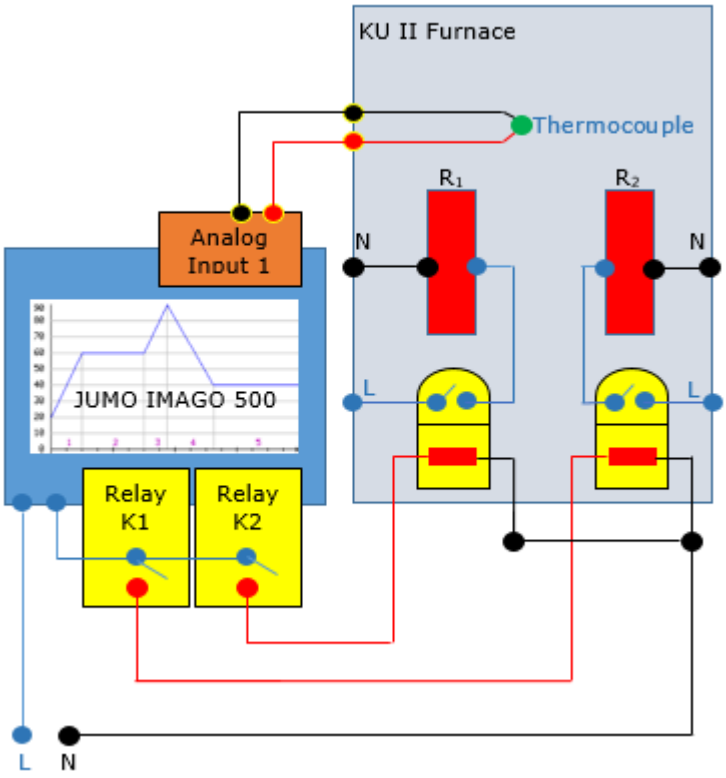


Figure 39: Electrical diagram for heating process using KU II + JUMO IMAGO 500

The process regulator has two functions: to record and display the temperature reached in furnace and to control the heating speed, cooling speed and to maintain the temperature at a certain level. However, due to the fact that the furnace does not have a programmable power supply, it is impossible to control the heating using only the process regulator. In this case the relays from IMAGO 500 will only work with to levels of the amps: 60 A and 180 A. The working cycle of that automation for temperature monitoring is explained below:

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- After the heating process have been started, the regulator will close relay K1 which will introduce the resistance R2 into electrical circuit.
- The circuit breakers from the furnace are designed to work separately, so when the K1 is closed only R2 is active and the position of the contact from the second breaker is open.
- In addition, the IMAGO 500 regulator has the K1 and K2 set to have different positions (when K1 is closed, K2 is open and when K2 is closed, K1 is open). Through these settings is avoided a misunderstanding between the normal positions of the relayes contacts (K1 and K2) and circuit breakers contacts.
- The temperature is monitorized using the B type thermocouple connected to the analog inputs terminals of the regulator
- The regulator can display the current temperature, setpoint temperature, heating ramp and the position of the contacts of the relays. In addition, the regulator can provide graphic charts with temperature evolution in time that can be saved as picture or exported as Excel file [16 -----43].

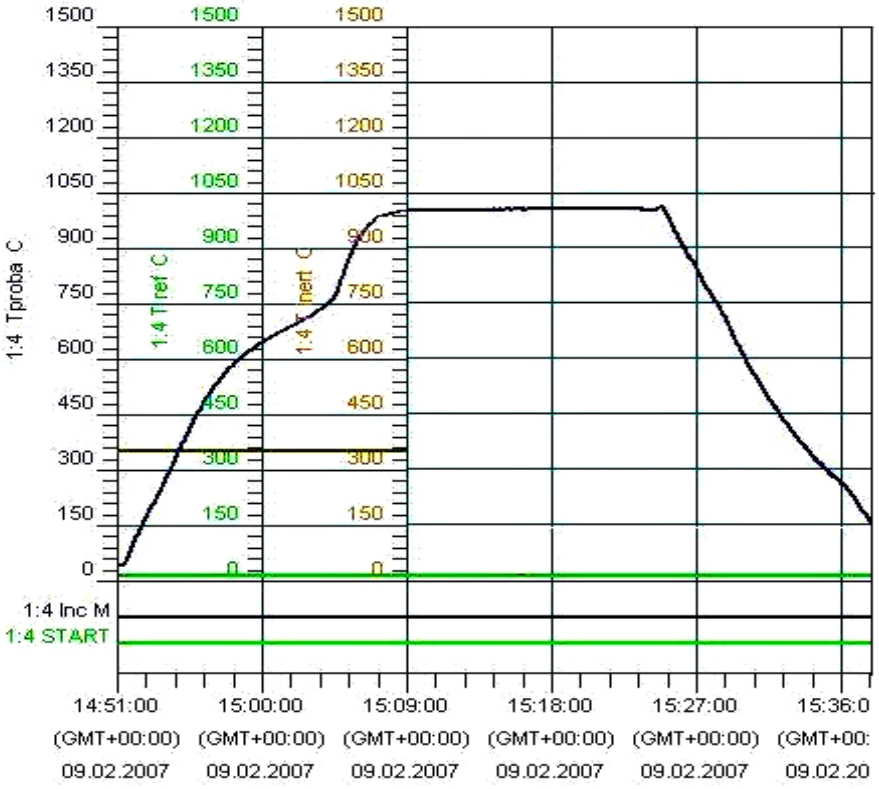


Figure 40: Monitoring the temperature using JUMO IMAGO 500 regulator [16]

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Also, the temperature can be monitorized using non-contact sensors like infrared pyrometers. This can be done in special application when the heating speed is high and the thermocouple measures only the temperature inside the furnace. Several specific heating applications require the monitoring of the temperature on the surface of the products (samples). If the heating speed is high, the thermocouple will sense only the temperature inside the furnace and therefore sometimes exist situations when the temperature on the sample surface differs by the temperature in furnace. For these applications is recommended to monitor the temperature using high precisions non-contact sensors. Obviously, after a certain time, both temperature will be the same due to the thermal equilibrium established in furnace.
The application proposed in figure below presents how the temperature can be measured on the metallic surface of a box with samples in argon atmosphere.

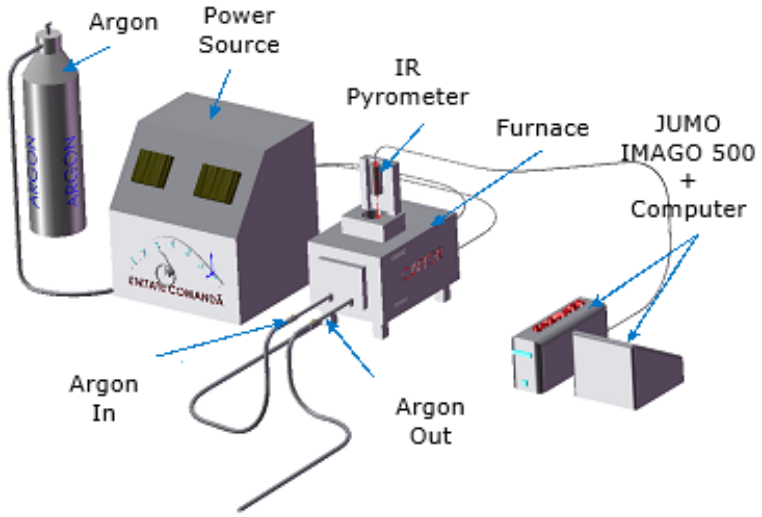


Figure 41: Application for temperature measurement using IR pyrometer [17]

4.2 Sensing temperature in microwave heating

Microwave heating represents one of the newest technologies in terms of pre-sintering, sintering, waste treatment and industrial applications like welding. However, from temperature measurement point of view the only way to sense this parameter is to use infrared pyrometers or thermal cameras. In this subchapter are presented several applications for sensing temperature using IR pyrometers.

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The main issue when the IR technology is applied for sensing the temperature is represented by the emissivity of the materials. This parameter is well known for most common materials and the scientific literature presents tables with emissivities for each material, but in case of composites materials the emissivity must be determined using experimental procedure.

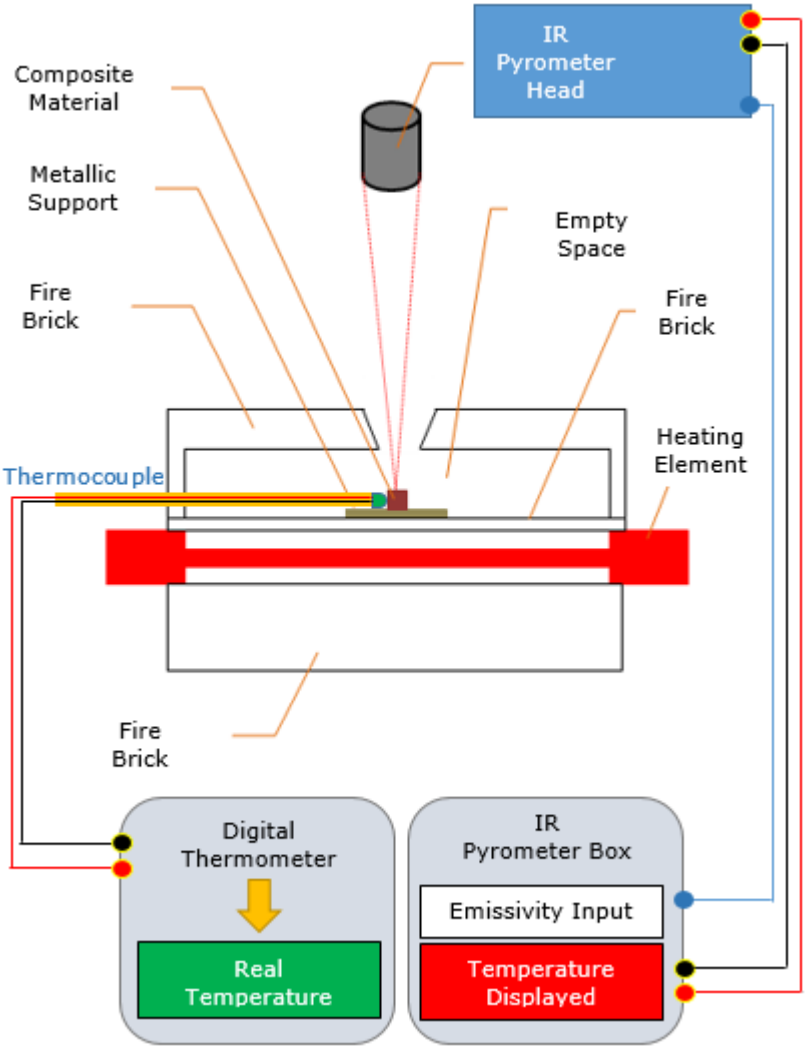


Figure 42: Determination of IR emissivity for composite material

The realization of the heating and monitoring system actually involves the creation of a miniature heat treatment furnace in which the temperature sensing system by

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thermoelectric effect must be in contact with the composite material to detect its temperature and not the temperature inside the furnace as it happens at the moment. This technological solution will allow the prescribed temperature to be reached on the surface of the part in a very short time without the need to establish the thermodynamic balance in the oven. The device is made of two overlapping refractory bricks that simulate a heat treatment hearth. Inside the lower refractory brick, a channel is made in which the forced resistance is positioned. The channel follows the profile of the resistance so that it rests on the surface of the brick with the two ends with larger sections. This solution was adopted in order to make electrical connections to the power source, these ends being used only as a connection area not being subjected to the electrocaloric effect. The middle section of the thinner section of the resistance in the forced is not in contact with the lower refractory brick to avoid overheating of the resistance and obviously its thermal destruction. It should be noted that the extremities subjected to electrical contact are located below the level of the normal surface of the lower refractory brick. This solution was adopted to have a support area for the metal support of the composite material. The K-type thermocouple is placed in contact with the composite material.

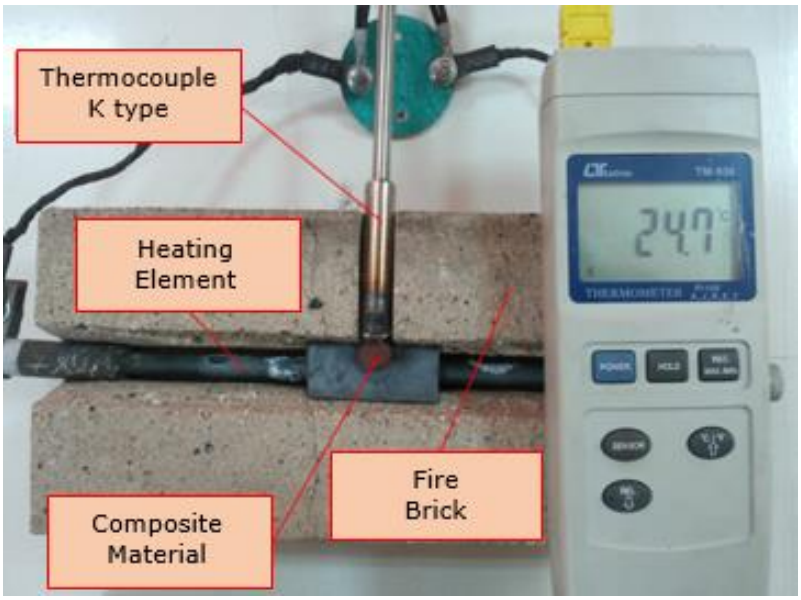


Figure 43: Experimental device used in emissivity determination

The second (upper) brick is placed on the lower refractory brick. In order to avoid the overheating of the resistance, a cut was made in the upper refractory brick so that the

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radiant space created simulates the hearth of a heat treatment furnace. In the central area of the upper refractory brick, a perforation was made in the form of a cone trunk for the access of the infrared pyrometer marking laser. A perforation in the form of a cone trunk was chosen because the laser marking beam and the focal principle of the pyrometer have a conical geometric shape. A cylindrical perforation would have led to the risk that the marking laser would touch the inner walls of the upper refractory brick and thus to an erroneous temperature measurement.

The manual determination of the emissivity is performed by directly introducing the emissivity until the temperature indicated by the pyrometer with infrared radiation is the same as the measured temperature of thermocouple type K. However, this method is difficult given that of titanium oxide, at some point there will be an oxidation phenomenon that will change accordingly the degree of emissivity of the material. For the present application it is proposed to use an Optris G5H CF4 pyrometer with conical spot and marking laser having the sample diameter / focal length ratio according to the following figure.

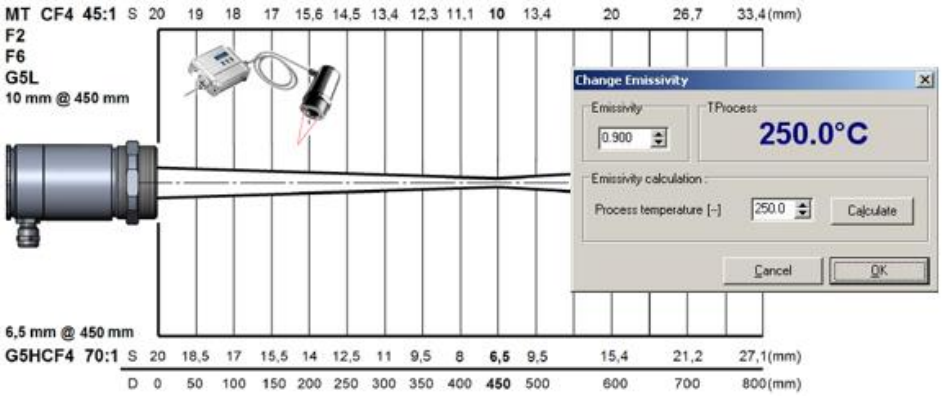


Figure 44: Technical specs for G5H CF4 IR pyrometer

The procedure for determining the emissivity consists first of all in establishing the temperature level or the temperature range. In this application, a composite material based on TiO_2 is subject of experimental procedure and the IR pyrometer must record a temperature between 300 ^{0}C and 450 ^{0}C.

In order to avoid changes in emissivity, the determination will be performed for a wider range, namely 50 ^{0}C – 750 ^{0}C. The steps of determination are:

- the resistive element is supplied with an initial voltage of 10 V a.c. by means of an autotransformer with a power of 15 kW.

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- the temperature value for each voltage level is monitored until the resistive element and the TiO_2 sample reach thermal equilibrium
- the emissivity is calculated using the pyrometer software application for the temperature indicated by the thermocouple K type.
- Resume the process for another temperature level until the complete coverage of the range 500 C - 750^0 C

The values recorded during the emissivity determination procedure were recorded at 1 minute intervals for 20 minutes. It is noted that a default emissivity of 0.9 was chosen for the material used.

Time [min]	$T_{thermocouple}$ [^{0}C]	$T_{pyrometer}$ [^{0}C]
1	87	55
2	215	105
3	289	167
4	344	244
5	400	335
6	489	426
7	534	501
8	604	570
9	623	599
10	635	609
11	644	611
12	659	621
13	669	628
14	689	637
15	694	645
16	713	689
17	728	701
18	744	718
19	753	721
20	753	721

Figure 45: Temperature recorded during experimental program

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Representing graphically the recorded values, it is found that although titanium oxide is a ceramic material, the chosen emissivity is not appropriate, even if the temperature evolution is similar to that recorded by the thermocouple K type.

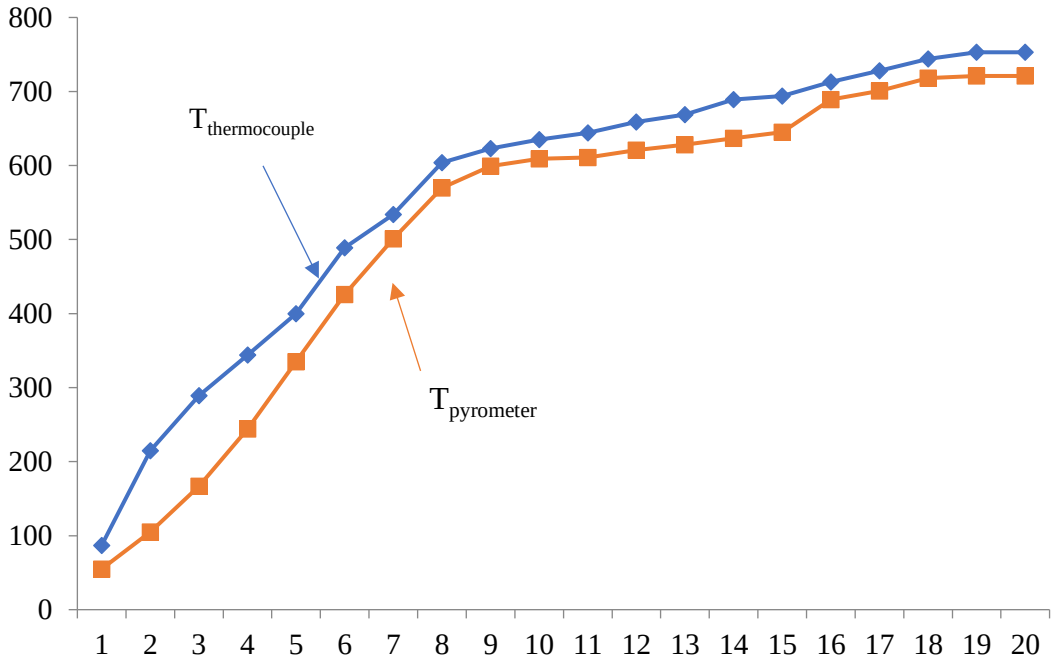


Figure 46: Temperature measured by pyrometer and thermocouple

4.3 Digital monitoring of temperature in silos

A modern system for real-time monitoring and saving of temperature in silos is presented in the following lines. The data is collected and transmitted using a standard WiFi connection, it is not necessary to install cables to transmit data to the central monitoring point. The elimination of data transmission cables practically reduces to zero the possibility of destruction of the system by accidental overvoltages, the most common cause of failure of similar systems. The WiFi system works completely independently (it does not depend on a router or a possible pre-existing WiFi network). The main facilities offered by this system are:

- automatic collection of data from temperature sensors
- intuitive and easy to use graphical interface
- automatic data backup and protection system

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The system consists of 4 main modules:

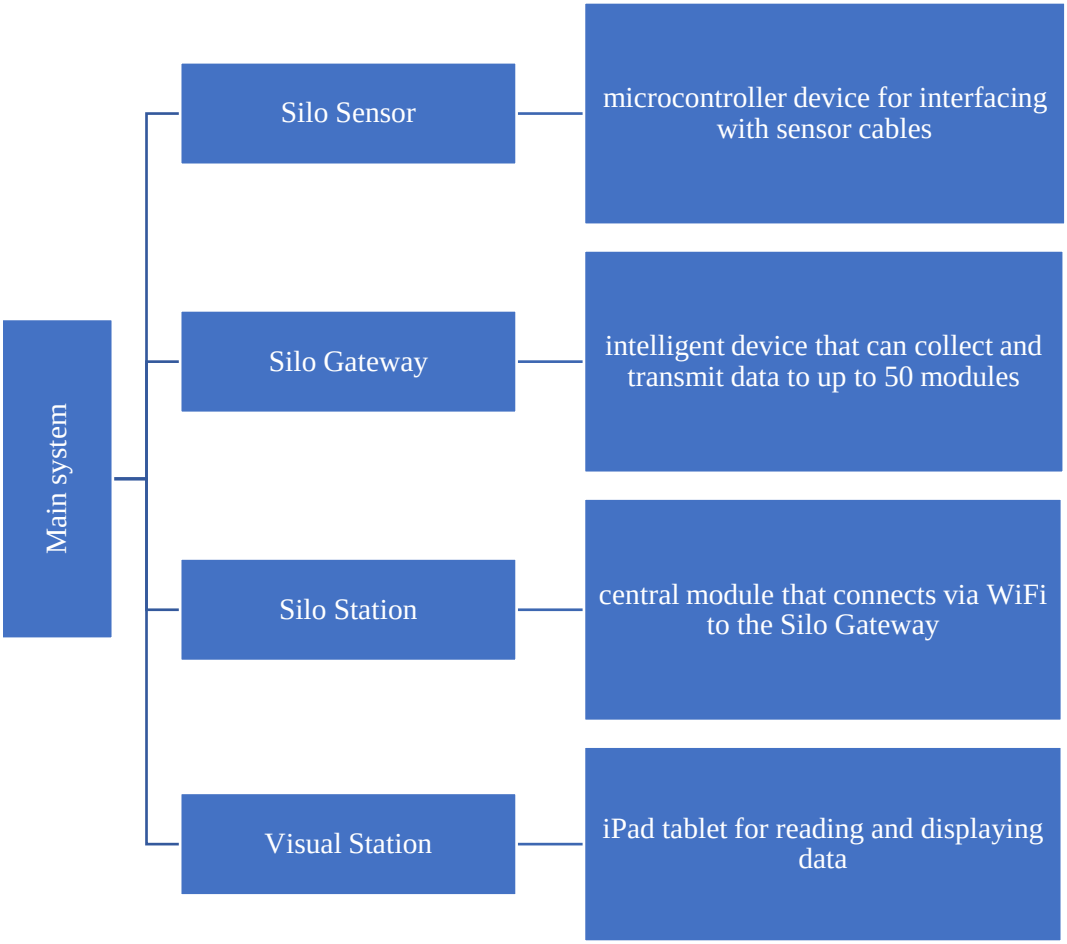


Figure 47: Digital monitoring system (MTS-326)

Silo Sensor

This module has a simple and robust construction, allowing connection with virtually any type of measurement line. In standard versions, the module is programmed for common cables with NTC thermistors. The maximum number of sensors monitored on a line is 8.

Silo Gateway

The connection with the sensor modules is made using the CAN-BUS protocol for which, in most cases, there is a pre-existing wiring. The data collected by the sensor modules is processed and formatted in the JSON data transmission standard, for later use in compatible devices. This module creates a WiFi access point to which various other data

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reading modules can be connected. The data is transmitted securely, and access to this module can be done exclusively with the user and password.

Silo Station

The function of this device is to connect to the Silo Gateway module, access, process and save data at the sensor level. The device receives the data in JSON format and saves them in an internal memory, SD card, where historical data can be stored for a period of up to 7 years. The device can also provide data via secure WiFi connection to other processing / display devices. The module has an internal battery that offers an operating autonomy of up to 36 hours, in case of an interruption in the power supply system. Silo Station also has a real time clock (RTC) that can be synchronized with an ntp server to synchronize time with atomic precision.

Visual Station

To display in graphic format, an iPad tablet is used with a software specially made for reading data from Silo Station. Unlike the usual systems in which PCs are used, this option offers a high degree of safety in operation, simplicity, mobility and the reduction to almost zero of the usual cases of non-functioning due to the human factor.

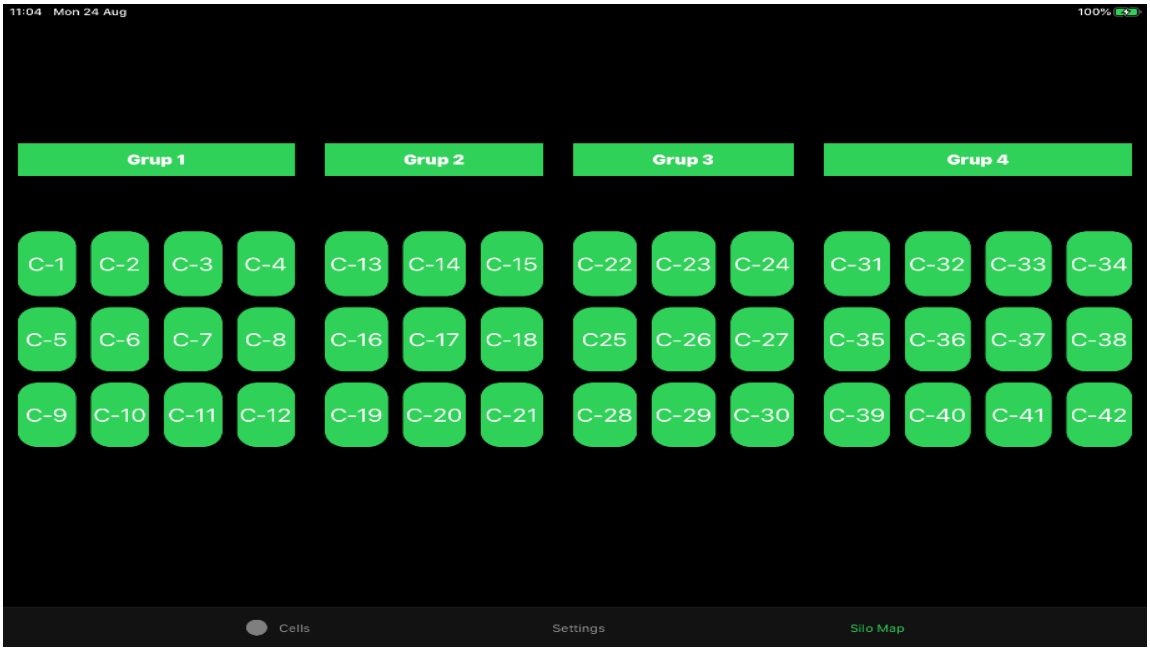


Figure 48: Main user interface

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The software works exclusively, allowing access to the tablet settings only by authorized personnel who know the login data. Another advantage is the mobility and the possibility of long operation without an external energy source (up to a week without recharging). This device also backs up all data available in the Silo Station.

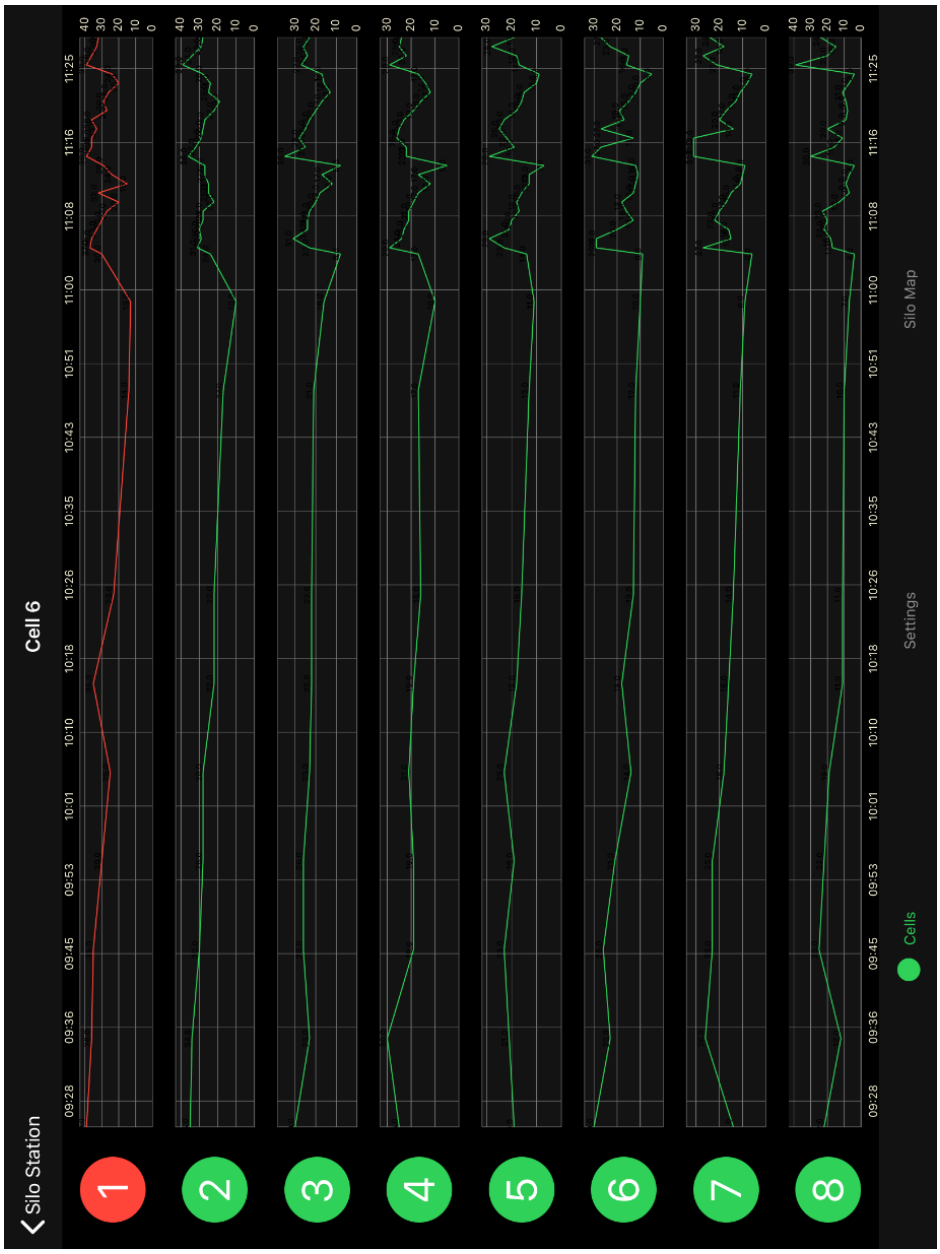


Figure 49: Overall real-time monitoring of temperature sensors

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Software facilities:

- Intuitive graphical interface that allows fast data interpretation
- data available in real time
- real-time 3D visualization allowing exact identification of the place where there are problems
- complete historical data for understanding the evolution of the phenomenon
- data transmission and reception in standard JSON format allows the interconnection of other devices that can work with data in this format

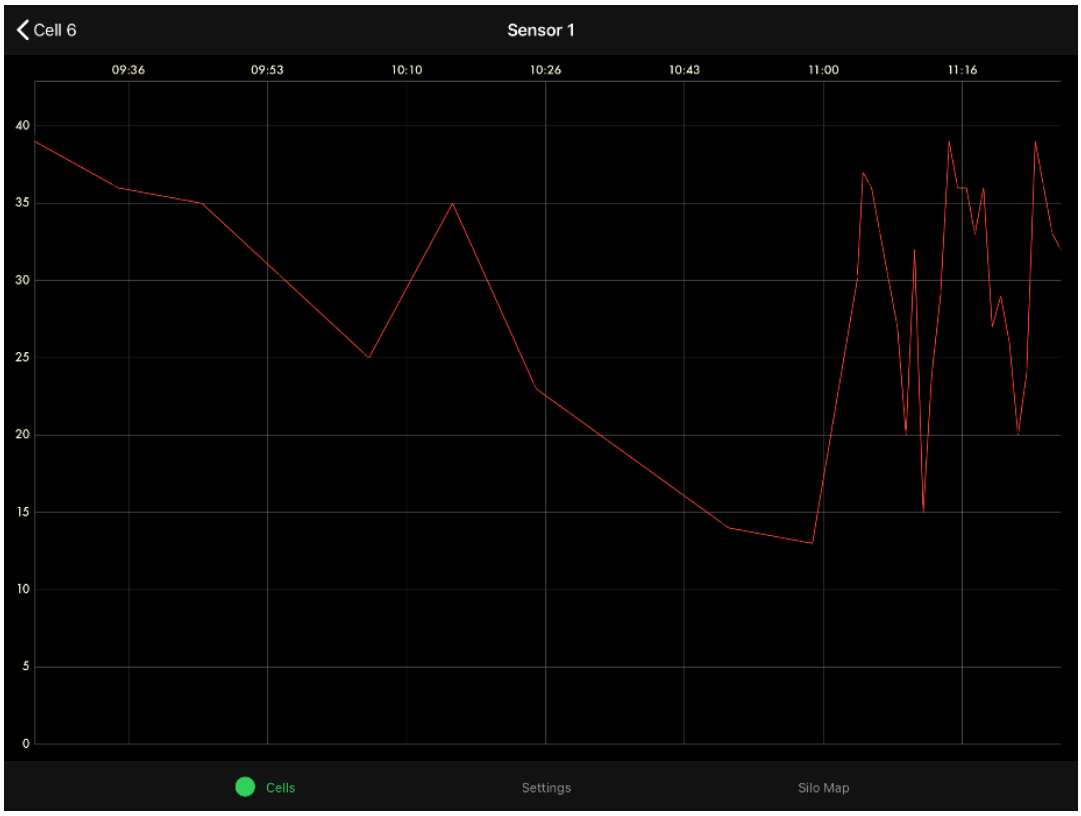


Figure 50: Detailed temperature evolution for specific analysis

The digital monitoring system of the temperature has a special diagnostic and testing system for authorized personnel, which can test the functionality of the system using an Android or iOS smartphone. This system allows the rapid diagnosis of possible problems in operation and the detection of defects at the level of each module.

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Digital **Man**ufacturing Master's degree to set specialists for the dawn of the industry 4.0



Project number:

2019-1-RO01-KA203-063486

ROBOT SYSTEMS IN JOINING PROCESSES

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MODULE 2. ROBOT SYSTEMS IN JOINING PROCESSES

1. OBJECTIVES

The purpose of this module is to introduce students to basic concepts related to simulation in welding processes in order to obtain the necessary skills demanded in industry 4.0 and promote insertion in the labour market. The module deals with aspects related to welding simulators (especially with Soldamatic), a brief introduction to the main welding processes and execution of welding practices on simulator.

2. LEARNING OUTCOMES AND COMPETENCES

On successful completion of this module a student should be able to:

1) Understand different industrial robot types and their usage in industrial applications.
2) Understand the main components of a robot system.
3) Explain the main components in a robot system.
4) Understand the structures of different robot welding systems and advantages and disadvantages in different applications.
5) Understand the main safety hazards in a typical robot work cell. Safe working procedures in robot programming will be introduced.
6) Achieve basic knowledge about the most common welding processes to robotize.
7) Identify welding methods and their merits for a given workpiece.
8) Outline possibilities to increase productivity in robot welding.
9) Understand the main programming methods for industrial robots in different applications.
10) Explain the difference between robot programming methods.
11) Understand the meaning of seam tracking and different kind of methods of seam tracking.
12) Explain seam tracking systems

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13) Get acquainted with general matters that influence multi-robot welding and also will be acquainted with different kinds of multi-robot systems.
14) Get acquainted with welding Simulators:
15) Know about Welding Simulators Systems and types.
16) Differentiate between welding simulator and real welding system.
17) Set-up of Soldamatic welding simulator.
18) Understand maintenance planning, daily routines in maintenance and the meaning of risk analysis.
19) Outline the importance and purpose of maintenance.
20) Explain fully daily maintenance routines.

The professional competences to be acquired are:

1) Explore concepts associated with the physical principles of engineering.
2) Explore mechanisms and simple machines and sensing systems to create working robots.
3) Explore concepts associated with computer programming as it relates to robotics.
4) Design and write a program for controlling a robot.
5) Identify the limits of applying robot welding in specific applications.
6) Design the groove and welding geometry.

The transverse competences to be acquired are:

1) Integrate previous STEM knowledge and skills necessary to be a successful learner.
2) Demonstrate how to think competently.
3) Demonstrate how to communicate competently.
4) Continuous acquirement of knowledge related to robot welding.

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3. STRUCTURES OF A ROBOT SYSTEM

3.1. Basics on robots

Accordingly, with standard ISO 8373, a robot is an “actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks.” The International Federation of Robotics (IFR) also uses the same standard to approach the industrial robots, meaning as “an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.”

Although the initial purpose of robots was to do tasks that would be harmful for the human being, the application fields are growing and the industry depends even more on these programmable machines. The desired products are becoming more complex and constantly demanding more precision and effectiveness. To respond to this need, the market has developed an enormous number of different types of robots and appeared the need to divide them in the following main characteristics:

1) Coordinate systems;
2) Power source;
3) Method of control;
4) Programming method.

As the normal approach is to designate the robots by their coordinate systems, this will be explained first.

Robots can be classified by their coordinated systems as Cartesian/rectilinear, cylindrical, spherical, SCARA and articulated configuration robots.

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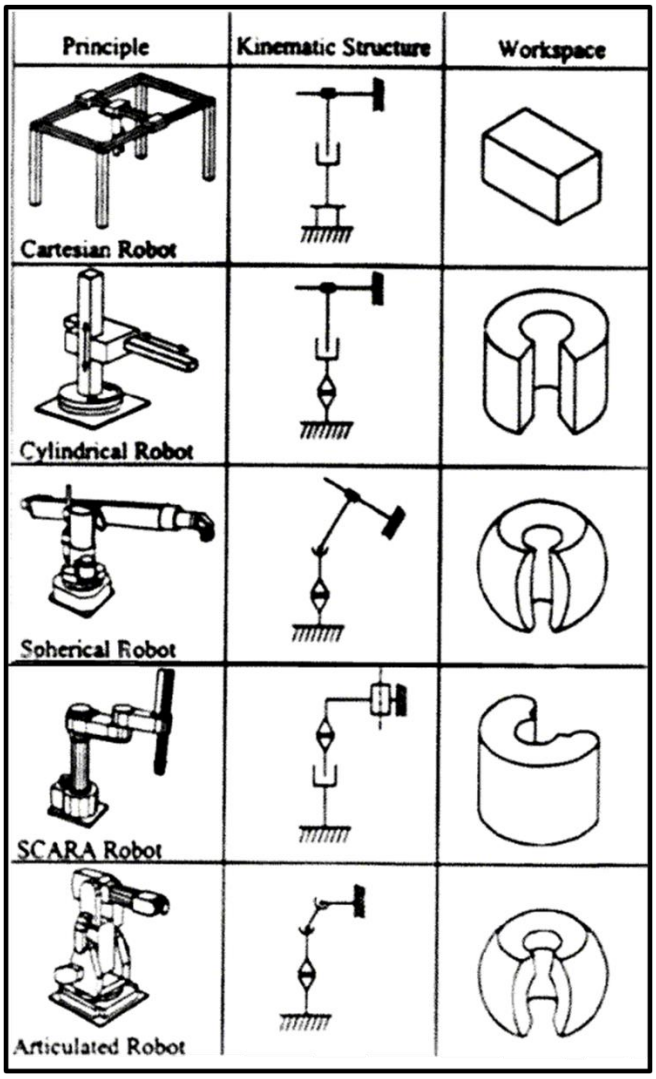


Figure 3.1 Type of robot structures, Source: http://www.robot-welding.com/robots.htm

3.1.1. Cartesian/Rectilinear Configuration Robots

As the name implies, these robots are based on the Cartesian coordinated axes (x-y-z) represented as three straight lines that intersect at a referential point. This robot has a column and an arm responsible for the workspace available. The arm can move up or down along the z-axis, slide along its bases along the x-axis, and telescope to move to, or from, the

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workspace along the y-axis. The Cartesian robots aren't usually used in industry applications due to their lack of mechanical flexibility and the insufficient speed in horizontal plane works, when compared to revolute base robots. The main advantages of the Cartesian robots are:

1) Easy computing and programing;
2) Simple controls due to totally linear movements;
3) High degree of mechanical rigidity, accuracy and repeatability;
4) Carries heavy loads not depending on the positioning.

The main advantages of the Cartesian robots are:

1) Limited to a small rectangular workspace;
2) Guiding surfaces exposed requiring corrosion and dust coverage;
3) Can only work the front face of the work piece.

These robots are used for:

1) Pick and place;
2) Sealant application;
3) Assembly operations;
4) Handling machine tools;
5) Arc welding.

3.1.2. Cylindrical Configuration Robots

Cylindrical robots consist of two orthogonal sliding arms that make a 90º angle with the rotary axis/base. The horizontal arm moves up and down along the vertical axis and slides forward and backward along the longitudinal axis. The rotary base allows the column and the horizontal arm to rotate 360º.

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This configuration permits the robot to lift heavy loads through a large workspace when compared to Cartesian robots. It must be taken in consideration that the cylindrical robot resolution is not constant because it depends on the tool horizontal distance to the vertical column. The main advantages of the cylindrical robots are:

1) Allows working in a 360º environment;
2) Relatively easy to program;
3) Rigid structure to deal with heavy loads;
4) Rotary axis easy to seal;
5) Good access into cavities and machine openings.

The main disadvantages of the cylindrical robots are:

1) Linear axis hard to seal;
2) Hard to cover drivers from liquids and dust;
3) Can’t reach space above itself;
4) Reduced accuracy and repeatability in the rotary movements direction;
5) Requires more sophisticated control system than CR.

These robots are used for:

1) Machine loading and unloading;
2) Assembly operations;
3) Handling die-casting machines;
4) Spot welding.

3.1.3. Spherical Configuration Robots

Also known as polar robots, they consist of a rotating base, lifting part and telescopic arm. This configuration allows movements inwards and outwards accordingly with spherical

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coordinates. As this design allows a great flexibility, tasks with small vertical actions are more adequate.

The main advantages of the Spherical robots are:

1) Larger work envelope;
2) Simple design;
3) Good weight lifting capabilities;
4) Adequate to small amount of vertical movement tasks.

The main disadvantages of the Spherical robots are:

1) Reduced mechanical rigidity;
2) More sophisticated control system;
3) Reduced accuracy and repeatability in the rotary movements direction;
4) Vertical movement is limited;
5) Low speed due to the required coordination of multiple axes.

These robots are usually used for:

1) Machine loading;
2) Material handling;
3) Spot welding.

3.1.4. SCARA Configuration Robots

Selective Compliance Assembly Robot Arm (SCARA) is based on a particular design from the late 1970's and can be considered as a cylindrical robot with articulated arms. This robot has more than three axes and the rotary joints are positioned vertically, instead of horizontally, in order to prevent the problems caused by the deflection while carrying an object at a programmed speed.

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The main advantages of the SCARA robots are:

1) Large workspace;
2) High speed;
3) Good payload capacity;
4) Moderately easy to program
5) Excellent repeatability.

The main disadvantages of the SCARA robots are:

1) Few fields of application;
2) Hard to program offline;
3) Arm of extreme complexity.

These robots are usually used for:

1) Pick and place tasks;
2) Assembly operations;
3) Application of sealant;
4) Handling machine tools.

3.1.5. Articulated Configuration Robots

Also called Joint-Arm Robots, these robots are structured with rotary joints which allow a versatile and flexible arm. The movement of these robots is similar to that of a human arm.

These robots can be divided in two types, according to the number of axes:

1) Three axis jointed arm (A1, A2 and A3) that are always the basic structure of any robot with this configuration (three rotary arms);

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2) Six-axis jointed arm (+A4, A5 and A6) that have the three-axis jointed arm described before but also include the pitch, roll and yaw axis. With these extra axes, the end effector can achieve any point in space with any orientation.

The rotary joints of these robots allow for a full range of motion and multiple rotatable planes. An articulated robot can also have other kind of joints, depending on the robots' design, but must always have at least one rotary axis.

Nowadays, the articulated robots of six rotary axes are the most common choice for welding robot. These robots can engage in very precise and diverse movements - due to their rotary joints - and bend in a variety of directions. These features provide a large flexibility and allow greater control to conduct multiple tasks, which is often necessary in industrial welding procedures.

The main advantages of the Articulated robots are:

1) High speed for three degrees of freedom;
2) High mechanical flexibility;
3) Easy sealing of all joints.

The main disadvantages of the Articulated robots are:

1) Extremely hard to control and program;
2) Poor accuracy;
3) Limited work volume.

These robots are usually used for:

1) Die casting applications;
2) Assembly operations;
3) Arc and gas Welding;
4) Spray painting;
5) Fettling machines.

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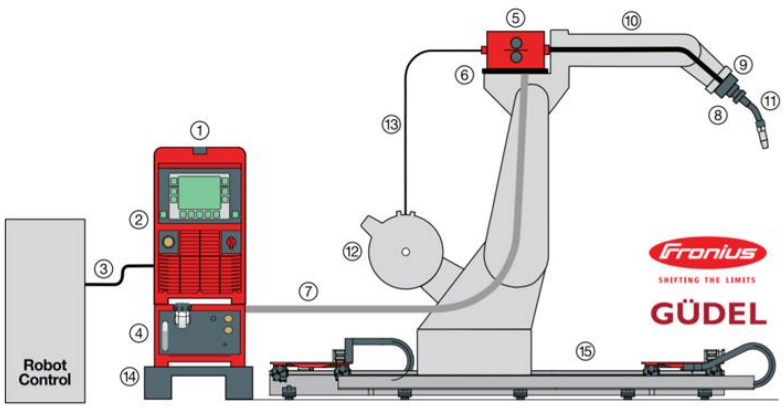
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3.2. Basics on Robot systems

A robot system is a system composed of distinct inputs, distinct outputs and a transformation process which is based on robot service. It can be divided in the following main components:

1) Teach pendant;
2) Auxiliary axis;
3) Positioners;
4) Material feeding;
5) Sensors;
6) I/O signals;
7) Control Systems;
8) Collusion Detection Systems.

Bellow all these components will be presented and described in detail.



1. Welding power source
2. Interface robot controller - welding power supply
3. Interface communication cable
4. Torch water cooler
5. Wire feeder
6. Wire feeder bracket
7. Hose package
8. Torch breakaway, or collision box
9. Insulation disc
10. Torch cable, or whip
11. Torch neck
12. Weld wire holder
13. Weld wire conduit
14. Power source stand
15. Linear tracks

Figure 3.2 Robot system for welding, Source:
https://www.roboticstomorrow.com/article/2017/08/robotic-welding-101/10470

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3.2.1. Teach pendant

The teach pendant is a device designed to control the robot motions remotely. This typically hand-held device, also called “teach box” or “teach gun”, allows the control of a wide variety of settings by experienced people in the robotics field.

The teach pendant has several features such as: an emergency stop button, to shut down operations immediately; a display screen which shows the commands and the history of the given commands and allows the user to edit them; and a keyboard that varies depending on the type of robot.

This device can also improve the robotics experience due to its remote control, allowing the worker to have a free range of movement around the robot instead of having to interface with the robot in a work terminal. This will not only increase safety, but also make the robotics work easier, by providing the commands to the robot and receiving feedback remotely.

Teach pendants are usually used for industrial applications controlling the robot through a teach-and-repeat technique, where the programmer defines a specific task, range of motion and speed. The device provides feedback information about speed, delay times and execution functions and can also establish a physical relationship with other machinery that might be involved in the process. This allows a constant check-up of the process and a possible correction 5646of it while it proceeds.

3.2.2. Auxiliary axes

Often, there are products that demand a larger workspace than the robots’ work envelope. Instead of replacing the existing robot, auxiliary axes can be introduced to the robot or to the positioning systems.

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The auxiliary axis can be linear or rotary motion equipment to extend the robots' reach. This equipment can be installed on the robot or it can be given by a positioner rotary system (ex. turntables) providing the auxiliary axis exteriorly to the robot. These extra components are usually connected to the motion of the robot, i.e., the movement of the positioner and of the robot complement each other, instead of working separately. This gives the opportunity to work in a larger workspace and with higher accuracy.

In conclusion, by using a 6-axis welding robot - for example, when it is mounted a single linear auxiliary axis rail - this robot becomes a 7-axis integrated robot. For a two linear axis rails, that configures X-Y table, it becomes an 8-axis integrated robot.

The auxiliary axes don't only increase the work envelope, but also the applicability of the robot. The robot becomes more versatile, and the user can manage the sustainability of the project. For example, it can be more reliable to buy a robot with fewer axes and complement it with auxiliary external axes. This option depends only on the desired result and it is the user's responsibility to make the correct approach.

3.2.3. Positioners

While the welding process occurs, the work pieces must be precisely positioned and well secured by positioners and/or jigs. These fixtures need not only to ensure that the parts are individually aligned, but also that it allows a quick and easy loading. The welding gun also needs to have direct and undisturbed access to each weld point.

The positioners must be able to support the tooling fixture and the parts load and provide a current path for the welding power supply. In some cases, the positioners must also manipulate or turn the part to optimize the welding process and orientation.

The large variety of robotic welding positioners includes simple flat tables to very complex multi-axis devices, to be used accordingly with the different application desired. The most

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commonly used for welding are the servo-driven head and tailstock positioners, known for their versatility and simplicity.

The head and tailstock positioners process in only one axis of rotation and have a frame between them, on which fixtures are mounted. Depending on the weldment, the central frame can be replaced by the work piece, attaching it to both the positioners. In this case, as the additional frame has been excluded, the robot has more access to all sides of the work piece, allowing easier and faster tasks.

The headstock positioners are powered by either an indexer or a programmable servo motor and resolver. The tailstock positioners are simply supported by an idler bearing.

The main disadvantage of these positioners is their difficulty to reach the inner part of certain objects due to their fixed structure. As it was seen before, this can easily be solved by the robot's placement in one of the auxiliary axis systems, such as a track or shuttle.

For simpler tasks there are other options available. A good example is the turntable. This positioner is a simple system where the operator can load and unload the working table while the robot is welding on the other side of it. These speeds up the process and keeps the robot welding almost continuously, improving the process efficiency.

The key to improve the welding process is to bring the welds to the robot, giving it access to a higher percentage of welds on a specific work piece. Keeping in sight the application challenges, such as the load manipulation, suitable safety interlocks and weld ground return paths, the user should choose the appropriated positioner.

4. WELDING PROCESSES FOR ROBOT SYSTEMS

In arc welding the weld uses an electric arc which is the main feature of an electric arc welding circuit. The power in the arc is the product of the welding current and the arc

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voltage. Nevertheless, the power generated from this process is mainly dissipated into heat which is used as heat source to melt the material. In arc welding, the welding speed also determines the specific power acting on the joint; the heat provided per each millimetre of weld is evaluated as the ratio between the ar power and the welding speed.

The welding power source provides the current flow across the circuit and the necessary voltage. The arc sparks between two electrodes: one is the electrode in the welding torch and the other one is the workpiece. Two welding processes are mainly used in robotic applications: one with a non-consumable electrode and one with a consumable electrode.

In the first, the arc provides heat for melting the base metal and the filler metal but, the electrode itself doesn't melt and filler metal may be added (i.e. TIG or GTAW). In the second, the arc triggered between the electrode's releases heat and melts both the surface of the base metal and the consumable electrode metal, which then crosses the arc and becomes the deposited weld metal (i.e. GMAW or MIG/MAG,).

In case of arc welding, the duty cycle for mechanized, orbital and robotic welding equipment operates in the range of 50% to 95%. Water-cooled rather than air-cooled torches are preferred when higher duty cycle rating are necessary. Whereas air-cooled torches rely on no additional cooling medium (water, compressed air), water-cooled torches require more frequent maintenance as well as the inclusion of suitable flow sensor.

4.1. Gas Metal Arc welding

The welding process widely used for robotic application is the arc welding with continuous filler metal electrode, also known as GMAW (Gas Metal Arc Welding) and also as MIG/MAG. According to EN ISO 4063, the process is classified as 131 and 135.

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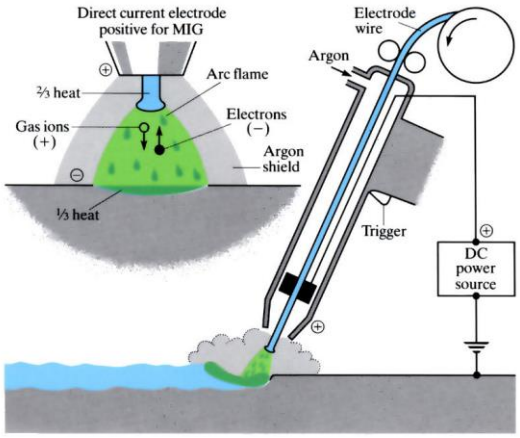


Figure 4.1 Gas Metal Arc Welding process, Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/gas-shielded-arc-welding-processes-tig/mig/mag

The arc strikes between the consumable electrode (filler material) and the workpiece causing the fusion of the base material and filler metal itself. Wire electrode, molten pool, electric arc and near zones of the base material are enveloped by an atmosphere of protection gas, which flows across the welding torch, exits from it and protects the welding area.

The main advantages of this process are:

1) Continuous feeding of the filler material
2) Absence of slag
3) Welding pool visibility
4) Higher current density

But a series of disadvantages may occur:

1) More complex equipment
2) Big welding torch (trouble for small spaces)
3) Need of gas cylinders
4) No depuration of molten pool (hot cracks may occur)

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The welding equipment for GMAW process is composed by: power generator, protection gas circuit (gas cylinder, manometer, pressure regulator and one-way valve), cooling system of the welding torch (if present), wire feeder, welding torch (self-cooled or water-cooled)

The most interesting feature of this process is the controllability (auto regulation of the parameters) where the intrinsic autostability of the process allows to obtain good results.

Different gases are used as protection, even mixtures are common. The main protection gases are: carbon dioxide, argon, helium, their mixtures and also oxygen in little percentage as mixture. Basically, the major differences among protection gases are:

1) Argon: inert, heavier than the air, with a low heat conductivity allows to achieve good penetration and narrow welding pool. The low ionization potential permit to obtain easy arc ignition and stable functioning during welding.
2) Helium: inert, lighter than the air, with high heat conductivity, allows larger welding pools. The higher ionization potential requires higher welding parameters.
3) Carbon dioxide: active, at high temperature it dissociates in carbon monoxide and oxygen, the subsequent re-association develops great amount of heat which contributes to the arc heat ensuring good penetration but porosity and spatters may occur.
4) Oxygen: small amounts in the gas mixture guarantees more penetration and improve the surface appearance.

Typically, GMAW employs solid wires as filler material (hence electrodes). In order to achieve good penetration, direct current with electrode positive, DCEP, should be used, both for steels and aluminium.

Typically, DCEN, direct current electrode negative, is used for overlaying application.

In the GMAW process the transfer of the filler material can be:

1) Short Arc transfer;
2) Spray Arc transfer;

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3) Pulsed Arc transfer.

In Short Arc the electrode contacts the molten weld pool at a steady rate in a range of 20 to over 200 times each second; as the wire touches the weld metal, the current increases. It would continue to increase if an arc did not form so, the rate of current increasing must be high enough to maintain a molten electrode tip until filler metal is transferred. It should not occur so fast that it causes spatters by disintegration of the transferring droplet of filler metal. On the other hand, the open circuit voltage of the power source must be low enough so that an arc cannot continue under the existing welding conditions.

In spray arc transfer the deposition of the filler material occurs through the fusion of the filler material in a sort of shower of molten metal droplets, due to the higher currents employed. Typically, this transfer can be achieved with gas mixture containing 80% or more of argon or helium. Due to the nature of the deposition, spatter and porosity are avoided but the resulting welding pool is more fluid due to the large current density employed.

In pulsed arc transfer, in order to obtain weld pool and deposition control, the welding current is managed with a program to change from a high current (HC) to a low current (LC) on a repetitive basis (pulsed welding). The level of both high and low current is adjustable. In addition, the length of time for the high and low current pulses is adjustable. This gives to the process the necessary control over the arc and weld pool. This transfer mode allows a good control of the welding, with low heat input and a good penetration while avoiding spatter and porosity.

More sophisticated systems provide seam-tracking based on the current variation related to the stick-out or the arc voltage. Laser identification system are seldom used. In this welding system an automatic cleaning system is also available to provide the removal of the debris and melt spatters stuck on the torch nozzle.

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4.2. Gas Tungsten Arc welding

The process uses an arc striking from a non-consumable electrode, mainly constituted of Tungsten. The filler metal may be used or not. The process is known as TIG and GTAW. According to EN ISO 4063, the process is classified with 141 to 147.

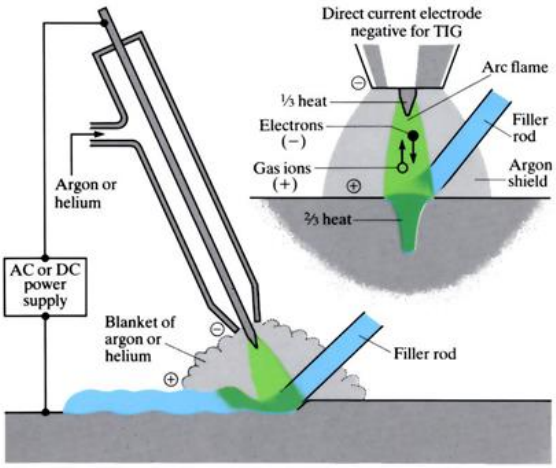


Figure 4.2 Tungsten Inert Gas / Gas Tungsten Arc Welding, Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/gas-shielded-arc-welding-processes-tig/mig/mag

In robotic welding the possibility to weld without filler metal become particularly useful.

TIG is an autogenous welding process in which the heat is produced by the arc which is ignited between the tungsten electrode (non-consumable) and the workpiece. The tungsten electrode has a high melting temperature and thermionic properties, allowing high arc stability. The main features of this process are:

1) Good electric arc control, which means remarkable regularity of the metal deposit
2) Good metal transfer without resulting in depletion of alloying elements
3) Welding parameters, current and voltage, very adjustable within in a wide range
4) Heat source small and concentrated

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Typically, this process is used for the root pass when gauging and/or back weld are not possible. GTAW is the optimal choice for welding pipes and tubes of any material, thanks to the inert nature of the protection gas (argon or helium). GTAW is also typically used for thinner materials but thicker material can also be welded with the multi-pass technique.

In GTAW, the power generator with constant current characteristic is used to maintain the current constant during welding, even if the arc length changes slightly.

The power supply can be provided both in direct current (DC) and alternate current (AC). Negative electrode, direct current is typically used for steel welding while alternating current is usually the best choice for aluminium alloys because of the effect knows as ionic blasting which disintegrates the refractory film of alumina.

Shielding gases used in GTAW are argon and helium:

1) Argon: inert, heavier than the air, with a low heat conductivity allows to achieve good penetration and narrow welding pool. The low ionization potential permit to obtain easy arc ignition and stable functioning during welding.
2) Helium: inert, lighter than the air, with high heat conductivity, allows larger welding pools. The higher ionization potential requires higher welding parameters.

In some cases, when welding very reactive materials (e.g. high chromium and stainless steels, titanium alloys etc.) a backing protection is required at the backside of the weldment. For certain application, a gas trailer is used in order to provide more effective protection.

4.3. Other welding processes for robot welding (resistance, laser)

4.3.1. Resistance welding

Robotized applications of resistance welding processes are very common, thanks to their features of controllability and reliability of the process and the contact between the welding

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gun and the workpiece represents a big advantage in respect of other robotized welding application. However, the heavy weight of the clamp represents one of the critical issues of this process. This is the reason why massive and bulky robots (with high payload capacity, about 80 Kg) are required. The size of these robots can be up to ten times higher that arc welding robots. Besides their size, the pneumatic piping and electrical cables can restrict the movement speed, thus it is sometimes preferred to use fixed clamps and moving the workpiece underneath them. Great innovation in this field is the introduction of medium frequency generators, which are more compact than the common types and the introduction of electrical actuators and related pressure control.

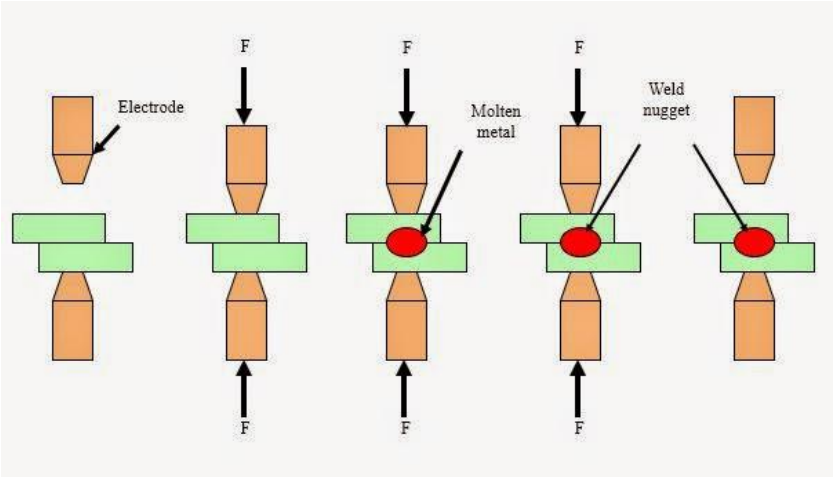


Figure 4.3 Resistance welding, Source: http://mechanicalinventions.blogspot.com/2014/09/resistance-spot-welding-rsw-working-principle.html

Concerning the sensors, the contact between workpiece and electrode allows an easy position control, whereas adaptive controls are available on medium frequency generators, which allows adaptive control of welding parameters for every single spot.

Resistance welding operations involve the coordinated application of electric current and mechanical pressure of sufficient magnitude and duration (forging pressure). The welding

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current must pass from the electrodes through the workpieces. The first requirement in the sequence of operation is to develop sufficient heat to raise a confined volume of metal to the molten state. The fused metal is then allowed to cool while under pressure until it has adequate strength to hold the workpieces together. The current density and pressure must be high enough to form a nugget, but should not be so high that they cause molten metal to be expelled from the weld zone. The duration of weld current must be accurately timed to prevent excessive heating of the electrode faces that could fuse an electrode to a workpiece and greatly decrease the service life of the electrode itself.

As noted, heat in the resistance welding process is produced by the electrical current flowing through the workpiece causing it to heat by means of electrical resistance. Because metals have a relatively low resistance the welding current must be relatively high to produce sufficient heat to develop welding temperatures at the desire location. Weld current also must exceed heat loss by thermal conduction in the workpiece and loss to the relatively cool electrodes in contact with the workpieces. The heating time is fixed to a certain period, generally a fraction of second and contemporary welding pressure is guaranteed by the mechanical clamp. This may be activated by electrical servo-motors or hydraulic systems.

The amount of heat generated in an electrical conductor depends on the following factors:

1) Amperage
2) Resistance of the conductor
3) Duration of current

These three factors affect the heat generated, according to the Joule law.

4.3.2. Laser welding

Laser welding processes are typically robotized; application with a solid state source (e.g. Nd:YAG and fibre) are typically coupled with anthropomorphic robots, whereas gas (CO2)

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sources are used with a mirror optical system in a Cartesian axis robots. In general, robot laser welding must have high level of accuracy and precision (small diameter of the incident beam). This is of great importance for workpieces joined in butt welding, where capacitor sensors are used to check the torch-workpiece distance; to reduce this issue a lap-joint can be taken into account. Hence, using a laser process in substitution of a traditional process, must be assessed by taking into consideration the following: the major requirements of accuracy in the preparation of the pieces and in its fixturing, the greater complexity of the system and last but not least, the larger investment related to the equipment, the usage and the maintenance.

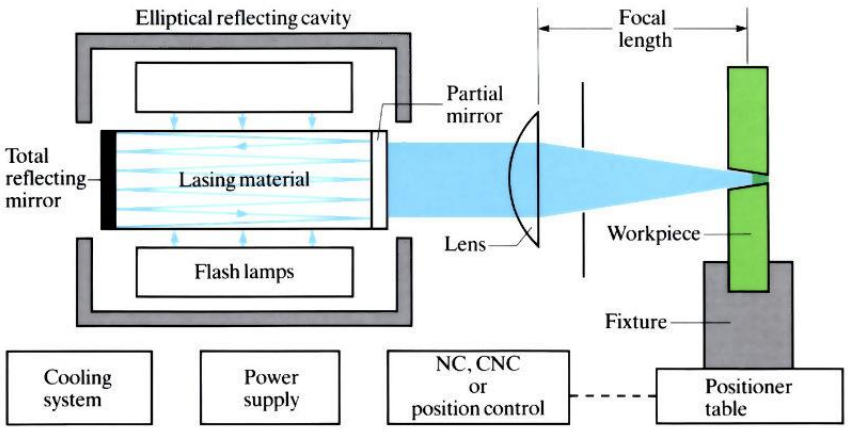


Figure 4.4 Laser welding process, Source: https://www.open.edu/openlearn/science-maths-technology/engineering-technology/manupedia/laser-beam-welding

Laser beam welding (LBW) produces weldment with the heat from a laser beam impinging on the joint. This process is generally used for autogenous welding but, occasionally a filler metal may be used.

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation. Laser beam is an electromagnetic radiation characterized by a particular wavelength, frequency and intensity.

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A laser is a device that uses an optical resonating system incorporating a crystal or a gas medium and reflective mirrors or focusing lenses to amplify and synchronize light waves into coherent beam. Coherence of the beam is produced by stimulated electronic or molecular transitions to lower levels of energy (related to the energetic levels of the electronic shell which envelopes the atomic nucleus). The laser emits this concentrated beam of light which is focused on the weld joint heats the material and makes the weld. Laser, as mentioned before, can be produced by different medium, as gas or in solid state from a crystal.

In particular, depending on the medium, they can be distinguished in:

1) Solid state laser Nd:YAG. Cylindrical rods or flat disc of crystalline Yttrium-Aluminium garnet, doped with Neodymium. The activation energy is provided by a flashing light. These LASERS produce a near-IR radiation, continuous or pulsed.
2) Gas laser: most used gas as medium is the carbon dioxide CO2, activated with N2 (nitrogen). About 10-15% of the activation energy is converted into light radiation, generally only continuous.
3) Fibre/diode laser. The emitter is the optical fibre itself, doped with Ytterbium and the activation energy is provided by a diodes system. This setting permits to obtain high quality beam and very high energy yield, about 50%.

Laser beams have different properties:

1) Monochromatic and coherent light that can be precisely focused, by optical devices, into focal spots very small in diameters (smaller than 0.1mm)
2) Laser beams can pass through air and other gas mediums without much energy attenuation (compared to electrons beams)
3) Laser beams can be reflected by metallic surfaces
4) Laser beams with adequate power and proper wavelength can be transmitted by optical fibres without energy loss.

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5) Metallic vapours and ionized gases absorb laser energy.

Features 1 and 2 permit to avoid vacuum chamber (as requested in electron beam welding), hence laser can operate in air. Features 2, 3 and 4 permit to carry the beam anywhere and to have one power source capable of supplying more working cells. Features 3 and 5 generate the major inconvenient, because at the start of the welding process the workpiece reflects some energy of the beam. However, as the welding pool is formed, most of the energy released by the beam is absorbed into the molten metal generated.

In keyhole welding another issue is the vaporization of metal that can create a plasma cloud of metal vapours which absorb part of the energy. This quantity of vapours is higher as the depth of the key-hole increases, thus limiting the thickness of the workpiece to be welded. Nowadays, even though very powerful laser sources are available, the maximum weldable thickness achievable seldom exceeds 20 mm.

5. PROGRAMMING OF A ROBOT SYSTEM

A robot is a system composed of smaller simple components working together to perform a series of tasks determined by its user. In order to get a robot to complete the desired operations (whether it is welding or any other action) it is necessary to program it.

Robot programming defines precisely which tasks will the robot execute and how they are carried out. This permits to define each one of its movements, trajectory, speed, applied forces, among several other parameters.

5.1. Online Programming

This is the most commonly used programming method in industrial robots. It is usually achieved with a teach pendant, a tool capable of controlling the robot's motion (somewhat

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like a gaming pad). The worker responsible for robot programming must guide the robot along the desired path and, at the same time, record its movement with the teach pendant.

This enables an easy and accessible low-level programming tool, which does not require a strong training in programming, allowing workers to use it.



Figure 5.1 Programming of a robot, Source: https://robodk.com/blog/robot-programming-methods-pros-and-cons/

5.1.1. Teach Pendant

The teaching pendant contains controls to guide the robot and to control its operation. It usually operates through an intuitive graphical interface where a menu presents several options.

The pad contains buttons for the robot control. In the example shown below, it is possible to see, in light blue, the buttons for directional control along the x, y and z axes and rotation around each of these axes.

Along with several other controls for menu browsing and programming, the pad must also contain (in red) a switch for an emergency stop.

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Figure 5.2 Examples of teach pendant, Source: https://www.assemblymag.com/articles/96022-long-live-the-robot-teach-pendant

5.1.2. Coordinate Systems

In robot control several different coordinate systems may be used, each suited for different applications. It is important to be able to understand and identify each of the coordinate systems.

1) $WORLD: Although not widely used, this coordinate system may be helpful when programming several robots sharing the same reference points.
2) $ROBROOT: In this case, the reference point is located at the robot's base.
3) $FLANGE: The reference point is located on the exterior face of the robot's face. If no other TCP is defined, this is also the default Tool Centre Point.
4) $TOOL: The coordinate system corresponds to the robot's tool. This is particularly useful in welding operations at irregular angles.
5) $BASE: It is a local tool coordinate system to which the robot will relate in X, Y and Z in relation to the workpiece base, facilitating the robot programming.

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5.1.3. Robot Motion Types

c.1. Point to Point (PTP) Motion

In this type of motion, the user must merely identify the trajectory's starting and ending points as well as its speed. This is used whenever the programmer wants the robot to go from point A to point B, regardless of its trajectory and position along the path. Tasks such as pick and delivery are commonly defined with PTP motion.

PTP mode could be MOVJ (Joint movement), MOVL (Rectilinear movement), and JUMP (From point to point) movements. The trajectory of playback depends on the motion mode.

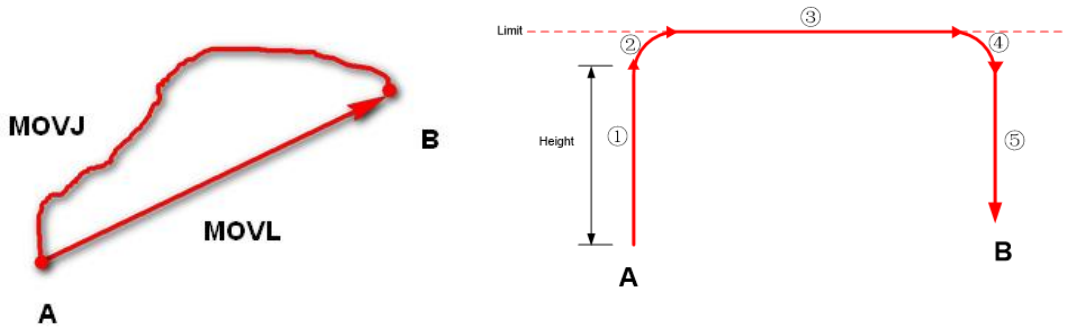


Figure 5.3 Point to point motion, Source: https://www.dobot.cc/online/help/dobot-m1/16.html

It is, however, very important to be aware of potential collisions or other hazards resulting from the robot's trajectory.

c.2 Linear Motion

In many applications, such as welding or cutting, the tool must be moved along a linear path. In these cases, the robot must describe a linear motion. For that, the programmer must define its trajectory and speed. When compared to PTP motion, linear motion is safer, as the whole trajectory is defined by the user, but also more computationally demanding.

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c.3 Circular Motion

Although similar to linear motion, in circular motion the robot may describe non-linear more complex movements.

The pros of Online Programming are:

1) Easy to program (does not require a strong formation in programming);
2) Most widely used.

The cons of Online Programming are:

1) Robot inoperational during programming;
2) Robots must be programmed individually.

Online programming via teach pendant is usually performed in the work cell by a programmer when the robot is taken off production. The principle behind online programming is simple, the operator controls the robot and "teaches" it how to perform the given tasks. The torch is jogged into a position and orientation at which an event occurs, e.g. where the robot changes direction, orientation, welding parameters or where the robot starts or stops welding.

The robot is controlled using its own teach pendant, entering specific coordinates by moving it by hand to the desired configuration, by setting the robot into a "limb" state. When the torch is at its correct configuration for each position, the current joint coordinates for each joint are saved in the robot's memory. The execution parameters are also selected and stored for each position and the velocity in between points is selected.

Depending on the process, the programmer also incorporates secondary inputs in the program. The robot may then "play back" the stored motion and execute the stored tasks. Finally, small adjustments are made as the robot test-executes the planned trajectory before it is placed back into production.

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Each robot manufacturer has its own teach pendant, although the architecture is more or less similar. Below is an example of a teach pendant and the description of its features.

5.1.4. Structure and Syntax of Robot Program Coding

Due to the lack of standards for robot programming, most robot manufacturers develop their own programming language. There are, however, certain similarities between the several languages, being possible to establish a link between the different languages.

Below is shown an example of code to perform a simple task of picking an object and placing it in a different location. The robot starts by moving to P1, a safe position. From there, moves to P2 and, consecutively, P3. An order to close the gripper is given, grabbing the object. It is then moved to P4 and P5, where the object will be dropped. It is instructed to open the gripper, releasing the object. The task is completed when the robot returns to P1.

```
Move to P1 (a general safe position)
Move to P2 (an approach to P3)
Move to P3 (a position to pick the object)
Close gripper
Move to P4 (an approach to P5)
Move to P5 (a position to place the object)
Open gripper
Move to P1 and finish
```

Figure 5.4 Sequence of program

5.1.5. Programming of welding robot

Next are disclosed some specific topics regarding the programming of a robot designed to perform welding operations.

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Entering welding routines. For a robot to enter a welding routine, it is necessary to supply it with a set of welding data, parameters that are used for the welding process. The welding data is composed of start data, main data, end data and weaving data.

a. Start data

Start data generates arc start data and stabilizes electric power. Start data contains the following parameters:

3) Ignition voltage and current;
4) Gas preflow time: the time between shield gas flow and arc start;
5) Hot start voltage and current: to stabilize the arc in the first stage;
6) Restrike amplitude: minor change in the position of the torch to start the arc;
7) Restrike cross time: Time to stay in the restrike position;
8) Arc welding start maximum time. The robot stops the process if the arc does not start in this time interval.

b. Main data

Main data contains the following parameters for the actual welding process:

1) Welding voltage;
2) Welding current;
3) Welding speed.

For higher productivity, the welding speed should be increased to the maximum value. Therefore, a new system should be put through a number of try-outs until the parameters for maximum speed are determined.

c. End data

At the end of the welding process craters or cracks may appear, therefore, several parameters for appropriate finish are required.

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These parameters include:

1) End voltage and current;
2) Gas postflow time;
3) Burnback time;
4) Cool time;
5) Fill time.

d. Weaving data

A large work piece, to be welded with large penetration, demands a long working time and requires a motion plan from the weld start position. Carrying out this type of welding in one pass is possible due to weaving. Weaving has various patterns such as zig-zag, V-shape, triangular, and wrist weaving. Wrist weaving uses only the sixth-axis of the robot and enables weaving in a narrow space, where weaving with the lower arms of the robot is impossible. Also, it is useful when high frequency weaving is necessary.

5.1.6. Proper orientation of parts for programming and welding

The position and orientation of the parts to be welded in the workspace are important both in terms of cycle times and weld quality. The joint design must consider the mechanical properties required by the final product, but also allow the torch to access and follow the joint.

In terms of weld quality, it is important that the proper torch angle is maintained with constant velocity during the operation. Joint limits and fixtures may be in the way for proper execution of the trajectory.

Well-designed parts and positioning systems routines in this respect, make the programming a lot easier and guarantee better final results.

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Figure 5.5 Positioning of pieces to be welded, Source: https://commons.wikimedia.org/wiki/File:FANUC_6-axis_welding_robots.jpg

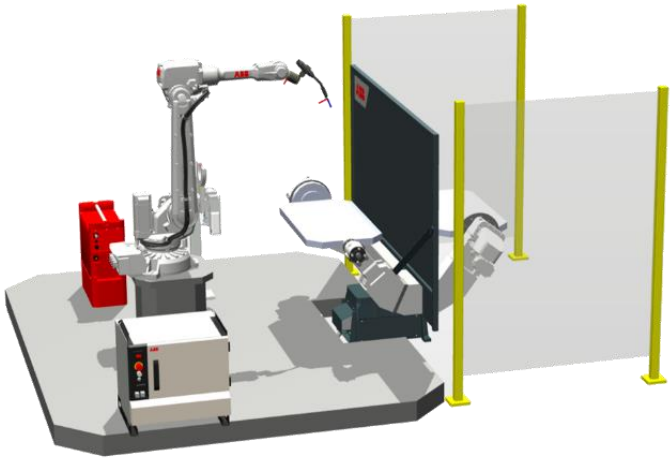


Figure 5.6 Robot cell containing auxiliary devices for fixing, positioning and rotating the pieces, Source: https://www.tropimatica.com/en/welding-cell.php

Torch and wrist alignment procedures. Robots are repeatable, but the key aspect to keep them operating correctly is to make sure that the end of the weld wire, or tool centre point (TCP), is just as repeatable.

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Tip wear, wire cast and torch crashes can cause the wire position to vary, even though the robot is positioned consistently. If welds are placed off location, it is common to hear users complain that “the robot is not repeating”. However, several issues can lead to a missed weld location and a few peripheral products can speed troubleshooting and recovery to reduce downtime.

Manufacturers typically place a punch mark or pointer on some fixed object inside the robot work cell to create a reference point for the tool.

If there is some reason to suspect the robot is not repeating, the technician should call up a program to move the wire to that reference point. The technician then can see how far the tool centre point is off and in which direction it has deviated.

This process normally indicates the cause of the problem and leads the technician to the proper corrective action. If the technician can get the wire back to its reference position, it is likely that the problem has been fixed.

Robot and system error recovery. The errors can be met in robot systems are the errors of detection and errors of recovery.

The detection problem involves the use of suitable sensors for identifying the error occurred in an operation. In addition, the sensor signals are read by the related intelligence in order to classify the errors accurately.

The error recovery system helps in providing a proper plan by a robot to correct the existing malfunction or irregularities in the work cell. Generally, a specific recovery plan must be prepared for dealing with each type of error that is found during error detection.

The errors that commonly occur in a manufacturing process can be categorized into three types such as:

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1) Random errors: such errors are resulting from a stochastic event and they are described with the help of their statistical nature;
2) Systematic errors: these types of errors are described by some preconception that takes place in the operation;
3) Illegitimate errors: these errors are obtained either by the mistake of a human worker or equipment.



Figure 5.7 Errors of positioning, Source: https://blog.robotiq.com/bid/72831/What-are-the-Sources-of-Robot-Inaccuracy

Some possible malfunctions and irregularities that occur in an operation can be determined using above three errors. A disadvantage in the error detection and recovery system is that it cannot be designed for a particular application.

6. EXPLAIN SEAM TRACKING SYSTEMS

The application of robots to welding requires particular attention to details, such as robot guiding and control. Ensuring correct robot behaviour depends to great extent on sensoring.

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Seam Tracking Sensors are devices used to acquire information about the weld seam and give instructions regarding adjustments to the weld torch position and welding process parameters (voltage, current, weld speed and wire feed rate, for example). These sensors work by scanning the position just ahead of the weld pool and, should any misalignments exist between the joint path and the weld torch, give precise instructions towards correcting the robot's path, either by moving the workpiece or the torch itself. This operation is carried in real-time, which is why the sensors must be fast enough for the welding operation to be completed efficiently. Depending on the type of information they obtain, we can consider two different types of sensors: geometry-oriented and process-oriented sensors.

In geometry-oriented sensors the information obtained refers to the geometry of the groove itself. These can be classified in two sub-categories: contact-sensor or non-contact sensor.

a. Mechanical Sensors (contact)

A mechanical sensor is considered to be a tactile sensor. These are the simplest and most limited of all tactile sensors and work by using pins, rollers or balls to scan the pathway. With this, a considerable distance between the sensor and the torch is required and therefore can only be applied to grooves with large dimensions or straight seam paths.

b. Electric Sensors (contact)

This type of sensor works by establishing a connection between the workpiece and a component of the welding equipment (per example the gas nozzle) that has been subjected to voltage. When the gas nozzle touches the workpiece, a current flow is established, and the robot uses this information to make adjustment to the pathway.

c. Thermal sensors (non-contact)

These sensors consist of thermocouples placed on each side of the torch to measure the lateral temperature along the weld path.

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If the values registered by the thermocouples do not match, the torch is misaligned and the robot's position needs correction.

d. Inductive sensors (non-contact)

These sensors work by flowing a current in a coil, creating a magnetic field close to the workpiece. By shortening or increasing the distance between the coil and the workpiece the magnetic field strength will vary. Those fluctuations are detected by the sensor and indicate whether the robot's trajectory needs correction.

In process-oriented sensors the sensor acquires information about the process parameters like voltage or current. The path is corrected by measuring the welding current and voltage, which are proportional to the distance between the electrode and the workpiece. With that information, the robot can maintain the same distance to the workpiece along the whole path.

One of the most important sensing systems in this category is "through the arc" sensor technology. This type of technology has been used successfully in several different welding processes such as TIG, MIG or submerged arc-welding. The main disadvantages are the fact that these sensors cannot be used to weld thin joints like sheet metal, nor detect the welding starting point, since the information can only be obtained after the arc is established.

Vision systems refer to non-contact sensors. These usually use a camera to produce 2-D images of the workpiece, which are then analysed by the robot in order to determine its current position and its work path laying ahead.

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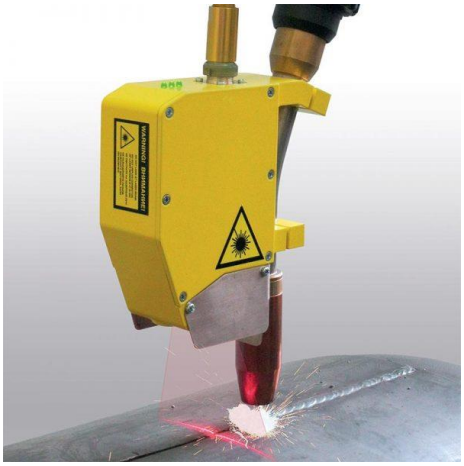


Figure 6.1 Vision system, Source: http://rovicor.com/en/products/vs-for-robots/sts-200-r/

It's a device mounted in front of the welding torch so it can scan the pathway of the tool. These devices detect the position of the joint and guide the tool through it, sending trajectory corrections to the robot in real-time. There are a couple of vision systems technologies being used nowadays, namely laser vision and image-based systems.

a. Laser Vision Systems

Laser vision systems are used to obtain a three-dimensional profile of the groove and the weld seam. It may not only be used for seam tracking and robot guiding but also for weld quality inspection. One of the main advantages of laser vision is its invulnerability to external interferences such as fumes or light variations.

b. Image-based Systems

Image-based systems operate similarly to laser vision, although in this case a camera is used to obtain actual footage of the workpiece. The image is then processed by a computer and the robot is instructed on whether it should perform any adjustments. Unlike laser vision, image-based systems are affected by poor lighting or other interferences.

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Force and Torque sensors are used to detect external forces applied to the robot. These devices are particularly useful in applications where the robot is intended to be controlled by a human worker who moves the robot by applying a certain amount of force.

Force sensors are commonly used in collaborative robots and safety systems designed to stop when an exterior force (greater than a pre-set level) is detected (in order to prevent injuries from being inflicted to workers).

7. HEALTH AND SAFETY IN USING OF A ROBOT SYSTEM

Robots are powerful tools often used to increase productivity or simply to perform tasks undesired by humans (dangerous, difficult, repetitive or unpleasant operations).

Their presence can however, in some cases, introduce a threat to workers' safety, as robots are machines designed to, more often than not, operate with extreme speed and produce very high amounts of force.

The danger inherent to the use of robots in the workplace is due to the injuries caused by robot failure or human error. These situations can often result in severe injuries to any nearby workers and must be carefully analysed.



a. b. c.

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d.

Figure 7.1 Specific sign to aware on risks, Source:
https://www.creativesafetysupply.com/collaborative-robot-safety-signs/

Depending on the source of the injury, robot accidents may fall into 3 categories: 1) engineering errors, 2) human mistakes or 3) environmental conditions.

1) Engineering errors refer to situations caused by failure of mechanical components, controllers, faulty programming, etc. These situations are usually caused by mistakes made in the design, construction or assembly stages and are difficult to predict and foresee. Engineering errors may result, for instance, in undesired uncontrolled robot movements.
2) Human mistakes may occur due to factors, such as, inattention, fatigue or inadequate training. These are commonly avoidable.
3) Environmental conditions, such as, extreme temperature or poor lighting may contribute to improper robot operation, leading to an incorrect machine response.

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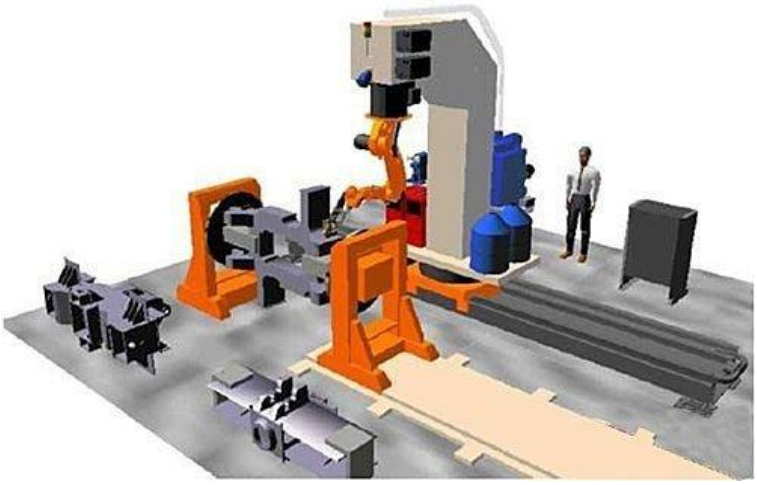


Figure 7.2 Robot workspace, Source: https://www.machinemfg.com/robot-arc-welding-station-safety-protection-classification/

Those who have direct contact with the robot are, logically, the ones under a potential threat. The nature of the contact with the robot may vary depending on the type of task to perform.

For this purpose, we shall consider three different types of personnel to interact with the robots: 1) robot operators, 2) maintenance workers and 3) programmers.

1) Robot operators work in cooperation with the robot in situations, for instance, where it is necessary to hold a component to be welded or to place a part in a work station. These tasks are often repetitive and the workers may not be prepared for improper machine behaviour.
2) Maintenance workers often operate in situations where robots are known to be functioning incorrectly being, therefore, more prepared and aware of potentially dangerous events.
3) Robot programmers often deal with unfinished robot code prone to bugs and errors, which can result in hazardous situations.

Depending on the situation itself, injuries can be classified as pinch or impact injuries.

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Pinch injuries occur when a worker (or a portion of his/her body) becomes trapped between the robot and another object.

The safety conditions in using robots or robot systems are specified by ISO 10218-1:2011 and ISO 10218-2:2011 respectively.

Impact injuries refer to situations when a robot directly collides with a worker.

One must also account for other types of injuries, such as, electrical shock, burn (either due to heat or radiation), noise hazards, intense vibrations or even the use of dangerous materials.

The most basic and simple way to prevent robot related incidents is using a physical barrier. These can either be fixed (walls or fences surrounding a robot) or movable (gates or flaps), but all have the same objective, preventing the worker from inadvertently entering the robot's area of operation (work envelope).

Non-physical safeguards may also be used to protect those working near robots. These do not prevent the user from entering the robot's work envelope but, in such event, ensure that any dangerous machinery or robots are stopped, acting as an interlock and avoiding any potential hazardous situations. Light curtains, scanners or safety mats are all examples of non-physical safety devices.

Situations where a robot is forced to stop and re-initiated may also be a source of hazards. It is of utmost importance that upon power recovery (after a blackout, for instance) this type of machine is not automatically re-initiated, as it could lead to serious injuries. The robot should be restarted manually from a safe position.

Worker safety may not only be achieved by avoiding direct contact between humans and machines. If the robot's motion is restricted to low-speed movements (either by actuator or software limitations), safe working conditions may also be ensured. ISO 10218 defines safe slow speed to a robot as 0.25 m/s.

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Collaborative robots combine these safety measures in order to create a system that allows the user to approach and work closely with the robot. An example of collaborative robots is shown below, where a robot is used for lifting a heavy gearbox. As soon as the user activates the light curtain, the robot automatically switches from fully-automated mode to reduced-speed mode, thus protecting the worker.

Force/Torque sensors or tactile sensors can be used to detect an object (or a body part) trapped by retractable components of a robot.

8. WELDING SIMULATORS

8.1. Welding Simulators Systems

The technological evolution has allowed the use of simulators for the training of welded apprentices in order to obtain the necessary skills for insertion in the labour market. Most modern simulators are run by a personal computer and employ software, which enables a variety of processes. These include setting up (i.e. selection of materials, weld type and weld settings), performance assessment, and provision of feedback, in line with the second and third training principles [1].

Welding simulators are built using modern technologies like Virtual Reality (VR) or Augmented Reality (AR). These technologies provide the simulator display and visual feedback. In VR systems, a Head Mounted Display (HMD) creates the LVE. The welder cannot see the actual gun and welding surfaces; instead, they see a virtual representation of these projected onto the HMD. In AR systems, a digital image or animation is superimposed on the real image that can be viewed through monitors. Unlike the VR systems, in the AR systems, the welder can see the gun and welding surfaces they are interacting with. In both VR and AR systems, virtual imagery is used to provide visual feedback. A separate monitor

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is also generally included to allow instructors to view student performance and review feedback after welding completion.



Fig. 8.1 SOLDAMATIC AR welding simulator

8.2. Difference between welding simulator and real welding system

The use of welding simulation presents many differences from real welding system. The following table shows you the most relevant ones:

Welding Simulator	Real Welding System
• Practices in an Augmented lab • Less pollutant • More safe – Less accidents • Less costs • Unlimited AR/VR practices • Less time • Reduce the environmental impact • More qualified welder	• Practices in small space • Gas emission • Burn risks • Expensive – More money • Numerous repetitions • More time • More emissions • Less qualified welder

Fig. 8.2 Differences between welding simulator and real welding system

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8.3. Set-up of welding simulators

We can find different configurations depends on the manufacturer that we choose. In all cases, the welding simulator includes a complete user manual (pdf-doc, online or both). These tend to be more or less extensive depending on the benefits they offer. For example, the first and one of the most completed welding simulation solution called "SOLDAMATIC" includes an owner´s manual with a dedicated section about set-up tasks. Normally these tasks are grouped in:

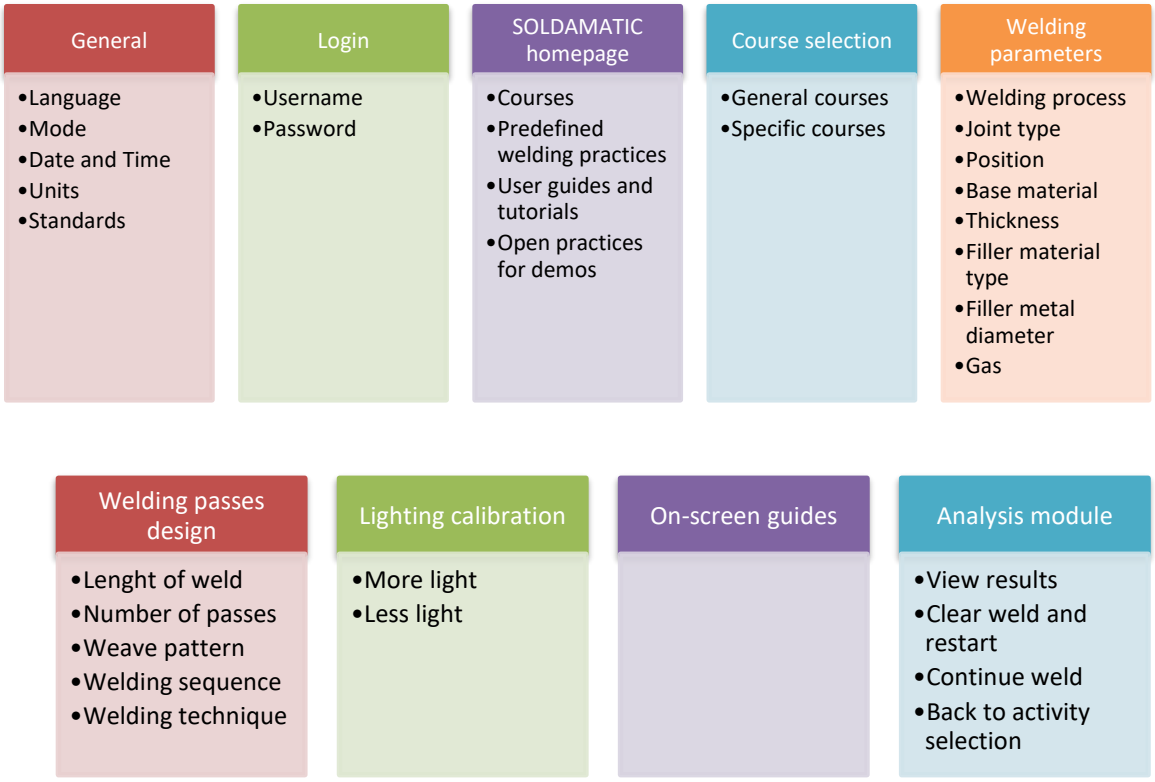


Figure 8.3 Set-up SOLDAMATIC welding simulator

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9. SOLDAMATIC WELDING BASICS

9.1. Welding with Soldamatic

Soldamatic is the name of the simulator where the Augmented Reality welding practices are performed.

Both its external elements (welding torches, helmet, etc.) and its functionalities (welding sound reproduction, vision module, etc.) have been designed to make this experience as close to reality as possible.

The simulator has been designed to be configured in the European Standards (based on the EWF regulations) and in the American Standards (based on the AWS regulation); and in the Metric and Imperial system.

9.2. Welding processes

This simulator can reproduce in Augmented Reality 5 welding processes:



SMAW/MMA



GMAW/ MIG-MAG

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FCAW-G and FCAW-S **GTAW/TIG**

Figure 9.1 Welding processes covered by SOLDAMATIC welding simulator

NOTE: You also have the possibility of choosing a "Multi-process" exercise to perform in a single coupon. This selection offers you the opportunity of designing welding practices with just one or different welding processes for a single coupon.

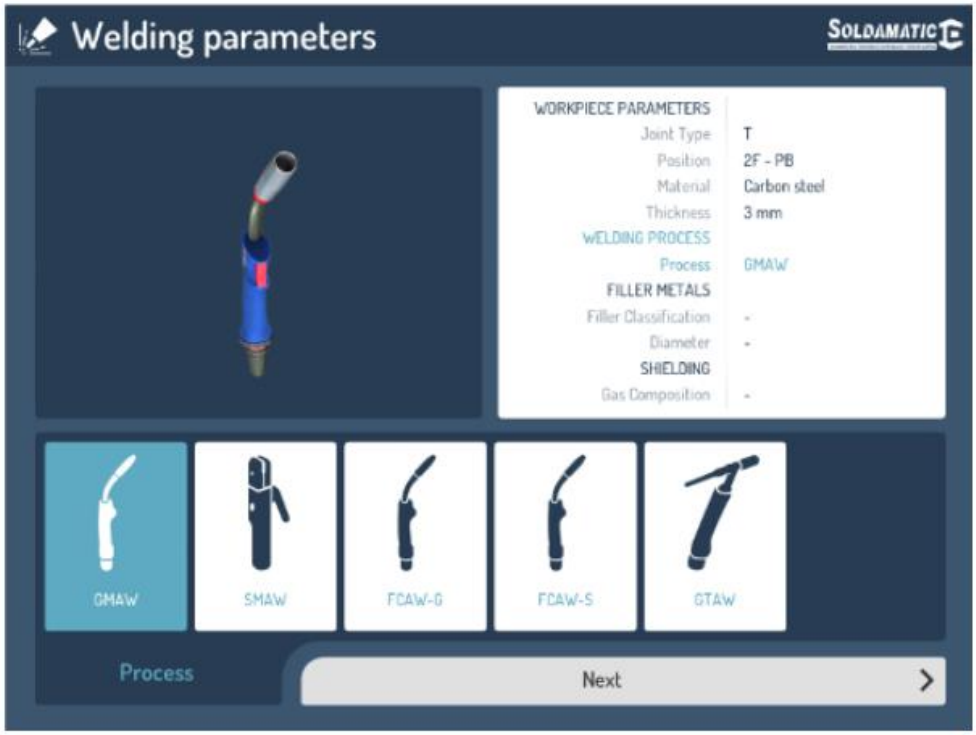


Figure 9.2 Welding Processes menu

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9.3. Welding positions

In Soldamatic you can perform fillet and butt joints. All the previously mentioned welding processes can be performed in the simulator in the following welding positions:

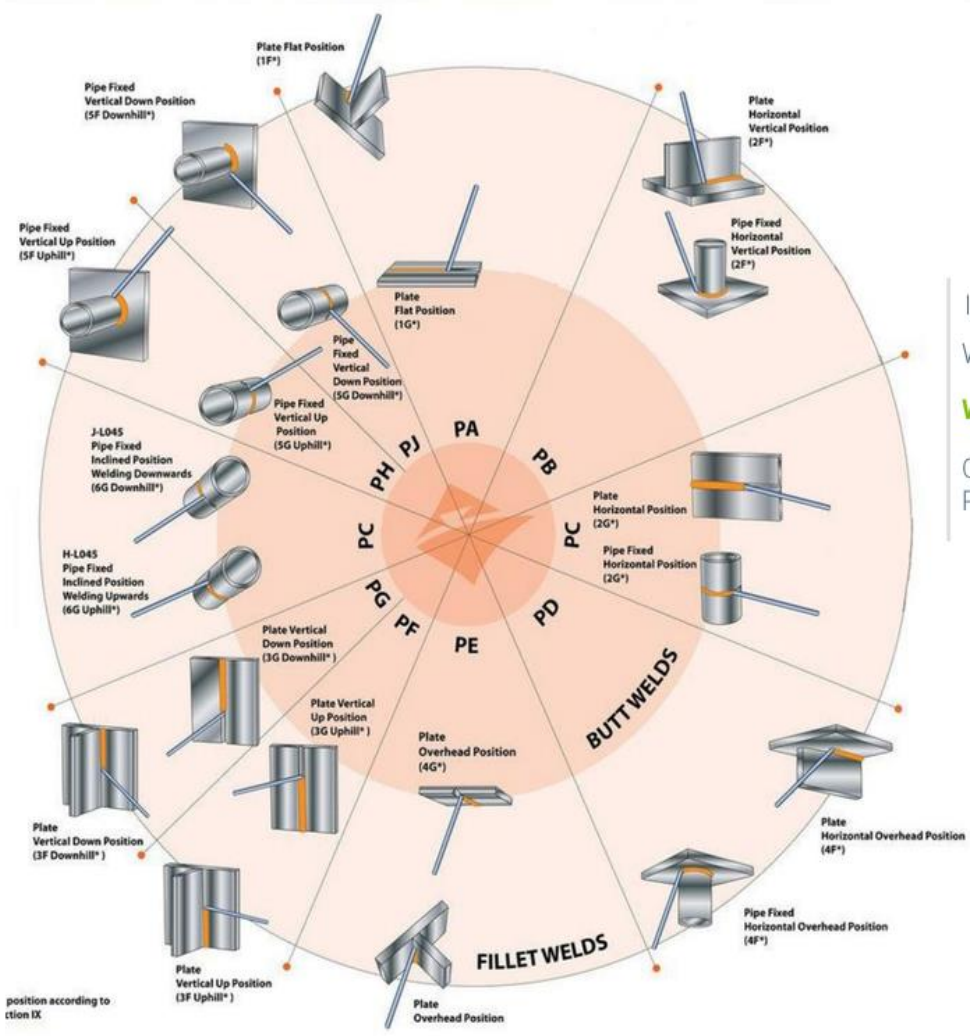


Figure 9.3 Welding Processes menu

All these welding positions can be performed in the following coupons using a work stand to get all angles.

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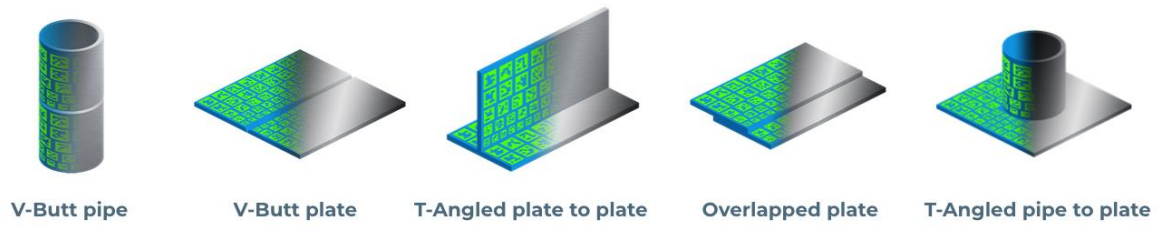


Figure 9.4 Welding Processes menu

Apart from the previous coupons, you can also perform welding practices in 15 Multijoints coupons that has been developed for the Industrial sector:

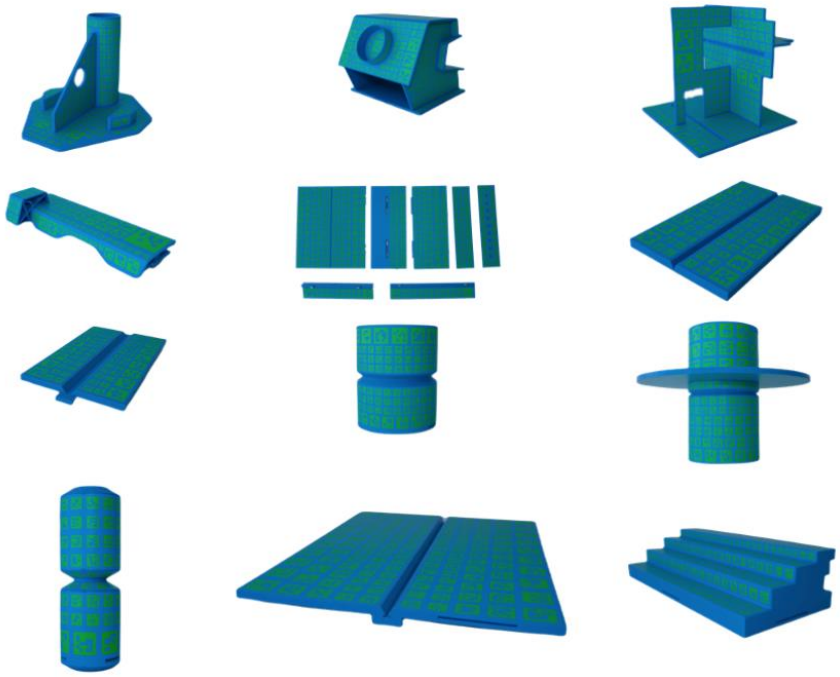


Figure 9.5 Welding Processes menu

The available base materials are: carbon Steel, Stainless Steel and/or Aluminum.

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9.4. Configurable parameters according to a WPS

In both the Soldamatic E-Learning platform and in the simulator, you can configure the parameters of the welding practice. However, Soldamatic E-Learning offers a more accurate customization of the technical parameters as we will see in the Soldamatic E-Learning module. Soldamatic supports the following technical parameters:

- Base material thicknesses: 3mm (1/8 inches), 6mm (1/4 inches) 10mm (2/5 inches) and other thicknesses on demand in pipes and multijoints coupons: 2 mm, 9,525 mm (3/8 inch), 12,573 mm (1/2 inch), 15 mm y 25 mm (1 inch).
- You can perform a single pass or multiple pass.
- Welding patterns and technique: straight, triangular, balance and circular. Welding techniques available: Drag and push.
- Process-related welding parameters:

Table 9.1 Welding parameter recommended by the simulator

Process	Base Material	Filler material	Filler material diameter	Gas composition
SMAW/MMA	Carbon Steel	E7018	2,5 mm 3,25 mm 4,0 mm	
		E6013		
		E6010		
	Stainless Steel	E316L		
GMAW/MIG MAG	Carbon Steel	ER70s-6	0,8 mm 1,0 mm 1,2 mm	Argon-CO_2
	Stainless Steel	ER316LSi		Argon-O_2
	Aluminium	ER5356	1,0 mm 1,2 mm	Argon
FCAW-G	Carbon Steel	E71T-1	1,0 mm 1,2 mm	Argon-CO_2
FCAW-S		E71T-7	1,0 mm	No gas
GTAW/ TIG	Carbon Steel	ER70s-6	2,0 mm 2,4 mm	Argon
	Stainless Steel	ER316L		
	Aluminium	ER5356		

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		Range of Values
	Voltage	10 - 38 V
	Wire feed Speed	Ipm (50), ipm (1000)/ 1.3 - 25.4 mm/min
	Amperage	50 - 425 A
Protection	Gas Flow	0 - 30 l/min

- **Technical parameters:** Work angle, Travel angle, Arc length, travel speed and Aim.

9.5. Welding defects

In a welding practice there can be different defects that are detected through a visual inspection or a destructive test. Soldamatic assesses the following defects: porosity, spatters and contamination or slag inclusion. All these can affect the quality of the welding bead.

10. WELDING PROCESS

10.1. General introduction and applications

Welding is a process of joining materials where the contact surfaces of two or more parts are fused and joined by fusing the edges with or without filler metal. Welded joints are the only joints which achieve mechanical and physical continuity between parts, and this enables the transmission of tension between the joined pieces. The base metal is the material to which the welding operation is applied with the aim of fusing it, and the filler metal is the material which is added during the welding process.

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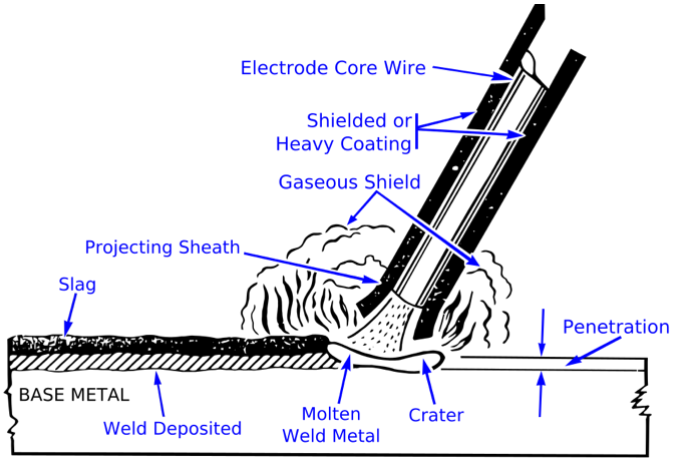


Figure 10.1 Welding process principle

Normally, to achieve fusion by welding it is necessary to:

- Apply energy: electrical, chemical, mechanical, etc.
- Use a filler material, although this is not always essential.
- Use protection systems which prevent the harmful action of oxygen during the welding process such as coatings, active shielding gases , inert gases or mixtures of both, fluxes, etc.
- Depending on the type of energy applied, provision of a filler material if used, and the applied shielding system, different welding processes can be used, whose key features are described below.

Electric arc welding is most used in the following sectors: shipbuilding, structures and the construction of bridges and buildings, the aeronautics and space industries, the automobile and rail industries, fluid transport pipelines, tanks, storage spheres, pressure containers, boilers, the construction of thermal plants, nuclear power plants, the chemical sector, oil

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refineries, oil pipelines, gas pipelines, and any type of work related to welding and forging in general.

The process is applicable to all types of steels: carbon steel, alloyed steel, stainless steel, refractory steel, etc., as well as non-ferrous metals such as aluminium, magnesium, copper, nickel, and their respective alloys. It is frequently used in combination with other welding procedures, either in root passes or fillings.

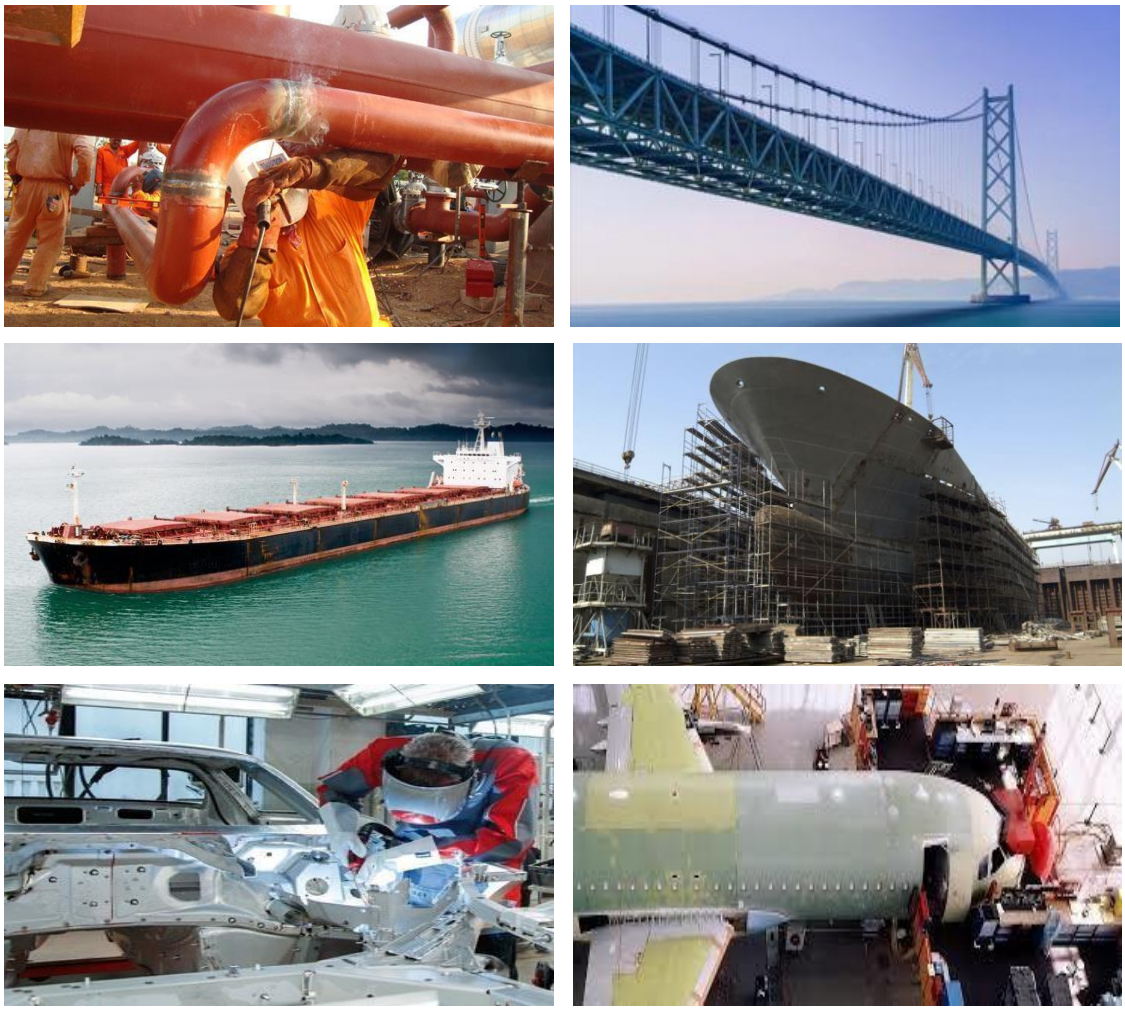


Figure 10.2 Applications of the welding processes

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10.2. Manual welding with covered electrode/SMAW

10.2.1. Principles And Applications

Manual metal arc welding is a process in which metal fusion is achieved by the heat energy produced by an electric arc established between the end of a covered electrode and the parent metal of the joint to be weld. The filler material is melted in form of small drops, which together with the melted base material become the weld. A slag is obtained by the electrode coating, which acts as a protection of the melting pool from the environment.

Manual metal arc welding is known by following designations

- SMAW, Shielded Metal-Arc Welding (ANSI/AWS A3.0)
- 111, Manual metal arc welding (metal arc welding with covered electrode) (EN ISO 4063)
- MMAW, Manual Metal-Arc Welding (United Kingdom).

An open electric circuit is created for this purpose. It requires an alternating or direct current generator or power source, with two terminals:

- One of these should be connected with a cable to the electrode holder clamp where the coated electrode is clamped.
- The other is connected via a return lead and a work connection to the piece which is to be welded.

Coated electrode welding is a relatively inexpensive procedure and is also very simple to use. It is one of the most common types of welding and is used in production, maintenance, in the workshop or in the field.

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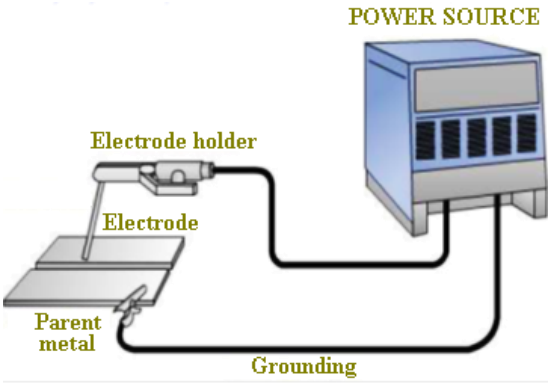


Figure 10.3 Applications of the welding processes

10.2.2. Equipment

10.2.2.1. Power supplies

As far as welding is concerned, high intensity power between 20 and 1,000 Amps and low voltages between 20 and 90 Volts are most commonly used. Equipment with an **Alternating current** or **Direct Current** is required. Companies supply electricity via a **low intensity, high voltage alternating current**, which is suitable for both domestic and industrial use.

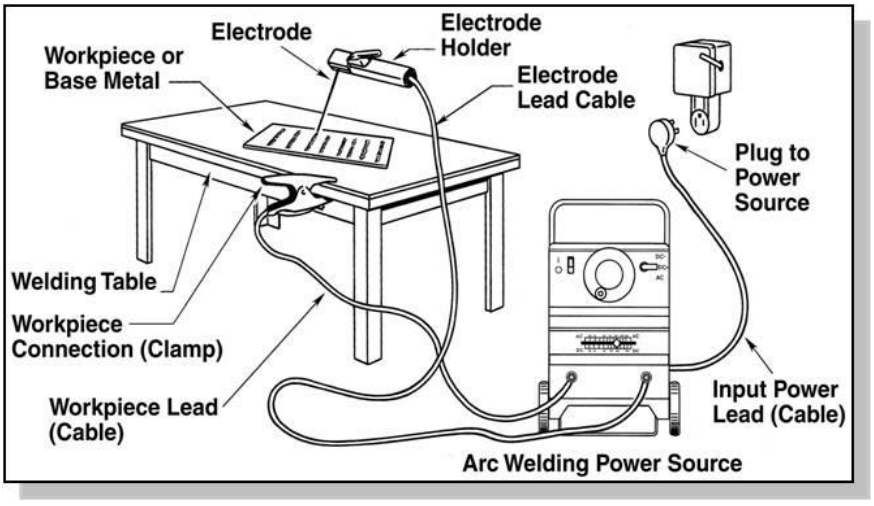


Figure 10.4 Applications of the welding processes

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Therefore, welding equipment should **transform** and/ or **convert** the electrical current of the network in question into another **alternating** or **direct** current, featuring the appropriate voltage and amps which are required to create and stabilize the electric arc.

10.2.2.2. Impact of current

As commented previously, welding with coated electrodes can be undertaken with both the Alternating Current and Direct Current and if the latter is the case, this is when the polarity plays a key role.

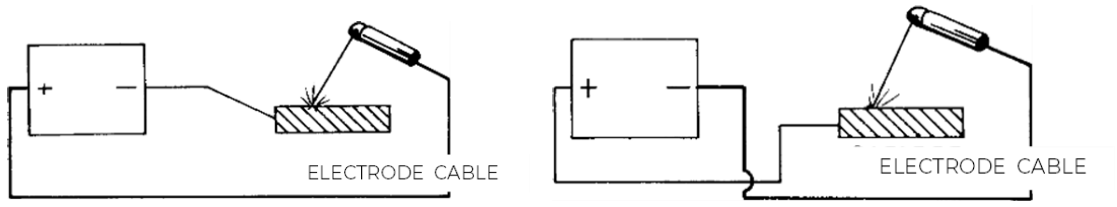
Connecting the electrode clamp to one pole or another will determine the polarity of the circuit.

If we connect the electrode to the positive pole and the piece to the negative pole, this is called **inverse polarity.**

Its main features and effects are:

- Relatively wide pools with little penetration.
- Heat accumulation on the electrode and rapid deterioration

If, on the other hand, we connect the electrode to the negative terminal and the piece to the positive terminal, **direct or negative polarity** is generated.



a. **b.**

Figure 10.5 Electrical circuit of welding with inverse polarity (a.) and direct polarity (b.)

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10.2.3. Operational Technique

In order to undertake a welding process, it is vital to be aware of the technical characteristics of welding and the steps which should be taken.

10.2.3.1. Main parameters to be taken into account

During the welding process, it is essential to be aware that different parameters can have a significant impact on both the finished product and the quality of the welding.

- **Amps:** refers to the amount of electricity which flows for a second. The choice of electricity depends on the type of join, position and thickness of the piece to be welded, its diameter etc. The higher the amps the greater the penetration.

- **Diameter of the electrode**: This is the thickness of the electrode. The diameter to be used will depend on the position of the weld, type of join and thickness of the material in question.

- **Thermal contribution**: This is the heat produced by the electric arc to undertake the welding. This is directly related to intensity, speed and amps and how all these factors relate to the diameter of the electrode. The greater the diameter, the greater the thermal contribution.

- **Arc length:** This is the distance between the tip of the electrode and the surface of the piece. An arc which is too long will lose intensity and directionality. It may generate porosity and contaminate the weld metal with oxygen and hydrogen from the air. However, if the arc is too short, it may prove to be erratic and short circuit during the metal fusion.

- **Welding speed:** This refers to how quickly a joint can be welded. The increase or decrease of the weld modifies the degree of penetration, width of the bead and its geometric shape.

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10.2.3.2. Preparation of the pieces

Tacking the pieces

Before starting to weld, and to avoid pieces moving about, some joins are tacked together.

When the piece to be welded is long, tacking will commence in the middle and extend to the edges.

Before starting welding, one must check that:

- The pieces are clean.
- The plates and sections are aligned.
- The tacking has not created pores, cracks or bulges.

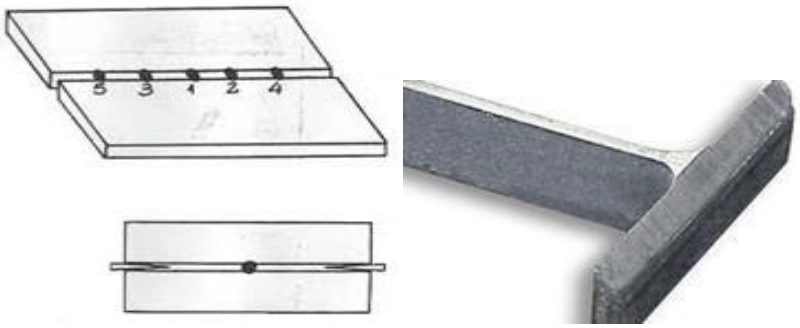


Figure 10.6 Tack welding of pieces to be welded

Striking the arc

Striking the arc means that the arc should be set a few millimeters in front of the area where the welding will take place.

The arc can be initiated in two ways:

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- Gently tapping the end of the electrode on the piece.
- Scratching as if one were going to light a match.

In both cases, once the arc has been struck, the electrode should be shifted slightly and maintained at this distance during the actual fusion. One should ensure that the distance between the electrode and the piece does not exceed the diameter of the electrode, and this should be maintained throughout the welding process.

10.2.3.3. Execution of welding

During the welding operation, the welder must ensure the arc length and speed of movement are as constant and stable as possible, and also ensure the advance and work angles are not subject to sudden changes which may affect the deposit of the welding bead.

Depending on the requirements of the procedure, the beads can be created by using the following movements: zig-zag, spiral, swinging from side to side, or back and forth, etc.

Welding positions

The position in which the welding operation is carried out determines:

- How easily the operation can be executed where manual processes are concerned (Welder skill).
- Whether certain processes can be applied.
- Productivity.
- The probability of defects occurring.

The four basic welding positions are:

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- Welding, flat and **horizontal.**
- Horizontal welding against a vertical piece**.**
- **Vertical** up and vertical down welding.
- **Overhead** welding.

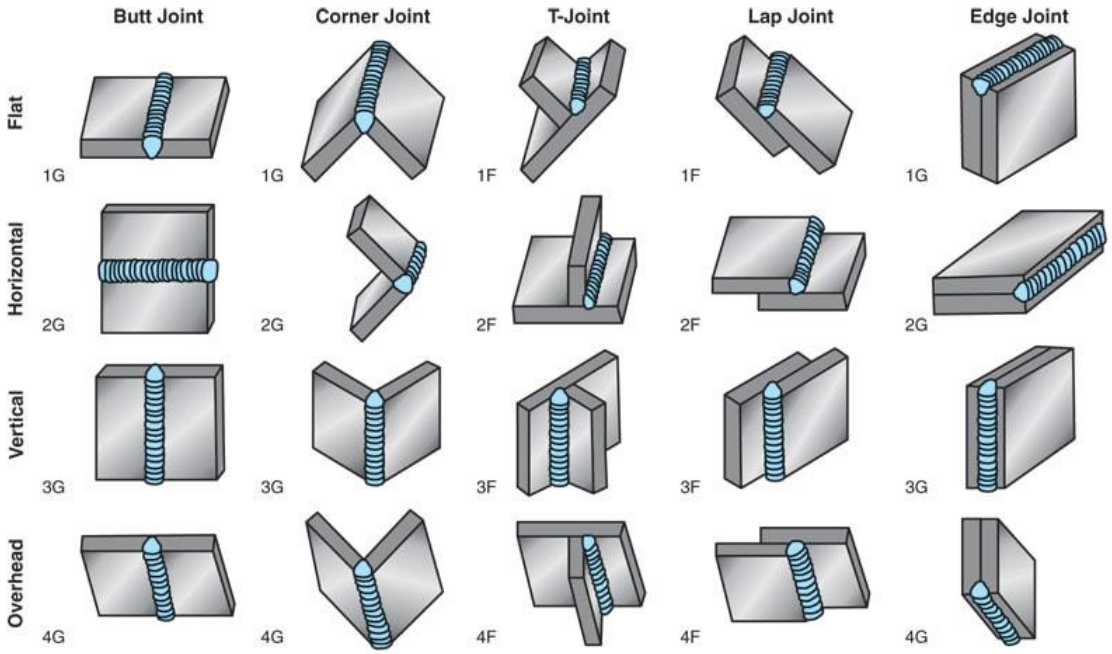


Figure 10.7 Positions of welding according to ISO 6947 and AWS D1.1

Preparation of edges and types of joint

Considering the relative position of the pieces and the way in which the bead transmits stress, there are two types of joint:

- Butt joint.
- Using fillet welds.

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Butt welding

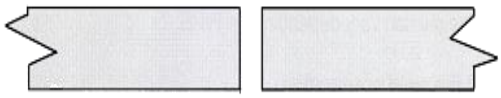
Butt welding is a technique used to join two components together in such a way that the welding has achieved a perfect transition between the welded elements.

To achieve this, it is necessary to render the edges which are to be joined (this is called **edge preparation**).

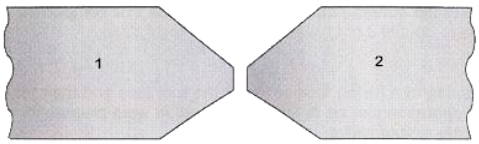
The most common types of bevels are:

- Without edge preparation**,** used in plates and components which are not thick.
- **A "V** or a **Y"** bevel**,** bevel and bead. For plates and components of small and medium thickness.
- **An "X"** bevel used for plates of a medium or great thickness.
- **A "U"** bevel**, although** more difficult to obtain, reduces the volume of the weld for larger thicknesses.

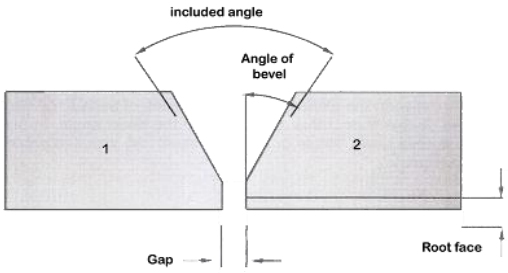
Open Square Butt Preparation



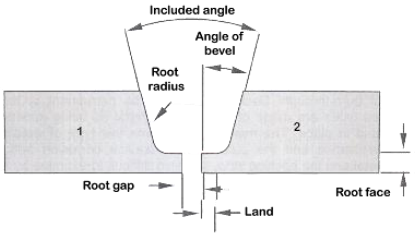
Double V Preparation



Single V Preparation



Single U Preparation



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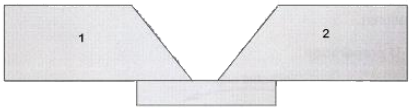
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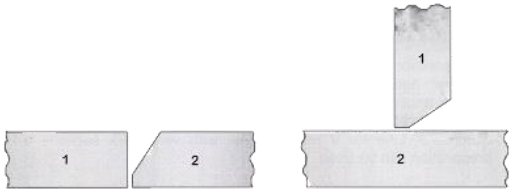
Double U Preparation



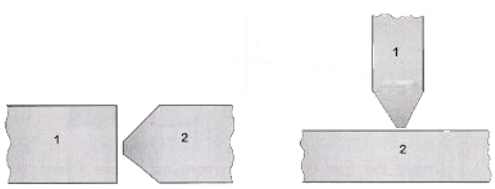
Single V Preparation with Backing Strip



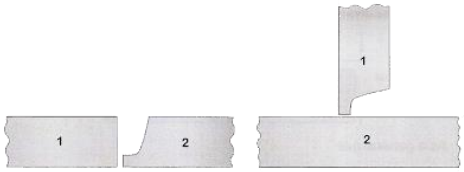
Single Bevel Preparation



Double Bevel Preparation



Single J Preparation



Double J Preparation

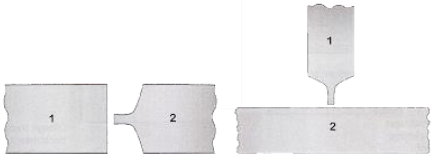


Figure 10.8 Types of bevels for welds according to ISO 9692

Angled welds

Depending on the relative arrangement of the plates to be joined, this type of welding is adopted, which, in many cases, does not require any preparation.

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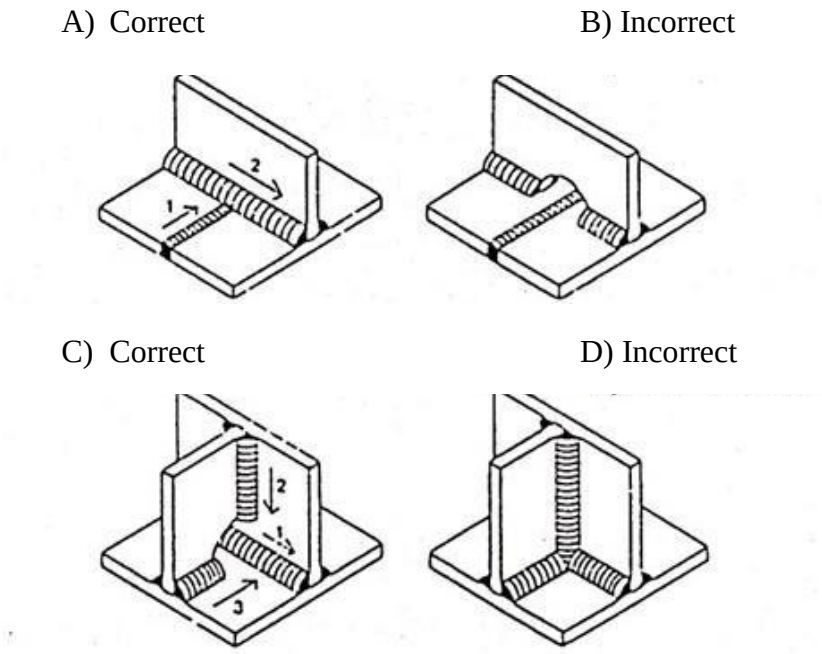


Figure 10.9 Fillet welds

10.2.3.4. Cleaning the beads

After finishing the weld bead, it is very important to clean the area, removing the slag with a chisel, brushing with a wire brush which is suitable for the type of welded base material and removing any weld spatter with a hammer and chisel.



Figure 10.10 Tools to clean the bead

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11. WELDING PRACTICES ON SIMULATOR

11.1. SMAW: Test Plate – Overlay in flat position

11.1.1. Objective of the practice

Make four overlay beads on a plate keeping the arc length constant.

11.1.2. How to do it

Now you know how to strike and establish the arc, you are going to start making the first weld beads.

We are going to make overlay beads on the plate and we will increase progressively the number of factors to be controlled.

The practices in SMAW are going to be performed with two types of electrodes: rutile and basic electrodes. Ideally, you make all these practices with rutile electrode and then repeat them with the basic one.

In any case, as the practices are parallel, explanations would be related to the rutile electrode and then some small differences would be commented on when changing to the basic electrode.

11.1.3. Shall we start?

Keep in mind the purpose of this practice: "To keep the arc length constant while you are welding".

Take a look to figure 1. In this practice you should follow the travel direction, putting your hand closer at the same time to compensate the electrode consumption and maintain a constant arc length. This is the main aspect to be controlled in manual metal arc welding, but as we will see subsequently, there are many factors you should be aware of.

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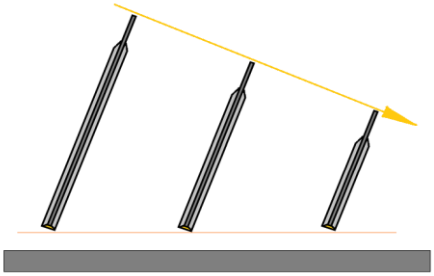


Figure 11.1 Control of the arc length

We start with a rutile electrode using an arc length equal to the diameter of the electrode. That is:

- For beads 1 and 2 use an electrode of 2.5 millimeters and an arc length between 2 and 3 millimeters.
- For beads 3 and 4 use an electrode of 3.25 millimeters and an arc length between 3 and 4 millimeters.

In short: The purpose of this first practice is to make four overlay beads keeping the arc length constant, progressing with a travel speed.

To do this practice, you should follow the recommended parameters included in the Welding Procedure Specification (WPS). It is important that you become familiar with the WPS format, since it is the one used in Europe. This allows you to use the WPS regardless of the country or language.

For this exercise you only need to control the pointed out parameter.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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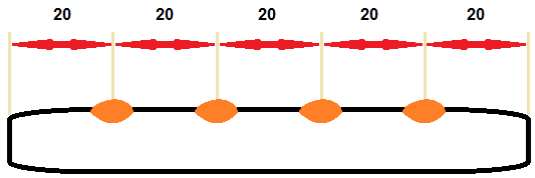
Welding procedure specification: WPS-111-001-R

WPQR number: WPQR-111-001-R
Manufacturer: CESOL
Mode of metal transfer: N.A.
Joint type and weld type: Overlay
Welder: ---
Coupon test: ---

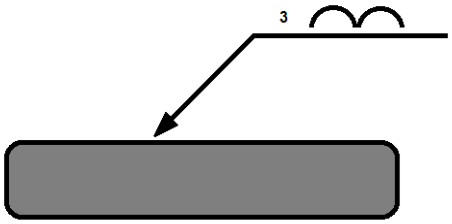
Preparation and cleaning method: Brushing
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA

Details of the weld preparation (sketch):

Weld design.



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 2	111	2.5	Straight	75-85	---	CA	---	15-20	---
3 - 4	111	3.25	Straight	105-115	---	CA	---	15-20	---

Description and brand of welding consumables: EN ISO 2560-A: E 38 0 RR12

Special drying requirements: N.A.
Gas/flux designation:

- Protection: N.A.
- Backing: N.A.

Gas flow rate:

- Protection: N.A.
- Backing: N.A.

Tungsten electrode, type, size: N.A.
Gouging/backing details: Base metal
Preheating temperature: 15 ºC
Interpass temperature: N.A.
Post heating: N.A.
Preheating temperature maintenance: N.A.
Post weld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude, frequency, stop duration: N.A.

Pulsed welding details: N.A.
Arc length: 3 mm/4mm
Plasma arc welding details: N.A.
Inclination angle: 70 º

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: CESOL-SMAW-001-R Date: 2015/05/13 Supporting PQR Nº: CESOL- SMAW-001-R

Revision Nº: 0 Date: 2015/05/13

Welding processes: SMAW (Stick covered) Type: Manual

JOINTS (QW-402)

Details:

Joint design: Build-up

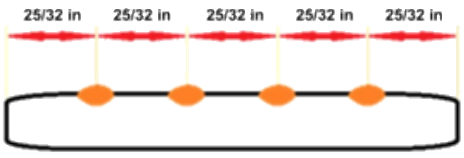
Root spacing: ---

Backing: Yes: X No: ---

Backing material (Type):

X Metal --- Non fusing metal

--- Nonmetallic --- Other



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 23/64 – 7/16 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: X No:

Other: ---

FILLER METALS (QW-404)	1	2
Specification Nº (SFA):	SFA-5.1	---
AWS Nº (Class):	---	---
F-Nº:	2	---
A-Nº:	1	---
Size of filler metals:	1/8 in	---
Filler metal product form:	---	---
Supplementary filler metal:	---	---
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	---
Fillet:	---	---
Electrode-flux (Class):	---	---
Flux type:	---	---
Flux trade name:	---	---
Consumable insert:	---	---
Other:	---	---

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 1G

Welding progression: Up: --- Down: ---

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: 60°F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	---	---	---
Trailing:	---	---	---
Backing:	---	---	---
Other:	---	---	---

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-2	111	E6013	1/8 in	AC	75-85	---	---	---	5.9-7.9 ipm	---
3-4	111	E6013	1/8 in	AC	105-115	---	---	---	5.9-7.9 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: ---

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String bead

Orifice, nozzle, or gas cup size: ---

Initial and interpass cleaning: Brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Simple

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: Arc length 1/8 in - 5/32 in

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11.2. MMAW: Test Plate – Overlay in vertical uphill position

11.2.1. Objective of the practice

The purpose of this practice is to get initiated in the vertical uphill issues.

11.2.2. How to do it

Basically, it is the same as in previous practices, that is, control of the arc length and electrode orientation. The electrode should be placed with an orientation as shown below.

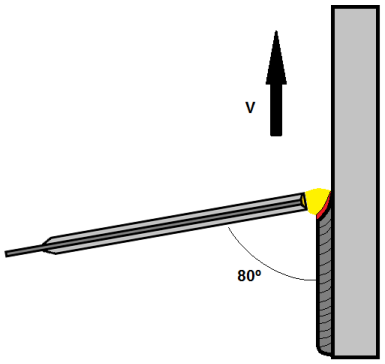


Figure 11.2 Welding technique

Take into account that you should let the slag sag and slip down the metal piece, so it is essential that you distinguish between the welding puddle and the slag. The travel speed will be slightly lower than the used in PA position.

We will make two beads with a 2.5 mm electrode diameter and another two beads with a 3.25 mm electrode diameter. In both cases, we will oscillate around 1 mm. This slight oscillation is made in order to go up with a more comfortable uniform motion.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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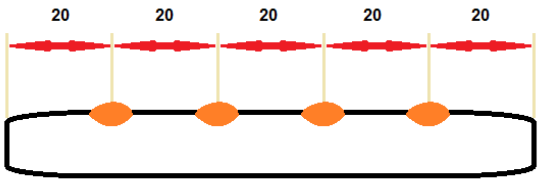
Welding procedure specification: WPS-111-021-R

WPQR number: WPQR-111-021-R
Manufacturer: CESOL
Mode of metal transfer: N.A.
Joint type and weld type: Overlay
Welder: ---
Coupon test: ---

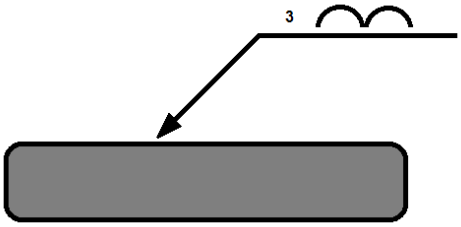
Preparation and cleaning method: Brushing
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PF

Details of the weld preparation (sketch):

Weld design.



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 2	111	2.5	Straight	60-70	---	CA	---	12-15	---
1 - 4	111	3.25	Straight	90-100	---	CA	---	12-15	---

Description and brand of welding consumables: EN ISO 2560-A: E 38 0 RR 12
Special drying requirements: N.A.

Gas/flux designation:
- Protection: N.A.
- Backing: N.A.

Gas flow rate:
- Protection: N.A.
- Backing: N.A.

Tungsten electrode, type, size: N.A.
Gouging/backing details: Base metal
Preheating temperature: 15 ºC
Interpass temperature N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: 1 mm

Pulsed welding details: N.A.
Arc length: 2 mm/3 mm
Plasma arc welding details: N.A.
Inclination angle: 100 º

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: CESOL-SMAW-021-R Date: 2015/05/13 Supporting PQR Nº: CESOL- SMAW-021

Revision Nº: 0 Date: 2015/05/13

Welding processes: SMAW (Stick covered) Type: Manual

JOINTS (QW-402) Details:

Joint design: Build-up

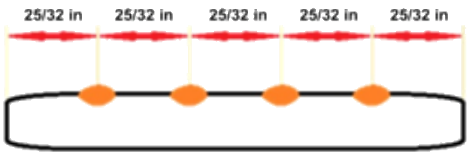
Root spacing: ---

Backing: Yes: X No: ---

Backing material (Type):

X Metal --- Nonfusing metal

--- Nonmetallic --- Other



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 23/64 – 7/16 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: X No:

Other: ---

FILLER METALS (QW-404)	1	2
Specification Nº (SFA):	SFA-5.1	---
AWS Nº (Class):	---	---
F-Nº:	2	---
A-Nº:	1	---
Size of filler metals:	3/32 in, 1/8 in	---
Filler metal product form:	---	---
Supplementary filler metal:	---	---
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	---
Fillet:	---	---
Electrode-flux (Class):	---	---
Flux type:	---	---
Flux trade name:	---	---
Consumable insert:	---	---
Other:	---	---

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 3G

Welding progression: Up: X Down: ---

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: 60°F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	---	---	---
Trailing:	---	---	---
Backing:	---	---	---
Other:	---	---	---

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-2	111	E6013	3/32 in	AC	60-70	---	---	---	4.7-5.9 ipm	---
3-4	111	E6013	1/8 in	AC	90-100	---	---	---	4.7-5.9 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: ---

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String bead

Orifice, nozzle, or gas cup size: ---

Initial and interpass cleaning: Brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Simple

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: ---

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11.3. GMAW: Test Plate – Overlay in flat position

11.3.1. Objective of the practice

The purpose of the practice is to perform four overlay beads on a plate keeping a constant gun-piece distance and a constant travel speed.

11.3.2. How to do it

We are starting with a simple exercise: To start, we are NOT going to weld for joining two pieces. This practice is intended to make stringer beads on a steel sheet. The aim of this first practice is to perform four overlay stringer beads, keeping the gun-piece distance at around 15 mm with a constant travel speed. To get a stinger bead is nothing but to trace with the wire fed from the gun, a line passing as exact as possible on the guide, but, as we are going to see progressively, there are many more factors to keep an eye on them. In this exercise, we are going to start taking a look to some of them. More specifically:

- **Gun-piece distance:** It is very important to keep a constant distance between the welding tip and the sheet as you will learn during the next practices.

- **Travel speed:** Also, the travel speed must be constant. If you are wondering why, you must think that the amount of metal which is to be deposited on the sheet surface depends on that, if you weld slowly, you will deposit more material (which gives a wider bead), if you weld fast depositing less material and if you weld using different travel speeds during passes, you will see that the bead is anything except a straight line with uniform width and height. It is just what we do not want to achieve.

Important: Before starting you have to decide the sense of welding. If you prefer "backhand welding", go to the left edge of one of the guide marks and if you decide to go for "forehand welding" you should go to the right edge of one of the guide marks and to give the same inclination to the gun (take a look to the picture). To start, place the contact tip with the specified electrical stick out (ESO) and then you are ready to start.

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ERASMUS + KA2: 2019-1-RO01-KA203-063486

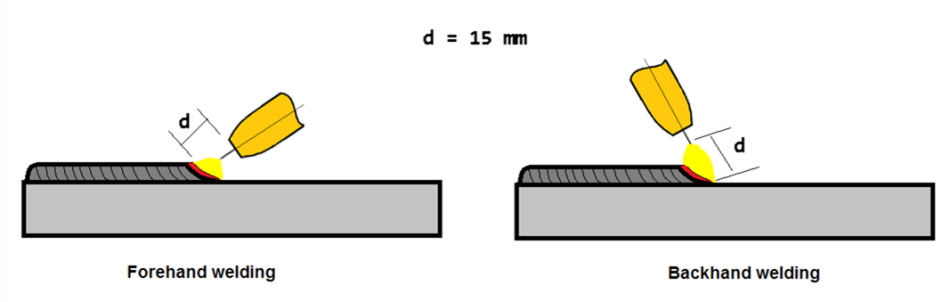


Figure 11.3 Welding technique

What we propose to you is to practice two beads with the backhand strategy and another two using the forehand strategy since it is very important for you to learn how to weld on both ways. To make the practice, you have to follow the recommended parameters in the WPS. It is important to you to familiarize with the WPS format, since it is used Europe-wide. It allows you to use the WPS with independence of the country or language.

Right now, in this practice, you only have to control the remarked parameters.

rrent A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	He inp kJ/c
)-140	19-20	DC+	4 - 5	20-30	--

Pulsed welding details: N.A.
Piece/contact tube distance: 12 mm
Plasma arc welding details: N.A.
Inclination angle: 75 °
Work angle:90°

Figure 11.4 Welding parameters

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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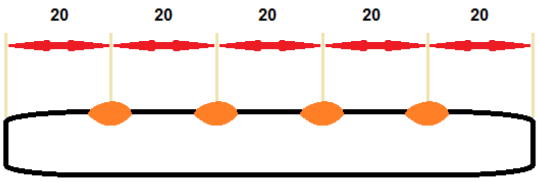
Welding procedure specification: WPS-135-011

WPQR number: WPQR-135-011
Manufacturer: CESOL
Mode of metal transfer: Short arc
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

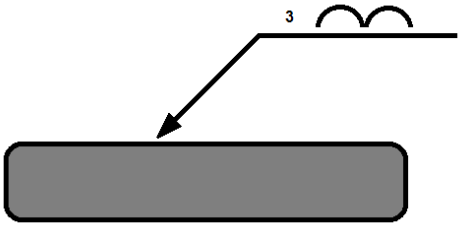
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1-4	135	1	Straight	120-140	19-20	DC+	4 - 5	20-30	---

Description and brand of welding consumables: EN ISO 14341-A-G3Si
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: M20
- Backing: N.A.
Gas flow rate:
- Protection: 12 l/min
- Backing: N.A.
Tungsten electrode, type, size: N.A.
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Piece/contact tube distance: 12 mm
Plasma arc welding details: N.A.
Inclination angle: 75 °
Work angle:90°

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ERASMUS + KA2: 2019-1-RO01-KA203-063486

WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: WPS-GMAW-011 Date: 2015/05/13 Supporting PQR Nº: PQR-GMAW-011

Revision Nº: 0 Date: 2015/05/13

Welding processes: GMAW (Gas Metal Arc Welding) Type: Semiautomatic

JOINTS (QW-402)

Joint design: Build-up

Root spacing: ---

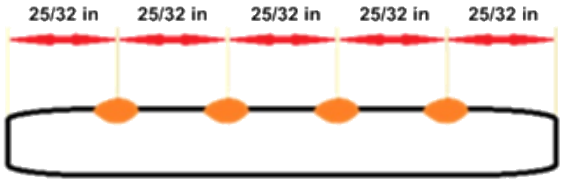
Backing: Yes: X No: ☐

Backing material (Type): ---

X Metal --- Non fusing metal

--- Nonmetallic --- Other

Details:



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 23/64 – 7/16 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: X No: ☐

Other: ---

FILLER METALS (QW-404) 1-4

Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	0.04 in	
Filler metal product form:	Bare	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 1G

Welding progression: Up: ☐ Down: ☐

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 M20	X	3 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-4	GMAW	A5.18	0.04 in	DC+	120-140 A	155-200 ipm	---	19-20 V	8-12 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: ---

Mode of metal transfer for GMAW (FCAW): Short circuiting

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/32 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: 15/32 in

Multiple or single pass (per side): Single

Multiple or single electrodes: Single electrode

Electrode spacing: ---

Peening: ---

Other: ---

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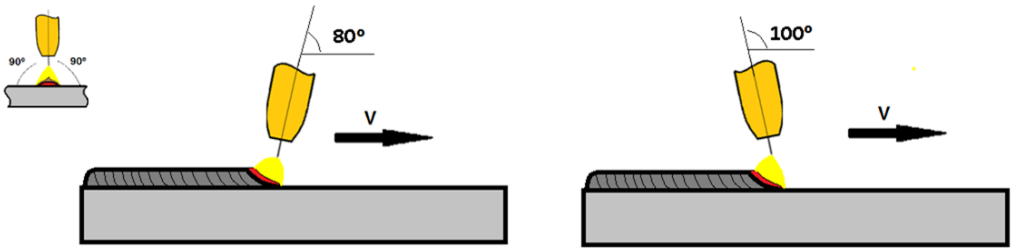
11.4. GMAW: Test Plate – Recharge in horizontal position

11.4.1. Objective of the practice

The purpose of the practice is to perform four overlay beads on a plate (two by forehand welding and two by backhand welding) keeping constant the inclination angle and the travel speed.

11.4.2. How to do it

The inclination angle has to be 80º from the beginning to the end (in the case of backhand welding. For forehand welding the inclination angle should be 100º). You also have to keep constant the gun-piece separation as well as the travel speed.



Backhand welding *Forehand welding*

Figure 11.5 Welding technique

It is important to review the workshop subject where the differences between backhand welding and forehand welding are explained.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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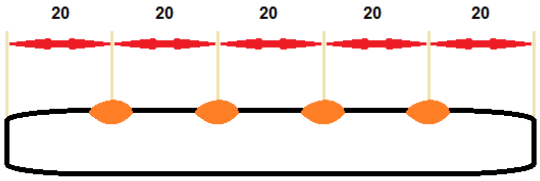
Welding procedure specification: WPS-135-012

WPQR number: WPQR-135-012
Manufacturer: CESOL
Mode of metal transfer: Short arc
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

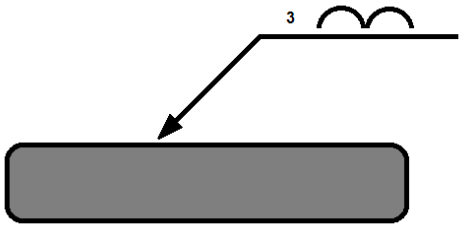
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1-4	135	1	Straight	120-140	19-20	DC+	4 - 5	20-30	---

Description and brand of welding consumables: EN ISO 14341-A-G3Si
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: M20
- Backing: N.A.

Gas flow rate:
- Protection: 12 l/min
- Backing: N.A.

Tungsten electrode, type, size: N.A.
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Piece/contact tube distance: 12 mm
Plasma arc welding details: N.A.
Inclination angle: 80°
Work angle: 90°

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ERASMUS + KA2: 2019-1-RO01-KA203-063486

WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: WPS-GMAW-012 Date: 2015/05/13 Supporting PQR Nº: PQR-GMAW-012

Revision Nº: 0 Date: 2015/05/13

Welding processes: GMAW (Gas Metal Arc Welding) Type: Semiautomatic

JOINTS (QW-402)

Joint design: Build-up

Root spacing: ---

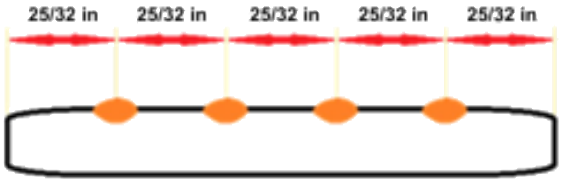
Backing: Yes: X No: ☐

Backing material (Type): ---

X Metal --- Non fusing metal

--- Nonmetallic --- Other

Details:



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 23/64 – 7/16 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: X No: ☐

Other: ---

FILLER METALS (QW-404) 1-4

Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	0.04 in	
Filler metal product form:	Bare	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 1G

Welding progression: Up: ☐ Down: ☐

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 M20	X	3 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-4	GMAW	A5.18	0.04 in	DC+	120-140 A	155-200 ipm	---	19-20 V	8-12 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: ---

Mode of metal transfer for GMAW (FCAW): Short circuiting

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/32 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: 15/32 in

Multiple or single pass (per side): Single

Multiple or single electrodes: Single electrode

Electrode spacing: ---

Peening: ---

Other: ---

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11.5. GMAW: Test Plate – Overlay in the vertical position

11.5.1. Objective of the practice

The aim of this practice is to get initiated in the vertical uphill issues.

11.5.2. How to do it

Control the gun-piece distance and the orientation as the welding puddle tends to slip and sag. Once this is done and before starting, review the parameters in the WPS and the indications: Slope (5-10 ° above horizontal, around 100º in the travel direction, see figure) stick-out and current, straight forward movement. The proper travel speed will be acquired soon if you do before a test where you first ascend slowly and then faster.

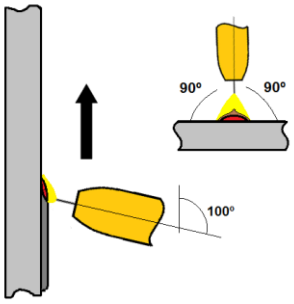


Figure 11.6 Welding technique

Use the gun with no oscillation and, in the case of moving it, do it carefully. Try to give it a slight lateral movement as you go up, and choose the movement you feel more comfortable with to get the best result. It is essential to find the combination of travel speed + voltage + wire feed speed.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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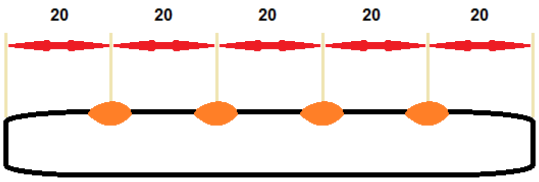
Welding procedure specification: WPS-135-021

WPQR number: WPQR-135-021
Manufacturer: CESOL
Mode of metal transfer: Short arc
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

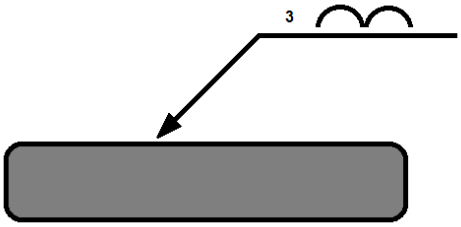
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PF.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 4	135	1	Straight	110-120	18-19	CC+	4-4.5	15-20	---

Description and brand of welding consumables: EN ISO 14341-A-G3Si
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: M20
- Backing: N.A.
Gas flow rate:
- Protection: 15 l/min
- Backing: N.A.
Tungsten electrode, type, size: N.A.
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Piece/contact tube distance: 12 mm
Plasma arc welding details: N.A.
Inclination angle: 100°
Work angle:90°

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

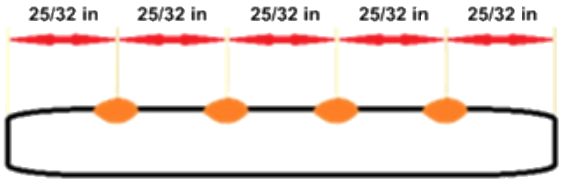
Welding procedure specification Nº: WPS-GMAW-021 Date: 2015/05/13 Supporting PQR Nº: PQR-GMAW-021

Revision Nº: 0 Date: 2015/05/13

Welding processes: GMAW (Gas Metal Arc Welding) Type: Semiautomatic

JOINTS (QW-402)

Details:



Joint design: Build-up

Root spacing: ---

Backing: Yes: X No: ☐

Backing material (Type): ---

X Metal --- Nonfusing metal

--- Nonmetallic --- Other

BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 23/64 – 7/16 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: X No: ☐

Other: ---

FILLER METALS (QW-404) 1-4

Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	0.04 in	
Filler metal product form:	Bare	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 3G

Welding progression: Up: X Down:

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 M20	X	3 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-4	GMAW	A5.18	0.04 in	DC+	110-120 A	155-175 ipm	---	18-19 V	6-8 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: ---

Mode of metal transfer for GMAW (FCAW): Short circuiting

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/32 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: 15/32 in

Multiple or single pass (per side): Single

Multiple or single electrodes: Single electrode

Electrode spacing: ---

Peening: ---

Other: ---

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11.6. GTAW: Test Plate – Overlay in flat position

11.6.1. Objective of the practice

Make four passes without filler metal on a sheet, while maintaining a constant arc length

11.6.2. How is it done?

Now that we know establish the arc, you will begin to make passes without filler metal. We are going to make passes without filler metal on a sheet and we will increase the number of factors to control. This practice has to be done with sheet thickness of 10 mm, using a tungsten 2.4 millimeters in diameter. Before starting practice, pay special attention to the superficial state that have the sheet. To carry out this practice of welding without filler metal, the plate has to be free of rust, grease, paint, etc.

11.6.3. Beginning?

Remember the purpose of this practice: "Keeping the arc length as we move forward in the welding". Look at Figure 11.7. In this practice you must establish the arc and move it in the direction of welding, keeping the height and angle of the gun steady as you go. Once you have developed sufficient skill in this exercise, will explain how to provide the filler metal to produce the beads of welds.



In short: The purpose of this first practice, is to make 4 passes without filler metal material, keeping the arc length, and go advancing to a suitable speed.

Figure 11.7 Welding technique

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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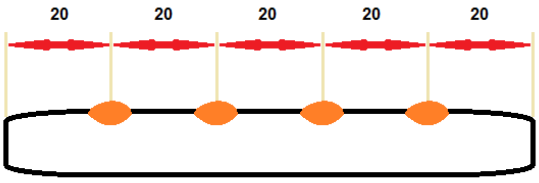
Welding procedure specification: WPS-141-011

WPQR number: WPQR-141-011
Manufacturer: CESOL
Mode of metal transfer: ---
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

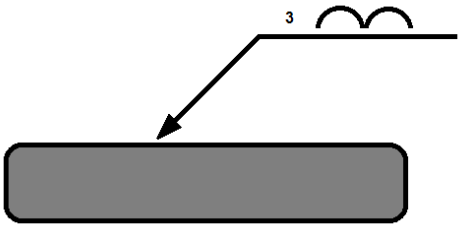
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 2	141	N.A	Straight	90-105	---	CCPD	---	15-20	---
3 - 4	141	N.A	Straight	105-120	---	CCPD	---	15-20	---

Description and brand of welding consumables: EN ISO 636 - A - W42 5 W3Si1
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: I1
- Backing: N.A.
Gas flow rate:
- Protection: 8-12 l/min
- Backing: N.A.
Tungsten electrode, type, size: WLa10, 1.6 mm
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Arc length: 2 mm/3 mm
Plasma arc welding details: N.A.
Inclination angle: 80 °
Working angle: 90 °

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: WPS- GTAW-011 Date: 2015/05/13 Supporting PQR Nº: PQR- GTAW-011

Revision Nº: 0 Date: 2015/05/13

Welding processes: GTAW (Gas Tungsten Arc Welding) Type: Manual

JOINTS (QW-402)

Joint design: Build-up

Root spacing: ---

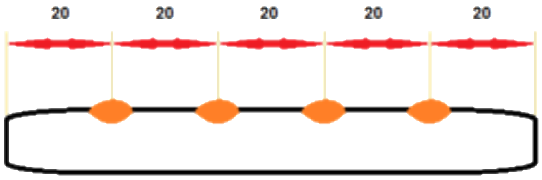
Backing: Yes: X No: ---

Backing material (Type): ---

X Metal --- Nonfusing metal

--- Nonmetallic --- Other

Details:



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 25/64 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: --- No: ---

Other: ---

FILLER METALS (QW-404)

	1	
Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	---	
Filler metal product form:	Rod	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 1G

Welding progression: Up: --- Down: ---

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 I1	X	4 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-2	GTAW	A5.18	---	DC-	90 - 105 A	---	---	---	6 - 8 ipm	---
3-4	GTAW	A5.18	---	DC-	105 - 120 A	---	---	---	6 - 8 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: WLa10, 3/32 in.

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/64 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Single

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: ---

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11.7. GTAW: Test Plate – Overlay in horizontal position

11.7.1. Objective of the practice

The aim of this practice is to initiate you in the problem of welding in horizontal position.

11.7.2. How is it done?

To make these beads you must be positioned in opposite side your dominant hand. You must position the torch at an angle of about 80 degrees with the vertical, as shown in the figure, to avoid that, the weld pool can sag. The torch also has to be maintained at about 100 degrees in the forward direction so we can see clearly the weld to control it at will.

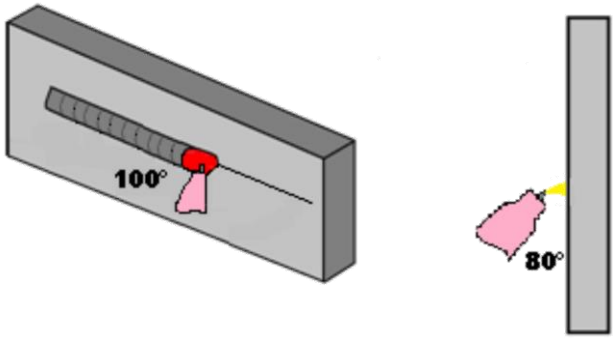


Figure 11.8 Welding technique

The utmost caution to be taken in carrying out this exercise is that the weld pool does not sag what is very common in this welding position. We will make four passes without filler metal.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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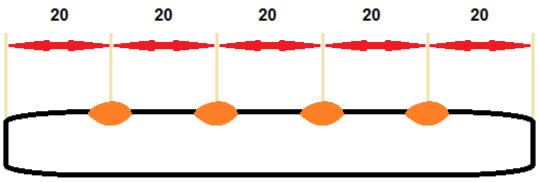
Welding procedure specification: WPS-141-031

WPQR number: WPQR-141-031
Manufacturer: CESOL
Mode of metal transfer: ---
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

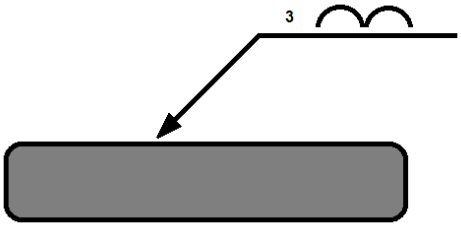
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 2	141	N.A	Straight	90 - 105	---	CCPD	---	12-15	---
3 - 4	141	N.A	Straight	105-120	---	CCPD	---	13 -16	---

Description and brand of welding consumables: EN ISO 636 - A - W42 5 W3Si1
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: I1
- Backing: N.A.
Gas flow rate:
- Protection: 8-12 l/min
- Backing: N.A.
Tungsten electrode, type, size: WLa10, 2,4 mm
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Arc length: 2.0 mm/ 3.0 mm
Plasma arc welding details: N.A.
Inclination angle: 80 °
Working angle: 90 °

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: WPS- GTAW-031 Date: 2015/05/13 Supporting PQR Nº: PQR- GTAW-031

Revision Nº: 0 Date: 2015/05/13

Welding processes: GTAW (Gas Tungsten Arc Welding) Type: Manual

JOINTS (QW-402)

Details:

Joint design: Built-up

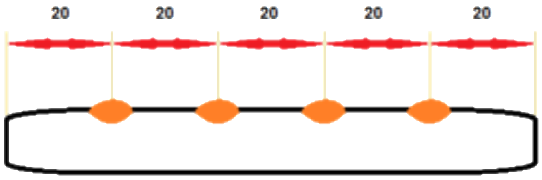
Root spacing: ---

Backing: Yes: X No:

Backing material (Type):

X Metal --- Non-fusing metal

--- Nonmetallic --- Other



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 25/64 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: --- No: ---

Other: ---

FILLER METALS (QW-404)

	1	
Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	3/32 in	
Filler metal product form:	Bare	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in.	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 2G

Welding progression: Up: --- Down:

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 I1	---	4 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-2	GTAW	A5.18	3/32 in	DC-	90 - 105 A	---	---	---	4.7 - 5.9 ipm	---
3-4	GTAW	A5.18	3/32 in	DC-	105 - 120 A	---	---	---	5.1-6.3 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: WLa10, 3/32 in.

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/64 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Single

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: ---

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11.8. GTAW: Test Plate – Overlay in vertical upward position

11.8.1. Objective of the practice

The aim of this practice is to get you started on the problem of welding in vertical upward.

11.8.2. How is it done?

Basically, we have to do the same as in past practices, that is, control the arc length and orientation of the torch. The torch must be placed in an orientation as shown in the figure.

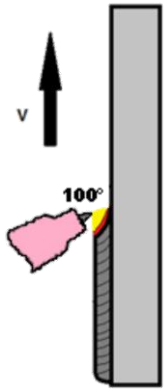


Figure 11.9 Welding technique

You have to put yourself on the left of surfacing, (if you are left, on the right) and your eyes have to be a little higher than the end of the joint in order to have a good vision from the beginning to the end. We will make four surfacing of material without filler metal with an electrode of diameter 2.4mm. We employ a slight oscillation of 1mm. This slight oscillation is used to make it more comfortable ascend with a uniform movement considering that this oscillation is negligible, that is, we use a technique of stringer pass.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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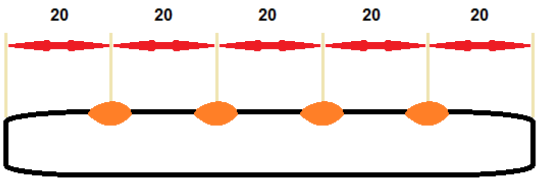
Welding procedure specification: WPS-141-021

WPQR number: WPQR-141-021
Manufacturer: CESOL
Mode of metal transfer: ---
Joint type and weld type: Overlay
Welder ---
Coupon test: ---

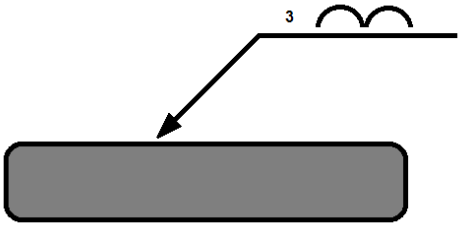
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 10
Outer diameter (mm): N.A.
Welding position: PA.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1 - 2	141	N.A	Straight	90 - 105	---	CCPD	---	12 - 15	---
3 - 4	141	N.A	Straight	105 - 120	---	CCPD	---	14 - 17	---

Description and brand of welding consumables: EN ISO 636 - A - W42 5 W3Si1
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: I1
- Backing: N.A.
Gas flow rate:
- Protection: 8-12 l/min
- Backing: N.A.
Tungsten electrode, type, size: WLa10, 2,4 mm
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Arc length: 1,5 mm / 2.5 mm
Plasma arc welding details: N.A.
Inclination angle: 80 °
Working angle: 90 °

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

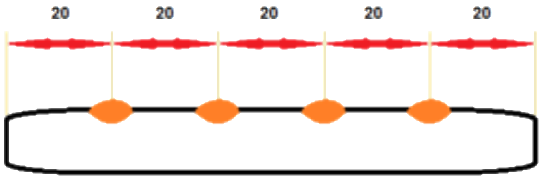
Welding procedure specification Nº: WPS- GTAW-021 Date: 2015/05/13 Supporting PQR Nº: PQR- GTAW-021

Revision Nº: 0 Date: 2015/05/13

Welding processes: GTAW (Gas Tungsten Arc Welding) Type: Manual

JOINTS (QW-402)

Details:



Joint design: Build-up

Root spacing: ---

Backing: Yes: X No:

Backing material (Type):

X Metal --- Non-fusing metal

--- Nonmetallic --- Other

BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 25/64 in.

Base metal: Groove: X Fillet: ---

Maximum pass thickness ≤ ½ in. (13mm) Yes: --- No: ---

Other: ---

FILLER METALS (QW-404)

	1	
Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	---	
Filler metal product form:	---	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	1/8 in	
Fillet:	---	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: 3G

Welding progression: Up: X Down: ---

Positions of fillet: ---

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 I1	X	4 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1-2	GTAW	---	---	DC-	90 - 105 A	---	---	---	4.7 - 5.9ipm	---
3-4	GTAW	---	---	DC-	105 - 120 A	---	---	---	5.5-6.7 ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: WLa10, 3/32 in.

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/64 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Single

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: ---

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11.9. GTAW: Plate T-Joint. Fillet. 1F/PA

11.9.1. Objective of the practice

The aim of this practice is initiate us into the fillet welding by TIG process.

11.9.2. How is it done?

In order to make this fillet welding, it is essential that the placement and orientation of both the pistol and the filler metal rod are correct. You have to control the following aspects.

1. All times, the torch must point to the edge of intersection of the pieces, otherwise you shall melt more a piece than the other and the bead will be asymmetric.
2. Torch must be oriented at an angle of 45 work, that is to "attack" the two pieces alike. Really we oscillate the torch between the two pieces, taking into account two factors:
    a. The piece that makes base, has twice the area to dissipate heat and it will need more heat to melt.
    b. The piece that makes the base, by the fact that is under, will tend to receive more of the weld pool by gravity.
3. The torch should slope slightly in the forward direction. Approximately 100°, as shown in fig 1.
4. The filler metal rod must be inclined about 10 ° with respect to the direction of welding so as to form approximately a 90 ° angle with the torch.
5. You must advance at a constant speed, so that the bead you generate remains as homogeneous as possible.
6. Do not forget to keep an adequate length of arc, as you have seen in the theory of the workshop.

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A tip to adjust the size of the tungsten is out of the nozzle when making fillet welding, is to do it with the equipment off and as follows.

The nozzle is placed in contact with both sides of the pieces that form the angle so that we can appreciate the distance between the nozzle and the board that we will perform. After we will place too the rod of filler metal, just in the joint to get an idea of the size that will have the bead that will be performed. Finally, we adjust the length of the tungsten which is outside of the nozzle to avoid touching the weld pool while performing welding.

7. In practice you will see that you have less visibility in a fillet welding (FW), therefore it is often advisable if the standard and the geometry of joint permits it, it mounts the torch with one ceramic wider nozzle, increase shielding gas flow and extracts the electrode a little more. Thus, it remains protected the joint union and allows greater visibility.

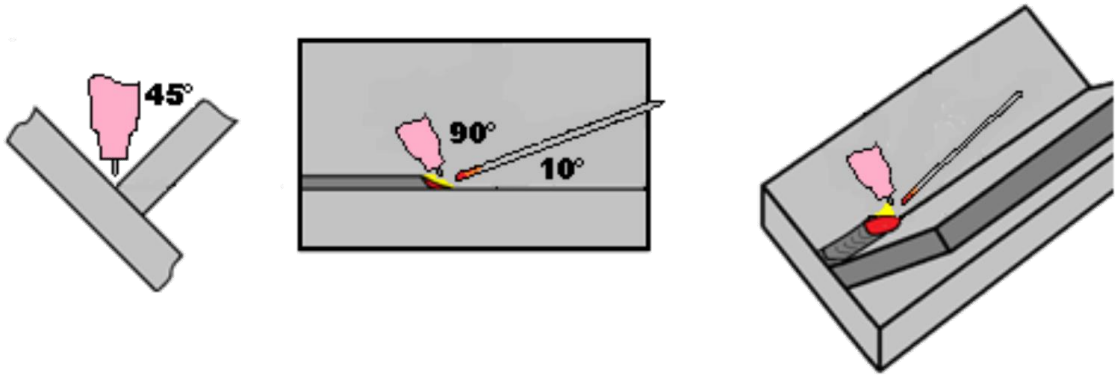


Figure 11.10 Angles of torch and filler metal rod in fillet welding.

Pay attention to the SOLDAMATIC signals while you are doing the practice. It will help you to correct your mistakes. Try to position yourself correctly and to do it naturally and 'automatically' as soon as possible, so that you can concentrate on the new part of each practice.

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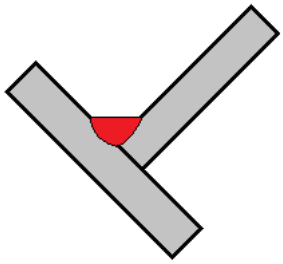
Welding procedure specification: WPS-141-041

WPQR number: WPQR-141-041
Manufacturer: CESOL
Mode of metal transfer: ---
Joint type and weld type: FW
Welder ---
Coupon test: ---

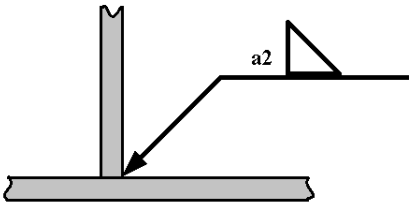
Preparation and cleaning method: Grinder and brush
Base metal designation: EN 10025-2 S275JR
Base metal thickness (mm): 3
Outer diameter (mm): N.A.
Welding position: PA.

Details of the weld preparation (sketch):

Welding design



Welding symbol



Welding details

Pass	Welding process	Filler metal size ϕ mm	Technique	Current A	Voltage V	Current type and polarity	Wire feed speed m/min	Travel speed cm/min	Heat input kJ/cm
1	141	2.4	Straight	95-110	---	CCPD	---	9 -12	---

Description and brand of welding consumables: EN ISO 636 - A - W42 5 W3Si1
Special drying requirements: N.A.

Gas/flux designation:
- Protection: EN ISO 14175: I1
- Backing: N.A.
Gas flow rate:
- Protection: 8-12 l/min
- Backing: N.A.
Tungsten electrode, type, size: WLa10, 1,6 mm
Gouging/backing details: Base metal.
Preheating temperature: 15 °C
Interpass temperature: N.A.
Postheating: N.A.
Preheating temperature maintenance: N.A.
Postweld heat treatment and/or aging: N.A.

Other information: N.A

Oscillation: amplitude: N.A.

Pulsed welding details: N.A.
Arc length: 2.0 mm/ 3.0 mm
Plasma arc welding details: N.A.
Inclination angle: 80 °
Working angle: 45 °

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WPS according to ASME IX (Form QW-482. Page 1)

Organization name: CESOL By: Larry Smith

Welding procedure specification Nº: WPS- GTAW-041 Date: 2015/05/13 Supporting PQR Nº: PQR- GTAW-041

Revision Nº: 0 Date: 2015/05/13

Welding processes: GTAW (Gas Tungsten Arc Welding) Type: Manual

JOINTS (QW-402)

Details:

Joint design: ---

Root spacing: ---

Backing: Yes: X No: ---

Backing material (Type): ---

X Metal --- Non-fusing metal

--- Nonmetallic --- Other



BASE METALS (QW-403)

P-Nº: 1 Group Nº: --- to P-Nº: 1 Group Nº: ---

Specification and type/grade or UNS Number: ---

to specification and type/grade or UNS Number: ---

Chemical analysis and Mechanical properties: ---

to chemical analysis and Mechanical properties: ---

Thickness range: 5/64in.

Base metal: Groove: --- Fillet: X

Maximum pass thickness ≤ ½ in. (13mm) Yes: --- No: ---

Other: ---

FILLER METALS (QW-404)

	1	
Specification Nº (SFA):	SFA-5.18	
AWS Nº (Class):	ER 70S-6	
F-Nº:	6	
A-Nº:	1	
Size of filler metals:	3/32 in	
Filler metal product form:	Bare	
Supplementary filler metal:	---	
Weld metal:		
Deposited thickness:		
Groove:	---	
Fillet:	5/64in.	
Electrode-flux (Class):	---	
Flux type:	---	
Flux trade name:	---	
Consumable insert:	---	
Other:	---	

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WPS according to ASME IX (Form QW-482. Page 2)

POSITIONS (QW-405)

Positions of groove: ---

Welding progression: Up: --- Down: ---

Positions of fillet: 1F

Other: ---

PREHEAT (QW-406)

Preheat temperature, minimum: ≥ 60 F

Preheat temperature, maximum: ---

Preheat maintenance: ---

Other: ---

POSTWELD HEAT TREATMENT (QW-407)

Temperature range: ---

Time range: ---

Other: ---

GAS (QW-408)

	Percent composition		
	Gases	Mixture	Flow rate
Shielding:	AWS A5.32 I1	---	4 gal/min
Trailing:	---	---	---
Backing:	---	---	---
Other:			

ELECTRICAL CHARACTERISTICS (QW-409)

Weld passes	Process	Filler metal		Current type and polarity	Amps (Range)	Wire feed speed (Range)	Energy of power (Range)	Volts (Range)	Travel speed (Range)	Other
		Classification	Diameter							
1	GTAW	A5.18	3/32 in	DC-	95-110 A	---	---	---	3.5 - 4.7ipm	---

Pulsing current: --- Heat input (max.): ---

Tungsten electrode size and type: WLa10, 3/32 in.

Mode of metal transfer for GMAW (FCAW): ---

Other: ---

TECHNIQUE (QW-410)

String or weave bead: String

Orifice, nozzle, or gas cup size: 25/64 in

Initial and interpass cleaning: Grinding and brushing

Method of back gouging: ---

Oscillation: ---

Contact tube to work distance: ---

Multiple or single pass (per side): Single

Multiple or single electrodes: ---

Electrode spacing: ---

Peening: ---

Other: ---

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Digital **Man**ufacturing Master's degree to set specialists for the dawn of the industry 4.0



Project number:

2019-1-RO01-KA203-063486

Quality Assurance and Quality Control in AM

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2 Objectives

This module will enable students to understand the Importance of Quality Management, Standards, Quality Control and Measurement in metal Additive Manufacturing.

2.1 Learning outcomes

On successful completion of this module a student should be able to:

1. Identify Understand the concept of part quality.
2. Understand how part quality is measured.
3. Identify all the factors which can affect part quality.
4. Understand the relationship between standards and use standards to achieve required part quality.
5. Identify the basic principles of the different NDT techniques.
6. Understand the probability of occurrence of the different defect types for a selection of materials and AM techniques.
7. Assess the potential of each technique for practical applications.
8. Identify appropriate ND techniques for AM parts,
9. Select the appropriate NDT techniques for analysing the quality of MAM parts.
10. Define the materials mechanical properties.
11. Outline the most common destructive tests.
12. Determine the metals mechanical properties regarding each destructive test results.
13. Select the appropriate destructive test to evaluate the MAM part properties.
14. Interpret the test results and take decisions.

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2.2 Introduction

Technology is changing the way people live, work, and do business. Digitalisation and automation are framing our future. This creates new and exciting opportunities, but at the same time challenges.

Interest in additive manufacturing (AM) is continuing to increase year-on-year across many different industrial sectors as it can provide significant design flexibility for generating highly complex components. However, present barriers preclude the potential of additive processes from performing optimally. Some of the barriers/challenges are recognised as: i) development of standard procedures for powder recyclability to potentially reduce direct manufacturing cost and provide a positive impact on the sustainability of additive processes; ii) finishing features such as internal pathways or lattices which still present a huge barrier as good surface quality may be a critical variable for certain applications within medical and aerospace industries; and iii) geometric limitations, particularly for Directed Energy Deposition (DED) AM methods. Therefore, eliminating any additional post processes for finishing operations could be beneficial for the efficiency of these additive processes. These challenges are still under investigation, particularly for manufacturing small and medium size components [1].

3 Importance of Quality Management, Standards, Quality Control and Measurement Sciences in Additive Manufacturing

Despite the growth of AM processes in the recent years, the pace at which consensus standards and the measurement science, upon which they are based, are being developed hasn't mirrored the accelerated evolution of the technologies.

For AM to be adopted in an even wider scale, most organizations require a more sustainable and feasible approach to qualifying and certifying parts. Machine and material manufactures seek to differentiate their products' capabilities based on their ability to print high-quality parts. Many argue that quality assurance (QA) remains the biggest issue in AM.

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Currently there is the need to: comparatively benchmark the performance of different additive processes; improve the buyer/seller dynamic by enabling increasingly accurate specification of production requirements and offer the research community a mechanism to provide repeatable results capable of independent test and verification. The previous points are only possible to meet through the establishment of uniform and consistently applied language, specifications, test methods, classifications, and practices for industry consumption – Standards.

The value of a consensus standards program is beyond contestation, but within the rapidly evolving world of AM, not just any program will do. To be truly effective, standards development must be nimble, flexible, open, transparent, living and timely. The marriage of these attributes creates an environment where standards development for AM technologies will thrive, putting to rest the contention that standards stifle innovation [1].

The standards for AM were developed by its own standards bodies independently, prior to any form of collaboration. However, independent works from different bodies resulted in duplicate standards. To rectify the situation, ASTM and ISO/TC 261 came to a cooperation agreement to jointly develop international standards for AM.

Standards are grouped into key categories to achieve a common structure for easy reference. The approved structure, that can be seen in Figure 1, consists of three levels, which are:

- General standards – standards that specify general concepts, common requirements, or are generally applicable to most type of AM materials, processes and applications.
- Category standards – standards that specify requirements that are specific to a material category or process category.
- Specialized standards – standards that specify requirements that are specific to a material, process or application.

Qualification (action of proving that any premises, systems and items of equipment work correctly and actually lead to the expected results) and validation (action of proving and documenting that a process consistently produces a product meeting its predetermined specifications and quality attributes – standards) are important in establishing and maintaining a controlled quality management system during manufacturing. A validated manufacturing process can be monitored continuously through statistical process control approach to ensure product quality. Generally, process qualification includes the following

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aspects of manufacturing: facility, utilities, equipment, personnel, manufacturing process flow and process monitoring.

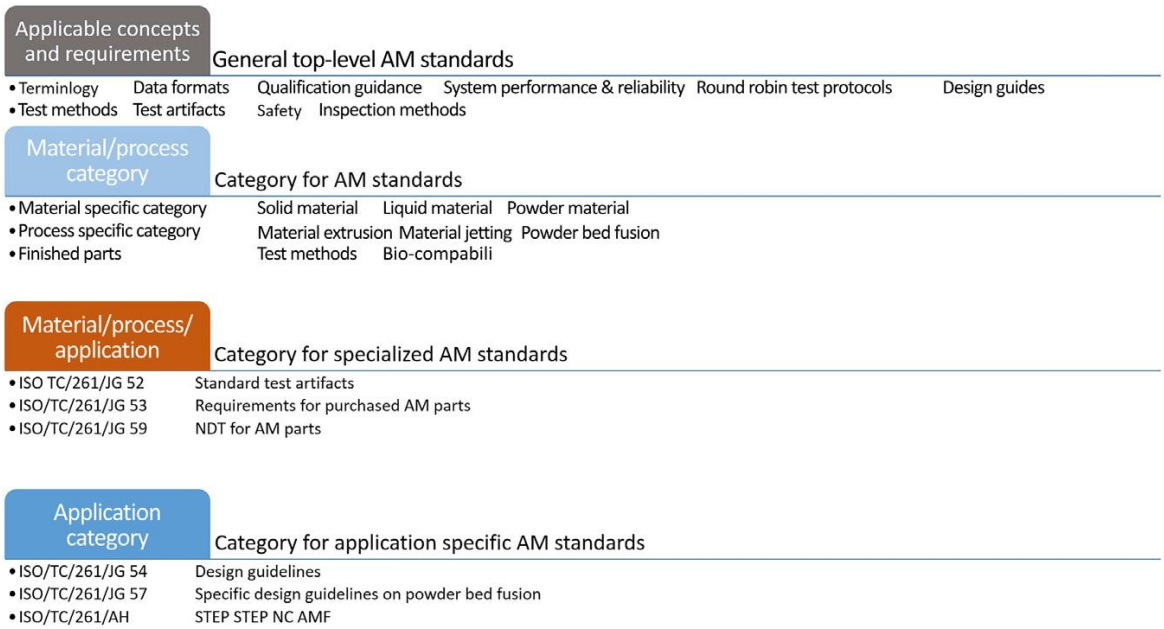


Figure 1– Structure of AM Standards [1].

A typical equipment qualification (EQ) plan consists of the stages illustrated in Figure 2, and summarised below:

1. The first step of the continual loop is the design qualification (DQ) – defines the functional and operational specifications of the equipment and details the conscious decisions in the selection of the supplier. Evaluate if the equipment comes with the required functions and performance criteria to meet user requirements.
2. Installation qualification (IQ) – establishes that the equipment is as specified and is properly installed.
3. Operation qualification (OQ) – is needed during the scaling-up from product development to actual manufacturing equipment or when optimizing the process by testing different operating parameters.
4. Performance qualification (PQ) – is the process of demonstrating that the equipment consistently performs as intended and meets all preestablished acceptance criteria.

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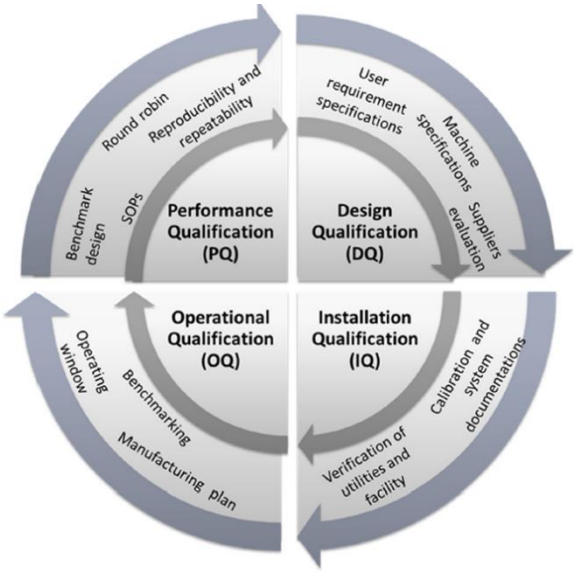


Figure 2- Four stages of qualification in a typical equipment qualification plan [1].

Another important consideration in the qualification of AM equipment is the validation of the computer system. The quality of a part manufactured is directly related to the quality of the input file and hence the processing software of the machine.

In order to a part be certified fit for use, there needs to be sufficient confidence that the components are free from any undermined defects that may be induced during the AM process. The ideal method to overcome this concern is to be able to continuously monitor and control the AM process, identify causes of defects, make necessary in-process corrections or amendments and provide data deterministic of the quality of the fabricated parts.

Effective in situ/online closed loop monitoring and feedback systems are deemed essential for increased adoption of AM processes for industrial applications. Through effective process monitoring, optimized parameters can be derived through analysis and interpretation of the measurements obtained. This can greatly improve process reproducibility, as well as better assurance of quality and reliability of the AM produced parts. Process control should also ensure the overall safety during manufacturing.

A framework that can assist an organization in planning their Quality Management System (QMS), based on everything expounded on this chapter, is a Plan-Do-Check-Act cycle (PDCA). A PDCA adapted, as an example, to suit the context of AM is shown in Figure 3:

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- **Plan** by establishing the objectives of the system and processes in AM, deliver results that meet the required standards and customer requirements.
- **Do** all the steps to ensure the manufacturing is set to reach what was planned. Ensure that you are using the right material and process parameters.
- **Check** and monitor processes, products and services, by performing the required measurements, against relevant company policies, objectives, requirements and standards and report results.

Act on what is reported and improve the performance if needed.

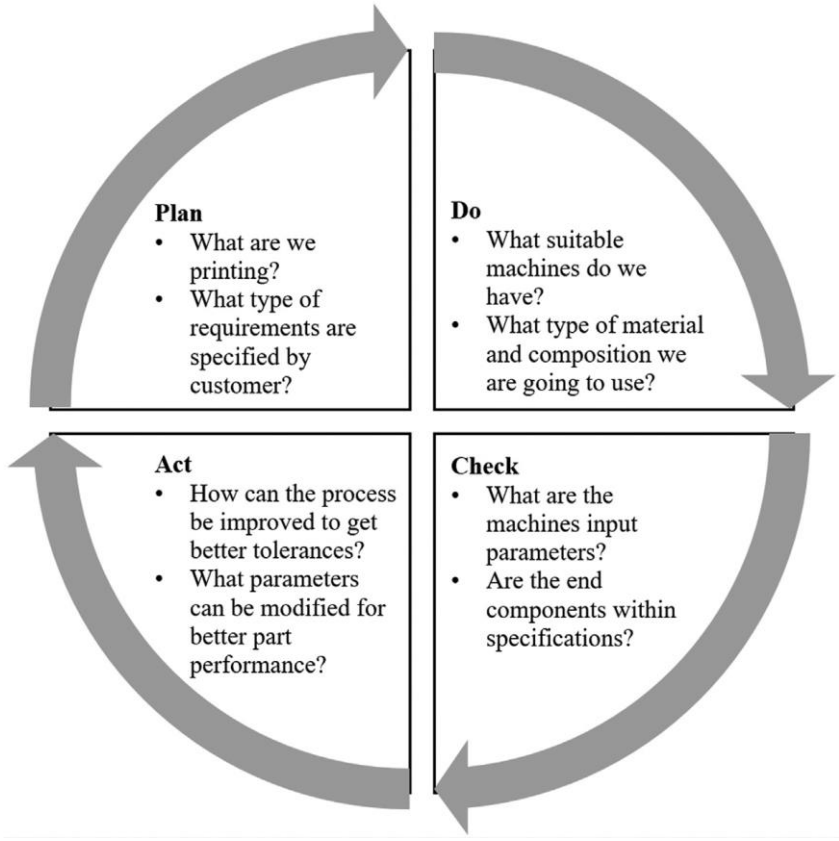


Figure 3 – Example of a PDCA cycle integrated with AM [1].

4 Standards in additive Manufacturing

4.1 Introduction: The need for standards

Standards are technical documents that define requirements, specifications, or guidelines to specify test procedures or quality and safety attributes of materials, products, processes and

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services. the lack of standards is an important barrier to the more general adoption of AM, mainly in those sectors under strict rules of regulation (medical, aerospace, automotive, etc.). Several factors influence the limited applicability of conventional standards to AM, being the anisotropy and the modification of mechanical properties, depending on the process parameters, the key issue to deal with (Puebla et al. 2012). Nevertheless, for the last years, several international organizations have been working on the development of new standards for AM (ASTM F42 since 2009, ISO TC261 since 2011 and CEN/TC 438 since 2015), with significant number of standards approved so far.

A relevant landmark for further standard development of AM standards resulted from the meeting held in Nottingham, UK, in July 2013, ISO TC261 and ASTM F42 where it was agreed to develop jointly AM standards. Another relevant highlight agreed between ISO TC261 and ASTM F42 was the general structure of how the developed standards should be fitted. In this structure, there are three levels and different target areas in each level (Monzon et al. 2014). From the top to the bottom, the levels are:

- General AM standards;
- Category AM standards;
- Specialized AM standards.

.

In 2013, the National Institute of Standards and Technology (NIST) created a roadmap to address challenges in metal AM concerning the following topics [1, 2]:

- AM materials.
- AM processes and equipment.
- Qualification and certification of materials, processes, and products.
- Modelling and simulation of AM.

4.1.1 Material qualification for metal AM

Material qualification for metal AM is still under development, with few available materials on the market, due to the lack of research on this topic. The quality of the printed part depends greatly on the quality of the material. Taking as an example the most common process in metal AM (Power Bed Fusion), the knowledge of raw materials cannot be applied

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to predict the final properties of an AM printed part, especially concerning the microstructure and the morphology of the powder. Currently, there is not enough information to create an adequate database for materials to ensure a proper cross reference, which leads to time-consuming iterative processes to determine the correct printing parameters [2].

Not only raw materials qualification can affect the final part, but also its quality. It is important to maintain the purity of metal powders during manufacturing, especially for highly demanding applications (aerospace, medicine, etc.), where the material cannot be contaminated at the risk of tempering with the final part. The contamination of a part happens before processing, during storage, transportation and handling. From the blending of two different powders in the build platform to the reuse of already processed materials, it can change the final properties of the part [3]. Testing methods and post-processing of a component is required to attain the desired properties and to assure the lack of contamination. As for any other manufacturing method, AM requires that the user follows certain rules of engineering design. Some, particularly valid for AM, are presented. This field is quite new and is in continuous development. The part's material properties are determined not only by the raw material, but also by the AM process as well, with the overall part quality being influenced by a variety of parameters. Therefore, material, build process, and engineering design cannot be regarded separately but rather all of them need to be addressed.

Anisotropic Properties: When materials properties are discussed, it is commonly assumed that the final parts will exhibit isotropic behaviour. Isotropic means constant characteristic properties in any direction and identical values at any point of the part's volume. Isotropic material behaviour is usually a requirement for traditional tool-based production and consequently provides the basis for engineering design calculations.

With AM processes, anisotropic part behaviour must be compensated in the part design phase and when the build parameters for AM are set. This requires information about the directional differences of the material properties. In many cases, this information is not readily available, and the proper calculation of the part is subject to experience.

Basic Materials: Nowadays AM techniques allow to process materials of all material classes, namely plastics, metals, and ceramics. The number of different materials within each material class is still quite limited, although this number has increased significantly over the

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last years and grows continually due to international research activities. The reason for the limited number of materials is that in most cases a simultaneous material- and process development is require. Therefore, AM materials are usually developed by or under the responsibility of the machine manufacturer who treats the material as a proprietary product and exclusively sells it to his machine customers. Some users are sceptical, mainly because of economic reasons; but on the other hand, this approach guarantees a proper build [5].

4.1.2 Qualification of additive manufacturing processes and equipment

When it comes to AM processes, there is a wide range of factors that can influence the structure of a part. The technology currently applied to measurement, monitoring and control is still on its initial phase and growing, where most is based on “open-loop” systems that need a manually input through human intervention. Faults occurred during printing are detected, based in a method of trial and error, and production is put on pause by the machine’s operator. Corrections and testing on the final part are usually necessary. By implementing a close-loop system, where feedback control is added to the planning and monitoring of the AM system, it is possible to provide higher quality parts with faster and reliable quality assurance. Measurements and active control of the process in real-time with the proper algorithm is important to achieve consistency of the part [1, 2].

A close-loop system is divided in three essential parts, planning the build, monitoring the build and feedback control. The first step it is achieved through simulation, which enables engineers to analyse different processes that occur during printing and use its data to plan and select the most successful part orientation and support structures [3].

In-process monitoring systems are crucial to detect defects in AM parts, such as voids, inclusions, high thermal gradients, etc., Sensors and camaras, measurement devices and algorithms can be used to measure and predict multiple aspects during fabrication, document the process and ensure the quality of the part. Note that the devices are subjected to calibration within a certain scope. It is also possible to predict and avert the likelihood of future defects using the available data. Here is a list of properties of AM components, which can be measured [2]:

- Dimensions.
- Geometry.

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- Roughness.
- Surface finish.
- Structural (microstructure and mesostructure).
- Defects (porosities, flaws, warpages, etc.).
- Energy source measurement (amount of energy to create a melt pool).
- Temperature range.

Sigma Labs is one of the companies currently on the market that offer a solution for in-process AM quality assurance. The PrintRite3D system is designed to discover potential anomalies that occur during laser-based Powder Bed Fusion (PBF) Systems and incorporates machine learning in conjunction with developed metrics to map those metrics to the post-process data. For instance, it analyses the melt pool and thermal signature of a laser in real-time using a sensor developed by Sigma Labs. This gives the ability to reduce post-production testing and costs by reducing printing failure. The company is also currently working on a solution for Direct Energy Deposition (DED) systems [6].

The feedback control is based on the ability to detect discrepancies during the printing process and automatically adjust the system to counteract, which enables manufactures to produce higher quality parts with complex and consistent geometries, surface finishes and greater assurance of performance properties [3

Post-processing, which refers to the final stages of part processing for application purposes, is usually manual. This may involve abrasive finishing, application of coating, chemical or thermal treatment of the part or the use of infiltration. Depending on the AM process or final application, different results in terms of accuracy can be achieved. Removal and cleanup are also included in this manufacturing stage. Regardless of the process, the part must be either separated from the baseplate or removed from excess material, such as secondary support material. Even though there are some methods to reduce human interference, it certainly increases the risk of damage of the part [7]. Identification and inspection, by checking a list of requirements may also be necessary to validate its quality, which can damage the workflow of a production chain. One way of reducing human error is to implement the concept of industry 4.0 for quality assurance. There are commercial tools that provide a

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workflow automation software that allows companies to streamline and manage their end-to-end additive manufacturing workflows. Its Digital Part Identification tool allows production engineers to automatically identify finished parts post-build, to compare them to requirements and prepare them for additional post-processing and delivery. It also allows users to track the rate of successful vs failed parts, with all failed parts automatically returned to the platform's internal production queue to be reproduced [8].

4.1.3 Qualification of additive manufacturing modelling and simulation

As previously mentioned, modelling and simulation can be considered the first part of the printing process. With physic-based simulations it is possible to forecast some of the proprieties presented in section 2.2 of the final part without producing it. Part distortion, excessive deformation and unsupported overhanging structures of an AM component are some of the issues that can be anticipated and avoided by simulations. Planning the build can lead to optimization of the process related to manufacturing cost and production time, determining the viability of creating a part reducing empirical trials [2]. By integrating a simulation software on the initial stages of production (design and planning) will help to eliminate guesswork [11].

To optimize the cost of manufacturing AM component parts, modelling and simulation of the component and the AM process by means of physics-based simulation will help to determine the feasibility of producing the end component without empirical trials. Potential issues that may arise during the AM process, such as excessive deformation, unsupported overhanging structures, etc. can be predicted by simulations and therefore to be addressed prior to actual fabrication. This will be only feasible if there are databases and predictive models that can be used for AM simulation before the parameters are imported over to the AM system.

With physics-based simulations, it is possible to predict the properties (microstructures, defects, surface topology, residual stress etc.) of the final component, without physically fabricating it. For example, part distortion, which is caused by poor temperature control or

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how the part is oriented, can be eliminated with a proper understanding of the process through simulation.

Although simulation software will cut time and cost by reducing the number of physical prints needed for empirical trials, it is only as good as the algorithms and models of AM elements input into the system. Until there are proper models developed for the simulation software, the AM community would have to resort to trial prints to determine fabrication. Feasibility [15].

4.2 Additive manufacturing: Standards Developments

Throughout the years, in addition to ASTM and ISO, many organizations have tried to reach global consensus by developing committees dedicated to additive manufacturing such as German Institute for Standardisation (DIN), the American Welding Society (AWS) and the Society of Automotive Engineers (SAE) International [9]. Focusing on the two main international organizations, ASTM Committee F42 on Additive Manufacturing Technologies was formed in 2009, following the following structure:

- F42.01 Test Methods.
- F42.04 Design.
- F42.05 Materials and Processes.
- F42.90 Executive.
- F42.91 Terminology.
- F42.94 Strategic Planning.
- F42.95 US TAG to ISO TC261.

Soon after, ISO Committee TC 261 on Additive Manufacturing Technologies was established in 2011 with a similar structure:

- ISO/TC 261/WG1 Terminology.
- ISO/TC 261/WG2 Methods, Processes, and Materials.
- ISO/TC 261/WG3 Test Methods.
- ISO/TC261/WG4 Data Processing.

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Table 1 and Figure 4 provide a list of some of the standards for metal AM under the care of ASTM F42 and ISO TC261, approved up to 2019, due to limited resources. Note that some are common between organizations, arranged by negotiations, where each part provides an input.

In 2013, ASTM F42 and ISO TC261 committees came together to create the development structure for standards presented in **Error! Reference source not found.**, centred around the subcommittees previously mentioned [10]. Note that the intent of this framework was not to limit the work of other standards organizations, but to provide a guideline. As shown, AM standards can be developed in three different levels:

- General top-level AM standards: General concepts, common requirements, generally applicable.
- Category AM standards: Specific to material or process category.
- Specialized AM standards: Specific to material, process or application.

Table 1 - List of current metal AM technology standards developed by ASTM F42 and ISO TC261.

Area	Organization	Standard	Title
Terminology	ISO	ISO 17296-2:2015	Additive manufacturing—general principles — part 2: overview of process categories and feedstock
	ISO / ASTM	ISO/ASTM 52900:2015	Additive manufacturing: general principles—terminology
		ISO/ASTM 52901:2017	Additive manufacturing – General principles – Requirements for purchased AM parts
	ASTM	ASTM F2792-12a	Standard Terminology for Additive Manufacturing Technologies
Materials and Processes	ASTM	ASTM F2924–14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium with powder bed fusion
		ASTM F3001–14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium ELI (Extra Low Interstitial) with powder bed fusion
		ASTM F3049–14	Standard guide for characterizing properties of metal powders used for additive manufacturing processes
		ASTM F3055–14a	Standard specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion
		ASTM F3056–14e1	Standard specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion
		ASTM F3184–16	Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion
		ASTM F3187–16	Standard guide for directed energy deposition of metals

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Test Methods	ISO	ISO 17296-3:2014	Additive Manufacturing -- General principles - Part 3: Main characteristics and corresponding test methods
	ISO / ASTM	ISO/ASTM 52921:2013	Standard terminology for additive manufacturing-coordinate systems and test methodologies
		ISO/ASTM 52902:2019	Additive manufacturing – Test artefacts – Standard guideline for geometric capability assessment of additive manufacturing systems
	ASTM	ASTM F2971–13	Standard practice for reporting data for test specimens prepared by additive manufacturing
		ASTM F3122–14	Guide for evaluating mechanical properties of metal materials made via additive manufacturing processes
Data and Design	ISO	ISO 17296-4:2014	Additive Manufacturing -- General principles -- Part 4: Overview of data processing
	ISO / ASTM	ISO/ASTM 52915:2016	Standard specification for additive manufacturing file format (AMF) Version 1.2
		ISO/ASTM 52910:2018	Additive manufacturing – Design – Requirements, guidelines and recommendations

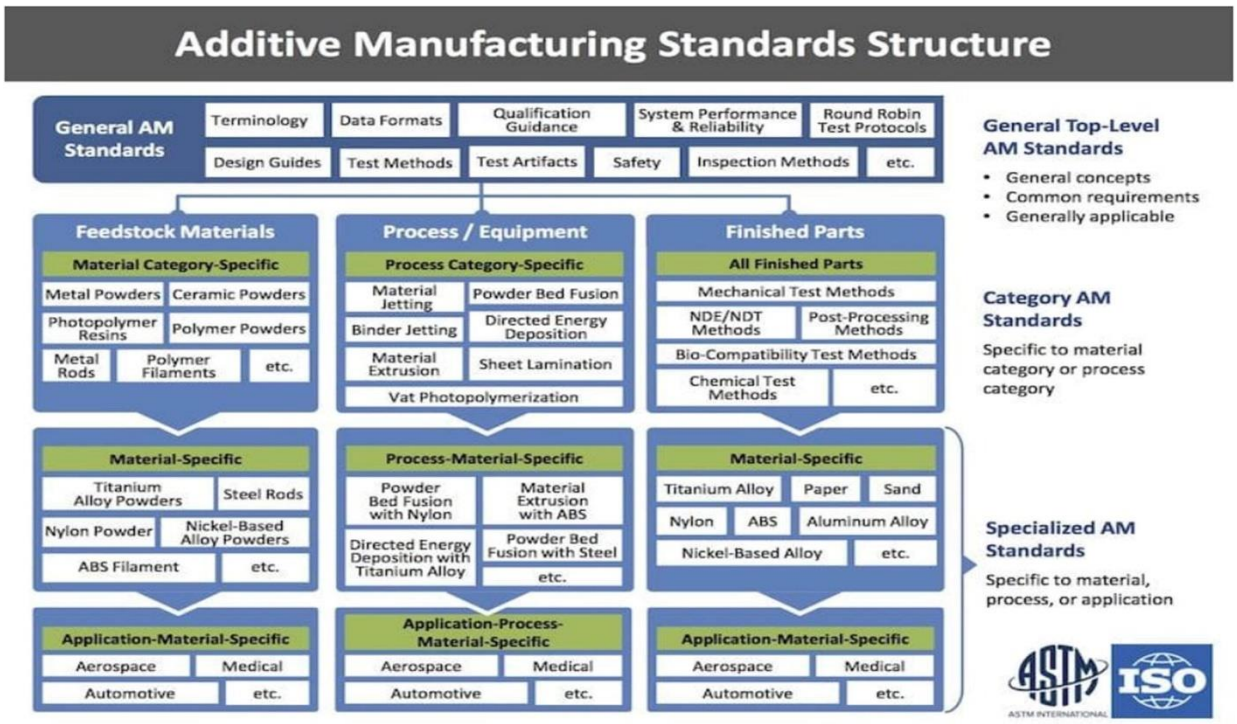


Figure 4 - Additive manufacturing standardization framework (developed and approved by ASTM F42/ISO TC261).

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4.3 Understand the principles of quality management.

4.3.1 General introduction to part quality

Quality enables a user to characterize and determine which product is better than the other. The quality level of products and services indicates not only their intended function and performance but also their perceived value and benefit to the customer. Despite the growing role of additive manufacturing (AM) in the industry, an appropriate quality management framework has yet to be established to ensure quality and process consistency in manufacturing. This can be achieved by focussing on continuous feedback on the existing process to refine and improve on the current practices. Therefore, in the AM industry, organizations are required to have a quality framework that addresses the new concerns specific to AM, in addition to adopting and committing to the approaches and expectations defined in quality management standards, such as (International Organization for standardization) ISO 9001

International quality standards are published by ISO and other relevant standards bodies, like American Society for Testing and Materials (ASTM). However, any qualification must be certified, being that step performed by the relevant national certification bodies, business management consultancy companies, and auditing companies. These auditing companies are usually accredited by a national body for auditing. To attain approval for an organization's quality management system (QMS), the organization must be audited by an accredited consultant company.

Therefore, any manufacturer using AM would have to be aware of and compliant to the requirements imposed by both their customers and the regulating authorities to be able to proclaim the quality of the parts manufactured. Organizations using AM as a service should adopt ISO 9001 to form the fundamental basis of proper documentation of the processes. Although this methodology does not guarantee product quality, it ensures that the process is performed in a quality manner. Thereby, as part of the adaptation of ISO 9001, the AM organization has to conduct reviews of their processes, products, and services to establish that they meet the following requirements:

- Requirements by customer;
- Requirements by organization;
- Requirements by statutory and regulatory bodies;

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- Contract / orders requirements;
- Requirements not yet specified but necessary for certain situations when the information is made known.

The operation of any AM process has to be planned by the organization to ensure that the products and services are in accordance with the defined requirements. The organization needs to set up the criteria for all AM processes, establish acceptance level of products and services, determine the resources required for operation, ensure proper implementation of process control, and document all relevant information necessary for the process to function with conformity. Some examples of criteria for part quality may include standards for:

- Size, length and angle dimensions – dimension tolerances standards;
- Geometrical tolerance;
- Appearance, surface finish/texture and colour;
- Tensile, Impact and Flexural Strength;
- Compressive properties;
- Shear resistance;
- Creep;
- Crack extension;
- Fatigue testing;
- Ageing;
- Hardness;
- Feedstock materials – morphology, size, density, surface, distribution, microstructure and physical and physical-chemical properties.

Moreover, the AM organization can then prove that their process is optimized and stable and that product quality requirements are consistently met by referring to the standards related to materials, processes and test methods for qualifying the fabricated products. For more information: ISO 17296-3:2014 General Principles – Part 3: Main characteristics and corresponding test methods [8]. It covers the quality characteristic of the fabricated components, test procedures, scopes, content of test and supply agreements.

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A complementary way to quantitatively evaluate and compare different machines could be achieved by producing the same benchmark test artefact on several machines. These items could include various features, such as thin walls, rectangular and cylindrical bosses, through and blind holes, inclines, notches and can also be specially designed to assess the product quality in terms of surface finish, dimensional accuracy and tolerances, repeatability and other geometrical limitations.

Benchmarking also allows the users to identify the parameters tested, for instance, layer thickness, raster width, nozzle speed, and so on, that give the lowest dimensional accuracy discrepancies for the benchmarking model, therefore identifying the best achievable practices and processes. As examples, in the USA, the National Institute of Standards and Technology (NIST) has developed test artefact models, seen in Figure 5, which have a range of features to assess the performance and capabilities of the AM polymeric (three dimensional) 3D-printers.

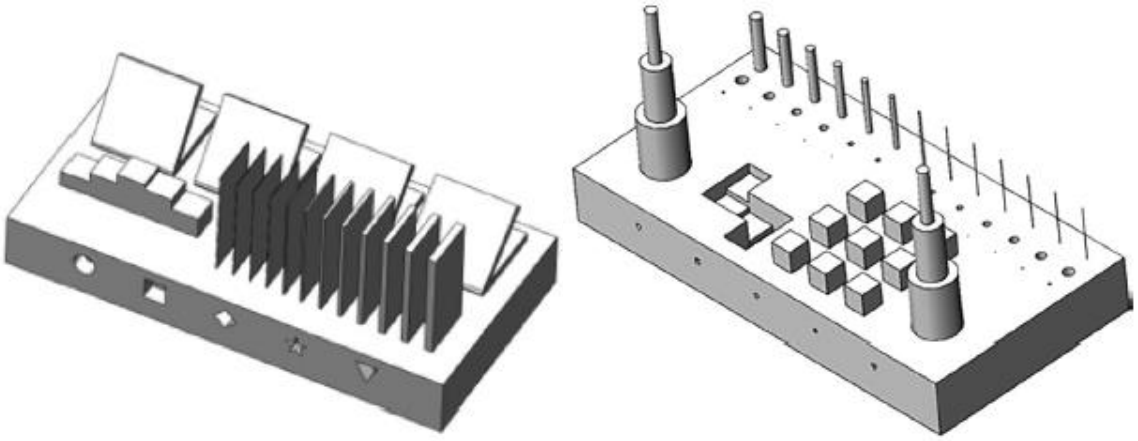


Figure 5 - Test Artefacts developed to quantitatively evaluate and compare the performance of different AM machines [1]

Given time, a database for processes and respective compatible materials should become available for query by the costumers, allowing them to compare and choose which organization could better fit their needs. AM simulations could then be created before the parameters are imported to an AM system using these databases and predictive models of the parts to be manufactured. Potential issues that may arise during the AM process, such as excessive deformation, unsupported overhanging structures, etc. can be predicted by simulations and therefore to be addressed prior to actual fabrication. On top of that, modelling and simulation of the component and the AM process by means of physics-based

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simulation will help to determine the feasibility of producing the end component without empirical trials.

There are many forms of quality-oriented programs introduced by different companies throughout the history of manufacturing. Lean manufacturing, total quality management, six-sigma, zero defects, etc., are some of the manufacturing methods commonly employed by companies to improve their workflow. Such processes and workflows can be adopted for AM and be integrated into the QMS defined specially for AM industry.

With the joint endeavour of ISO and ASTM the first standard to state the general requirements for purchased AM parts was created – ISO/ASTM 52901:2017 [2] (ASTM F42).

4.3.2 Measurement of metal additive manufacturing parts quality

The appliance of principles of quality management in AM is critical, however, it must be coupled with reliable measurement techniques to assure the parts quality and contribute to the creation of new sciences in AM research.

Measurement science certifies the worthiness of components to be used in commercial and industrial products, and in turn promotes competitiveness between companies. However, it is difficult to develop and adapt measurement techniques to AM due to these main factors:

- AM technologies, being relatively new and emerging, require collaboration between different disciplines of studies;
- Material knowledge for AM systems is limited, making it difficult to measure its properties;
- AM systems are complex in nature. Therefore, the evaluation of these machines and respective manufacturing processes is challenging;
- Many AM machines are built as “black boxes” with technological hardware hidden from any end users and process developers. In order to integrate new software and hardware as extended system capabilities, process developers will have to work with AM vendors right from the early machine design and development stage to ensure proper optimization of their system;
- AM processes have special limitations for measuring techniques compared to other manufacturing methodologies. This is caused by features such as the surface finish

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and the complex shapes of the parts and the high temperatures involved in their production.

Agencies such as NIST develop new test methods, processes and artefacts, like the ones mentioned on the previous subchapter and shown in Figure 5, to improve the AM measurement science. However, those techniques may be able to assess the product quality in terms of surface finish, dimensional accuracy, tolerances, repeatability and other geometrical limitations by quantitatively evaluating those features after the part is manufactured but fall short in many other demanding aspects. Areas such as material characterization, real-time process control and systems integration are essential.

The variety of AM materials used in AM systems are limited, with the majority of material being polymer or metal based. In metal additive manufacturing (MAM) the type of feedstock materials used could be powder, wire or sheets depending on the process. The powder-based processes are the most studied so far and wire ones just started being researched in recent years, whereas there isn't much information available about sheet-based AM processes.

There are several factors related to the feedstock material that will influence the quality of the manufactured part, as enumerated in the previous subchapter. It is relevant to mention that an important advantage of using wire in MAM is that it is possible to avoid many of the challenges associated with powders, such as control of particle size and distribution, which affect the process performance. The wire used is common welding wire, therefore for the same material, it is a cheaper form of feedstock.

There are several welding wire diameters available in the market for certain materials, which are already listed in a database/catalogue where their properties can be taken into account during selection. For the powders it has been harder to create such database since new techniques that measure features such as size, particle distribution, mechanical properties and microstructure specially tailored towards AM are required.

There are readily available techniques and corresponding standards for the characterization of materials for MAM, however, the suitability and adaptability of these specifically for MAM remain to be evaluated. Without proper measurement techniques and documentation to the feedstock material, parts produced by MAM have to be subjected to testing after the bulk material is transformed.

The methods available to measure powder characteristics and that are backed up by standards, whose suitability of application in MAM is yet to be evaluated, include:

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- **Powder size measurements**, for example using a series of sieves with different mesh openings to separate the powder into different sizes – ASTM B12-07 Standard test method for sieve analysis of metal powders.
- **Powder morphology**. A suitable description is given in a qualitative way to the silhouettes of the observed particles in a list of terms defined in ASTM B243-11 and shown in Table 2.

Table 2 - Terms describing powder shapes in ASTM B243-11

Term	Definition
acicular	needle-shaped
flake	flat or scale-like, whose thickness is small compared with other dimensions
granular	approximately equidimensional, nonspherical shapes
irregular	lacking symmetry
needles	elongated and rod-like
nodular	irregular, having knotted, rounded, or similar shaped
platelet	composed of flat particles having considerable thickness
plates	flat particles of metal powder having considerable thickness
spherical	globular-shaped

- **Chemical composition**. It is important to evaluate the composition of powder regularly because it degrades with time and repeated usage/recycling. One of the methods for chemical composition analysis is the energy dispersive X-ray spectroscopy – a microanalysis method that uses a beam of X-ray to excite the electrons in the analysed sample, resulting in unique responses according to the elements identified by the energy dispersive spectrometer. An example of a result can be seen in Figure 6.

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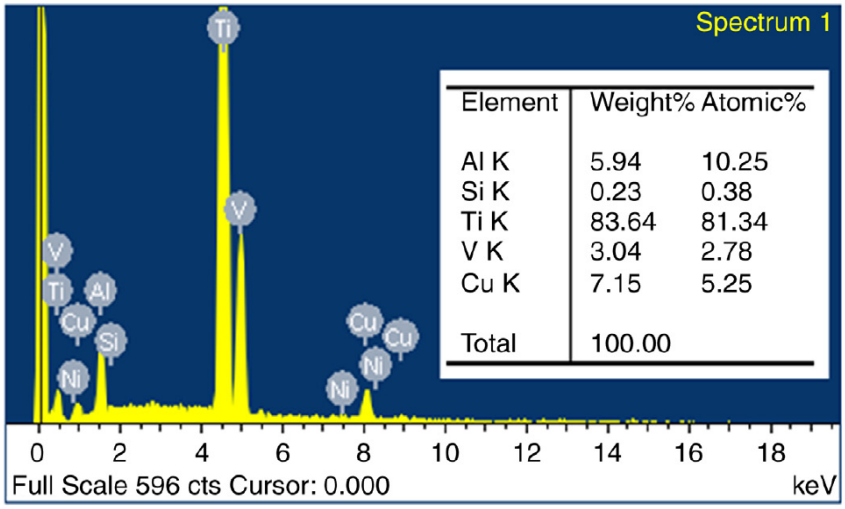


Figure 6- Output from energy dispersive X-ray spectroscopy measurements

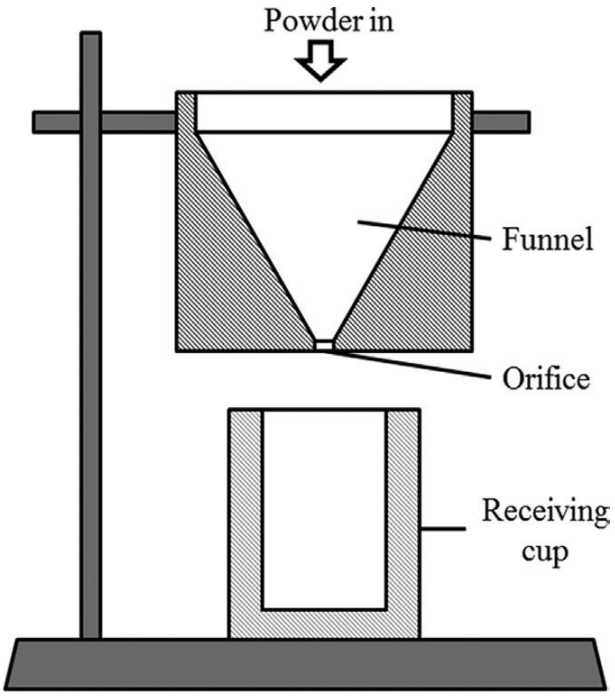


Figure 7 - Schematic of Hall and Carney flowmeter design [1]

- **Flow characteristics**. There are two types of flowmeter which can be used to determine the powder flow rate. Each type of flowmeter as a standard backing up the test method: the ASTM B123-11 related to the Hall flowmeter and the ASTM B964-09 to the Carney flowmeter. The main difference between the two is the size of the orifice, the Carney's is the wider one. A schematic of the test is shown in Figure 7.

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However, these flowmeters are used assuming that the particles are spherical, which may not be the case in MAM feedstock material.

- **Density**. The density is an important measure of a material characteristic of the powder that is useful to the powder producers and powder users in determining quality and lot-to-lot consistency. The apparent density can be measured according to ASTM B212-09 using the flowmeter shown in Figure 3. Knowing the volume of the receiving cup and the mass of powder required to fill it up is possible to calculate the density of the material.

- **Interaction between the energy source and the powder material**. For example, the laser absorption characteristics of powders. The absorptivity of powder particles values between 0.0 and 1.0 for a laser of a particular wavelength and can be obtained through experimental techniques. The absorptivity of a powder bed is usually higher than that of a flat surface due to the multiple reflections and absorption within the powder bed, as illustrated in Figure 8. Powders with low absorptivity can only be fused at higher laser intensities and vice versa.

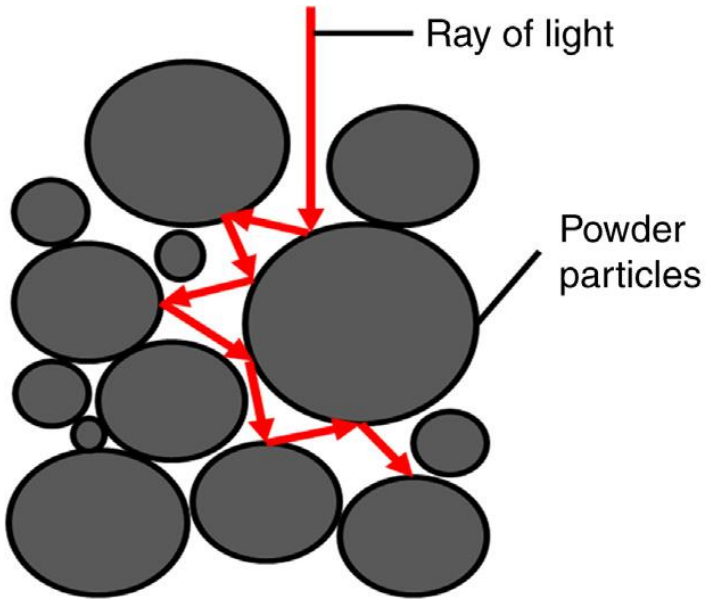


Figure 8 - Multiple reflections of light within a powder bed [1]

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To achieve optimal part quality, in situ/online monitoring with active process measurement and control is vital. One of the primary reasons behind any existing flaw, loss of integrity or lessen geometrical accuracy in a manufactured part is the improper selection and control of the processing parameters. Therefore, there is the need to implement a system capable of not only the online monitoring (OLM) but also control those parameters in real-time after receiving feedback. Part of the feedback should be given through Non-Destructive Testing (NDT): monitoring the thermal cycle of the deposition; measuring the shape and geometrical characteristics of the layers; assessing the properties and the microstructure of the part; and, finally, detecting any defect within the part that could affect its structural integrity or that wouldn't comply with the quality requirements imposed by standards, which are still in development [1-3].

Sensors, measurement devices and algorithms are required to measure and predict the following properties of AM components during fabrication:

- Dimensions;
- Geometry;
- Roughness;
- Surface finish;
- Structural (microstructure and mesostructure);
- Defects (porosities, lack of fusion, warpages, etc.);
- Energy source measurement;
- Temperature range.

Different cameras have been used in distinct experiments to MAM processes. An Infrared (IR) Thermography camera has the capability to monitor the thermal cycle that the part goes through during manufacturing and should also be able to locate defects, however more testing is required to gauge the total capacities of this NDT method [4]. In another experiment, a charge-coupled device (CCD) camera was used as a sensing device to optimize a MAM system. It was possible to achieve a consistent melt pool width by using a closed feedback loop monitoring with the CCD camera, which also resulted in more uniform microstructures and evenly distributed thermal residual stress in the component after the process [1].

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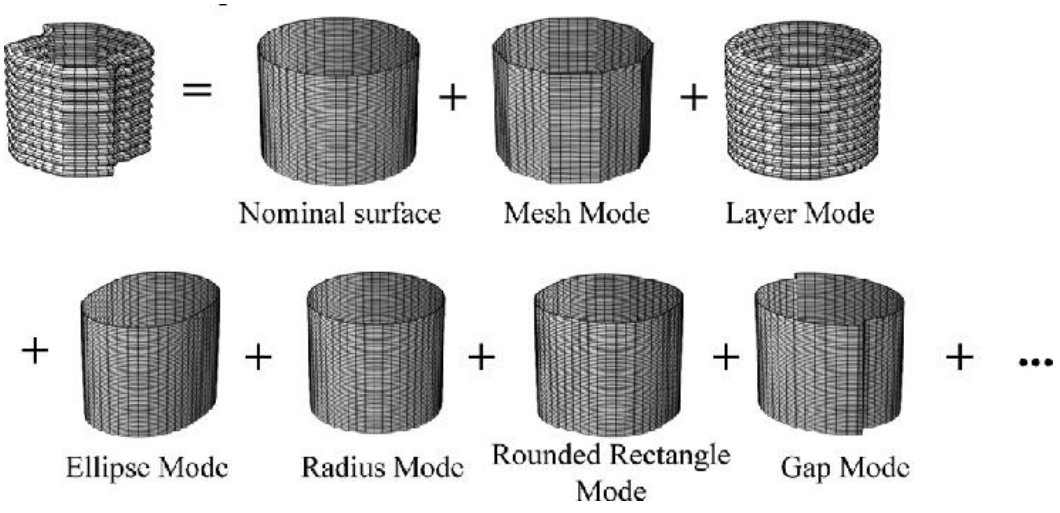
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A coordinate measuring machine (CMM) could be used to measure the total part size and dimensions [1] while for measuring its shape layer by layer a range-resolved interferometric sensor is suggested [3]. Laser-based microscopy can be used to measure surface topology [1] and spatially resolved acoustic spectroscopy, a NDT technique which is part of the Laser Ultrasonic methods category, is suggested to assess the grain refinement [3].

X-ray computed tomography (XCT) seems to be one of the more complete techniques to perform surface texture metrology for MAM parts by dealing with both the measurement (the process of acquiring topography data from a surface) and characterisation (the process of extracting useful quantitative information from topography data) on a volumetric (3D) approach while other techniques have 2D or lower capabilities [5].

Relatively to the form/shape metrology for MAM parts, several techniques are suggested in [6] for use depending on the resolution required and the measurement range needed. All the techniques suggested work on optically rough surfaces.

A skin model representation is proposed to predict the geometrical quality of AM parts. This representation is simplified to obtain a finite description like a discrete shape. Usually, to define the discrete shape model, the nominal shape is sampled into a set of points and the discrete skin model shape is apprehended by the displacement of each point, leading to an enormous number of parameters. To reduce the number of parameters, a geometrical deviation decomposition based on the definition of process oriented geometrical defect modes that may occur is proposed [7] and illustrated in Figure 9. With this operation the accuracy of the predicted model of a printed cylinder is ten times greater.



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Figure 9 - Cylindrical prediction surface generation with process oriented geometrical defect modes [7]

Lastly, the detection of defects will be expounded in this document in the NDT chapter.
Any sensors or measurement devices have to be calibrated to within an acceptable margin of error or uncertainty as they are critical to ensuring the quality of parts produced by AM. To control part uncertainties, measurement is required throughout the entire process, from the raw material, to during fabrication, and lastly when the product is completed, prior and after the post-processing methods. The scheme in Figure 10 illustrates these necessities.



Figure 10 - Uncertainties in raw material and process will result in more uncertainties in the final part

4.4 Factors affecting the quality of MAM parts

Products produced by AM could be defective for various reasons, examples include: corrupted CAD files, faulty equipment, incorrect materials, material deficiencies, incorrect process parameters, file format deficiencies, human error in setting up the machine, human error in implementing the digital design, lack of reliability and reproducibility, etc.
The feedstock material, mainly powder or wire based, used for MAM processes have certain requirements, which are critical to the success of the build process. The morphology, flowability and distribution of powders; the size of the powders/diameter of the welding wire; the density, the microstructure and the physical and chemical properties of the materials; the interaction between the energy source and the feedstock material.
The morphology and shape of powder particles affect its flowability and the packing of the powder particles. Powder particles with poor flowability may not distribute evenly leading to lower density regions in the part.
Knowledge of the microstructure of the powder will aid in predicting the effect on the strength and quality of the final part. Most components made by powder bed fusion (PBF) systems retain the original microstructure of the raw material, without any post-process treatment. However, there are some exceptions where microstructures formed during AM

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process may change, owing to different powder compositions. It was found that the powder microstructure is determined solely during atomization. Furthermore, no two powder manufacturers will be able to produce identical microstructure if they use different processes. Not all metals can be additively manufactured because materials lacking formability contain inherent cracks due to the high thermal gradients and rapid solidification rates experienced during fabrication. Compositions of the metals should be modified in order to withstand large thermal fluctuations. Rapid cooling rates during the sintering process may also result in poor bonding ability between layers of powder, leading to poor densification of the component. This poses issues to the component, as it may shrink below the allowable tolerance and also cause embrittlement.

Although powder and wire-based processes have significant differences, there are some common material processing issues that occur in both technologies. Like with any metal processing methods, including traditional ones, porosity is a common concern.

Additively manufactured products, in general, lack reliability and reproducibility as compared to the counterparts fabricated conventionally due to inherent inconsistencies in the former process. As an example, the inevitable differences in arrangement and size of powder particles between the layers. The melt pool, therefore, varies in dimension between scan lines at different positions. Such random discrepancies accumulate and lower the reproducibility of AM products.

The interaction between the energy source and the feedstock material also influences part quality. For powder bed fusion (PBF) systems, which usually employ a laser or electron beam energy source, beam quality is one of the key factors determining the quality of the final component. For example, laser-based processes are influenced by: the variation in the reflective and refractive properties among different materials and differences in recoil pressure and energy experienced by the powder at the very first instant the laser beam hits on the powder bed and when the laser beam is already scanning at a constant speed. This causes the melt pool to vary in geometry across the different scan lines, while errors accumulate as the build proceeds.

For more information on metal powders: ASTM F3049-14 Standard guide for characterizing properties of metal powders used for additive manufacturing process.

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MAM parts tend to have random poor surface finishes. Melt pool experience surface tension at liquid-air interface, resulting in its spheroidisation and unevenness at the surface. The fluidity of the molten material is also difficult to control during fabrication, causing poor surface finish and lowering the reproducibility of parts. Therefore, post-process machining is required to finish a part.

The flow of file formats usually follows the order illustrated in Figure 11, starting with a file format output by the CAD software, usually a 3D parametric modelling platform, such as SolidWorks, and converted to STL (stereolithography) format for printing on a 3D printer. The slicing software slices the STL model into many different layers and generates a set of toolpath instructions, such as G code for the 3D printer. The 3D printer depending on the type of process used, refers to machine instructions or G code to execute the print, such as moving the printer head to a certain coordinate and begin the deposition while moving the head to a new coordinate.

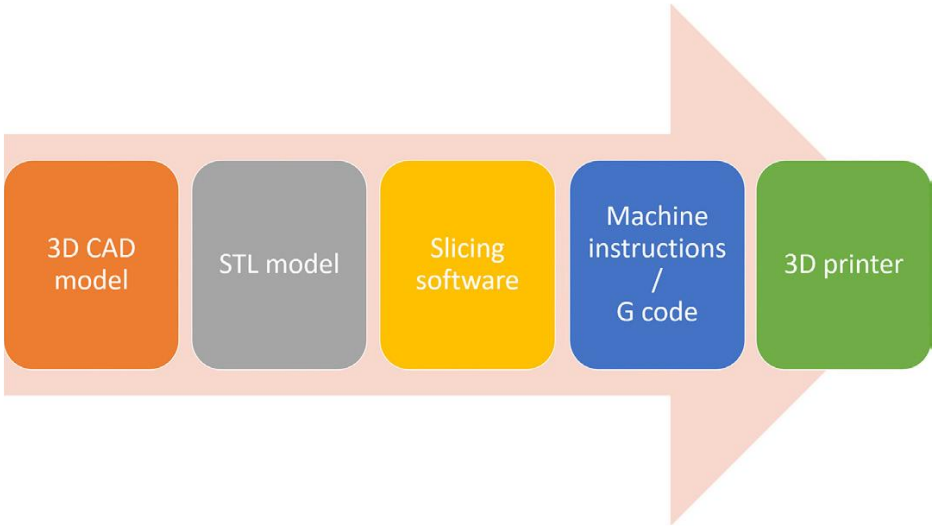


Figure 11 - The flow from a 3D model to a printed part [1]

The user has to check if repairs are needed to smoothen the part model, improving the part quality. The layer-by-layer addition of material results in step formations on the surfaces of the fabricated parts which compromises the surface finish quality of the part – stair stepping effect, illustrated in Figure 12. Therefore, there are different slicing techniques that can be used to dissect the STL into different layers for AM process.

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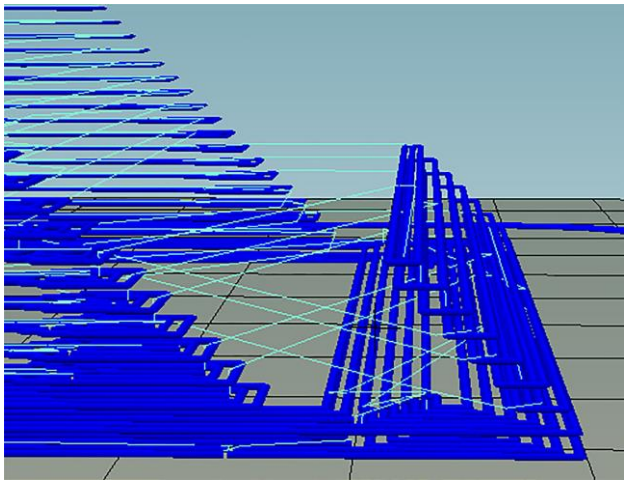


Figure 12 - Stair stepping effect from slicing

Typical slicing methods depend on the layer thickness required. A thicker slice will result in a poorer surface finish. However, if the slices are too thin, it will result in a longer fabrication time.

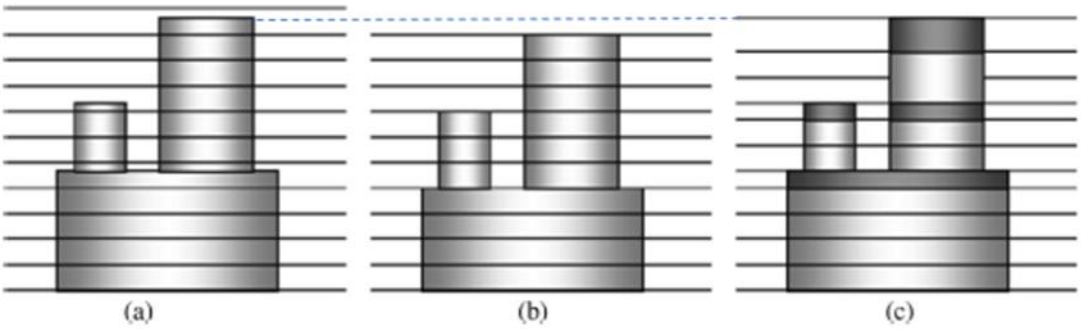


Figure 13 - The principle of layer thickness adjustment [11] (a) original slicing display of the model, (b) un-matched model with constant layer thickness and (c) sliced model with automatically adjusted layer thickness.

A model of a part sliced with a constant layer thickness should have the original display shown in Figure 13(a). There will be differences between the finished part and the original model if a lack of accuracy occurs due to a resolution problem and the slicing with a constant layer thickness starts un-matching the original model, as shown in Figure 13 (b). Therefore, the layer thickness should be adjusted automatically (adaptive slicing technique) in order to maintain the possible resolution of the technology used and avoid the un-match, as demonstrated in Figure 13(c).

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4.4.1 Potentials of Measurement Science

Measurement science certifies the worthiness of components to be used in commercial and industrial products, and in turn promoting competitiveness between companies. To overcome the process challenges, as referred before, standards and techniques must be established for adoption. These challenges are taken on by federal agencies such as NIST that develops new test methods, processes, and artifacts for AM. By establishing common benchmarking guidelines, improvements in AM measurement science would foster greater competition between companies as customers will be able to fairly compare between different AM systems. These goals are achievable through areas, such as material characterization, real-time process control, process and product qualification, and systems integration.

A materials database for AM will consist of a large library of material properties, knowledge of material, process parameters and possible defects [2]. With a proper materials database, side by side comparison of materials would be convenient. Processing parameters can be easily ported from one machine to another, as long as the machines are capable of processing that particular type of raw material. Materials for AM can be divided into 3 main types based on form: powder, liquid, and solid-based. They may also be further classified into metals, polymers and ceramics. Properties such as microstructure, strength, and part density, can be cross-referenced and compared. Cost could also be added so that users can select materials within their budget. A materials database could also link any raw material to a list of known vendors to reduce the time taken for sourcing of suppliers which in turn will generate a higher turnover for an AM company.

To achieve optimal part quality, in situ monitoring with active process measurement and control is vital, examples are the use of charge-coupled device (CCD) camera as a sensing device to optimize the deposition process in an AM system [16]. This will result in more uniform microstructures and evenly distributed thermal residual stress in the component after the process [16]. If a closed feedback loop is used it will ensure predictable and consistent part quality. Processes such as DMLS, SLM, and EBM will be able to achieve better part quality with a high-speed feedback control as any likely defects would be detected in real time during printing, and the algorithms will “correct” the potential defect in the next layer. Non-destructive examination (NDE) can be employed into AM for postprocess measurements. Current NDE techniques (X-ray, ultrasound etc.) that are used in the

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aerospace, medical, and other industries that make unique parts unsuitable for destructive testing can be adopted for use in AM. For example, laser-based microscopy can be used to measure surface topology, while coordinate measuring machine (CMM) can measure part size and dimensions. It is important to note that current NDE techniques may not be adequate for AM and hence new NDE techniques may be required.

Modelling and simulation have been widely used in conventional manufacturing to predict the properties of the bulk material, as well as the final product. Finite element analysis (FEA), for example, is one such technique that provides engineering information, such as stress, strain, deformation, natural frequencies, etc. about a component which cannot be obtained by using traditional analysis methods. The same approach could be employed in AM to determine the effects of the process and material on the final component.

Simulating an AM process before printing will also assist in detecting the type of defects that may occur with that particular set of process parameters. Physics-based simulation of the SLM process can be used to predict the mechanical properties of a solidified melt pool. With the right physics-based algorithms, many characteristics such as residual thermal stress, surface

Advancements in measurement science for AM will help to define criteria for certification and qualification of parts. This is key to instil confidence in AM especially in critical industries. Measurement science also enables development of more consistent and reliable AM processes by means of closed-loop monitoring and control systems. It also involves simulation models and promotes a good understanding of raw material properties and process parameters resulting in a consistent and reliable printed part.

5 Non-Destructive Testing of MAM parts

5.1 General Introduction to NDT

According to ISO/TC 18173, Non-Destructive Testing (NDT) is the “development and application of technical methods to examine materials or components in ways that do not impair their future usefulness and serviceability, in order to detect, locate, measure and evaluate flaws, to assess integrity, properties and composition, and to measure geometrical characteristics”. In contrast to NDT, other type of tests usually damage or destroy the

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inspected samples. Therefore, destructive tests are done in a limited number of dedicated samples that become waste afterwards, while NDT can be used for the in situ/online inspection of in-service components or even during the manufacturing process of the parts, being the latter, the ultimate objective to reach in MAM. However, NDT can also be performed after the part completion.

With a high-speed feedback control potentially, any likely flaw detected in real time during the manufacturing of a MAM part, signalling the layer inspected as defective. That layer or the faulty portion of it could then be removed, if necessary and if the machine in question has subtractive capabilities on top of the AM technology. The correction of the layer in question would be complete after filling up the gap created by the purging of the defect. On top of all of that, as an ideal goal, the control algorithms would provide automatic compensation abilities to reduce the possibility of defect recurrence in the following added layers.

Integrating online NDT in a MAM process could face many limitations such as material properties, surface finish, part geometry and size, deposition sequences, defects shape and orientation, minimum defect size and maximum defect depth able to detect, high temperatures involved, distance from the part, inspection velocity, machine and software compatibility, and others. With all these challenges, it is of extreme importance that the NDT equipment is correctly calibrated by specialized technicians prior to the testing, which has even more prominence if the afterwards inspection is done in real-time parallelly to the production of the part and autonomously. This procedure can minimize errors such as failing to locate a defect or a false positive result due to a malfunction of the NDT system or any punctual unplanned situation. The overseeing of the NDT by an expert is also highly suggested to keep the process in track, even if this is done automatically by a control system in real time and several robots or machines.

Even Though on-machine measurements grant a myriad of benefits it is also necessary to clarify that not all defects coming from the process can be detected by taking advantage of these methodologies, as some defects may originate underneath the visible layer, and even defects that can occur after the last layer is produced [1-5].

Those defects that can be detected and acted upon are grouped into four categories that depend on their root cause: design and job preparation, feedstock material, equipment and process conditions [1].

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5.2 Typical defects of MAM parts

The defects detected in MAM can be very easily related to the ones found in welding and joining processes as the production principle is the same.

Nowadays when an approach for quality assurance (QA) in AM is made, the first issue is the lack of standards and the ones that exist are mostly focused on more established AM technologies such as plastic based AM.

In order to establish some criteria for the defects, the ISO 6520-1:2007 (Welding and allied processes – Classification of geometric imperfections in metallic materials – Part 1: Fusion welding) [12], due to similarities between MAM and welding procedures [4]. Table 3 reviews the type of defects sorted by its location (surface or internal) and based on ISO 6520-1.

Table 3 - Mapping of possible defects in MAM based on ISO 6520-1

Designation		Reference to ISO 6520-1
Surface	Crack	100
	Lack of Fusion	401
	Continuous under cutting	5011
	Intermittent undercut	5012
	Excess weld metal (Humping)	502
Internal	Cracks	100
	Micro-cracks	1001
	Gas Pore	2011
	Uniformly distributes Porosity	2012
	Clustered Porosity	2013
	Linear Porosity	2014
	Lack of Fusion	401

In MAM the superficial defects of one layer do not present as many concerns when compared to the internal ones since when another layer is added on top of the previous one the superficial defects either disappear, due to new heat input and the deposition of more

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material or become internal defects – between layers. The more common defects in MAM are porosity, lack of fusion and/or delamination due to lack of fusion.

- **Porosity** can be caused by trapped gas or by **lack of fusion** between layers. Gas porosity is thought to occur due to high delivery rate which results in the shielding gas to be become entrapped within the melt pool.

Porosity can be feedstock or process induced. Now, comparing the porosity between powder and wire-based metal processes only, most of it, no matter the type of feedstock, is process-induced. However, with optimised process parameters, porosity can be reduced to very low levels in both powder-bed fusion (PBF) and direct energy deposition (DED) technologies, that is one of the reasons to keep an online monitoring (OLM) and control of the process parameters. Side machine hammer peening can also help refining microstructure – eliminating pores 2 mm within the material [3] as seen in Figure 14.

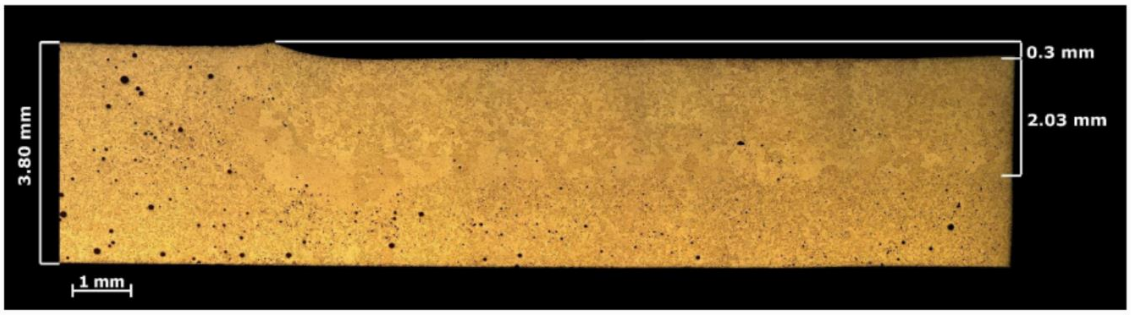


Figure 14 - Effect of side machine hammer peening on porosity [3]

Relatively to the feedstock induced porosity, wire-feed DED processes have minimal defects compared to powder because the technology for wire making is transferrable from mature welding consumable supply chains. No matter what, it is always important to inquire and maintain the feedstock quality both with powder and wire. When using powder there are also concerns about the control of particle size and distribution. Adding to this, gas porosity could be an issue within the powder production itself, whereas with wire it is inexistent**.**

- While setting the operation, it is important to choose the right substrate to deposit on, for the technologies that need one (making sure the feedstock material is compatible with the material of the substrate otherwise it may not be able to adhere to it - **undercutting**) and employ an effective clamping on the substrate. Otherwise, as a result of residual stresses, substrates can experience a distortion phenomenon called **warping**, as illustrated in Figure 15, which affects the accuracy of the part and may

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lead to damages like inter-layer **lack of fusion** or complete delamination. Using a substrate of the same material as the build can reduce this effect. Lack of fusion happens when there is insufficient energy density in the melt pool or poor feedstock quality (impurities).

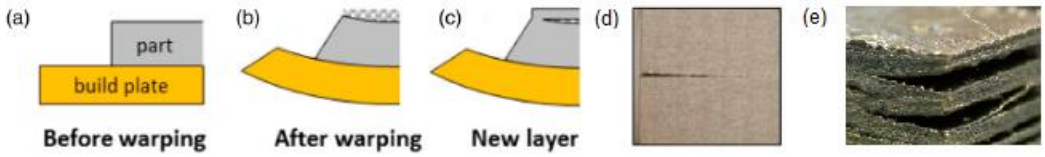


Figure 15 - Schematic of build plate warping effect during processing (a – c) and resultant lack of fusion (d) or delamination (e) [9]

Humping is the uneven deposition of material, leading to excess or lack of it. The main cause is an imbalance in the feedstock delivery speed or feedstock distribution (depending on the type of process) and the travel speed ratio of the energy source. An example of humping is illustrated in

- Figure 16.



Figure 16 - Example of humping [4]

5.2.1 Microstructural Inhomogeneity and Impurities

Inhomogeneity in the microstructure may include impurities and disparities in grain sizes and textures, the impurities may be inclusions, contamination or the formation of oxides [1].

- **Balling:** This phenomenon consists on the formation of a melt-ball, the solidification oof the material in to spheres instead of layers, resulting from surface tension in combination with a deficient heat input which prevents the underlying layer from being wet. This defect is a severe structural problem as it is detrimental to the connection between layers [1], Figure 17.

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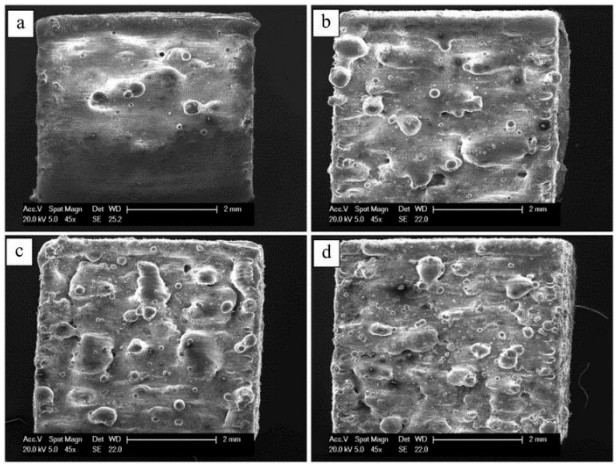


Figure 17 - Balling [1]

- **Dimensional and geometric deviation:** These defects are grouped into the following categories:
  - ✓ Shrinkage and oversize.
  - ✓ Warping and curling.
  - ✓ Dross formation on down facing surfaces.
  - ✓ Super-elevated edges.

- **Surface details:** The superficial texture of the part is highly reliant on many factors such as process parameters, the contour scan strategy, size of powder particles, the orientation of the face in the part. Downward and upward facing surfaces are recognized to have vastly different textures properties (see Figure 18). Poor texture quality can be very prejudicial to the parts fatigue performance [2].

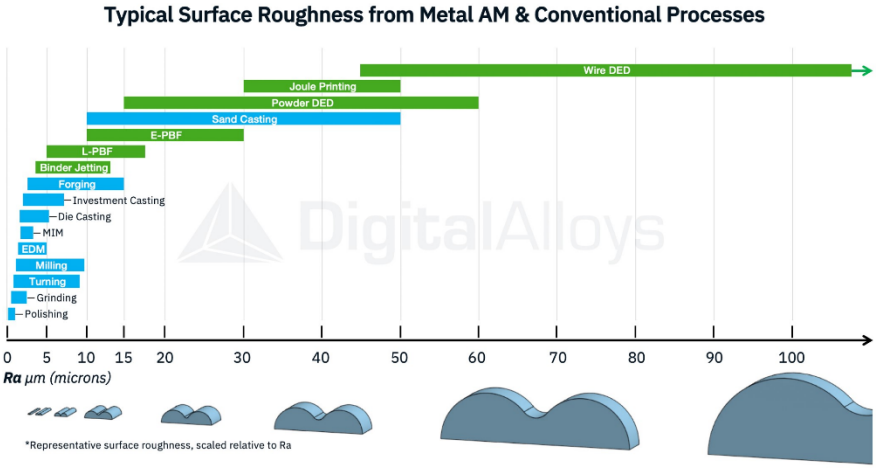


Figure 18 - Typical Surface roughness of metal AM and conventional processes. (Source: https://manufactur3dmag.com/)

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5.3 Characteristics and application range of the different NDT methods

To establish the NDT suitable for MAM a review of currently available NDT techniques along with their fundamental principles and applications is presented in Table 4[13]. In Additive Manufacturing as any other manufacturing procedure there is a need to implement quality control to guarantee that the standards and precision defined are in compliance with the final part measurements. These precisions are done with non-destructive and destructive testing which will be explored in more depth in the following pages.

The main types of discontinuities related to Additive Manufacturing are volumetric discontinuities (porosity and lack of fusion), planar defects (cracking and delamination), geometrical accuracy, surface roughness and microstructural issues.

5.3.1 Radiographic Testing

Radiographic testing (RT), more commonly referred as X-Ray, is an inspection methodology where a radiation source emits energy waves, usually X-rays or Gamma-rays, through a test specimen into a film or detector. An internal representation of the part is therefore created due to differences in material density and thickness that have direct impact in the absorption rate. Typical industrial RT uses X-ray equipment or radioactive isotopes such as Ir_{192} or Co_{60} that will emit electromagnetic waves with lengths inferior to 10 nm. The inspection object/structure properties, such as crack type and positioning, object thickness, as well as the source power should always be taken in account since they will influence the setup parameters and the operation's time. Due to the radioactivity involved in this type of testing, it is of paramount importance to ensure that the safety rules are strictly implemented during operation. This type of testing is only suitable for an offline inspection (after manufacturing) of the part [4].

Figure 19 exemplifies the results obtained using RT in WAAM samples. Porosity, inclusions and lack of fusion were detected by RT. It is known that X-ray is a reliable test for detecting 3D defects, however it is not able to show planar (2D) defects and small defects in the perpendicular direction of the radiation orientation. Moreover, the technique allows to reliably scale the defects, however it does not fully locate them (in this case of incidence, the depth of inclusions is unknown) [13].

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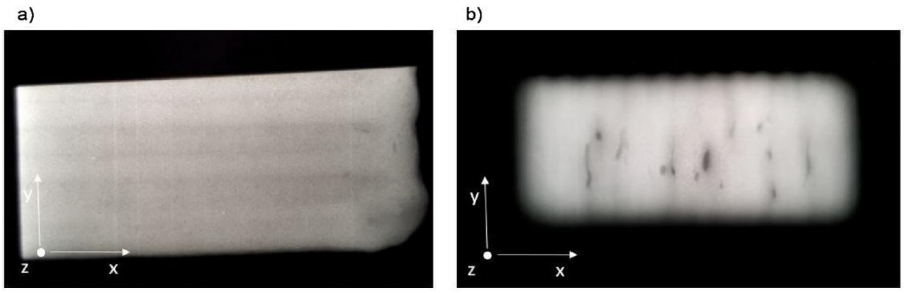


Figure 19 – X-ray results. (a) Aluminium and (b) Mild-steel samples produced by WAAM [13]

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Table 4 - Review of Metal Additive manufacturing NDT techniques

	NDT Technique	Physical Phenomena	Fundamentals	Applications
Imaging	Radiographic Testing	Electromagnetic radiation (ionizing)	Requires the incidence and penetration of radiation energy on and through an inspected material, which is absorbed homogeneously by the material, except in the regions where thickness, density variations or defects arise. The radiation that passes through material impinges an image in a sensing medium revealing the defects.	Detect deep or embedded defects (virtually no limits); Poor sensibility for defects perpendicular to the radiation direction; Poor sensibility for small defects compared to the sample dimension; Not suitable for on-line inspection. Human health concerns.
	X-ray Backscatter	Electromagnetic radiation (ionizing)	Backscatter X-ray detects the radiation that reflects from the target as opposed to conventional X-rays.	Detect deep or embedded defects (virtually no limits); It can operate even if only one side of the target is available; Inspecting times can be unacceptably long.
	Computed Tomography	Electromagnetic radiation (ionizing)	Method of forming reliable three-dimensional (3D) representations of an object by taking many x-ray images around an axis of rotation and using algorithms to reconstruct a 3D model.	Detect deep or embedded defects (virtually no limits); Not suitable for online inspections. Time-consuming and size limitations.
Ultrasonic	Conventional Pulse-echo Ultrasonic Testing	Mechanical vibration	A beam of high-frequency sound waves is introduced into a material, travel through it and are reflected at interfaces or defects. The reflected sound is analyzed to identify the presence and location of defects.	Can be used for flaw detection, location and measurement; It cannot be used for high-temperature inspection (typically > 300 °C); Surface treatment dependent. Not adequate for locally non-planar surfaces.
	Phased Array Testing	Mechanical vibration	PA systems utilize multi-element probes, which are individually excited under computer control. By exciting each element in a controlled manner, a focused beam of ultrasound can be generated. Software enables the beam to be steered. Two and three-dimensional views can be generated.	Can be used for flaw detection, location and measurement; Fast inspection times; Able to penetrate thick sections; Cannot work at high temperatures; Requires coupling; May require several probes.
	Immersion Ultrasonic Testing	Mechanical vibration	Immersion or water-column (squirt) US techniques allow a more efficient coupling between the US probe and the inspected material. It facilitates the automation of the inspection process providing C-scan images of the test pieces.	Improved probability of detection of the smallest defects; More accurate sizing and location of subsurface flaws; Good results independents of the geometry complexity; Cannot be used on-line and under high temperature; Requires immersion of the part.
	Electromagnetic Acoustic Transducer (EMAT)	Mechanical vibration and Electromagnetic induction	This inspection method uses an electromagnetic acoustic (EMA) way of ultrasound excitation and reception.	Can be used for flaw detection, location and dimensional measurements. Contactless and couplant independent but requires proximity; Suitable for high temperatures; Geometry constrained. Low sensibility for small defects.
	Laser Ultrasonic Testing	Thermal expansion and optical measurement	A laser pulse is directed to the surface, heating it and inducing an ultrasonic pulse that propagates into the sample. This ultrasonic pulse may interact with a defect and then returns to the surface. A separate laser receiver detects the displacement that is generated when the pulse reaches the surface.	Can be used for flaw detection, location and measurement; Capable of detecting very small flaws (virtually no limits); Contactless and couplant independent; Can be used on complex geometries, curved or difficult to access areas; Can be used at very high temperatures.
Electromagnetic Based	Potential Drop	Electrical current	Measurement of the potential drop by an increase in the electric resistant between two measurement electrodes in a presence of a discontinuity.	Very good at estimating surface cracks depth; Penetration depth of few mm; Surface roughness reduces the accuracy of the sized cracks. Can be used at high temperature.
	Eddy Currents	Electromagnetic induction	A coil (probe) is excited with an alternating electrical current, producing an alternating magnetic field around a conductive test piece. Eddy currents are induced in the materials, but defects cause a change in eddy current, corresponding to a change in the impedance coil, allowing the identification of the defects.	Can be used for surface and subsurface flaw detection; Penetration depth of few mm (1/2 mm); Very sensitive to small defects. Contactless but requires proximity; Limited to conductivity materials.
	Magnetic Particle Testing	Magnetic field	The inspected material is magnetized. The presence of a surface or subsurface defect allows the magnetic flux to leak. Then magnetic (ferrous) particles are applied on material surface and attracted to the flux leak zone, indicating the presence of a defect.	Limited to ferromagnetic materials; Can detect subsurface defects. Not adequate for online inspection.

(*continued on next page*)

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	NDT Technique	Physical Phenomena	Fundamentals	Applications
Thermography	Infrared Thermography	Electromagnetic radiation	Infrared thermography aims at the detection of subsurface features, owing to temperature differences (DT) observed on the investigated surface during monitoring by an infrared camera.	Can detect subsurface defects; Risk-free (no radiation); Suitable for online monitoring; Requires heated working material; Large areas can be scanned fast.
	Laser Thermography	Electromagnetic radiation	A high-power laser source is used for external heat delivery and the energy will diffuse in the specimens' surface making discontinuities detectable with the analysis of the temperature distribution near the laser spot.	Can detect subsurface defects; Suitable for online monitoring; Contactless and requiring no surface finishing;
	Vibro Thermography	Electromagnetic radiation and mechanical vibrations	An ultrasonic transducer generates elastic waves within the test specimen. These waves will interact with the irregularities present in the object and due to the friction, energy will be dissipated in heat form and later detected by an IR camera.	Can detect subsurface defects; Requires contact; Very short measurement time (seconds). Difficult to apply in heated surfaces.
	Eddy Current Thermography	Electromagnetic induction and radiation	Use of induced EC to heat the sample and defect detection is based on the changes of the induced eddy currents flows revealed by thermal visualization captured by an infrared camera.	Can detect subsurface defects. May require time to deposit enough energy in the material; Suitable for online monitoring.
Others	Penetrant Testing	Capillary action	Components are wetted with a fluorescent penetrant and penetrant soak into a surface defect. The penetrant excess is removed, and a developer is applied to the surface, drawing penetrant from defects out, forming a visible indication of the defect.	Cannot detect interior defects; Cannot be implemented on-line; It is time-consuming (> 20 min).
	Acoustic Emission	Mechanical vibration	Elastic waves that are emitted in a medium due to crack can be captured by suitable piezoelectric sensors on the surface of a specimen.	Can be used for flaw detection and location; Perfect for parts in operation; Not suitable for post-manufacture inspection (prior to service). Not adequate for online inspection.

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5.3.2 X-Ray Backscatter

X-Ray Backscatter technology (XBT) can be considered an advanced form of X-ray application. In contrast to typical RT that evaluates variation in the X-Ray intensity, XBT detects the radiation that reflects from the target. The physical method uses spatial density distribution of an object by measuring the intensity distribution of scattered X-rays. XBT can be an attractive testing procedure for defect detection due to its ability to detect cracks below surface. The material properties such as density and surface roughness do not impact the test results. The setup can be made to be contactless and the X-ray source and the detector can be located on the same side of the object, enabling testing of massive extended structures. The setup is exemplified in Figure 20.

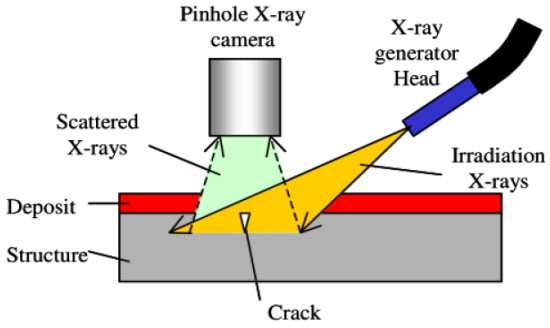


Figure 20– XBT setup [4]

The results shown in Figure 21 were obtained during an XBT inspection of a subsurface defect using a pinhole with a diameter of 1.0 mm. It was required a significant amount of time to complete the inspection but there was no need for surface treatment and/or preparation.

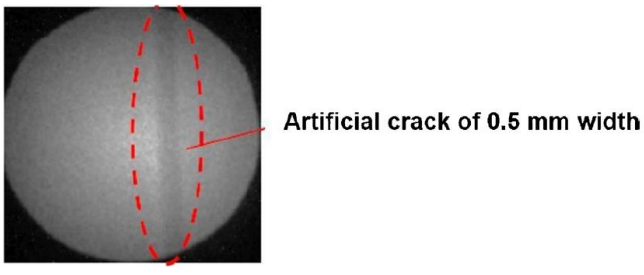


Figure 21– Image (11 mm x 11 mm) of XBT when using a pinhole of 1.0 mm diameter [13]

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5.3.3 Computed Tomography

Computed Tomography (CT) scanning is a method of forming 3D representation of a specimen by taking a set of large X-ray images around an axis of rotation and using algorithms to reconstruct a 3D model. Different methods of data collection have been tested over time and each new development has decreased the operation's time. The three main methods of CT are represented in Figure 22. The first uses a pencil beam that translates linearly along with the respective detector capturing density data, the setup is rotated in small increments until a full 3D model is created. The second method uses a 2D fan of X-rays that are able to range the full width of the specimen, detecting the radiation with a 1D sensor. The third model is very similar to the previous one but now utilizes a full 3D cone of X-rays in a 2D detector, increasing dramatically the speed of data collection.

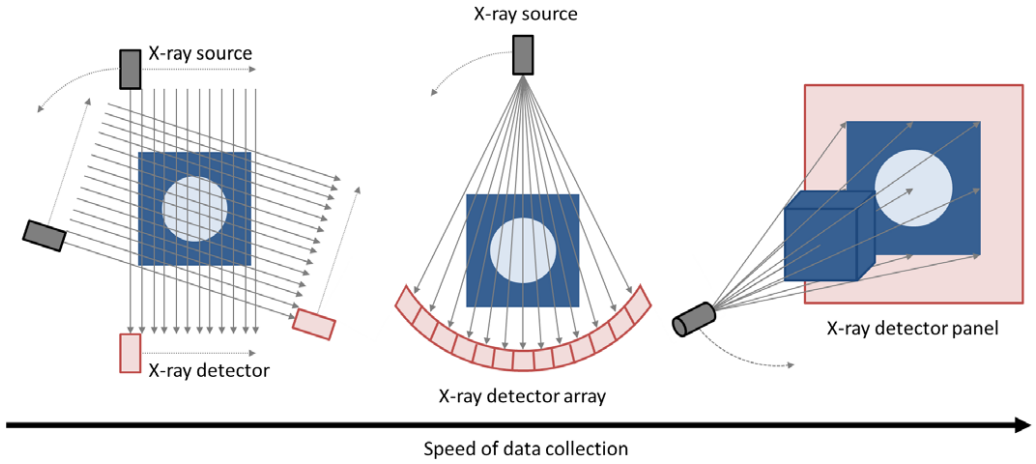


Figure 22 – Representations of pencil, fan and cone CT methods [4]

The resulting 3D reconstruction can then be used for a variety of applications, from simple visualisation purposes to direct measurement of geometries or conversion into an STL file for AM production. Nowadays there is no better method to evaluate and measure internal features then CT due to its volumetric nature.

5.3.4 Ultrasonic Testing

Ultrasonic Testing (UT) is the method of inducing a sound wave into a test sample and receiving the respective reflection. The reflection will occur when the wave gets to the bottom of the sample or when it finds discontinuities. The analysis of these signals, also known as echoes, will provide the information needed to map the discontinuities and their size. This type of testing must be adjusted with standard specimens in order to make

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necessary corrections and therefore be capable of achieving correct results. Typical ultrasound instrumentation measures a wave amplitude's as function of time. The probe is made by a piezoelectric element that when activated by an electrical signal will induce a sound wave on the part by means of a couplant (such as oil) or by water. UT is one of the most versatile NDT methods as it can be applied to any type of material (such as metal, plastic wood, composites, etc), as long as their properties are taken in account in the setup. Considering that UT cannot be applied to an irregular surface, an example of the analysis and scan made to a WAAM sample is illustrated in Figure 23, where it was made through the back of the plate.

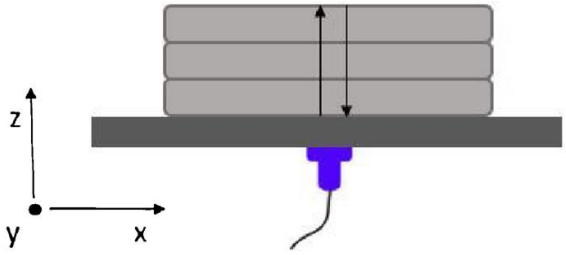


Figure 23 – Scheme of UT of a WAAM sample [13]

Using the Amplitude Scan the echo amplitude and transit time are plotted on a simple grid, showing the travel distance made by emitted and reflected wave, shown in Figure 24. Thus, if the peaks appear before the total thickness of the part, which is the case in Figure 24 (b), this means that there is an interface - a defect - that reflects the echo back to the probe. Results shown in Figure 24 represent the zones visualized in Figure 25 that were the most relevant for the inspection of these aluminium samples. The first spectre presents a no defect region (zone A in Figure 25) and the second one revels a defect in 13.38 mm from the substrate plate surface (zone B in Figure 25).

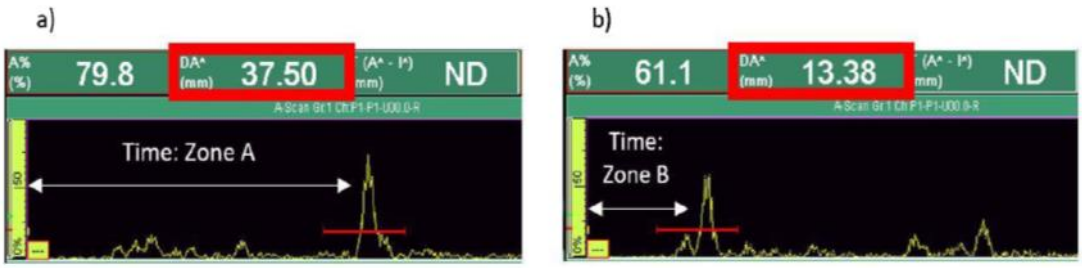


Figure 24 - Conventional UT analysis of an aluminium WAAM sample. (a) Zone A and (b) Zone B [13].

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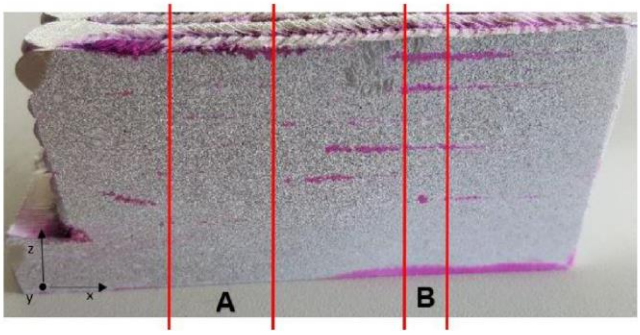


Figure 25 – Visualization of the application of UT method by posteriorly analysing the same aluminium sample through Liquid Penetrant Testing [13]

Through Figure 25 it is easily visualized that the defect in spectre B (Figure 24(b)) is lack of fusion with a round shape. This spectre represents a partial lack of fusion between layers, partial because otherwise if it were the entire width of the part no sound would go through an no other peak, although smaller, would exist.

5.3.5 Phased Array Ultrasonic Testing

Phased Array Ultrasonic Testing (PAUT) differs from conventional UT due the many piezoelectrical elements as opposed to a single one, as illustrated in Figure 26. Each one of these elements is independently controlled which allows each set of individual waves to be put together making an ultrasonic beam. Each element is configured by the software algorithm called delay law or focal laws. The delay law will define the time delay for each element according to the beam steering and beam focusing, therefore guiding the acoustic energy to the interest area.

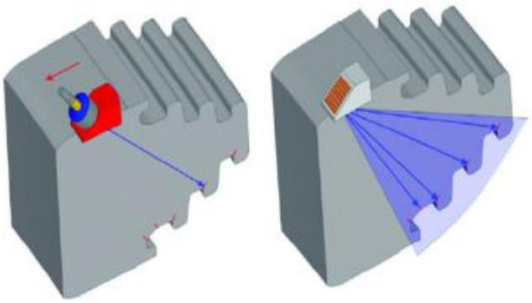


Figure 26 – Comparison between conventional UT (left) and Phased Array (PA) (right) [4]

PAUT allow for reduced times of inspection due to the elimination of “mechanical exploration” where a technician must move the probe back and forward, as well as increase

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reliability has no couplant is lost in the making of the movement. Different techniques of inspection using PA can be deployed manually on a weld, as exemplified in Figure 27, but in order to save time, line scanning should be used rather than raster scanning, increasing therefore productivity.

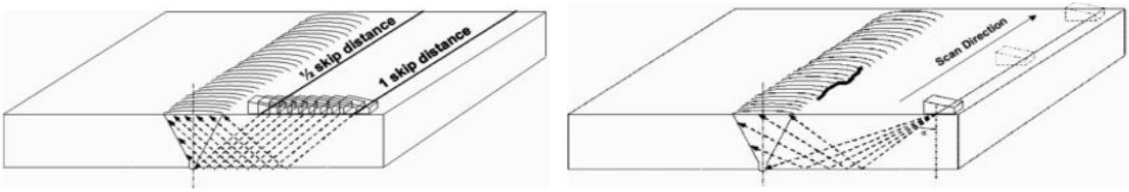


Figure 27 – Raster scanning (left) compared to line scanning (right) [4]

Despite the advantages indicated, there are limitations: PA equipment tend to be significantly more complex than conventional instruments, making it hard to operate, requiring specific formal training and experience to ensure the full potential of the equipment is taken; setup times may be very time consuming as the input parameters of inspection angle, focal distance and scan pattern, among others, must be determined and selected, in order to establish the focal laws. However once established they may be saved and quickly deployed for subsequent inspections; The test specimen's surface can also be a key factor in the good performance of PAUT as maintaining good coupling is mandatory and may be proven to be difficult.

5.3.6 Immersion Ultrasonic Testing

Immersion Ultrasonic Testing (IUT) is a NDT ultrasonic method where the work piece is completely immersed in a liquid coupling medium, creating optimal working conditions for an UT probe, as even the shortest dead zones will be covered. This technique may be operated remotely and although different types of coupling medium's may be used, water is preferred for most operations. In IUT the visualization of the sound waves is slightly different, since between the initial pulse and the back wall echo there will be an additional echo caused by the sound wave going from the water to the work piece. For AM, IUT could be deployed post-process but the amount of effort for the setup when compared to other NDT methods makes a non-preferable option.

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5.3.7 Electromagnetic Acoustic Transducer

An Electromagnetic Acoustic Transducer (EMAT) is a ultrasonic NDT method that uses a magnet and an electrical coil to generate a sound wave in the work specimen. Generating alternating current (AC) through a coil, a time-varying magnetic field is created on the surroundings, which, in turn, induces a varying electromotive force in a conductor and, consequently, eddy currents (EC) will flow in a conductive component. When there is a change in the AC, there will be changes on both the electromotive force (Lorentz force) and the EC. These changes and their interaction with static magnetic field from the magnet cause the particles of the component to oscillate, generating an acoustic wave which propagates through the test sample. In Figure 28 is illustrated the differences between conventional UT and EMAT.

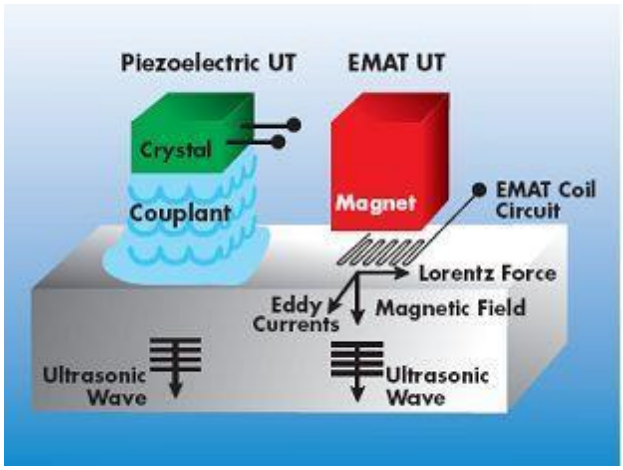


Figure 28 – Differences between conventional UT (left) and EMAT (right)

The EMAT solved several markets needs result of conventional UT handicaps such as the need to inspect objects with high surface temperatures common in power plants, chemical and metallurgy industries. UT for this type of situations was faced with the absence of couplants or with very expensive couplants. With EMAT, a special protection to the transducer from the high temperature of the object's surface can be made with a heat-resistant material with low thermal conductivity, due to the contactless operation of the EMAT. Therefore, EMAT has potential for online inspections.

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5.3.8 Laser Ultrasonic Testing

Conventional UT are the most used NDT methods and are widespread through several industries due to their reliability and cost effectiveness. Nonetheless, they have two major limitations. The first one, which was previously referenced when describing the need for EMAT and is also applicable in the case of Laser Ultrasonic Testing (LUT), is the non-contact inspection of parts at elevated temperatures. The absence of coupling or the expensiveness of this and the need for thermal protection resulted in the implementation of EMAT. However, EMAT still needs to be implemented in close proximity to the inspected part, making this NDT method unsuitable to inspect parts in a conveyor since the motion of the parts will not allow for a constant distance between the transducer and the object's surface. The second limitation is the requirement for proper orientation of the transducer with respect to the surface when this is in the pulse-echo mode, which is of most interest since it requires single sided access and provides flaw depth information. This information cannot be obtained using transmission mode, with the transducers located at opposite sides of the specimen. Precise orientation requirements follow from the fact that the transducer is a phase sensitive device that emits or receives from its whole surface. Angular tolerance is about a few degrees or much less if the amplitude of the ultrasonic echoes must be precisely monitored. Consequently, the inspection of curved or contoured parts requires a surface contour following device, which will be very complex and difficult to implement, especially in the case of acute discontinuities of the surface. LUT appears to resolve these two major handicaps present on other UT using lasers to generate and detect ultrasonic waves, as illustrated in Figure 29.

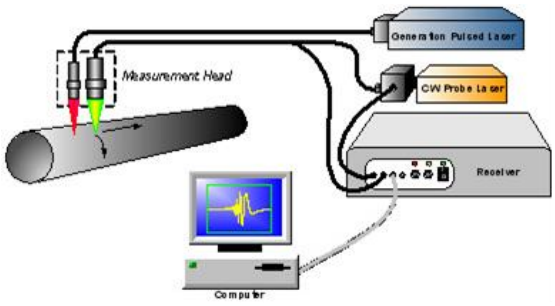


Figure 29 – Laser Ultrasonic Testing (LUT) setup (the CW in the figure stands for continuous waveform)

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With LUT, transduction of ultrasound is performed at a distance ranging from several centimetres to meters, and utilises two lasers, one for the source of the ultrasound at the object's surface and another for detection of ultrasonic motion off the same surface. This allows for examination at high temperatures and eliminates normalcy requirements. Since there is no requirement for the object's geometry. LUT is suitable to perform at greater speeds than robotic systems equipped with conventional UT.

5.3.9 Potential Drop

Potential Drop (PD) is another NDT method which has been proven helpful in identifying superficial and sub-surface cracks. The physical principle behind it relies on the measurement of the potential drop by an increase in the electric resistance between two measurement electrodes in a presence of a discontinuity. This method allows for the assessment of crack sizes and doesn't replace the usual methods for crack detection. When using the PD method, the surface of the specimens must allow the electrodes to make good contact to ensure that the current is induced correctly, since differences in the transition resistance can lead to false results. Meanwhile surface roughness also impacts the results by reducing the accuracy for the detection of cracks. The frequency will also have an important role since higher frequencies result in lower skin depths, therefore requiring greater quality of surface finish. Usually the probe has four electrodes, two of them, the external ones, inject current into the inspection sample while the ones in the middle of them, another two, measure the potential drop between each other, as illustrated in Figure 30.

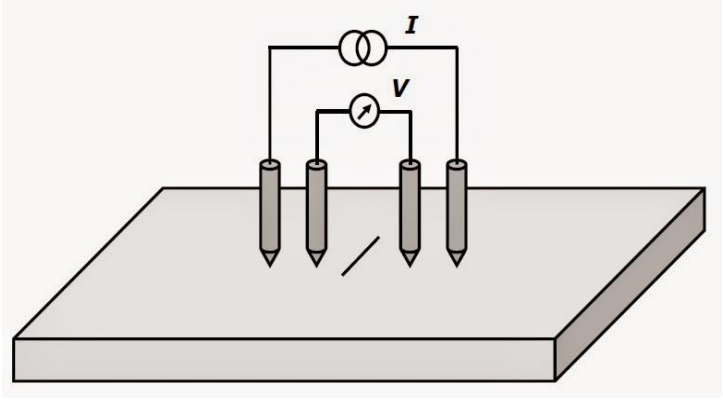


Figure 30 – Schematic of the Potential Drop method

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5.3.10 Eddy Current Testing

Eddy Current Testing (ECT) is one of the NDT methods based on the principle of electromagnetic induction discovered by Michael Faraday in 1831. This law states that: when an alternating current (AC) energizes a coil, it creates a time-varying magnetic field on the surroundings of the coil, which, in turn, induces a varying electromotive force around a conductor and, consequently, an electric current will flow through a closed path in this conductor – the fundamental operating principle of transformers and inductors (coils). Foucault is credited for discovering the Eddy Currents (EC) in 1855, therefore these are also called Foucault Currents. In 1879, Hughes gave a huge contribution to the ECT by demonstrating how the electric impedance of coil, energized by alternating current, changes when placed in contact with metals of different conductivities and/or magnetic permeabilities. However, ECT was only used as NDT in the Second World War.

In the conventional approach of ECT, this NDT method uses a helical coil around the length of a cylindrical former as a probe, which is the case of the coil used in Figure 31. Since this probe in particularly has no core (only air) it is referred as an air-core probe. Probes with this kind of shape and that have its revolution axis perpendicular to the surface of the test piece are also sometimes mentioned as pancake-type probes.

As explained before, when the coil is energized by an alternating current, a primary magnetic field (H_P in blue on Figure 31) is created, even if the probe is balanced in air and located far enough away from any conductive material as seen in green on Figure 31 (a), situation of infinite lift-off. By approaching the probe to a conductive material (Figure 31(b)), reducing the lift-off (impedance change due to variation of the distance of the probe to the conductive material), the primary magnetic field (H_P) will induce Eddy Currents (EC in red on Figure 31) on the test sample which, in turn, will generate a secondary magnetic field (H_S in yellow on Figure 31). In these conditions, both the primary current induced in the coil and the primary magnetic field (H_P) decrease when compared to situation of infinite lift-off. This variation corresponds to an increase in the resistance and a change in the inductance of the coil. The EC circulate parallelly to the surface of the test sample and perpendicularly to the H_P and H_S magnetic fields.

If the material has a defect or discontinuity (Figure 31 (c)) that, following the previous reasoning, will limit the trajectory of the EC, leading to a lessen H_S and, consequently, a smaller effect on the opposition of the H_P. If the defect is too small to introduce significant

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perturbations in the EC flow, the H_S won't affect the H_P, therefore the impedance change on the EC probe will be nearly inexistent and the defect won't be detected.

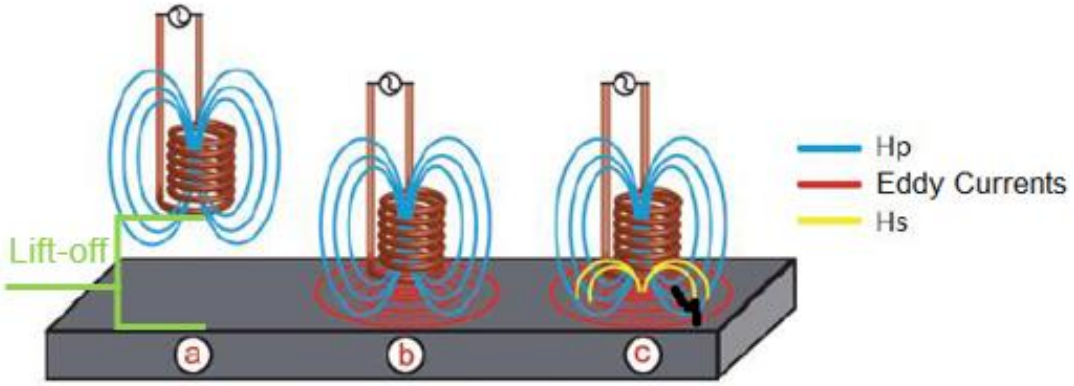


Figure 31 – Principle of the NDT method using EC [3]

Compared to other NDT methods, ECT has many advantages since:

- can inspect both ferromagnetic (steel) and non-ferromagnetic (aluminium) materials.
- doesn't need to use consumables or couplants.
- is possible to implement without any direct physical contact between the probe and the inspected piece.
- permits high-speed testing with practically instantaneous results.
- dedicated probes could be designed for a certain application and to fulfil a set of requirements.

The points mentioned above are the reasons behind the choice of this method to follow the strategy of an online layer by layer inspection of WAAM parts. However, like all the NDT methods, the fundamental variables of ECT have some specificities that could limit the method's application. The main limitations of the method are:

- Skin Effect: the EC aren't evenly distributed along the cross section of a conductive material, being denser close to the surface and exponentially decreasing their intensity as they flow deeper into the material. The thickness of the tested sample must be three times the standard depth of penetration, especially when using low frequencies, to prevent the EC from reaching the other side of the inspected part.

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5.3.11 Magnetic Particle Testing

Magnetic Particle (MP) Testing takes advantage of the magnetic field effect in a ferromagnetic material and, discontinuities can be identified with the application of ferrous particles and their accumulation. The magnetic field effect can be applied by direct or indirect magnetization. Direct magnetization occurs when an electric current is passed through the sample and a magnetic field is formed in the material while indirect magnetization occurs when a magnetic field is applied from an outside source, no electric current is passed through the test object. When a magnetic field is put into the sample discontinuities, a distortion in the lines of the field will be created. If the discontinuity is near the surface, a leakage in the magnetic field will occur and the ferrous particles will be attracted to it and therefore pinpoint the trajectory of the irregularity at the surface of the sample. Although, if the discontinuity is parallel to the field lines, then there will not be a build-up of particles. MT is one of the fastest, most economical and with higher sensitivity NDT methods with applications during fabrication, machining, thermal treatment or in service. Nowadays its range of application goes from the naval, auto to aeronautical industries and others. The main limitation of the method is the detection of only near surface defects and the difficult online implementation of all the required steps for the inspection, shown in Figure 32.

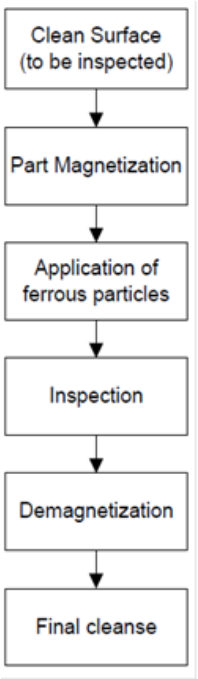


Figure 32 – Magnetic Particle (MP) procedure workflow

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5.3.12 Infrared Thermography

Thermographic testing is a NDT method which analyses the visual data about the thermal patterns of a specimen's surface. The physical principle uses thermal radiation to map the temperature, making this method contactless and able to be deployed in real time. It can be applied using passive or active techniques. In the first case an external source of heat must be provided to analyse the dissipation of the heat at the surface. The second method refers to the case where no heat source is required due to the high temperatures of the sample itself, as in welding techniques. Thermography has come a long way from a qualitative inspection method, which required other analysis by more established NDT methods, to a viable industrial inspection tool capable of retrieving significant results. This development was mainly due to improvements in Infrared (IR) camera technology and advanced signal analysis processes. The possibility to use this technology at a distance makes it able to inspect a relatively wide area in a short time.

An IR camera was used to record the WAAM process. The experimental setup is shown in Figure 33. The validation process was strategized to analyse the capabilities in detecting surface and internal defects. To do this, defects were manufactured and analysed prior and after adding another layer on top to evaluate the same defects as superficial and internal flaws, respectively. Four defects were manufactured after the layer cooled down. The four holes drilled can be analysed prior to the deposition of the third layer, the results are shown in Table 5. This table shows the thermographic image on the left with an analysis line in white (indicates maximum, average and minimum temperature) and on the right the temperature profile along the line [4].

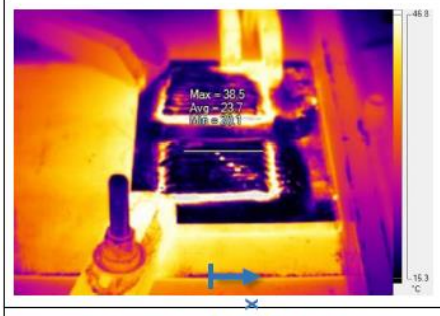
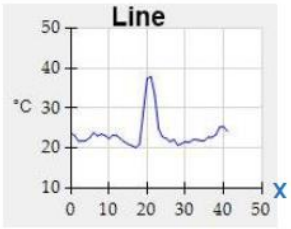
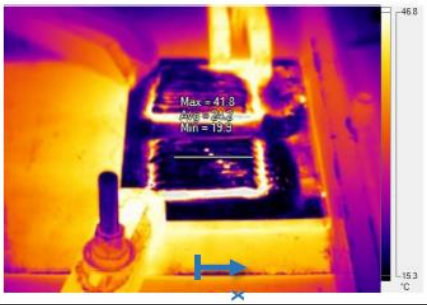
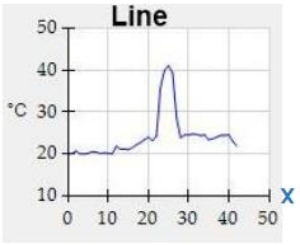
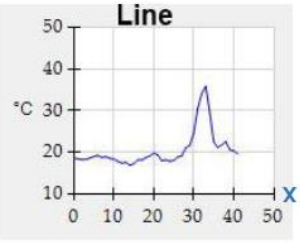
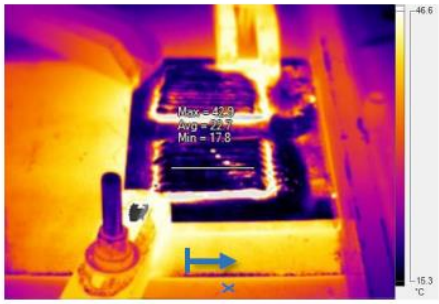
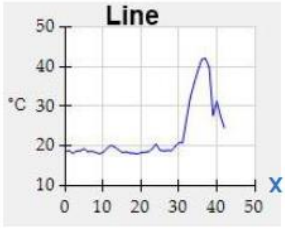


Figure 33– IR Thermography setup [4]

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Table 5– IR Thermography analysis of the sample after cooling [4]

Recorded Image	Temperature Graph
	
	
	
	

From the results obtained, it can easily be identified that each defect has a higher heat signature than the surroundings. It can probably be correlated to the dissipation of heat in the interior of the part, although reflectiveness may also impact these values and therefore must be taken in account in further trials. For the analysis of surface defects IR

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Thermography shows some potential in detecting discontinuities. However, for the evaluation of this method in terms of its capability in detecting internal defects, when another layer as added on top, the results weren't conclusive [4].

5.3.13 Liquid Penetrant Testing

Liquid Penetrant Testing (LPT) is a NDT method that utilises a penetrant followed by the removal and the application of a developer. This will allow visible indication of surface irregularities. The method is based on capillary action, where a low surface tension fluid penetrates into clean and dry surface-breaking discontinuities. This way, when removing the excess penetrant off the surface only the remainder placed on the irregularities will stay. This allows a developer agent to reveal the discontinuities. An example of liquid penetrant testing results is represented in Figure 34. The technician executing the test should be aware of the key factors that can influence the test, such as existing obstructions to the absorption of penetrant like contaminates, defect geometry, temperature and pressure. PT can be deployed in any material with a good surface finish, which is not the case in AM parts.

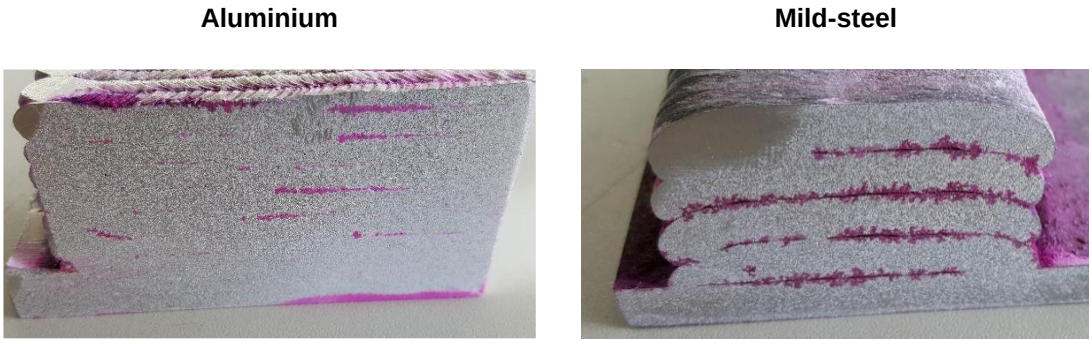


Figure 34 – Liquid Penetrant Testing results. Left – Aluminum; right – Mild-steel

5.3.14 Acoustic Emission

Acoustic Emission (AE) is a NDT method based on the detection of acoustic waves radiated by the material due to irreversible changes as a result of plastic deformation due to mechanical forces or temperature gradient. Elastic or stress waves are produced by this displacement with frequencies above the hearing range and can be detected with piezoelectric sensors of high reliability. During inspection the flow of energy must be generated by the material itself, making this NDT method suitable during the manufacturing of the part while defects are possibly being formed. The source can be detected through

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triangulation algorithms and analysis of the amplitude of the signal received. A schematic from the AE test principle and setup is shown in Figure 35.

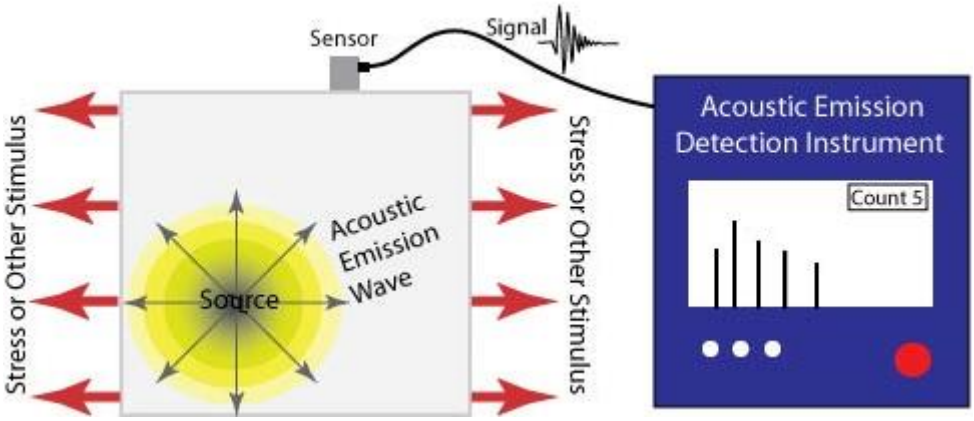


Figure 35 – AE test principle and setup

6 Destructive Testing

Samples of engineering materials are subjected to a wide variety of mechanical tests to measure their strength or other properties of interest. Such samples, called specimens, are often broken or grossly deformed in destructive testing (DT). These tests are generally much easier to carry out, provide more information and are easier to interpret than non-destructive testing (NDT). DT is most suitable, and economic, for objects which will be mass-produced, as the cost of destroying a small number of specimens is negligible. It is usually not economical to do DT when only one or a few items are to be manufactured.

Some of the common forms of test specimen and loading situation are shown in Figure 36. The most basic test is simply to break the sample by applying tensile force, as in (a). Compression tests (b) are also common. In engineering, hardness is usually defined in terms of resistance of the material to penetration by a hard ball or point, as in (c). Various forms of bending test are also often used, as is torsion of cylindrical rods or tubes [14].

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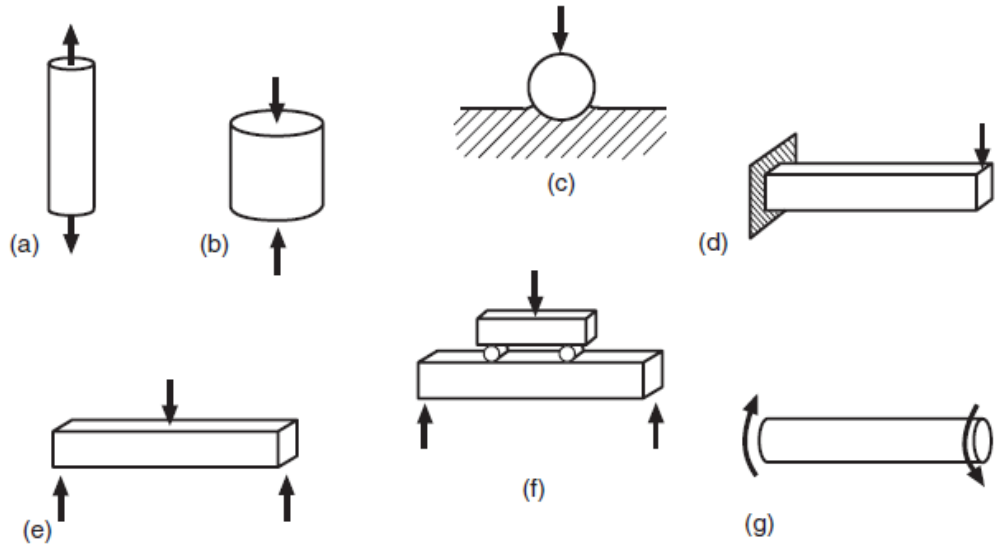


Figure 36 – Geometry and loading situations commonly employed in mechanical testing of materials: (a) tension, (b) compression, (c) indentation hardness, (d) cantilever bending, (e) three-point bending, (f) four-point bending, and (g) torsion [14].

The simples test specimens are smooth (unnotched) ones, as illustrated in Figure 37(a). More complex geometries can be used to produced conditions resembling those in actual engineering components. Notches that have a definite radius at the end may be machined into test specimens, as in (b) – the term notch is used here in a generic manner to indicate any notch, hole, groove, slot, etc. Sharp notches that behave similar to cracks are also used, as well as actual cracks that are introduced into the specimen prior to testing, as in (c).

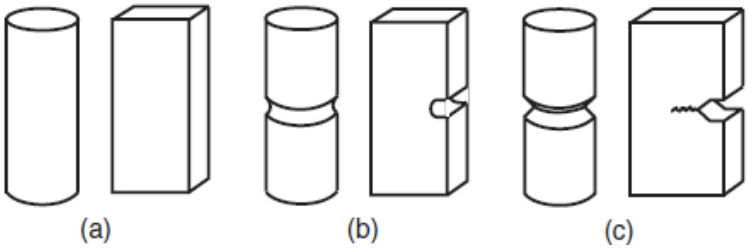


Figure 37 – Three classes of test specimen: (a) smooth or unnotched, (b) notched, and (c) pre-cracked. [14]

The destructive measurement methods presented in the following subchapters and respective standards are made for conventional manufacturing processes like casting, injection moulding and extrusion. However, due to the nature of the AM processes, MAM parts are often highly anisotropic, thus caution has to be taken to ensure the testing has taken anisotropy, build direction and other factors into account.

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ASTM has released ASTM F3122-14 for evaluating mechanical properties of metal materials made via additive manufacturing processes [15]. This standard serves as a guide to existing standards or variations of existing standards that may be applicable to determine specific mechanical properties of materials made with a MAM process.

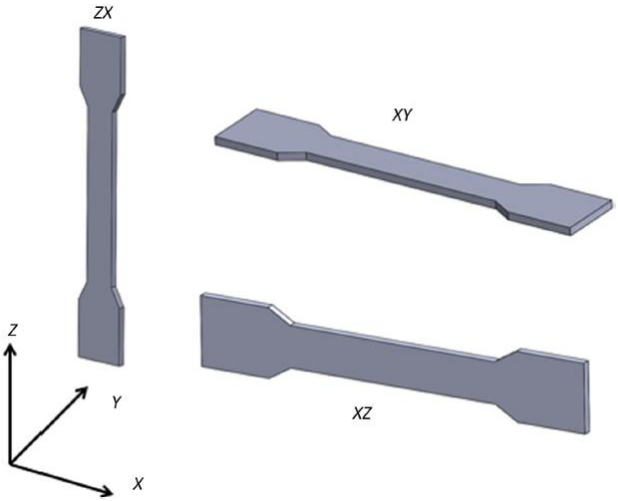


Figure 38 - Various build direction for tensile coupon

Suppliers that provide mechanical properties often give values in one build direction and build parameters. However, mechanical properties vary with build direction and build parameters. Figure 38 shows different tensile coupons manufactured in different build directions.

Anisotropy and build direction aren't the only factors influencing the reported mechanical properties during destructive testing. Method of material preparation, defects (such as porosity), method of specimen preparation, testing environment, specimen alignment and gripping, testing speed and temperature and build parameters like scanning strategy, travel speed of the energy source, temperature, heat treatment, etc. can interact together and affect the final part reported properties. In order to optimize a property, several parameters have to be considered together, making it complex to classify and test AM material mechanical properties.

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6.1 Tensile properties measurement methods

Properties such as yield strength (σ_y), ultimate tensile strength (σ_u), Young's modulus (E) or elastic modulus and elongation (%) of the material for a certain sample orientation can be given through a tensile test. The test specimen is subjected to a tensile load and the load vs deformation data is obtained against a constant strain-rate. The engineering stress-strain curve is then plotted from that data, as shown in Figure 39.

Standards such as ASTM E8/8M – Standard test methods for tension testing of metallic materials, and ISO 6892 – Metallic materials -tensile testing, could be used as reference.

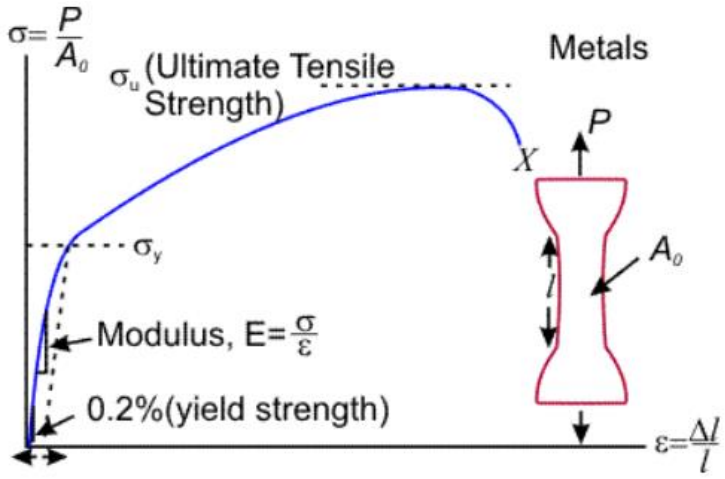


Figure 39 - Example of an engineering stress-strain curve

A typical tensile test set up and test specimen are shown in Figure 40 and typical parameters reported from tensile tests for MAM parts are presented in Table 6.

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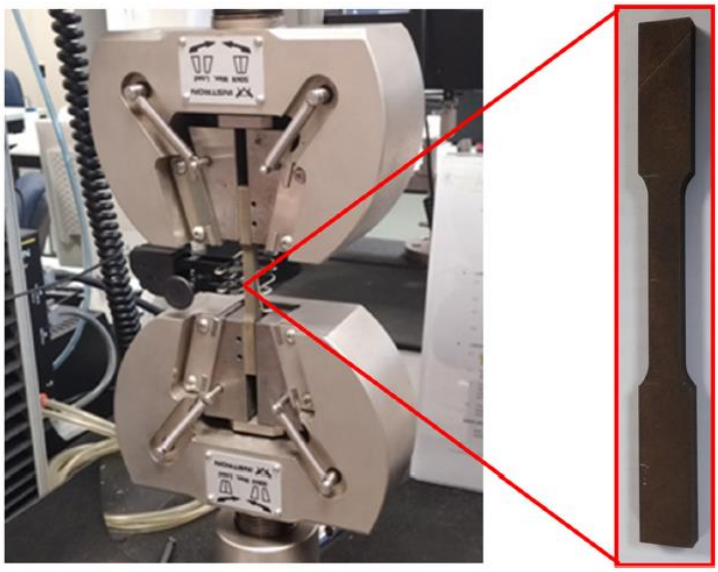


Figure 40 – Tensile test for a metallic sample

Table 6 – Results from tensile test of MAM samples

Process	Material	Sample orientation	Yield stress (MPa)	UTS (MPa)	Elongation (%)
Laser Melting	Ti6Al4V	XY	1093 ± 64	1279 ± 13	6 ± 0.7
EBM	Ti6Al4V	XZ	950	1050	14

6.2 Compressive properties measurement methods

The compressive properties of metals can be measured using the following standards:

- ASTM E9 – Standard test methods of compression testing of metallic materials at room temperature.
- ASTM E209 Standard practice for compression tests of metallic materials at elevated temperatures with conventional or rapid heating rates and strain rates.

These provide standards for testing compressive strength at room temperature and elevated temperature, respectively. The stress-strain curve, compressive strength and elastic modulus can be found.

A typical compression test set up and test specimen are shown in Figure 41 and typical parameters reported compression tests for MAM parts are presented in Table 7.

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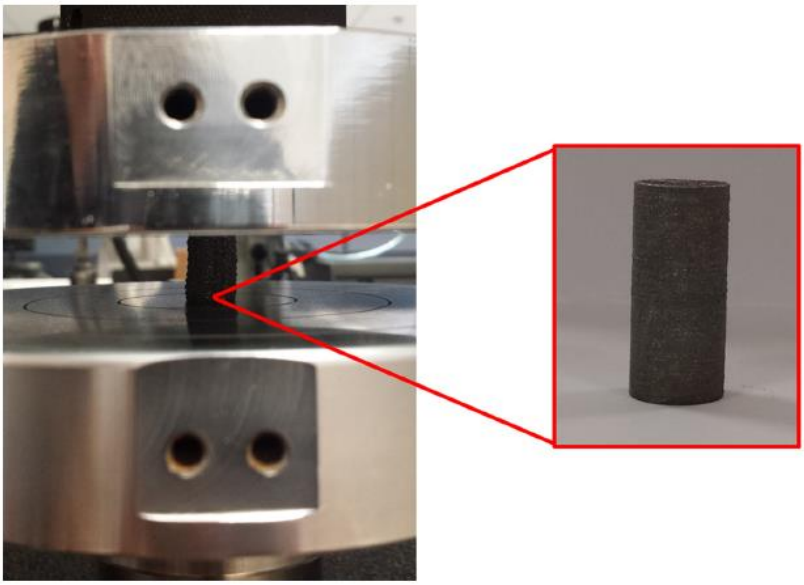


Figure 41– Compression test for metallic sample

Table 7– Results from compression test of MAM samples

Process	Material	Porosity (%)	E (GPa)	Compressive strength (MPa)
SLM	Titanium	55	0.687	N.A.
SLM	Ti6Al4V	70	5.1 ± 0.3	155 ± 7

6.3 Hardness measurement methods

Hardness is a measure of how resistant the metal is to various kinds of permanent changes in shape when a compressive force is applied. The following standards detail methods that can be used to measure hardness of metals:

- ASTM E10 – Standard test methods for Brinell hardness of metallic materials.

The Brinell hardness test consists of using a sphere to indent a hole on the test specimen surface and the diameter of the indentation is used to calculate the hardness value.

- ASTM E384 – Standard test methods for micro indentation hardness of materials.

Standard for Knoop and Vickers hardness test methods, which are similar to Brinell hardness test, but the indenter is pyramid shape and the measure distance is diagonal length of the indentation. The face angle of the pyramid is different between Knoop and Vickers test.

- ASTM E18 – Standard test methods for Rockwell hardness of metallic materials.

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The Rockwell hardness test can use either pyramid or spherical indenters to perform the indentation multiple times at a single spot with increasing force. The depth of the indenter is measured by the machine thus directly giving the indentation depth.
Typical parameters reported from hardness test for MAM samples are shown in Table 8.

Table 8 – Results from hardness test of MAM samples

Process	Material	Microhardness (HV)
SLM	Ti6Al4V	479–613
EBM	Ti6Al4V	358–387

6.4 Fatigue measurement methods

Fatigue is the weakening of a material due to repeated applied loads or cycles loading. The standards that can be used to measure fatigue of metals are:

- ISO 1099 – Metallic materials – fatigue testing – axial force-controlled method.

The test involves pulling a specimen axially with a periodic force function which is often sinusoidal. Typical parameters reported from fatigue tests for MAM samples are shown in Table 9.

Table 9 – Results from fatigue test of MAM samples

Process	Material	Fatigue strength (MPa)	Fatigue life (Cycles)
EBM	Ti6Al4V	441	N.A.
EBM	Ti6Al4V	N.A.	28961 ± 5557

- ISO 12108 – Metallic materials – fatigue testing – fatigue crack growth method.

Standard for notched samples to see how the material resists crack growth.

- ASTM E2714 – Standard test method for creep-fatigue testing.

The test is similar to a fatigue test but at elevated temperature, so that it is able to give strain/stress over time curve and stress-strain hysteresis curves.

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6.5 Fracture Toughness measurement methods

Fracture toughness describes the ability of a material containing a crack to resist fracture. The following standards can be used to measure fracture toughness of metals:

- ASTM E399 – Standard test method for linear-elastic plane-strain fracture toughness K_{IC} of metallic materials.

Typical parameters reported from fracture toughness tests for MAM samples are shown in Table 10.

Table 10– Results from fracture toughness test of MAM samples

Process	Material	Orientation	K_{IC} (MPa/m)
EBM	Ti6Al4V	XZ	78.1 ± 2.3
EBM	Ti6Al4V	XY	96.9 ± 0.99

- ISO 12135 – Metallic materials – unified method of test for the determination of quasistatic fracture toughness. Standard to give the fracture toughness from R-curves.

6.6 Other properties

There are some other standards for consideration when characterizing metals, such as:

- ASTM E111 – Standard test method for Young's modulus, tangent modulus and chord modulus.
- ASTM E132 – Standard test method for Poisson's ratio at room temperature.
- ASTM E143 – Standard test method for shear modulus at room temperature.

7 Quality assurance in the supply chain

Due to the increase in popularity of AM it is determinant to develop specifications and standards to level the playing field for most companies in this industry and assure the quality of parts produced using this method. Thus, creating trust in the manufacturing procedure and broadening its use for other industries.

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Creating standards, qualifications and certifications is what will bring trust to this process and allow its widespread use and assure quality to the whole supply chain.

In the early phases of a new and developing technology it is common for companies to develop proprietary materials and processes standards, which is a lengthy and expensive process, and can drive industries and companies off the new processes. Therefore, it is paramount to develop industry-wide accepted standards, that can simplify the work of regulatory agencies and increase safety by establishing minimally acceptable requirements across the industry.

For instance, a common issue within the supply chain, not exclusive to AM, is the random nature of material anomalies. Creating the need to characterize material anomalies (in addition to common fatigue and fracture properties of materials) through probabilistic damage tolerance assessment. Allowing focus on size distribution and frequency of occurrence of material anomalies. This is an example of one of the previously exposed standards, specifically, created by ASTM in the materials and processes section.

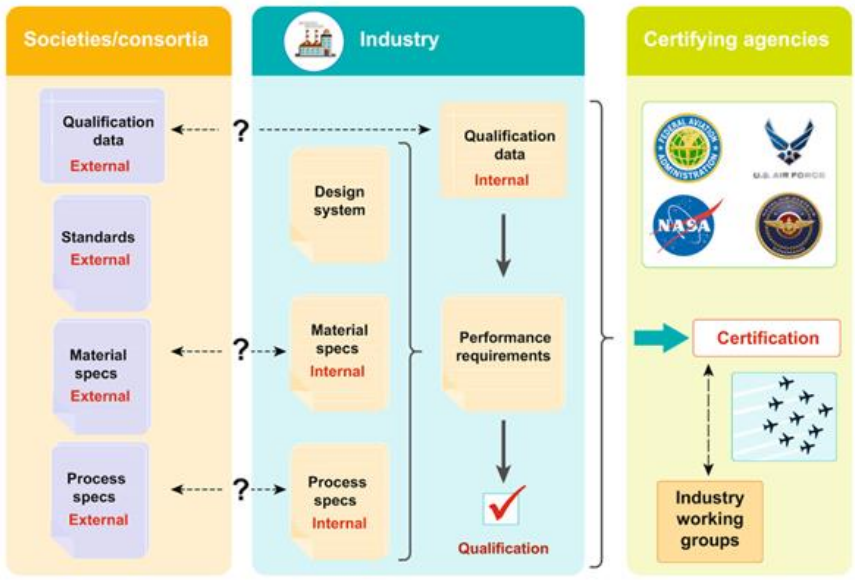


Figure 42 - Schematic representation of the Q&C landscape. [9]

One of the main needs identified to achieve widespread acceptance of AM are the lack of comprehensive relationships between processing, material microstructure and fatigue and fracture properties [9] Additionally, the following aspects should be analysed and considered:

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- Process variation, controls, and in-process monitoring
- Characterization and control of process-related defects and anomalies, and their impact on part durability
- Effects of post-deposit processing such as stress relief, hot isostatic pressing (HIP), and heat treatment
- Quality and control of feedstock (raw material) As built and post-deposit finishing processes and their effect on part durability
- NDE requirements and capability
- Orientation- and location-dependent properties.

Traditional and rapid qualification were also part of the talks in this reunion, and it was mostly agreed that regulatory agencies should be guiding figures in these efforts. The issue is that traditional qualification should be adapted to validate and verify techniques that standardize best practices in AM.

Similarly, to this, in 2012, the National Institute of Standards and Technology (NIST) in the USA created a roadmap with challenges and barriers that AM would need to be overcome. Table 11shows some of these issues with their priority level. This roadmap gives an idea to the urge in creating more standards in the AM process and equipment, as it is, at least, necessary to qualify these equipments based on a common standard. Qualification and certification are also stated as high priority especially in sectors like the aerospace and medical industries where life and death are at risk. Unfortunately, the difficulty in predicting the final quality on an AM part makes the lack of standards an even higher priority as it is of utmost importance that non-destructive quality control methods are the norm and destructive methods are reduced to a minimum and the only way to verify that parts are properly constructed is to certify that the standards are being respected and are accurate [1].

Table 11 - Barriers and challenges, in standards by NIST. [29]

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Materials	Medium priority
Lack of microstructure standards to enable evaluative criteria/judgments	
Limited certified measurement methods/specifications for powder chemistry and size distribution	
Process and equipment	High priority
Lack of metrics and standards for measuring and characterizing AM processes and artifacts	
Lack of standards for machine-to-machine consistency, measurement test pieces, sensors	
Qualification and certification	High priority
Non-standard guidelines for qualification and certification	
Lack of standards based on round-robin testing (how to build)	
AM modeling and simulation	High priority
Lack of standards to support consistent data inputs to modeling and simulation, such as dimensional accuracy, process capabilities, distortion and surface finish modeling to optimize build orientation, criteria for convergence time, accuracy calibration, comparison of machine performance, etc.	
Lack of validation and verification metrics for models and simulation tools	

Current destructive test methods may also not be appropriate for metal AM as they assume material homogeneity, which is rarely the case for AM. To solve this, it was suggested that that fatigue crack growth test methods with better crack growth rate resolution were needed [9].

A key factor to garner confidence in components produced with AM is the use of standardized tests to measure typical mechanical properties, for example, tensile strength and fatigue and crack resistance. Though, there is currently a concern regarding the similarities between test pieces and the actual parts that will be used in the industry as in AM any change in part geometry, design parameters or layer height will affect the thermal history of the part, which will affect the microstructure of the piece in question.

Another challenge is determining the extent to which additional AM standardization work is needed, and to what level currently existing standards, developed for conventional materials, can be adopted directly for AM materials. It is likely that a better understanding of the mechanical behaviour of AM components is needed before this can be fully addressed [9].

More than the need to be certified AM parts need to match the performance standards of typical machined parts. Industries may develop their proprietary testing rigs and quality assurance methods, but without the existence of standardized tests to benchmark them

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against there is no telling of the quality of these products and their utility to their industries. [1, 2]

Despite now being more than 30 years old this manufacturing procedure is still in its infancy when it comes to its use in most industries other than the peak of the medical and aerospace industry. Consortiums help to drive forward this procedure by gaining a better understanding of what is necessary to communalize it through clear standards and processes.

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Post-Processing for AM

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1 Objectives

This module aims to document post-processing technologies and their applications concerning different Additive Manufacturing (AM) processes, with emphasis on metallic materials.

Various types of post-processing treatments are reviewed and their integrations with AM processes are discussed. During this course, the students will be able to address the following objectives:

1. Describe the different post-processing techniques
2. Explain the benefits and limitations of each post-processing technique with respect to each AM process
3. Identify the most suitable post-processing technique for a specific AM process and application

1.1 Learning outcomes

On successful completion of this module a student should be able to:

1. Obtain advanced knowledge and critical understanding of the theory, principles and applicability of post-processing methods
2. Explain how post-processing fits in the AM chain
3. Describe the different post-processing technologies and their applications in AM, with emphasis on metallic materials.
4. Discuss the different methods that can be used to reduce residual stresses and distortion, for a variety of part geometries and with respect to different AM processes
5. Describe the effect of different heat treatment processes on the microstructure, mechanical properties, residual stresses, and defects
6. Explain the steps of the different post-processing technologies, according to each AM process, as well as its respective costs.

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2 Post-Processing: the last step in the manufacturing process

2.1 Introduction

Post-processing is a critical part of Additive Manufacturing. It is the final step of the manufacturing process, where parts receive adjustments, such as smoothing and strengthening. AM parts can still have poor surface finishes, and the production method can affect the mechanical properties of the component. The main objective of post-processing is to eliminate potentially dangerous defects and to attain the desired surface quality, these processes can include heat treatment, separating the components from support structure, as well as surface finishing and processes such as CNC machining, blasting and polishing. The post-processing of AM parts can be just as vital as the fabrication itself [1].

Industrials have spent the last twenty years singing the praises of additive manufacturing, but reality shows that if there is one thing that truly enables to appreciate the benefits and the results of this technology, it is post-processing. Post-processing is an umbrella term that covers a variety of stages that 3D printed parts have to undergo before being used for their final purpose. No matter at what post-processing stage the AM part is, the goal remains the same: removing the undesired properties that have been built-in the final product during the additive manufacturing process. Furthermore, as the name suggests, it takes place at the end of the manufacturing process, and the type of post-processing actions leveraged as well as the amount of work at this manufacturing stage depends on many variables. including applications [1].

2.2 Why post-processing: Mutually Linked Reasons

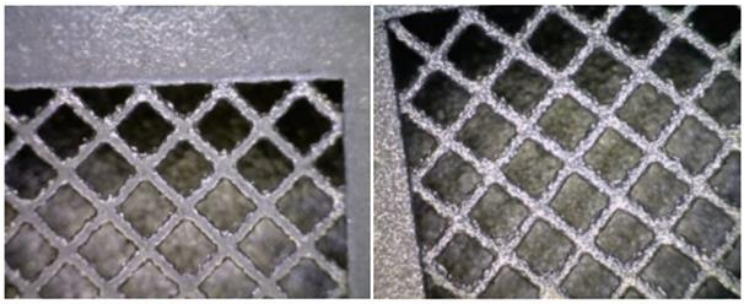
A post-processing stage can bring many improvements such as better aesthetics, geometric accuracy, mechanical properties, and desired surface characteristics. An example of this improvements can be seen in Figure 1, where surfaces were treated using water jet blasting and centrifugal disc finishing.

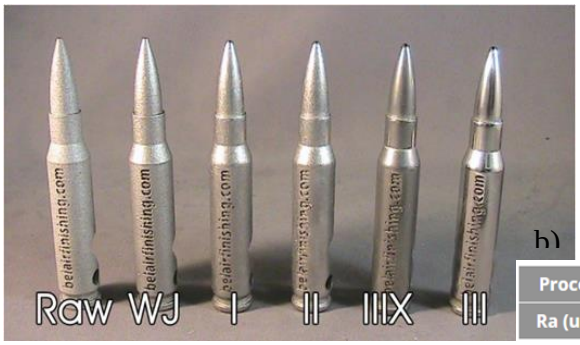
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The main benefits obtained by post-processing are summarized below:

1. Mitigation of structural defects: solid or liquid cracks, entrapped gas pores, oxide films, lack of fusion, contour defects, etc.
2. Enhancing the microstructural homogeneity: reduction of detrimental phases, bringing about desirable microstructure
3. Improving the (anisotropic) mechanical behaviour: tensile, fatigue, creep, etc.
4. Reduction of residual stresses
5. Functionality: surface finish, functional properties





Process	Raw	WJ	I	II	IIIX	III
Ra (uin):	140	59	24	11	7	9

Figure 1 comparison of metallic parts produced by AM before and after being post processed: a) Water Jet Blasting of PBF titanium and b) Centrifugal Disc Finishing (source https://belairfinishing.com/metal-process-techmology/)

To get the products in its "ready-to-use" form, operators face two main challenges [2]:

1. The first one is that a large proportion of the tasks carried out after the additive manufacturing process are manual. Currently, up to sixty percent of the manufacturing costs of an AM part are attributed to the highly manual steps of post-processing, by automating the post-processing workflow, manufacturers will reduce

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costs by producing end-use parts with technology that is reliable, repeatable, and reproducible.

2. The second issue is that be it resin, metal or ceramic, filament, powder or slurry, each AM process poses its challenges when it comes to post-processing. In this case, operators should first know the desired results they expect their part to have in order to determine the post-processing step that best suits their project. Furthermore, some post-processing tasks are mandatory for certain applications, others are not.

2.3 Post-Processing for AM: Why Not?

As it is well known post-processing add **costs**, increase **lead time** and disturb the **supply chain**. Post-processing may not help with some defects, namely:

- Cracks (surface connectivity).
- Pores: When heat treatment operations are required, gas pores (even collapsed by HIP) might re-open during subsequent HTs as thermally induced pores (TIPs).

Post-processing erases the fine microstructure resulting from the rapid solidification in AM, reducing the as-built strength.

Substrate used for building purposes are generally separated from the as-built part after heat treatment. Defects such as distortion or even cracking of the substrate can be a major concern.

For the reasons pointed above and in order to obtain good results it is important to know the necessary and sufficient property requirements of the parts to be produced.

The aim should be pushing AM boundaries to produce parts that do not require any post-processing (first-time right).

2.4 A step to AM post-processing

AM technology has undergone a fundamental change in the manufacturing principle, from raw material to component performance in comparison with traditional manufacturing processes [2]. Based on the process characteristics of point-by-point melting and layer-by-

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layer manufacturing, the AM technology can quickly produce three-dimensional complex structural parts [2].

When compared with other traditional manufacturing technologies, the surface quality of AM parts made by Direct energy deposition (DED) is commonly lower because of the layer-by-layer processing and the staircase effect. Different AM processes will result in different surface roughness. Usually, an insufficient understanding of process dynamics is the most influential factor in various challenges. For example, in the Powder bed Fusion – laser based (PBF-LB) process, the interaction mechanisms between the powder bed and the molten pool and between the powder and the laser beam, as well as the melting processes are difficult to understand due to the complicated metallurgical and thermophysical phenomena. In the SLM process, it is necessary to evaluate the strong bonding force in processing areas and the rapid solidification phenomenon under an ultra-high temperature gradient. The evolution of the internal structure of the parts and the change of thermal stress under cyclic conditions also require further exploration. During the manufacturing process, internal defects such as balling, porosity, cracks, powder agglomeration, and thermal stress can appear between different printing layers. Therefore, after the manufacturing of parts, post-processing operations are usually required to improve the mechanical properties and the surface quality, achieving their intended use. There are many post-processing technologies, such as thermal post-processing to release thermally induced residual stress and laser peening to reduce micro-defects and improve surface quality [71]. Post-processing methods can be divided in mechanical, chemical, and thermal.

1. **Mechanical:**
    - Shot peening/blasting
    - Abrasive (flow, centrifugal) polishing (e.g., extrude hone)
    - Machining (e.g., interfaces)
    - Laser polishing (mechanical/thermal)

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2. **Chemical:**
    - Etching
3. **Thermal:**
    - Hot isostatic pressing
    - Heat treatment (e.g., stress relief/solution)

In addition, several AM systems require support structures for components with overhangs and these support structures must be removed from the part by post-processing technologies Also, depending on the Additive manufacturing method, residual resin, metal and powder must be removed. And, finally, the surface of the printed components must be refined by edge radiusing, surface smoothing and, frequently, polishing. On average the removal processes (support structure, resin, powder) and surface finishing account for about 75% of the post-processing work. Other post-processing activities may involve vacuum drying and dyeing of the AM components. Optimizing the AM process parameters might lead to lower post-processing costs.

3 Post processing techniques

This session indicates and describes the most common post-processing technologies used in AM by introducing the procedures of different post-processing techniques and their effects on additively manufactured parts. Firstly, the most commonly used post-processing techniques in Additive manufacturing will be described, including support material removal, thermal post-processing, and machining. Afterwards, more specific post-processing techniques will be presented namely: laser peening, laser polishing, machining, and abrasive finishing.

3.1 Cleaning and powder removing

Depowdering, or powder removing, remains the most explicit word to outline the ability to remove residues. Depowdering comes into play when components have been produced with powder-based metal additive manufacturing technologies. It is the first step of the post-processing chain after the printing process.

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Since many technologies are powder-based processes, powder removal is a very important aspect to consider when designing a 3D model for AM.

3.1.1 Why does power need to be removed from most of the AM parts?

With some techniques, such as PBF-LB and PBF-EB, the powder is sintered around the part due to the hot conditions. Sintering means that powder grains are superficially melted and stick together, as if they were partially welded together in all the contact zones between the grains. This condition of heat-affected powder is called a “cake”, and the manufactured parts are inside that cake. It is possible to take that block of sintered powder out of the manufacturing chamber with your hands. The cohesion between the powder grains is strong enough to allow this. Therefore, it is also very difficult to remove this cake from the narrow internal cavities. Sometimes the only purpose of removing the raw material is to make the part as light as possible. However, it could also be for cleaning reasons, for example in the medical or aerospace field where no residues (powder grains, droplet of resin, …) may be released during the lifespan of the part. This is something important to take care of during the design phase [3].

3.1.1.1 Example of a cube

As example it can be referred a the design of a very complex (and thus optimised) cooling channel in a mould insert. A designer can spend hours of simulation to find the ideal shape to efficiently remove the heat after the injection step. But if he did not take care of the raw material that will fill all the channel during manufacturing, his perfect design won’t be usable and so will his expensive part be. For example, if this mould was made from a metal powder, and if the channel was about 1 mm in diameter but over 2 meters long when unrolled, how would it be possible to remove the metal powder from that very long and narrow channel? The basic consideration about raw material that must be considered in the design phase, is how to remove it afterwards.

A first example to illustrate the concern of removing raw material is the making of a simple cube, represented in **Error! Reference source not found.**, from powder, with the PBF-LB, where the cube was to be hollow:

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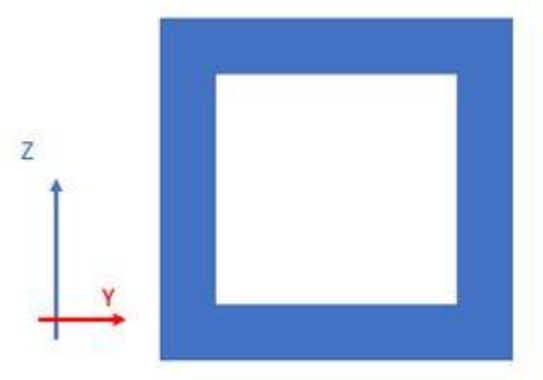


Figure 2 ***A hollowed cube, to be made*** **[3].**

For the first layers, the powder will be spread all over the surface and all of the squared area of the cube will be melted (red line in the left Figure 3). When the middle of the part is reached, only the vertical walls will be treated by the laser, but the powder will be spread all over the surface:

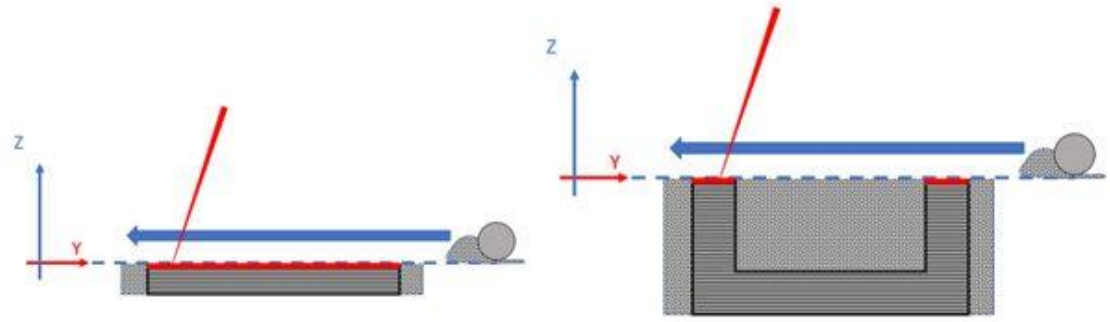


Figure 3 ***Left: manufacturing of the first layer, the whole area is processed by the laser; right: manufacturing of mid-layers, side walls are processed by the laser.*** **[3].**

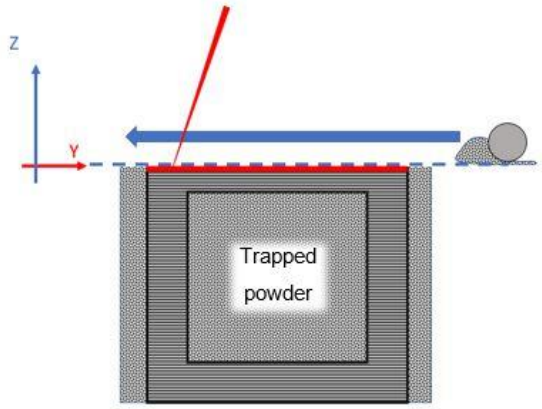


Figure 4 ***Processing of last layers seals the cube,*** **[3].**

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In Figure 4 it can be seen that a large quantity of the raw material used remains trapped inside the cube because, obviously, no outlet has been made through the skin of the cube to remove that trapped material after manufacturing. In this case, powder was used but it is also applicable for resins, sheets, wires. So, it's really important to take care of this raw material in the design phase, otherwise this hollowed cube will be much heavier than expected.

3.1.1.2 Configuration of the outlet

Sometimes an outlet to remove raw material is too narrow, or it is not possible to remove everything because of the internal configuration.

In Figure 5, a simple, small hole has been made to avoid excessive impact on the design. The technician, however, will need much more time to remove the internal raw material for accessibility reasons. Moreover, the sharp internal edges of the cube allow a better anchorage of the powder in those areas and an iron wire will be needed to try, blindly, to scrap off the powder in those areas. Finally, if the technician wants to suck out the powder with a vacuum cleaner or blow it out with compressed air, both will be very hard to do because no other outlet will allow an air flux to circulate through the part to remove the raw material. That's why the second option may be better than the first one. A third one could be providing a lot of smaller holes, all around the cube, through which the powder could leave the part without clogging.

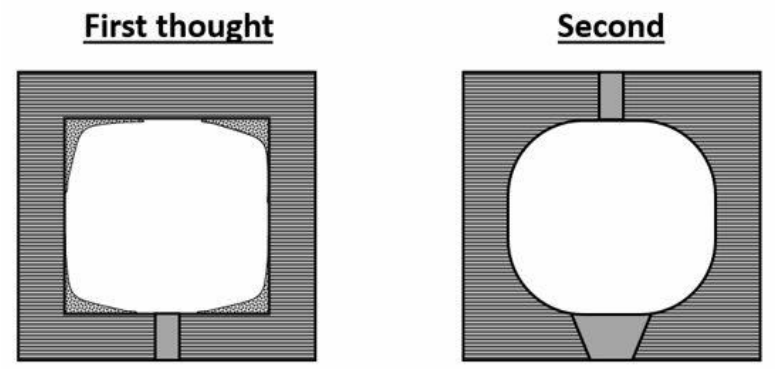


Figure 5 ***Design modification with "easier cleaning" consideration*** **[3].**

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3.1.1.3 Design with powder evacuation approach

An example of very difficult to clean raw material are heat exchangers with large lattice structures. Pre-trials have to be conducted to test the cleaning feasibility on samples beforehand. Examples of complex but cleanable parts are shown in Figure 6.



Figure 6*Complex parts which have been successfully cleaned inside* **[3].**

Finally, skilled technicians can come up with bright ideas to remove raw material after the AM process, but it will be costly and sometimes impossible to do. The best solution, which will reduce cost and time and improve the overall part quality, will be delivered by designers who are aware of this aspect. And each solution will be case-specific.

For objects without holes or complex designs, the process is relatively easy. The parts are first brushed, removing most of the loose powder, and then sandblasted to remove what the brush may have missed. An example of this can be in Figure 7, where a complex part was produced on a Powder-Bed Fusion system. Depowdering this part will usually require a brush and vacuum cleaner

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Figure 7 - Powder removal [4].

3.2 Material Removal

3.2.1 Support structures removal

Complex geometries made by AM include lattices, overhanging sections and inclined surfaces amongst others. To produce such parts, support structures are sometimes needed. These structures consist of sacrificial material utilized for supporting overhanging features such as those in holes or inclined surfaces as well as to reduce thermal distortions caused by the thermal cycle during the deposition process (Figure 8) [27].

Adding sacrificial material to the part increases waste, time and cost associated with its removal. Thus, the design of these structures is an essential stage of the deposition process, particularly for PBF. Extensive research has been performed at the design stage aiming to minimize the need of support structures, or the type of supports to be used for a specific component and orientation [28, 29].



Figure 8. sacrificial material utilized for supporting overhanging features being manually removed [5].

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Support structures could be considered a “necessary evil” in the Additive Manufacturing process. The more support structures you use, the more material necessary and the higher the post-processing costs – as well as a lower surface quality. On the other hand, these support structures are necessary to anchor your part to the build platform (they prevent curling and reduce the risk of the part getting dislodged by the recoater), conduct heat (process stability) and prevent molten metal from sinking through the powder bed (for downfacing areas and avoiding dross formation).

Applying a minimal amount of support is a matter of considering the part design and part orientation. Supports can be removed manually (Figure 8), using hands, drills, mills, grinding stones, or using CNC machines.

Most supports are not fully dense, particularly in the build direction. Since the supports will be removed from the finished part, it seems unnecessary to make them fully dense, so laser-path planning algorithms often skip every other layer of the supports, saving material and reducing build time.

There are also some types of supports that can be removed by heat or through a liquid solution. This supports, usually synthetic, are made from materials that are weaker, soluble in a liquid solution or melt at a lower temperature than the build material; and, so, the support removal is simplified. The removal is also affected by the orientation of the part. Another important aspect is that the orientation and location of the supports are important. The orientation of the supports affects the surface finishing, since, upon support removal, it leaves witness marks on the surface. And, if the supports are in an area of small features, the support removal may lead to the breakage of the small features.

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3.2.2 CNC Machining

A very common effect in AM parts is due to the nature of the way parts are fabricated, which is the addition of multiple layers of material, being subject to the Staircasing effect, Figure 9 a).

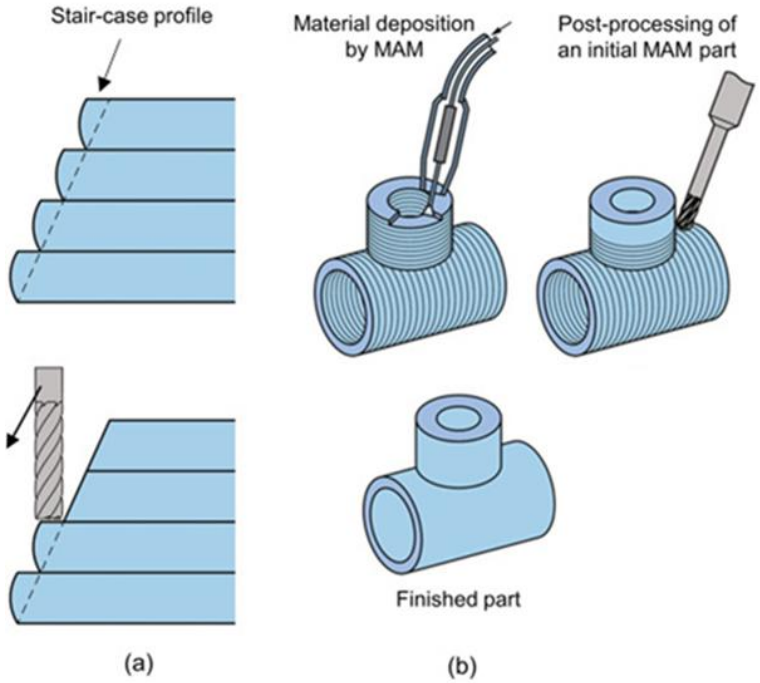


Figure 9. Schematic representation of the utilization of metal removal processes at post-processing level to eliminate the 'staircase' profile of metal-built parts, and (b) additive manufacturing process followed by material removal. [86].

This effect arises because current technologies do not allow printing metal with vertical curvatures. Also, this effect is more obvious for parts made from solid-state AM than fusion-based processes such as PBF, since metal particles are finer. The staircasing effect not only looks aesthetically unpleasing, the sharp indents near the steps also create regions of high stress concentration, so if the component is hollow, it is likely to fail if a load was applied directly to the part. A way to reduce the effects of the staircasing effect is to reduce the layer thickness of the printed material.

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Figure 10 – Schematic showing the effect of reducing layer thickness [19]

As seen on Figure 10, by reducing the layer thickness, the fabricated part will follow the desired curvature shown in red more precisely, because when the layer thickness is fine, the number of layers is tight together in a smaller space and thus the distance between two consecutive layers is smaller, thereby resulting in a smooth, continuous surface. However, if this is not possible,whether it is due to limitations with the machine or other factors, there are post-processing methods which aim to increase the quality of the surface finish of a component.

The easiest way to improve the surface finish of an AM-component is to simply remove material from the part until a smooth surface is achieved (Figure 11). Due to the complex nature of the components which are manufactured, hand-finishing is undesirable, since it is very time consuming, and the precision is very poor. The most ideal way to remove excess/unwanted material is to CNC machine the part, which can be done on a CNC milling machine with up to 6 axes of freedom, allowing it to follow very complex geometries and remove very fine material. Rotating drill is normally used with this process. Because of the machining operation on the surface for finishing purposes, there must be an offset considered for the dimensions in design stage.

Figure 11 clearly exhibits the sheer difference in terms of finish quality of a component that has undergone CNC machining compared to that of an unprocessed thread. CNC machining may also be used to remove structural supports for the fabricated components, for processes such as PBF.

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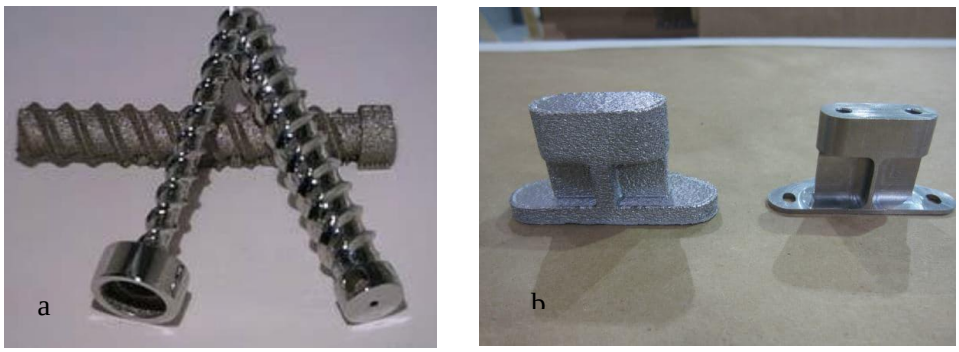


Figure 11 Difference in surface finish for an untreated and CNC machined part [21]; b) Two Ti-6Al-4V titanium alloy brackets 3D printed, before and after machining. (Image courtesy of NASA

On parts manufactured by DED, particularly by wire-based processes, it is achieved a very low surface quality (see Table 1), which is observed by a wavy surface and non-uniform wall thickness. Thus, finishing operations such as machining are a necessary post-process within the DED chain [16]. Features not produced during the deposition process need to be created during post-processing by subtractive methods such as machining.

Table 1. Classification of DED processes and typical values observed for the manufacture of titanium alloys [90]

	Directed Energy Deposition			
Nomenclature	EB-DED	DED-arc	WL-DED	PL-DED
Feedstock	wire	wire	wire	powder
Typical feedstock size		diameter 0.5-3 mm		particle 45-150 μm
Heating source	electron beam	electric arc/ plasma	laser	laser
Atmosphere	vacuum	inert gas (argon and/or helium)		
Deposition rate (kg/hr)	3	0.4 - 1	0.2 - 1	0.7
Typical as-built surface roughness, μm	50	500	150	13-25
Build envelope, L x W x H mm^3	5791 1219 1219	900 600 300	bespoke	4000 2000 750
Commercial Manufacturer	Sciaky Chernova Hvilya	Norsk Waammat	Trumpf (bespoke)	BeAM Optomec Trumpf

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As referred previously, techniques such as Direct Energy Deposition - Arc (DED- arc), parts are generally built with typically 1 mm of extra material over all surfaces to allow for the scalloped surface profile of the DED-Arc technique (typical depth of this is 0.4 mm). Figure 12 shows an outboard landing gear rib in titanium produced at Cranfield University. The detail of the surface finish can be observed as well as a part with machined surfaces. Currently, the deposition, measurement and finishing are done in different stages, on three machines, which greatly increases the cost and time of production. After manufacture by AM, the component is then measured for form, transferred to a CNC milling system, relocated and then finished through machining.

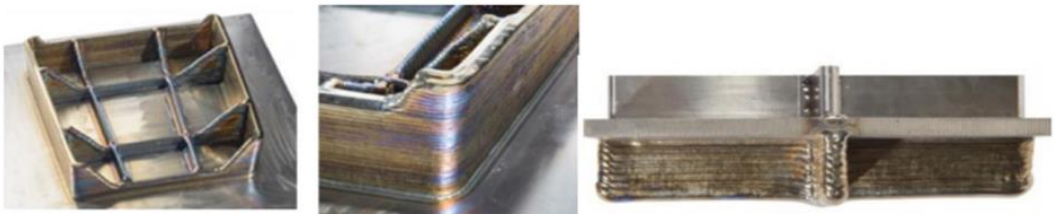


Figure 12 2- 0 kg landing gear rib built in titanium and the detail of the surface finish. Small part as deposited and machined. [6]

3.2.3 Other Finishing operations

Finish operations of AM parts are challenging, mainly due to their complex geometries, which can lead to problems with work holding and vibration. Furthermore, there is the problem of aligning complex components when they precise geometric datums in the as-built state.

DED-arc cannot produce features with very fine tolerances. Thus, machining as a post-process is often needed, to produce round holes, smooth and flat surfaces, and datum features.

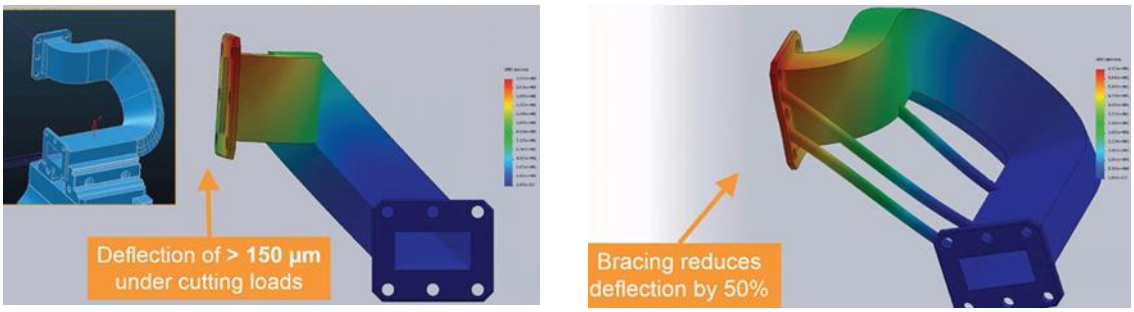
The first step, when considering applying any type of machining, such as milling or drilling, is to study the effect of the cutting forces on the build part. Is the part rigid enough to withstand the cutting forces that will be applied? If not, the part might deflect away from the cutting tool and spring back, which leads to vibration, tool chatter and gouging of the component surface. In this situation, the stiffness of the part must be improved before any

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machining operation. This enhancement can be achieved by changing the part design or the way the part is supported during machining.

In the first approach, which is changing the part design, if, for example, a microwave guide is considered, some braces can be added to connect the two ends of the components and to reduce the deflections during cutting. The drawbacks are the increased footprint of the part since that space could have been occupied by other components (see Figure 13).



a) b)

Figure 13 - Finite element analysis a) revealing deflection of a microwave guide due to cutting forces, b) with the ntroduction of braces to reduce deflection of the part, but they increase the mass and footprint of the part [38]

The way that the part is supported is also important since the support must be distributed across the part to minimize deflection and vibration. Some methods to perform this are adhesive that conforms to complex forms using an array of moving pins or even encapsulating 3D-printed jaws. Once the part is fixtured, the machining operation is ready to begin. However, metrology is important to ensure the geometric accuracy of the part. So, before machining, the part must be fixtured and aligned. Finally, after all the steps previously described, finishing operations can be performed, and the resulting part will have dimensions within the tolerances and will present a great surface finishing. [38]

As mentioned before, machining is a very important strategy for finishing AM parts. Adaptive raster milling of the surface, hole drilling and sharp edge contour machining can fulfil the needs of most AM parts when considering accuracy and machine efficiency.

Milling uses cutters to shape the part, often on a moveable tabletop, although some milling machines also feature movable cutters. One characteristic of milling is that the cutting mechanism is intermittent. For raster milling, the stepover distance between adjacent

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toolpaths is a very important parameter. For great machining accuracy and surface quality, a smaller stepover distance is required.

Sharp edges are critical and are often the intersection curves between features and surfaces. When applying raster milling to an AM part, the edges that are parallel to the milling direction can be missed. And for edges that are not parallel to the milling direction, the edge has a stair-step appearance, so raster milling is not effective to create a smooth edge. Thus, after performing raster milling, sharp edge contour machining must be run to machine along the sharp edges.

Hole drilling is sometimes performed, and it consists of machining holes present in the part. However, before this operation, the holes must be recognized by some software.

Thus, by performing a pre-processing of recognition of the surface to identify the features present on the part, and then by post-processing using raster milling, contour machining and hole drilling, it is possible to fabricate an accurate part. [39]

Besides the techniques previously mentioned, **grinding** can also be performed in an AM part. It can be done either with a rigid grinding tool (wheel or disk) or an abrasive paper, backed by a rigid plate. Also, the major movement in grinding is the rotation of the wheel or disk. And the main mechanisms involved include rubbing (corresponds to having elastic deformation of the material), plowing (plastic deformation) and cutting. At the end of a grinding operation, the part will present dimensional accuracy, form accuracy, surface texture and surface integrity.

Regarding **burnishin**g, it consists of plastic deformation of the surface due to sliding contact with another object, which can be either a sphere or a cylinder. Burnishing contributes to the increase of hardness and induces compressive stresses at the surface, meaning that it increases fatigue resistance.

Lapping is another common technique, and it involves the cutting and shearing action of loose abrasive particles and the fine grinding of abrasive particles embedded in the lap plate. Lapping can be done either with a hard lap (or a second workpiece) or with a soft metal lap charged with the abrasive particles, in the form of a paste or suspension. When referring to

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lapping, the term polishing can also arise since it is a variant of lapping. Polishing can be done using a soft cloth charged with the abrasive particles among its fibres.

All the mechanical finishing processes allow achieving high dimensional accuracy, high flatness and surface finish. However, some post-processing methods, like machining, can induce undesired properties to the part, like hardening the material, etc. So, the selection of the right post-processing method is crucial.

3.2.4 Base Plate removal by EDM wire cutting

EDM wire cutting is an Efficient method to rapidly separate AM parts from the base plate, also other cutting techniques can be used. Modern Wire EDMs for AM are equipped with a reusable Molybdenum wire feature, which quickly moves inexpensive wire from the source capstan to the receiving capstan, and then back again so that the wire is continuously moving back and forth through the workpiece.

The rapid speed of the wire (10 - 50 times higher than normal brass wire cutting machines) creates its own flushing so high-pressure pumps are not required (Figure 14). The Molybdenum wire is very resistant to wire breaks, offering an advantage over the brass wire that is typically used in a wire EDM



Figure 14 - Wire EDM separating 3D-printed metal parts from their baseplates.

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This post-processing technique allows for a very good accuracy, and uses a dielectric liquid, usually a mixture of water and oil to reduce oxidation on the part surfaces (Figure 15)



Figure 15 - Wire EDMs often are used for postprocessing to separate 3D-printed metal parts from their baseplates. Protolabs printed this part, which EDM Tech Center reportedly removed from its baseplate in 56 minutes with an SSG WEDM. EDM Tech Center Inc.

3.3 Hybrid fabrication

Additive manufacturing+ Machining

Additive manufacturing allows the production of a wide variety of parts, from simple parts to complex parts with intricate features. However, as seen for the powder removal, the use of metal removal operations at post-processing level is not always feasible due to restricted cutting tool access. In cases like this, machining of the overhanging edges, shallow sections or complex features must be carried out in conjunction with material deposition during the manufacturing route. The integration of metal additive manufacturing with material removal processes from the perspective of the above-mentioned second category began in the mid 1990's. This Hybrid fabrication is illustrated in Figure 16.

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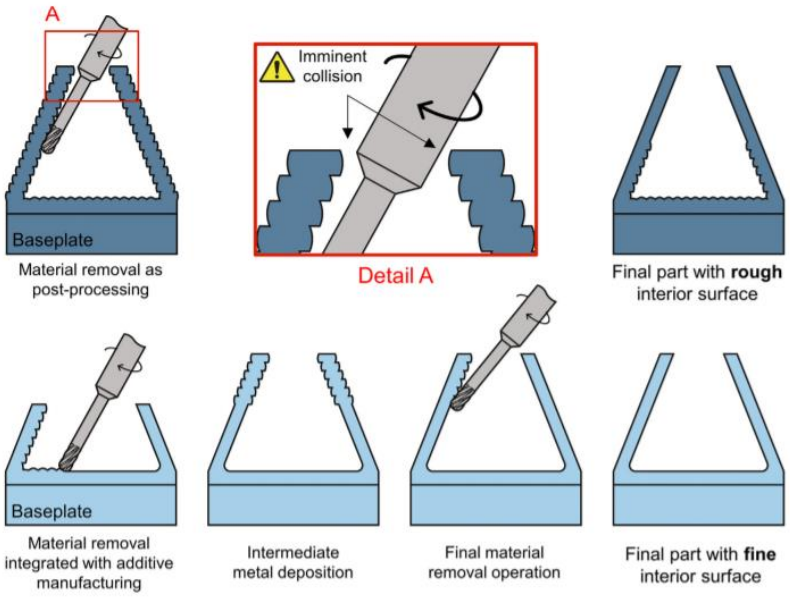


Figure 16 - combination of metal additive manufacturing and material removal during the fabrication sequence to allow building the final metal part. [86].

Additive manufacturing + Rolling

An effective post-processing technique, which enhances the mechanical properties of AM parts, is rolling (Figure 17). Despite the numerous advantages of DED-Arc the mechanical properties of the final parts display unpredictable mechanical properties due to the process-induced residual stresses and changes in the microstructure [1]. Moreover, a complex thermal stress distribution from the repeated deposition process gives rise to high residual distortion and subsequently crack formation in some cases [28]. Recent studies have explored various post-processing techniques to enhance the mechanical properties of DED-arc parts, such as shot peening and high depth rolling, as well as controlling the build path.

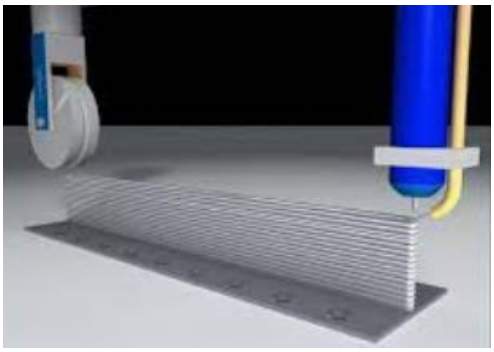


Figure 17 – Schematic representation of Additive manufacturing + Rolling

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3.4 Thermal post-processing

3.4.1 Introduction

Whilst a process like CNC machining can improve the physical appearance of an AM made part, it cannot homogenise and improve the mechanical properties of the component, since the process does not influence the microstructure of the material used for fabrication. This is where heat treatment of metals comes into use for post processing AM parts (Figure 18). The rapid heating and cooling of metal during AM creates a build-up of internal stresses, but additional heat treatments can further improve mechanical properties like hardness, elongation, fatigue strength, and more.



Figure 18 - A batch oven is used to perform thermal post-processing on 3D-printed metal parts.[87]

There are standards for Additive Manufacturing – Post Processing Methods; namely Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion ASTM F330 - Developed by Subcommittee: F42.05. This standard specifies the requirements for thermal post-processing of parts produced via metal powder bed fusion to achieve the required material properties and microstructure to meet engineering requirements. This standard is intended to be referenced by Material Part Property specifications for powder bed fusion. Currently, this standard includes thermal post-processing for materials including titanium alloys, cobalt 28 chromium 6 molybdenum, alloy UNS N07718, alloy UNS N06625, alloy, UNS 31603 and AlSi10Mg. This specification will be updated as new powder bed fusion material heat treatments are developed.

Different heat treatments (HT) may be used to achieve the properties desired for the AM metal. The layer-by-layer deposition can result in properties directionally dependent and can

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fluctuate with the orientation of the part within the build chamber. So, these treatments help to improve the strength, ductility, fatigue, hardness, or bulk properties, enhancing their wear resistance while keeping their core tough and relatively ductile. In addition, HT can assure stress relief – these are done to eliminate the internal stresses inducted in the metal parts during part building. Their presence is mainly due to the high temperature gradients produced during the AM process. Depending on the material, different heat treatments can be done.

Aging is a HT process where the properties of some alloys can change over time at near ambient temperatures. The most common metals used in this process are aluminium, stainless steel, copper alloys, other metal alloys.

This process can occur in a naturally or artificially, throughout the life of a metal. In natural aging, there is a formation of metal precipitates, which will block dislocations in the metal, increasing strength and hardness, while reducing its ductility. On the other hand, artificial aging is used to accelerate the natural aging process, increasing the temperature to a point below the recrystallization temperature of the metal.

In both cases, natural or artificial aging, once the precipitate has the correct size, the part is cooled rapidly to prevent any further change in the metal precipitates. If that does not occur, overaging can happen, which can result in a reduction of strength and hardness. [50]

Annealing is a heat treatment process used to increase ductility and reduce the hardness of the material. This improvement is a result of the reduction of dislocations in the crystal structure of the material. In addition, annealing adjusts the formability of the material, machinability and removes residual stresses. Some metals that commonly require this type of process are aluminium, copper, and brass.

Annealing has 3 main benefits:

1) Improves formability – by making the metal more ductile, it makes the sample easier to bend and press without fracturing.
2) Improves machinability – brittle materials can excessively wear out tools, especially if they require further post-processing via CNC machining.
3) Removes residual stresses – decreases the chances of cracks propagating on the metal surface.

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We can separate the annealing heat treatment into 3 main stages: recovery stage, recrystallization stage, and grain growth stage. During the recovery stage, the temperature is raised to one where the internal stresses present in the material are relieved, with the help of a furnace or other type of heating device. In the second stage, the recrystallization stage, the material is heated above its recrystallization temperature, but below its melting temperature, where new grains are created without pre-existing stresses forming. Finally, in the last stage, new grains fully develop, where this growth is controlled by allowing the material to cool at a specified rate. [51]

Annealing is the process of heating a metal part to a certain temperature, then cooling it at a specific rate, to produce the required microstructure. This is a result of the reduction in the number dislocations in the crystal structure of the material being annealed [23], caused by atoms migration in the structure, which reduces the hardness.

3.4.2 Hot Isostatic Pressing (HIP)

HIP (hot isostatic pressing) is currently used to modify the microstructures of metal AM parts, improving the desired metal properties, and obtaining the desired part performance (Figure 19). This process can reduce or eliminate the directional dependence of anisotropic properties of AM material, resulting in bulk properties in some cases that are equivalent or better than those of the corresponding wrought material. In addition, by optimizing the pressure and temperature cycles, it is possible to improve several mechanical properties such as elongation, ductility, strength, and enhance the structural integrity of the component. [46-47].

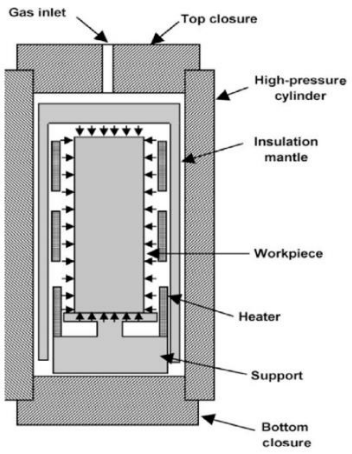


Figure 19. HIP system [48]

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The hot isostatic pressing, like the name suggests, applies a high isostatic gas pressure, which implies that the pressure acts on all surfaces of the part in all directions (Figure 19), and high temperatures in the range of 900-1000 °C. Furthermore, another important parameter is the hold time during the HIP cycle, which is dependent on the thickness of large parts depending on the thermal conductivity of the material. It should be noted that the heating and cooling rate will not directly affect the densification of the material, but it can affect the final microstructure hence improve its mechanical properties.

There are 3 different mechanisms of densification occurring in a HIP process: plastic deformation, creep, and diffusion. At first, plastic deformation is dominant, since the applied external pressure is higher than the yield strength of the material at the HIP temperature, therefore making the voids in the material collapse. Consequently, creep and diffusion make the pores collapse, close, and eliminate them, thus resulting in a material free of defects and stress concentrations are eliminated. Moreover, since HIP can eliminate all the defects, it enables that AM processed parts can have a “lower quality” which leads to cost and time saving by processing it faster. [46]

In summary, several Additively Manufactured metal parts require a heat-treatment solution with precise temperature uniformity. This ensures the printed parts adhere to the metallurgical properties of materials. To avoid major distortion, metal AM parts are usually stress relieved together with the build platform and heat-treated after being cut off from the build platform. This solution is often selected by companies because of the complexity of materials used in the AM process. For aerospace and medical applications, for instance, the AM process must comply with very strict rules, therefore the benefits of heat treatment lie in its ability to reduce surface contamination and to maximize mechanical properties.

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4 Other post-processing Techniques

4.1 Surface Treatments

4.1.1 Topographic Modification

Finishing operations do not include only mechanical processes. Chemical polishing and electro-polishing are also available and being applied to AM parts.

Chemical polishing results in microroughness smoothing and polishing along with the dissolution of an upper layer. Polishing requires preventing metal etching and results in the formation of a passivating film on a metal surface. And, after chemical polishing, the workpieces must be cleaned in running water and dried. This post-process is typically used for aluminium, copper, zinc and stainless steels.

The main advantages of chemical polishing are high accuracy surface finish, bright surfaces, complex shapes can be polished, and requires less labour and energy intensity than mechanical methods. On the other hand, the process is complex since it involves cleaning, immersion and rinsing, there is a high rejection rate, there is the risk of toxicity and fire, the equipment corrodes, and hazardous chemicals are disposed of.

Regarding **electro-polishing**, the part is immersed in a temperature-controlled bath of electrolyte and acts as the anode. A current pass from the anode to the cathode. And then, the surface of the metal is oxidized and dissolved in the electrolyte. Electro-polishing causes a release of oxygen, avoids hydrogen inclusions and embrittlement of the parts. To achieve electro-polishing of a rough surface, the protruding parts of a surface must dissolve faster than the valleys. Electrolytes used are most often concentrated acid solutions having high viscosity, such as mixtures of sulphuric acid and phosphoric acid. Electro-polishing is usually used for parts that cannot be polished mechanically due to the risk of thermal, mechanical or chemical damage. Some advantages are allowing the treatment of irregularly shaped parts and leading to higher polishing rates than chemical polishing.

When comparing electro-polishing and chemical polishing, both are applied to reduce the surface roughness. Chemical polishing is a very effective method in reducing simultaneously the internal and external roughness in the case of steel parts for any shape and geometry.

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While electro-polishing is effective in reducing the internal and external roughness if the counter electrode is positioned in the proximity of the surface to be polished.

However, electro-polishing exhibits a better performance in reducing the roughness of the external surfaces than chemical polishing [40].

4.1.2 Surface Texturing processes

To improve the properties of the part, surface texturing is required to modify its surface with a controlled topography (pattern) at the macro, micro or nanoscale. This process is a possible solution for enhancing the tribological behaviour of mechanical components because surface textures may act as reservoirs for lubricant, wear debris or hydrodynamic bearings. Moreover, it may modify the contact angle (wettability), inducing a transition from hydrophilic to hydrophobic surfaces.

Chemical Etching, also known as chemical milling or photochemical etching, is used to create complex and highly accurate precision components (Figure 20). Chemical agents are applied to specific areas of a surface to remove material by dissolution/corrosion and requires the use of masks to cover non-removal regions. The etching time controls the depth of the cavities (from 0.5 µm to 1 mm). Chemical etching produces smooth regular cavities, without mechanical or thermal damage to the material. It is applied in large area texturing, bearings or cutting tools. Typical materials could be steels and stainless steels, nickel and nickel alloys, copper and copper alloys, aluminium, titanium, and other metals including molybdenum and polyamide metallized film [41].

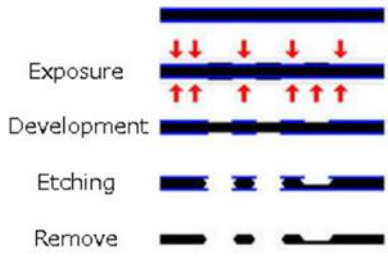


Figure 20 - Etching Process [42]

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Micro-grinding is a material removal method used for machining pins and grooves with small dimensions and for achieving flat surfaces with very fine finishing. Micro-grinding uses an abrasive tool to fabricate micro-grooves (Figure 21). Its width depends on the size of the tool (grinding wheel) and is typically tens of μm. This process is simple, inexpensive and increases the part accuracy. [42, 43]

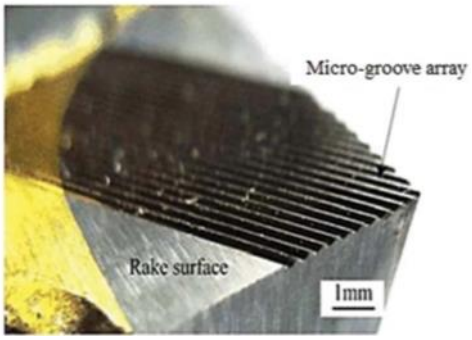


Figure 21 Grooved tool created by micro-grinding [44]

S**hot peening or shot blasting** is a cold working process that entails hammering a surface with shots to cause plastic deformation of metal surface to remove unwanted material (Figure 22). Shots are spherical particles (d=0.25-1 mm) made of either metal, glass, or ceramic. The Impact velocity is between 20 and 150 m s^{-1}. The precise control of the texture is difficult due to the varying shape, size, hardness, and speed of the particles, so random textures are produced in a wide range of surface finishes. Shot peening may be done with or without a surface mask, with no thermal damage. It is a low-cost process and is suitable for non-conductive brittle materials and heat-sensitive materials. This technique is suitable for surface homogenization and cleaning, it is specifically used to enhance fatigue strength of components. Introduces compressive stress at the surface and a work-hardened surface layer.

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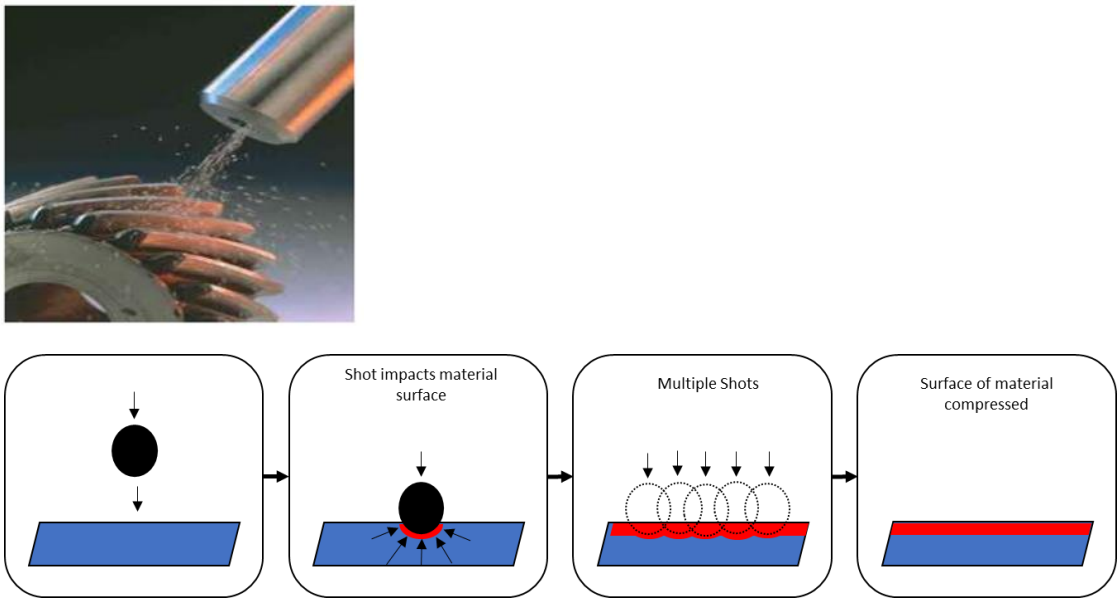


Figure 22 Shot blasting process [42]

Vibration mechanical texturing is based on a turning operation using a single point cutting tool that oscillates while the part rotates and advances along the x-axis. It is a new technique for creating micro-dimples with a depth of 2-50 µm and 100-500 µm diameter (Figure 23). [42]

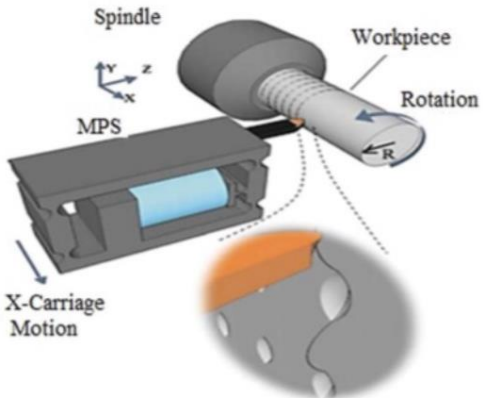


Figure 23 Vibration mechanical texturing [42]

In **electric discharge machining (EDM),** the material is removed from the part by a series of rapidly recurring electric discharges between two electrodes by vaporization and melting. The two electrodes are subject to an electric voltage. One electrode is the tool (graphite or copper wire) and the other is the workpiece, and they are separated by a dielectric fluid that

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isolates them, enhances the removal of material, cools the electrodes, and removes particles. The complete sparking cycle is repeated thousands of times per second, generating small craters that conform the final part geometry (Figure 24). This is a non-contact process, without deformation that textures and machines complex shaped parts with sharp angles and internal corners. EDM originates a smooth finish, however, the heat affected zone is significant, the removal rate is low (slow process), and it is limited to small parts. [44]

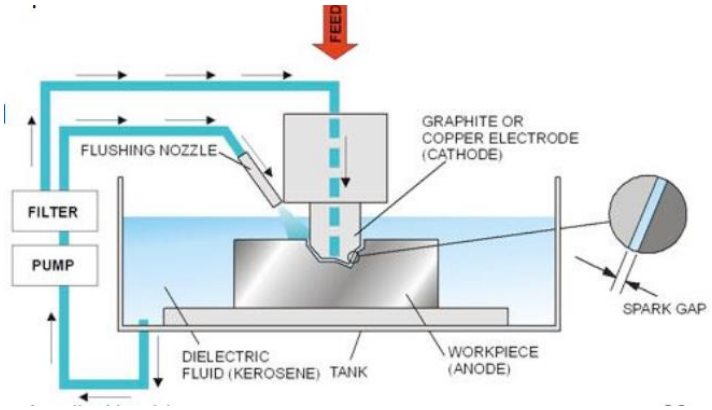


Figure 24. Electric discharge machining [42]

Electrochemical machining (ECM) is similar to EDM; however, the fluid is conductive, there are no discharges and no tool wear. The material is removed by anodic dissolution via an electrochemical process and is limited to electrically conductive materials. ECM produces a good surface finish, has a low production cost, has high efficiency, no heated affected zone, no tool wear and no contact. Normally used for mass production and for working extremely hard materials or materials that are difficult to machine using conventional methods. [42]

Ultrasonic machining removes material from the surface of a part through high frequency, low amplitude vibrations of a tool against the material surface in the presence of fine abrasive particles (Figure 25). This material removal technique is based on brittle fracture of the workpiece and is usually used on materials with a high hardness due to the microcracking mechanics. Ultrasonic machining allows extremely complex and non-uniform shapes to be cut onto the workpiece with particularly high precision.

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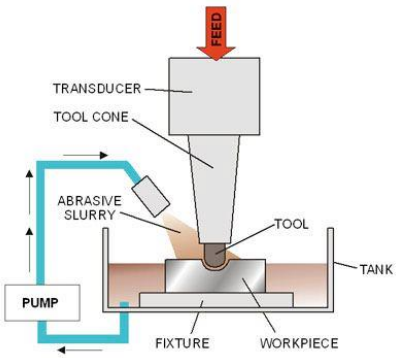


Figure 25. Ultrasonic machining [42, 45]

Centrifugal Grinding and Polishing uses centrifugal forces and grinding media to reduce surface roughness, producing mirror like finish and removing surface defects. It is a Flexible and consistent process, fast and economical (Figure 26). Can be used in a wet or dry medium. The main Influencing factors are:

- Media type
- Rotation
- Time
- Additives (lubricants, coolants)



Figure 26. Centrifugal Grinding and Polishing (source: https://www.belairfinishing.com/metal-process-technology/

Laser Surface Texturing process uses high energy laser pulses to ablate material (Figure 27). The direct absorption of laser energy above the threshold fluence (energy/area) promotes the material removal which depends on materials properties, microstructure, morphology, defects, absorption mechanism and laser parameters. It is a fast, non-contact and low environmental process that promotes a high accuracy of the final part and can produce extremely fine patterns in localized areas.

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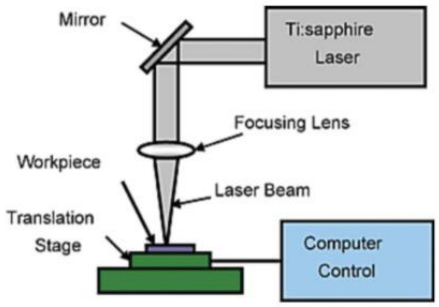


Figure 27. Laser surface texturing [42]

4.2 Thermal/thermomechanical treatments

Flame hardening is a heat treatment that uses an oxyacetylene flame torch to heat the surface of the part to its critical temperature (Figure 28). After that, the material is quenched where it is used a combination of water spray and the cold base metal. This type of process is commonly used for large and complex shape parts. One of the major drawbacks of this technique is that it can be difficult to control and has a high cost associated. [49]

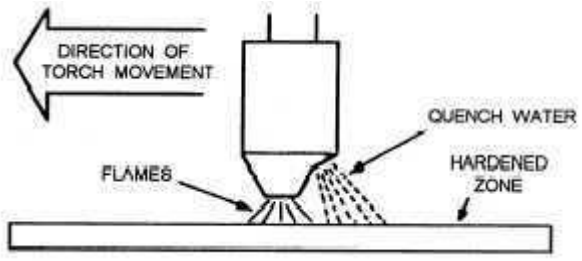


Figure 28. Scheme of flame hardening process [52]

Induction hardening is a heat treatment that uses a coil to induce heat at the surface of the part and then is quenched into a fluid. As current flows through the coil, it generates a magnetic field. The alternating magnetic field flows through the part section and induces a voltage. Voltage in the part induces current (eddy current) at the surface that heats the part due to its internal resistance. This process is fast and irregular shapes can be handled easily. The hardness of the resultant material is dependent on the carbon content. [49]

Laser hardening is a heat treatment that uses a laser beam to heat the surface of the part (Figure 29) and rapidly cool down by heat conduction to the bulk (self-quenching). This process allows a localized treatment, guiding the beam through mirrors and lenses, where

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the heat affected zone and distortion are reduced. It offers advantages over conventional HT processes, including high throughput, reproducibility, and product quality. No vacuum is required and hence any intricate and large components can be hardened. Even though it can occur surface oxidation so, sometimes, surface protection is needed. [49]

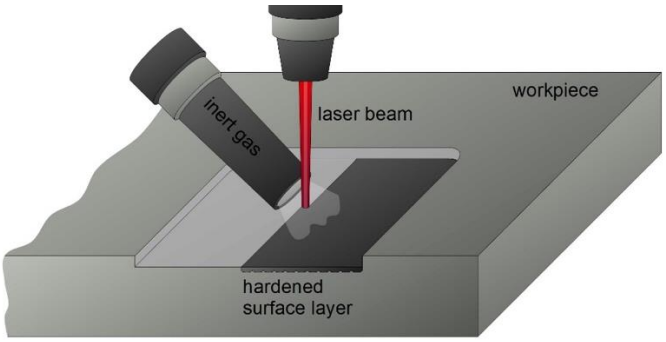


Figure 29. Scheme of a laser hardening process [53]

In electron beam hardening treatment, there is a martensitic hardening of ferrous materials using an electron beam as a source of energy. Since this is a localized treatment, several electromagnetic coils are used to guide the beam of electrons. Like laser hardening, after the heat treatment, the material undergoes through self-quenching procedure. This procedure has a reduced heat affected zone and distortion. The electron beam hardening requires vacuum so there is no surface oxidation. Since the thickness of the energy absorption layer is proportional to the square of the acceleration voltage and inversely proportional to the density of the material, it is possible to accurately control acceleration voltage and the depth of hardening throughout the process. [49]

Shock Hardening is a mechanical cold working process used to extend the life of a metal component by inducing compressive residual stresses at the surface, highlighting 3 different techniques: shock (shot) peening, explosion shock hardening and, laser shock hardening (peening). [49]

Shock (shot) peening besides being a Surface treatment, it can also be used for mechanical properties purposes, it. involves a jet of hard particles (metallic, ceramic, or glass) toward a component's metal surface at high velocities. The shock peening is used in components that experience metal failure due to high-cycle operating conditions.

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The impact of hard particles on the metal surface causes plastic deformation which changes the mechanical properties of the surface. Thus, this mechanical change of the surface metal produces beneficial compressive residual stresses and cracks, consequently preventing failure Overall, there is a fatigue improvement of the metal parts. This fatigue improvement can be determined by parameters like density, material, size, hardness, geometry, distance, and angles of the shot. [49] [54]

Explosion shock hardening is a process that uses a shock wave to produce defects on the crystalline structure, on an atomic scale, which leads to a strengthening of the metal part.

Although it is important to notice that, in conventional cold work processes, these defects interfere with the normal processes by which metals yield, making them stiffer but more brittle. Explosion shock hardening is, in contrast with the conventional cold work processes, very fast, producing much harder material for a given change in shape. Even though, if the shock wave applies a greater force for too long it can lead to a weakening of the material and often cause spall. Since the voids nucleate at large defects, such as oxide inclusions and grain boundaries, samples with a high purity so, with larger grain size, can withstand greater shock. [49]

Laser shock hardening (peening) uses a high energy, short duration laser pulse to produce a rapid expansion plasma burst on the surface of the part. The rapid rise of pressure generates a powerful compressive shockwave, that propagates into the material that places deep residual compressive stresses into key areas of the component, improving the overall resistance of the material surface (Figure 30).

Laser shock hardening does not use the thermal effects of the laser, instead it uses the dynamic mechanical effects of a shockwave that the laser creates. This process enables an increase in resistance to low cycle, high stress situations as well as high cycle, low stress situations in a deteriorating surface environment. It can also help with erosion, corrosion, fretting and strike damage.

During this process there is no contamination, providing a high precision and quality control of the surface topography. [49, 55]

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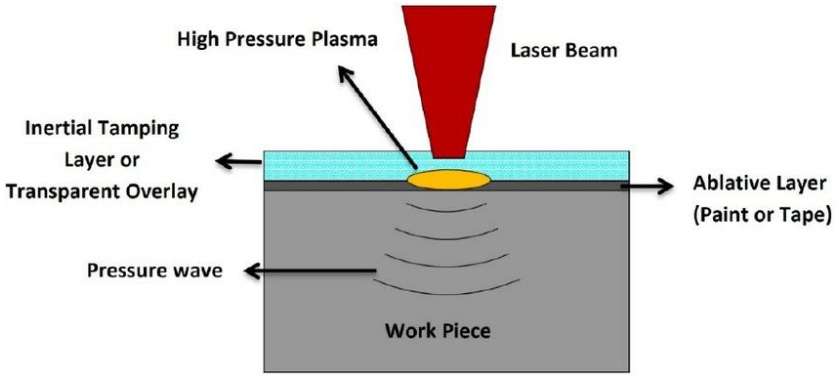


Figure 30. Laser shock hardening scheme [56]

4.3

4.4 Chemical and Structural Modification

4.4.1 Thermochemical treatments

Thermochemical treatments are performed to increase the surface hardness of ferrous metal parts (steels and cast irons), improving wear resistance. There is a change in microstructure, by heat treatment, and in surface chemical composition, by diffusion. This type of treatments involves the formation of a hard layer at the surface of the part, maintaining the core strong and tough.

Carburizing consists of increasing carbon concentration of a low-carbon steel part, by interstitial diffusion from the surface to the interior, improving wear resistance. This treatment is done at temperatures that correspond to the austenitic phase of the steel.

Pack carburizing (solid phase) is the process where the part is packed, surrounded by charcoal granules and placed in a furnace at 900-950°C (austenitic phase) for 12-72h. There is formation of CO2 by the charcoal, which will react with the excess carbon in charcoal, forming CO. The hard carbon skin gets deeper with the time it spends in the furnace, and finally, it's quenched, and martensitic transformation occurs.

Liquid carburizing (cyaniding) consists in exposing the parts to a temperature above the start of austenitic transformation, usually in cyanide molten salts that transport C and N into the metal. Due to environmental and health problems, cyanide salts are being replaced by other molten salts with a high grade of carbon, which results in a skin only carbon-hardened. This process has a high rate of carbon diffusion, making the process faster than pack carburizing

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(liquid carburizing only takes around 30 minutes), and the surfaces are free from soot. The hard skin is thin and harder than in pack carburizing. It is necessary to rinse the part after cooling.

In gas carburizing, the parts go inside a sealed furnace with gases that contain carbon, such as hydrocarbons, methane, ethane or propane, and they are heated. These gases are diluted with a mixture of other gases that works as an endothermic carrier, mainly N2, CO, and small amounts of CO2, H2 and H2O. This mixture controls the amount of C provided to the steel parts, preventing soot formation. Methane (or propane) reacts with the gas mixture, forming the carbon source for carburizing, CO. Then, CO breaks down for deposition in the surface, and carbon diffuses into the steel parts.

The diffusion of carbon can be controlled by maintaining a steady flow of the carrier gas and changing the flow of the C-rich gas. This method allows achieving accurate control of the carbon content in the case layer and its depth. Gas carburizing is more efficient and cleaner than pack or liquid carburizing, but it is more costly, as well as deals with toxic gases, with a higher risk of fire.

Nitriding is the process where steels (mostly low-carbon and low-alloy), Ti, Al or Mo parts are heat treated with the diffusion of nitrogen into the surface, creating a hardened layer, usually with Fe, Al, V, Cr, W or Mo nitrides, that results in parts with higher wear, fatigue and corrosion resistance. This treatment is performed in parts that have already been heat-treated and tempered, and quenching is not needed, so it has less probability of distortion compared to carburizing, but it is usually more expensive.

The main methods used are gas nitriding and plasma (or ion) nitriding, which have different mechanisms to form nitrogen.

In gas nitriding, nitrogen is delivered to the surface by heating the metal to a temperature below the start of austenitic transformation (495-565 °C) during 20-90h, while in contact with gas with nitrogen, usually ammonia, NH3, without the need of quenching.

Plasma nitriding uses glow discharge technology to deliver nitrogen to the surface of the part, followed by diffusion into the metal. This is done in a vacuum chamber with N2 gas, where a plasma is formed by high voltage, accelerating nitrogen ions towards the part. The

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bombardment of ions not only heats the part, but also cleans the surface. Compared to gas nitriding, this technique allows for more uniformity and chemistry control of the hard case, there is less distortion, it is a faster process (2-48 h) and it has a wider range of process temperatures (260-750 °C).

Carbonitriding is a similar process to carburizing, but with the addition of nitrogen by NH3 gas. The plain carbon or low alloy steel part is heated up to 820-900 °C in a gaseous atmosphere with C and N, with subsequent diffusion and quenching in oil. Finally, the part is tempered at 150-200 °C. The final piece has a hard case with usually less than 0.7 mm, harder than the achieved in the carburizing process, due to the diffusion of both C and N. This method leads to less distortion than carburizing due to the lower temperatures and shorter times.

Nitrocarburizing is a variant of nitriding, with enrichment of C and N. The properties obtained are not as good, but the process is faster, and the parts perform better under sliding loads. It is usually used for products with good adhesive and abrasive wear resistance, that need anti-sticking properties. The maximum service temperature of the parts is 350 °C [57,58]

Ion Implantation

It is a post-process operation used in a very specific applications, such as doping of semiconductors, biomedical devices and cutting tools. The ions of certain elements are accelerated up to a certain kinetic energy and bombarded towards the part. These ions penetrate in the part (they stay below the surface), slowing down by the loss of energy to the electrons of the material, until they stop at a depth between 10 nm and 10 µm. This process is performed at low temperatures, without the risk of distortion, and there is a change in the physical and chemical properties of the material. The changes achieved by this method can result in higher fatigue, corrosion and wear resistance, for example. The modified region is usually metastable, where a high density of crystalline defects can be found. Since there is lattice damage due to the collision of the accelerated ions, annealing is done for some applications that need an undamaged structure. However, annealing also promotes the diffusion of dopants, that will penetrate more and form a wider modified zone. [57, 59]

4.4.2 Surface Coatings

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Dyeing: If the visual appearance of your powder-based polymer parts needs to be improved, then you probably need a dyeing post-processing step. Dyeing can be performed, either manually in pots of hot water or using automated dyeing equipment. The results are most visible on parts that are subject to wear (glasses for instance), as the colour penetrates the surface of the part

Painting: Some parts produced by AM need aesthetic improvements, that can be related to surface texture or colour, for example. For parts produced by powder bed AM methods, which have some porosity, the pieces will absorb the dye when they are dipped into it. But when the parts require painting, they must be sealed before. Paints, varnishes and lacquers can be applied as a barrier made of organic resins, protecting the metal from the environment. A continuous solid film forms and adheres to the substrate.

Paints are pigmented coatings that form a layer with specific decorative, protective, or technical properties. Paints can be composed of a pigment, an extender, a vehicle and additives. The pigment confers anticorrosive properties, as well as colour, opacity and mechanical strength. The extenders or fillers are responsible for the properties of the paint, like viscosity or gloss level, and they are cheaper pigments that don't contribute to the colour but can minimize the cost of the paint. The vehicle is a colloidal suspension that contains the binder in a solvent. The binder is the material that holds all the paint constituents together

Lacquers or varnishes are similar to paint but without a pigment. They form a transparent hard and glossy layer. [60]

Metal Plating: Electroplating of metals consists of applying a metal coating on a metal surface (substrate), by electrodeposition, using an electric current. The substrate works as a cathode and the anode is the metal that will be deposited. The reaction occurs in an electrolytic solution with ions of the metal that will be deposited. An electric current is applied to the anode, that oxidizes/dissolves, releasing ions to the media. The positive ions move through the solution to the substrate, where deposition occurs.

Electroplating can be applied to most of the metals, and the formed coating is pore-free, with thicknesses from 50 nm to more than 500 µm.

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Copper metal plating is usually done because of its appearance combined with its good electrical and thermal conductivity. However, it is more susceptible to corrosion. After cleaning, a layer of copper is deposited onto the substrate by electrodeposition.

Nickel plating confers very high corrosion and wear resistance, and it is affordable. By modification of the composition of the electrolyte and operating conditions, nickel can have different appearances. However, nickel needs special attention since it is more prone to pore formation. Nickel plating can be applied by an electroless deposition, where no current is applied, and instead, there is a controlled reduction reaction, resulting in a very uniform coating.

Zinc plating is a cheap process that confers increased strength, ductility, and corrosion resistance since it works as a sacrificial coating. Therefore, zinc plating is mostly performed to protect the substrate material. It is done by electrodeposition of zinc ions onto the surface of the substrate. It is commonly used in small parts like screws, fasteners and springs. [61-64]

Coating or Infiltration: Coating consists of the infiltration of microporous components with polymers. The goal of this activity is to produce components that are completely gas-tight or liquid-tight.

4.5 Inspection and testing

This post-processing step allows for the validation of a part's dimensional accuracy and mechanical properties. It is usually seen as a benefit in on-demand manufacturing situations.

Additive manufacturing processes used for metals, present some unique issues associated with inspection, quality assurance, and testing. Metrology, inspection, and non-destructive testing using white/blue-light scanning, dye-penetrant testing, ultrasonic testing, computed tomography (CT) scanning and more will be needed after post-processing and possibly at multiple points during post-processing. The processes showed in the Figure 31 are related to non-destructive methods being applied to AM parts.

Visual inspections are used mainly to identify defects such as distortions, surface condition and gross anomalies, among others. Dimensional inspection utilizes measurements to ensure dimensional control of the AM parts. Various non-destructive methods may be used to assure

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the clearance of internal passageways and volumes such as by using a displaced liquid, pressure-volume-temperature, flow rate, or pycnometry. Radiographic testing has been used for many years to inspect welds in pipelines, pressure vessels, and a wide range of critical-use metal components to detect defects within a narrow field of view by means of 2D imaging. 3D digital scanning refers to several techniques used to capture the geometric extent of an object, generate a point cloud of data approximating the surface of an object, and fit a geometric surface or solid description to the point cloud creating a digital model. Ultrasonic testing uses ultrasonic sound waves that penetrate the parts until the signal bounces back in internal features and it is collected, allowing to inspect approximate size and location of these features. Vacuum leak testing can be an effective way to assure the hermetic seal of a volume or containment vessel. Flow testing may offer the means to assure clearance of complex passageways without the cost and complexity of a CT system.

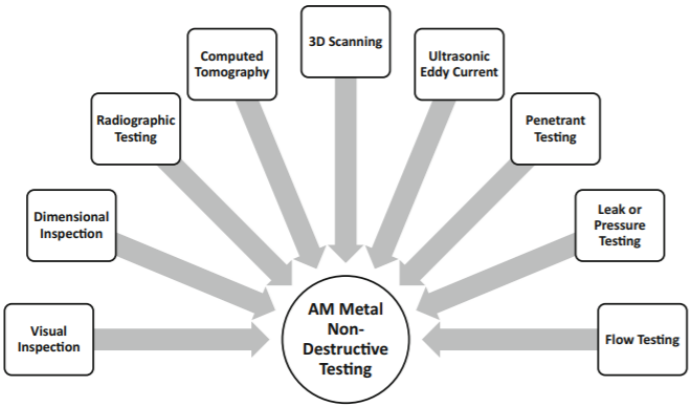


Figure 31. Non-destructive testing techniques [65]

Figure 32 shows the different destructive methods that can be applied to AM parts. Microstructural analysis will often entail preparing small samples of representative regions of interest within a part and by mounting, polishing etching the samples to reveal the structure of grains, phases, inclusions, and defects such as pores, voids, cracks, and other discontinuities. Hardness values and phase identification can be used to verify time-temperature transformations related to cooling rates and infer property determination confirmed by standard mechanical test procedures. Microstructural analysis coupled with non-destructive testing and proof testing is often all that is needed to qualify a non-critical component or process. Chemical analysis can be applied to verify the integrity and purity of materials and processing conditions used in AM. Samples may be sent to service providers

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to identify levels of contaminants such as oxygen, hydrogen, nitrogen, or trace elements such as iron, vanadium, or aluminium. This analysis can be useful to determine the pickup of contaminants or loss of alloying constituents. Standardized mechanical test specimens and testing procedures have been used for technical generations to assist in alloy development and process material and process certification. ASTM leads the development and delivery of voluntary consensus standards to improve product quality, enhance health and safety, strengthen market access and trade, and build consumer confidence. Other destructive tests that may be applied to AM material could include something as simple as the standard guided bend tests as applied to 3D weld deposits. [65]

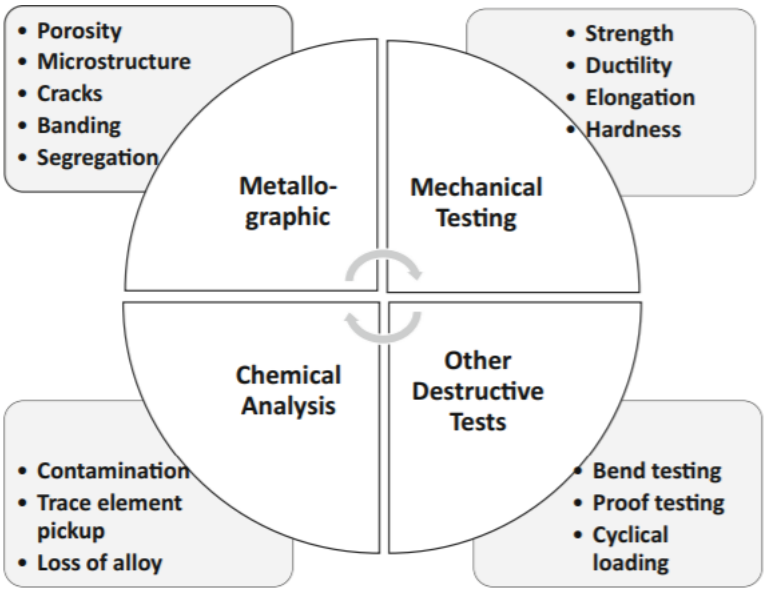


Figure 32. AM metal destructive tests [65]

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5 Can the same post-processing technology be compatible with several types of additive manufacturing technologies?

5.1 Introduction

First, it should be noted that specialists of post-processing technologies usually develop their solutions to respond to specific demand of the additive manufacturing industry. Over time, applications tend to extend their area of expertise to other technologies.

Moreover, choosing among the array of AM technologies the ideal process for one's project is quite complicated. However, despite the numerous post-processing techniques, the choice can quickly be made for a post-processing solution.

A small number of post-processing equipment, be it for removal of supports and residual resin, de-powdering & cleaning or surface finishing, can be used for whole groups of additive manufacturing technologies. Furthermore, experience in various applications might easily enable operators to determine the ideal post-processing technique for their project.

Lastly, similarities and disparities between additive manufacturing technologies must absolutely be considered. Binder jetting, for instance, presents post-processing requirements similar to Material Extrusion. Metallic parts produced by extrusion, on the other hand, might require further investments in post-processing. Indeed, with this AM technology, the raw material is made up of a filament with a plastic or wax binder heavily loaded with metal powder. The binder must be removed once the part is right out of the machine. Thereafter follow a debinding with heat or an acid bath and a sintering step.

It is not just about making parts look good, it's about improving the mechanical properties of the parts for high performance.

Different post-processing technologies and their applications in large scale production. Processing technologies include thermal post-processing, laser peening, laser polishing, machining and abrasive finishing methods. For metal AM technology, the post-processing covers a variety of stages that AM parts have to undergo before being used for the final purpose, such as powder removal, stress relief annealing, wire cutting, other finishing, hot isostatic pressing and so on. Some of these procedures still require manual operation, where skilled operators are necessary for key tasks. It may be cost-effective to complete the

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prototype or even dozens of parts manually, but if hundreds or even thousands of parts are produced, the demand for post-processing automation in AM becomes extremely urgent. Automated solutions can improve production efficiency, but there are only a few centralized specific solutions to help achieve automated post-processing, and these systems are mainly designed for polymer AM parts. In terms of metal AM, the post-processing technology of traditional manufacturing is still used. In order to further automate these technologies, some companies have also begun to implement robotic solutions that can install printing substrates, clean powder, unload parts and post-processing. The goal is to replace all manual work to promote continuous and large-scale production. Although this development is encouraging, the pace of innovation in this field is still relatively slow. The number of advanced automatic post-processing solutions would certainly increase in the future, so as to adapt to the growing development of the AM industry [88].

AM begins with designing a part specifically for additive, followed by programming it, optimizing the process, printing the part, and finally post-processing it.

The promise of an AM process that will spit out finished parts in the manner of serial production is unrealistic. Simple plastic parts, for example, may require post-processing steps like support removal and may need to be sanded, polished, vapor-smoothed, machined, filled, painted, sealed, dyed, and assembled.

In the AM marketplace, job shops are called service bureaus. This is because they must offer an array of services to turn a customer's concept into reality. Similarly, when companies buy 3D printers, they usually are seeking more than just to print parts. They want AM Printing parts that meet expectations will require a company's staff to apply service bureau-style expertise, including post-processing [88].

5.1.1 Unique Challenges

Each additive process presents its own challenges. Large-scale polymer parts, for instance, usually require significant finishing. They are built by extruding and stacking layers of hot, melted plastic one on top of the other. As the plastic cools, it shrinks about 0.5%. This may seem minor, but for 6 meters-long part that would equate to about 2.54 cm—a significant inaccuracy.

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Tooling is one of the main applications for large-scale AM. Parts right off the printer have a texture similar to corduroy. They must be machined after they have been printed and cool. The machining can take longer than the printing.

Prototype automobiles or showpieces are given Class A finishes. Oak Ridge National Laboratory famously 3D-printed a replica of the Shelby Cobra to celebrate the iconic racecar's 50th anniversary (Figure 33). Before being post-processed, the vehicle looked cool, but its surface was rough (Figure 34). With the help of finishing experts at Tru-Design LLC, a process was developed to finish such large-scale additive parts. [88].



Figure 33. 3D-printed Shelby Cobra. ORNL [88].



Figure 34. Oak Ridge National Lab's 3D-printed Shelby Cobra proved challenging to finish because the carbon-fiber-reinforced body's surface had the texture of concrete. ORNL[88]

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5.1.2 Post-Processing of Metal additive Manufacturing

3D-printing metal parts is a whole different story than printing plastic. Materials extrusion is a popular process for printing plastic parts that involves extruding melted plastic—also can be used to produce metal parts. However, for Metal parts significant postprocessing is usually required.

After debinding, the part is sintered. Significant shrinkage occurs during this phase. The good news is the shrinkage is predictable, allowing the printing of reasonably accurate parts.

Another process for metal printing is binder jetting; it has postprocessing requirements similar to extrusion. Binder jetting involves spreading a layer of metal powder upon which a printer head selectively sprays a binder in a pattern based on the part's design. The binder then is cured, and another layer of metal powder is spread.

When the part is finished, the powder surrounding it must be removed—a process called depowdering. It is then sintered, which also eliminates binder. Finally, the part is machined and polished.

A DED machine is equipped with a laser that melts sprayed metal powder or wire to build parts layer by layer. These parts typically need machining after printing to achieve an acceptable surface finish.

Hybrid machines, which feature deposition heads and full machining capabilities, are available to minimize part handling and approach the goal of getting a finished part right out of the machine.

LPBF (laser powder-bed fusion) is the most prevalent way of making metal parts. Layers of powder are stacked and fused together with a focused laser beam. While the LPBF process prints strong, accurate parts, they can still need postprocessing.

Once excess powder is removed from a 3D-printed part, the part typically needs to be removed from its build plate. Some people perform the job with a band saw, but most use a wire EDM.

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Depending on the application, parts can be heat-treated or put through a hot isostatic press to improve the material's microstructure. Some high-tolerance surfaces may be machined. Many polishing techniques, including sandblasting, can improve the finish.

5.1.2.1 Key to Serial Production

Clearly, additive manufacturing is a lot more than just 3D-printing parts. Postprocessing steps are as important as the additive process in making real a customer's vision of a part.

Expertise in postprocessing is critical to ensuring this happens. It's also critical to completing the transition from 3D printing to serial AM.

5.2 Post-processing Steps and Respective Costs for Metal AM

Metal additive manufacturing (AM) part is essentially "welded" to the build plate, and you will not be able to pull it off without some assistance. Even then, the AM part will need postprocessing before it is ready to use. Here are some costs associated with postprocessing AM parts [89].

Powder Removal: AM parts build "down" in a powder-bed fusion system as new layers are added to the top, which means that parts are buried in powder when they are done (Figure 35). After the build has finished and the parts/build plate have cooled, the machine operator has to remove all of the powder from the build volume and sieve/filter/recycle it for later use, assuming you want to reuse it. This is not an expensive step, but it does take time.



Figure 35. Metal AM parts are buried in the powder bed after the build is done [89].

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Stress Relief: The heating and cooling of the metal as the part builds layer-by-layer leads to internal stresses that must be relieved before the part is removed from the build plate. Otherwise, the part may warp or even crack. Stress-relieving the part requires an oven or furnace (preferably with environmental controls) that is big enough to fit the entire build plate. Many recommend using an oven with an inert environment to minimize oxidation on the part surface. Others prefer a vacuum furnace, which costs a lot more (€100,000 versus €10,000 to €30,000). Stress-relieving a batch of parts typically costs €500 to €600, plus shipping [89].

Part Removal: Most companies use wire EDM to remove parts from the build plate, however many machine shops are starting to use a bandsaw (Figure 36) because it is faster, and the bottoms of the parts must be finished anyway. Keep in mind that materials such as Inconel strain-harden as they are worked, making it difficult to remove them from the build plate with just a bandsaw. Using a local machine shop, we spend about €200 to €300 per plate for wire EDM, which can take a few hours depending on the number and size of the parts. A bandsaw can complete the task in minutes [89].



Figure 36. Metal AM prats being removed from the build plate with a bandsaw (source: Wesley hart, imperial machine) [89].

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Heat Treatment: Heat treatment (aging, solution annealing and so on) improves the microstructure and mechanical properties of the parts and is necessary for nearly all AM parts. In many cases, this step also requires an environmentally controlled furnace with the ability to regulate the temperature and cool-down schedule. Heat treatment may affect the dimensions of the parts, so most people prefer to heat-treat parts before they machine/finish them. The American Society for Testing and Materials (ASTM) has released a standard for thermal postprocessing of metal AM parts. Heat treatment can easily cost €500 to €2,000 depending on the material and how many parts are being treated.

Hot Isostatic Pressing: Instead of heat treatment, many aerospace companies are starting to use hot isostatic pressing (HIP), which is frequently used in the casting industry to improve the fatigue life of cast parts (Figure 37). A HIP system costs substantially more than a furnace/oven and comes with its own safety measures due to the high pressures (100 megapascals or more) at which it operates. Like heat treatment, HIP costs €500 to €2,000, but you often do not need to heat treat the part if you HIP it.

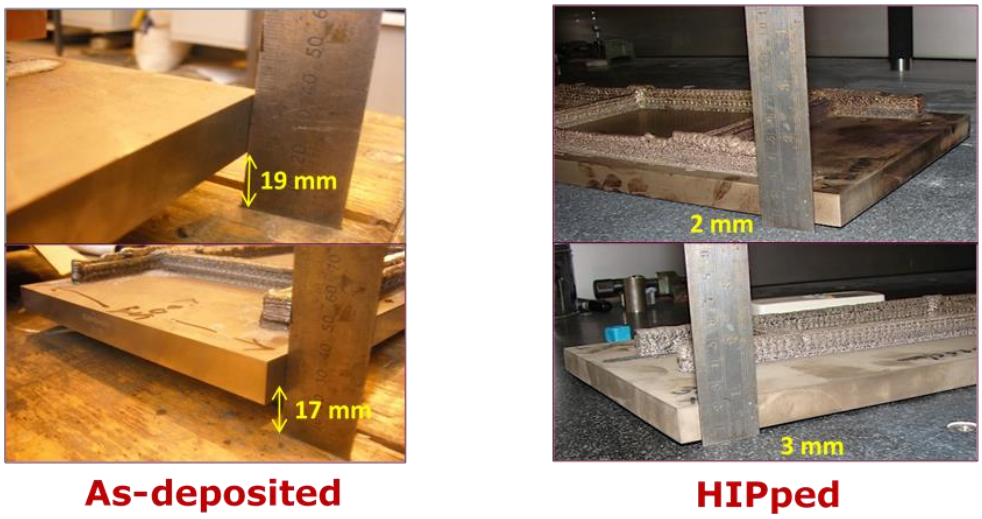


Figure 37- DED of Large Titanium Structures. As deposited and after HIP treatment to reduce distortion [90]

Machining: Machining of mating interfaces, surfaces, threads, support structures and more likely will be required to ensure dimensional accuracy of the finished part (Figure 38). Few AM parts meet specifications “as built,” and if nothing else, the surface of the part that was

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connected to the build plate will need to be finished. Most manufacturing companies already have machining systems on hand but registering parts and establishing datums for machining can be tricky, especially for complex, organically shaped parts made with AM. Accessing internal channels or cooling passages that need to be machined can also increase costs. The cost here is highly dependent on the material and the job as well as the fixturing needed to hold the part.

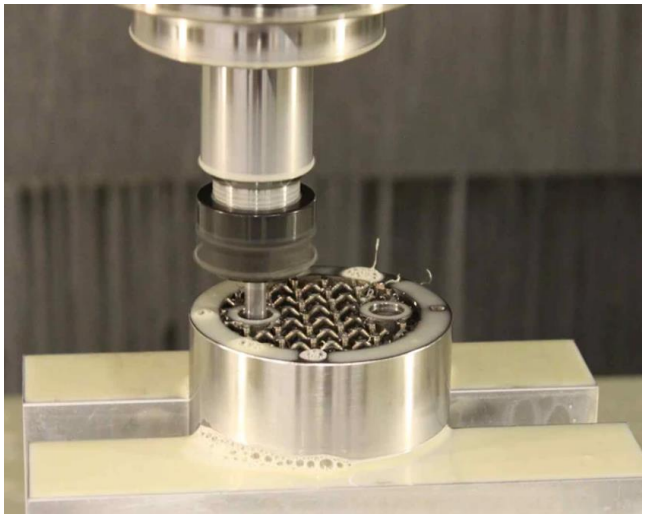


Figure 38. A metal AM part being machined to meet tolerances (source: Christian Joest, Imperial Machine & Tool Co.) [89].

Surface Treatments: Surface finishing also might be required to improve surface finish/quality, reduce surface roughness, clean internal channels or remove partially melted particles on a part. When outsourced, these costs can easily run in the hundreds if not thousands of Euros.

Inspection and Testing: Metrology, inspection and non-destructive testing using white/blue-light scanning, dye-penetrant testing, ultrasonic testing, computed tomography (CT) scanning and more will be needed after post processing and possibly at multiple points during post-processing. Destructive testing of sample parts and analysis of witness coupons (for example, tensile bars), powder chemistry, material microstructure and more also may be needed to gather data to help with process qualification and ultimately part certification. Most companies will have a range of metrology and non-destructive testing methods at hand, but AM parts with internal channels, lattice structures and other internal enhancements may

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require CT scanning to ensure clear passageways, evaluation of internal geometries and more. A CT scanner will easily cost 1 million € to buy, install and operate [89].

6 Conclusions

Post-processing plays a huge role in additively manufactured metal parts, in their design and future applications. The different post-processing techniques depend on how the parts are produced as well as on their properties.

The most used post-processing techniques for metal additively manufactured parts are the following: support material removal, surface treatments, surface coatings, and inspection and testing. Surface treatments include topographic modifications (finishing operations and surface texturing), structural modification (hot isostatic pressing, heat treatments and shock hardening), and chemical and structural modification (thermochemical treatments and ion implantation) and surface coating that englobes painting and metal plating.

Furthermore, metal parts fabricated by different additive manufacturing techniques require different post-processing. This is related to the characteristics and limitations that the AM technique confers to the metal part. For example, in powder-bed fusion, residual stresses are generated due to the high thermal gradients. Opposite to this, residual stresses do not occur during binder jetting. Thus, powder-bed fusion and binder jetting will require different post-processing.

To conclude, additive manufacturing is a technology that has been developing over the years, for its many advantages, such as the possibility to manufacture complex geometries, to have lighter structures and customization. However, the time and cost associated with the required post-processing are drawbacks for its development and implementation in the industry.

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Digital Manufacturing Master's degree to set specialists for the dawn of the industry 4.0

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master programme for digital manufacturing

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RAPID TOOLING FOR COMPETITIVE AM

Lesson Material

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1. MOVING AM FROM RESEARCH LABORATORIES TO INDUSTRIAL PRODUCTION

Additive Manufacturing is the name given to a host of related technologies that are used to fabricate physical objects directly from CAD data sources. These methods are unique in that they add and bound materials in layers, to form objects. Such systems are also known by the general names solid freeform fabrication and layered technologies.

AM and Rapid Tooling (RT) are good solutions, mainly when it is about rapid product development, or about low volume manufacturing of complex parts. There are no limits for the complexity of the parts produced by RP, no special tools are needed, the only necessary input is the CAD data, the time to market is a lot smaller and the costs are reasonable.

1.1. Design for AM and virtual prototyping

The objective of designing products is to meet the customer requirements. That's why the design will progress through a number of stages such as:

- Idea generation, as an inspirational thought or from an evolutionary process. The outcome would be a new concept aimed at meeting specific customer needs.
- Filter concepts, such as marketing filter, technical capability to manufacture the items, financial filters, etc.
- Preliminary design, when the concept is developed to a level sufficient to assess its capability of meeting the customer needs.
- Design iteration, when the design is reviewed several times to ensure that the customer needs are met and that the solution is cost effective.
- Final design, which should take into account design for manufacture aspects, in order to ensure that the design will have the ability to be produced.

A number of virtual prototyping tools and techniques are available to designer, in order to improve the communication process: visualizations, animations, concept models, virtual reality, neural networks, finite element analysis, simulations, etc.

Adjusting such parameters as colour, lighting, texture, material, transparency, luminescence, etc., the model will be transformed into a pictorial image. Depending on the capability of the CAD system, the model can generally be rotated and positioned on the screen, enabling all aspects of the design to be viewed and assessed visually. The items on the set can be moved to form a "fly through" and hence create the animation.

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Components and assemblies can be assigned constraints e.g. degrees of movement, through which they can move, enabling an animation sequence to be produced.

1.2. Transferring the CAD model to the AM machines

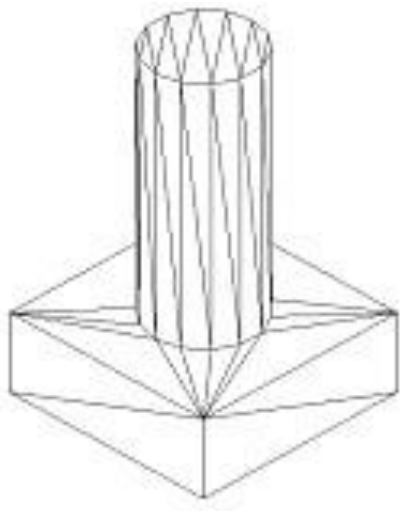


Fig. 1. The STL representation of a CAD model

The generally accepted interface to all the RP machines is the STL file format (patented by 3D Systems Inc.), which approximates the virtual model with a collection of planar triangles.

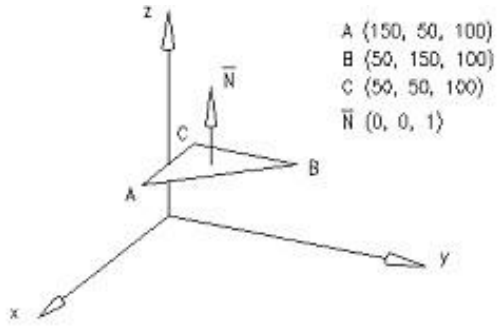
There are two types of STL files. The ASCII STL files are easier to be read, understood and modified, using an usual text editor, but their length is higher (they need bigger storage resources). The binary STL files are more compact.

Figure 2 presents the method used to describe every triangular facet, by:

- A set of (x, y, z) coordinates for all three triangle's points;
- The Cartesian components of a unit vector which is perpendicular to the facet, pointing to the outer side of the object.

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```
solid Exemplu
.
.
.
    facet normal 0.0000000e+000 0.0000000e+000 1.0000000e+000
        outer loop
            vertex 1.5000000e+002 5.0000000e+001 1.0000000e+002
            vertex 5.0000000e+001 1.5000000e+002 1.0000000e+002
            vertex 5.0000000e+001 5.0000000e+001 1.0000000e+002
        endloop
    endfacet
.
.
.
endsolid Exemplu
```

Fig. 2. A STL file's portion, corresponding to one triangular facet

All the CAD systems offer different parameters used to control the quality of the STL approximation, before saving a STL file, which could be transferred to any RP machine.

1.3. The need and importance of AM for RPD

AM is used mainly in Rapid Product Development (RPD) of new products. Functional tests are required to validate the new design of the industrial products. Complex parts need to be manufactured from final materials (not only simulant materials), in order to undertake functional tests.

Once the new product is validated, the tooling for mass production starts and the classical manufacturing technologies will be used further on, for large volume production.

AM and RT are efficient mainly for small volume production of complex parts. The same part, from the same material, will be made by a different technology later on, for large volume production.

Examples of corresponding technologies:

- SLM-SLS versus CNC and EDM, for steel parts
- Investment casting versus die casting, for aluminum parts

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- Vacuum casting versus injection molding, for plastic parts

Fig. 3 illustrates examples of innovative manufacturing of the complex metal parts made at TUCN, using the Realizer 250 – SLM machine.

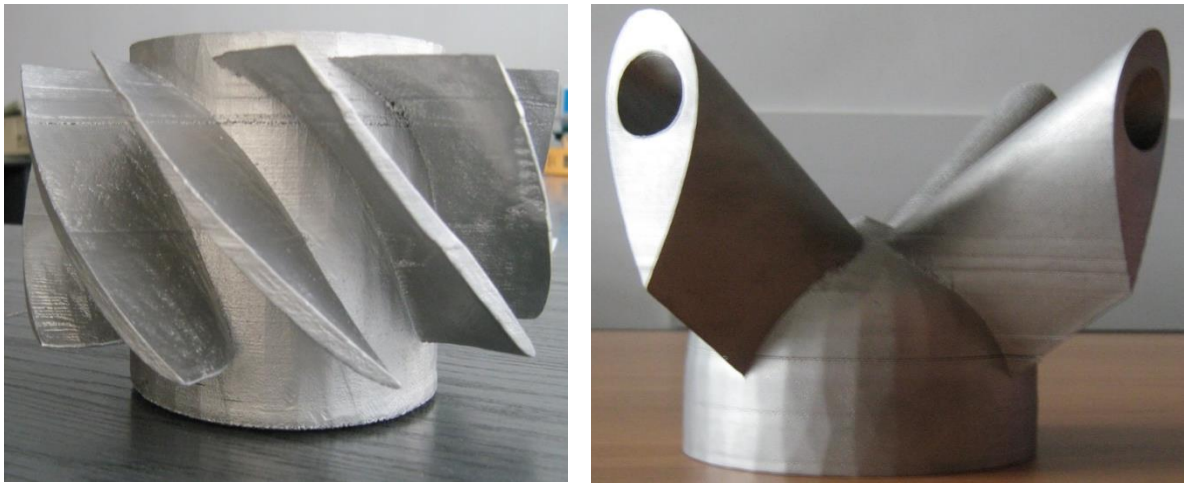


Fig. 3. SLM-SLS versus CNC manufacturing. Steel parts, made by SLM at TUCN

Limitations

AM isn't a solution to every part fabrication problem. After all, CNC technology is economical, widely understood and available, offers wide material selection and excellent accuracy.

However, if the requirement involves producing a part or object of even moderately complex geometry, and doing so quickly – AM&RT has the advantage.

The range of materials used in AM is limited dependent on the method chosen. However, the range and properties available are growing quickly: plastics, ceramics, metals ranging from stainless steel to titanium, and wood-like paper are available.

SLM technology is suitable to obtain fully dense metal parts, if the required accuracy is not high. The manufacturing costs are higher, as compare to similar CNC capabilities. Future research needs to be done in order to improve the accuracy on the SLS/SLM.

Rapid Tooling by SLS (Selective Laser Sintering) could become a quick solution for tool makers, when dealing with rapid product development and with low volume production of the complex plastic parts.

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1.4. How to select the adequate AM method, for specific applications

There are many routes to get to a final functional part or tool starting from a CAD definition. The choice depends on the application, volume of parts to be produced, final material and accuracy requirements, available AM process, etc.

Choosing isn't easy since most technologies are immature, have significant limitations, and there are usually several competing alternatives.

Table 1. presents some examples on how to choose the suitable RT method, according to different volume production of plastic parts, required for specific applications.

Plastic parts	**Rapid Tooling Technology**
1 … 10 parts	AM part made by: FDM – ABS / SL – Epoxy resin / SLS (Duraform PA)
10 … 60 parts	AM master model Silicon Rubber Molding (SRM) Vacuum casting of the parts into the silicon rubber molds
60 …300 parts	AM master model Metal spray tooling Injection molding of the parts into the metal sprayed moulds
300 … 5,000 parts	Selective laser sintering (SLS) or Selective Laser Melting (SLM) tooling (direct tooling) Injection molding of the parts into the SLS molds
5,000 parts +	Classical tooling by CNC milling / Heat treatment Finishing the tool cavities by EDM (Electrical Discharge Machining) Injection molding of the large volume production parts, into the hard tools

Table 2 presents a few examples on how to choose the suitable RT method for metal parts, according to the volume production required for specific applications.

Metal parts	**Rapid Tooling Technology**	
1 … 10 parts	Steel	SLS – AM from steel powder
	Aluminium Bronze Cast Iron	AM master model (SLA, SLS, FDM) Investment casting (or sand casting), direct from AM patterns

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10 … 100 parts	Steel	CNC machining
	Aluminium Bronze Cast Iron	AM master model Silicone rubber molding to produce wax models Investment casting (or sand casting) from RP patterns
100 … 1,000 parts	Steel	CNC machining
	Aluminium Bronze Cast Iron	AM master model – to get the negative geometry Investment casting steel dies Medium pressure die casting
1,000 parts +	Steel	CNC machining
	Aluminium Bronze Cast Iron	Classical CNC tooling / Heat treatment Finishing the tool cavities by EDM erosion High pressure die casting into hard laminated tools
Sheet metal parts	EDMWC (EDM wire cutting) of the active elements (punch and die)	

2. VACUUM CASTING BY SRM (SILICONE RUBBER MOLDING)

2.1. Introduction

Silicone rubber molds (SRM) are used for functional prototypes or for parts in small manufacturing series (10-50 pieces). Silicone rubber is a material that is suitable for making flexible molds. The silicone accurately copies the shape and the geometry of a part with complex surfaces. The number of parts that can be poured into silicone rubber molds depends on the material and on the part shapes.

The parts have a high-quality surface finish comparable to injection molding. SRM process allows the manufacturing of shape features that are difficult to process through other manufacturing technologies.

Because of its properties (flexibility, temperature resistance, dimensional accuracy, good fluidity, mechanical strength, precision in details reproduction, dimensional stability over time, hardness, etc.) the silicone is a material used for medical applications, aerospace, automotive, electronics, handcrafts, jewellery manufacturing, etc.

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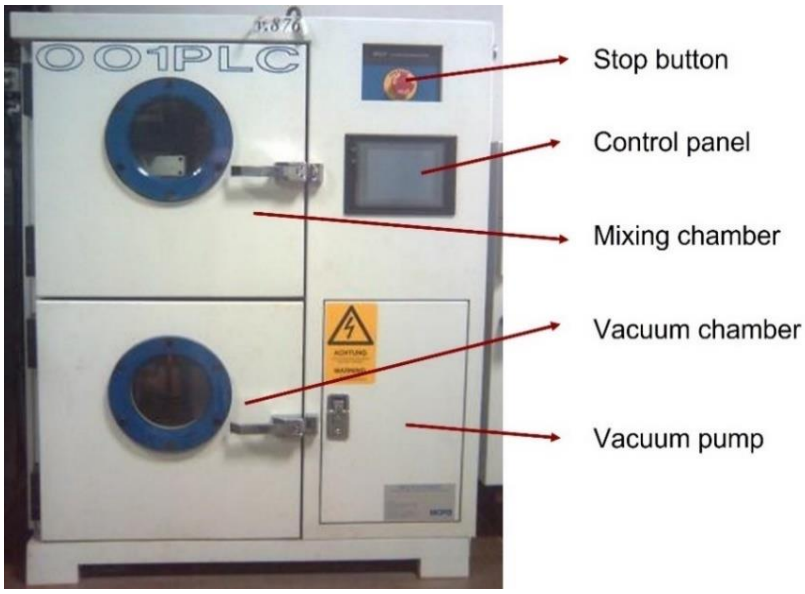
The silicone rubber is, according to its appearance, of two categories: transparent and opaque. When using opaque silicone, that is cheaper, it is recommended that the mold be made in 2 steps. In this way, the 2 half-molds are made one by one.

Fig. 4. Silicone rubber mold

It is recommended to use this technology, because it is difficult to cut the mold according to the separation plane, because the master model cannot be seen inside the silicone rubber mold. In figure 4 is presented a silicone rubber mold made of transparent silicone.

2.2. Equipment

The MCP 001 PLC vacuum casting equipment can be found at Technical University of Cluj-Napoca (TUCN) - Department of Manufacturing Engineering.



Vacuum casting (VC) equipment is used both for casting liquid materials and for high viscosity materials, such as silicone rubber. Using this equipment, both degassing and casting of different materials in silicone rubber molds could be done.

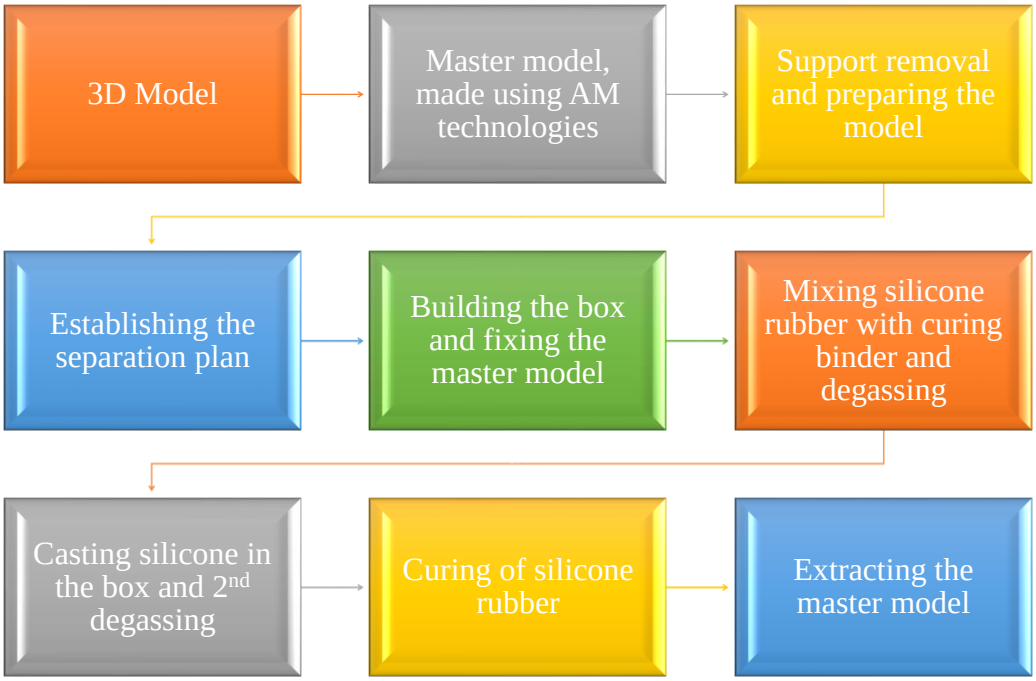
Fig. 5. Vacuum casting equipment - MCP 001 PLC

2.3. How does SRM works?

For manufacturing a silicone rubber mold, the following steps must be taken:

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The CAD model can be designed using any computer-aided design software, such as SolidWorks, Catia, Pro E, Inventor, etc. The 3D model of the part is converted into an STL file and then transmitted to the 3D printer, to manufacture the master model.

The master model can be easily obtained by any of additive manufacturing (AM) or conventional technologies: LOM (Laminated Object Manufacturing), FDM (Fused Deposition Modeling), SLA (Stereolithography), SLS (Selective Laser Sintering), etc.

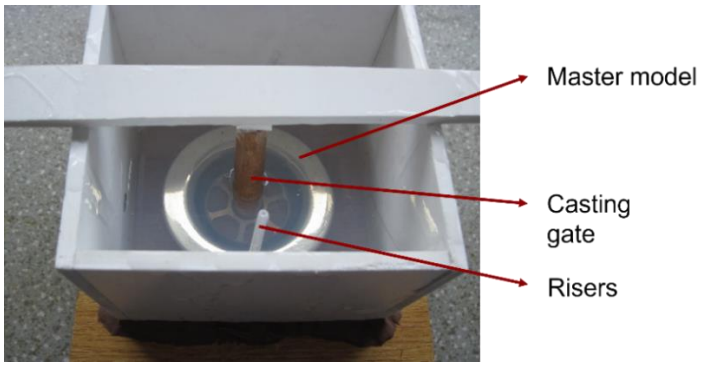
The master model must be cleaned and the supports must be removed before starting the mold manufacturing. It is recommended to use a silicone spray or a release agent to prevent sticking.

The next step is to choose the separation plan of the silicone rubber mold. It must be chosen so that the master model can be easily extracted from the mold. The separation plan can be marked with an adhesive tape, which can be coloured to make it easier to see.

The construction of the box in which the silicone rubber will be poured can be made of wood or other materials.

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The model is suspended in the box with a rod that will be removed later. The hole left by the rod will be used as a casting gate. Smaller diameter rods are also attached to the part. The channels left after their removal (risers) will be used to evacuate the air from the mold cavity.

Fig. 6. Master model inserted in the box

The silicone mixture is made of 2 components: silicone rubber and the binder for curing. During mixing, air bubbles appear in the silicone, which can cause some defects on the part surface. The silicone is introduced into a vacuum chamber machine for degassing (MCP 001 PLC equipment).

The silicone rubber is poured into the box, over the master model and then inserted again into the vacuum chamber, to eliminate the air bubbles accumulated when pouring it around the master model. The silicone is introduced into an oven for curing (for 2-3 h) or it can be left for 24 hours at room temperature.

After solidification, the box is removed and the silicone is cut manually, using a scalpel, following the separation plan. The two half-molds are opened and the master model from inside is taken out. The mold is cut in zig-zag. In this mode no additional systems are needed to lock the mold in the correct position.

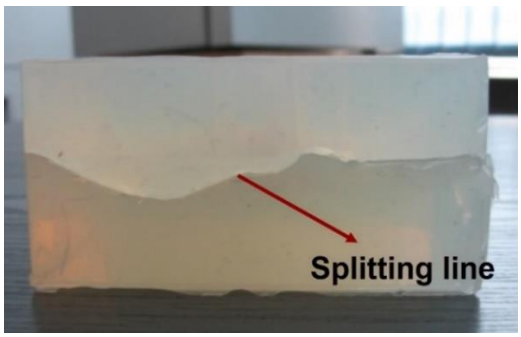


Fig. 7. Cutting the mold after splitting line



Fig. 8. Example of SRM

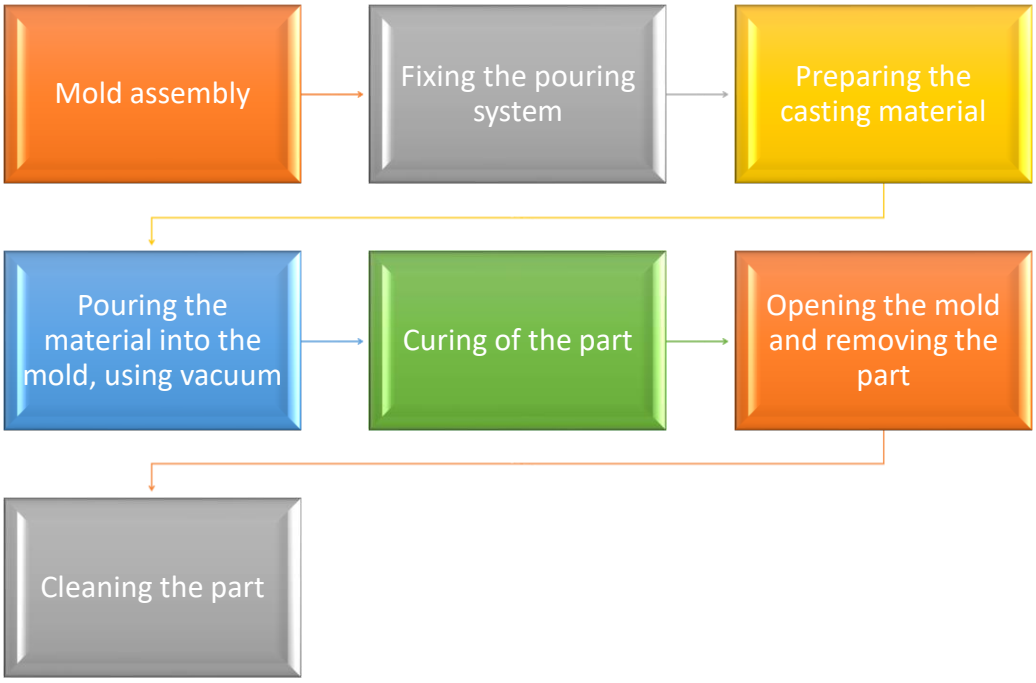
The silicone rubber is a flexible material and the master model can be easily extracted from the mold, even if it has complex surfaces.

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2.4. How to cast parts into SRM?

Into a silicone rubber mold, it is possible to cast complex parts made of resin or wax parts used for investment casting process. Fallowing the steps presented in the chart below we can cast parts with a good surface quality, using a vacuum casting machine.



The **resin parts** are made by mixing 2 components, which are part of the resin. The first component is the resin and for solidification must be mixed with the second component, which is a curing agent. The necessary quantities of the 2 components are given by the manufacturing company and must be weighed strictly. One of the most used types of resin is SG95. This resin has a transparent colour and the properties are similar to ABS. The curing temperature of SG95 resin is 65ºC-70ºC, for about 45 min, depending on part dimensions.

Also **wax patterns**, used for investment casting process are cast into silicone rubber mold. This type of wax it is used in jewellery casting.



Fig. 9. Wax patterns

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The melting point is around 72°-74° C and it can be removed from the mold very easy. To avoid sticking the mold to the part and to make the extraction easier, a chemical agent or a silicon spray will be used.

To decrease the shrinkage coefficient, the mold must be preheated into an oven, at a temperature of 50º- 60º C, before pouring the part. The 2 half-molds are heated separately, after which the mold is closed and fixed with an adhesive tape, to be sure that the 2 half-molds will not move during the casting process. Using the pouring system, the mold is filled with material.

In case of resin parts, the 2 components (resin and curing agent) are mixed using the mixer from the upper chamber of the vacuum casting machine (MCP 001 PLC). The pouring cycle is programmed from the control panel of the machine. When the casting material is ready, the mold must be fixed into the lower chamber of the equipment. The casting system (funnel and casting tube) is attached, and the mold is fixed inside of vacuum chamber. During casting, vacuum is produced in the machine to avoid any air pockets or voids.

The curing of the part is done at room temperature (for wax parts) or using a heating chamber (for resin parts) at 65ºC-70º C, depending on the resin type. The mold is opened, the part is removed, and the mold can be prepared for the next casting. The unwanted material from the parts is removed and the mold is cleaned of any waste left on the surface.

For using the parts, as functional parts (eg: mouse or telephone case, sockets, home appliances, etc.), coloured pigments could be added during the mixing of the resin with the curing binder.

The accuracy of the wax models or resin parts is influenced by the precision of the master model, casting parameters and the material type. The dimensional accuracy in case of complex geometries it is difficult to be controlled because of all dimensional changes caused by material solidification. The geometry of the parts also influences the cooling time and the internal stresses imposed by the shrinkage during solidification.

Silicone rubber molds have been developed because of company’s needs, to develop new products and launch them on the market in a short time. This is a good manufacturing method for prototypes or small series parts, in case of plastic parts.

In the figures below are presented some examples of the plastic parts made in silicone rubber molds.

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Fig. 10. Indicator covers made using SRM

Source: https://www.laserproto.com/



Fig. 11. MRE scanner parts made using SRM

Source: https://www.laserproto.com/

3. INVESTMENT CASTING OF METAL PARTS

3.1. Introduction

Investment casting (IC) is a modern technology used for manufacturing metal parts with complex shapes: prototypes and parts in small and medium series production. IC process is also called precision casting and it is considered to be one of the most accurate casting processes, because of the accuracy of the parts and the surface quality.

IC is the current leader in jewellery casting manufacturing, but the metal parts are used also in industry (brake pedal), medicine (titanium dental crowns), art (statues, medals), etc. The parts could be made from aluminum, copper, cast iron, titanium, gold, silver, etc.

There are many companies that have developed equipment for the vacuum metal casting process: Indutherm and Schultheiss from Germany, Topcast from Italy, Argenta fom Poland, etc. as they are presented in figure 12.

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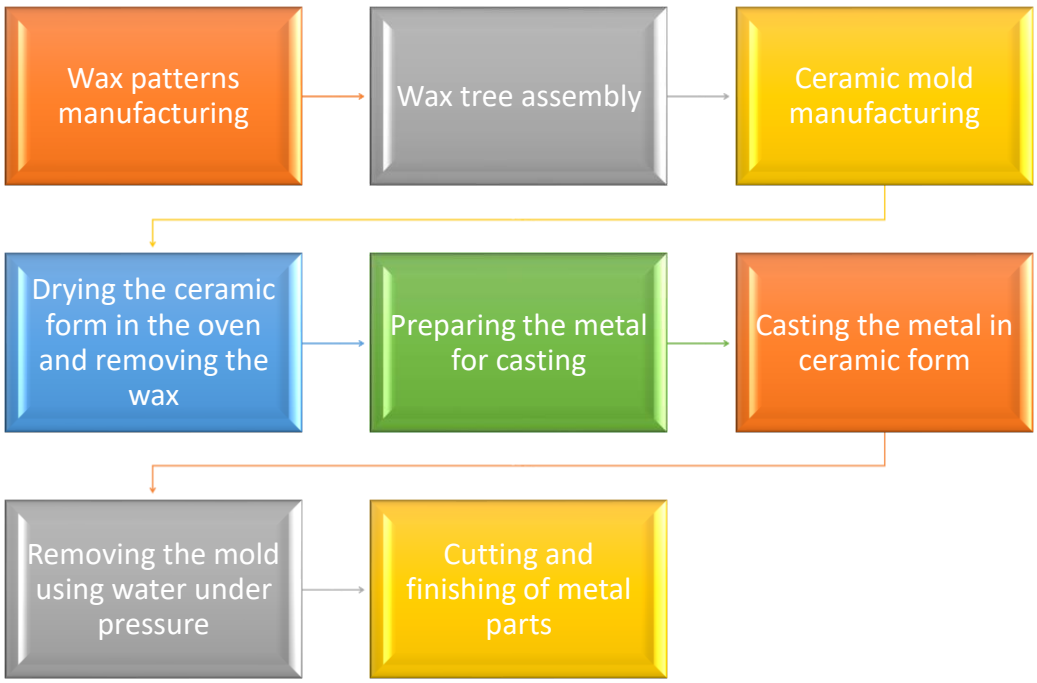


a) b) c)

Fig. 12. IC equipment: a) Indutherm - VC 400; b) Schultheiss - VPC 100; c) Topcast - TVCd

3.2. IC technology

For obtaining complex parts made of metal, wax patterns are needed. It is necessary to design the 3D model of the part, to manufacture a master model and to use it to do a silicone rubber mold. The main steps to be followed for investment casting of metal parts, are presented bellow:



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Wax patterns are required for casting metal parts. Those patterns could be obtained by 2 methods: casting in silicone rubber molds or a 3D printer could be used. The number of wax patterns must be equal to the number of metal parts.

Before assembling the wax tree, it is necessary to optimize the feeding network dimensions.

The feeding network must ensure:

- complete filling of the mold cavity, avoiding internal cracks, stress, etc.;
- to be optimized for avoiding an additional consumption of metal, especially in the case of precious alloys;
- have a low weight, but to be strong enough to support the parts.

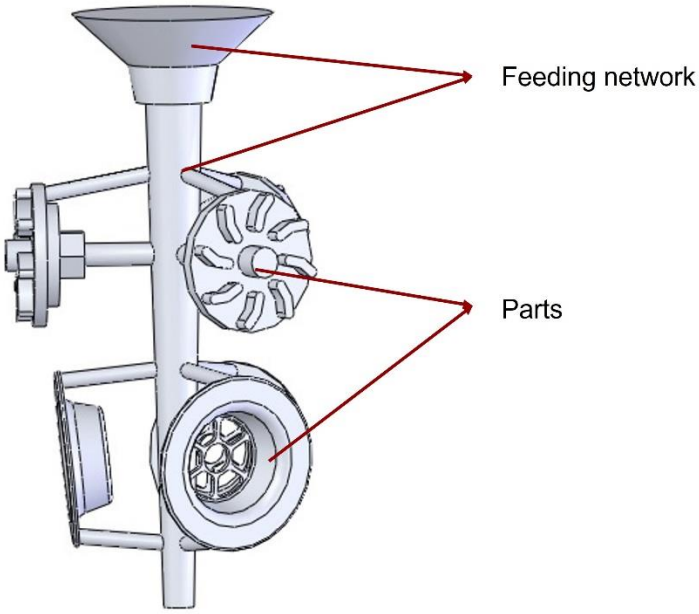


Fig. 13. Optimizing the feeding network

The feeding network has an important role in casting process, that of supplying the cavities with liquid metal. The feeders are designed to compensate the shrinkage, in order to eliminate the porosity that occurs.

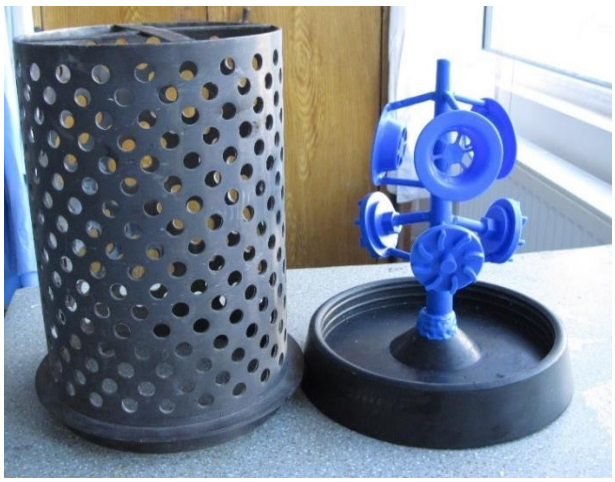


Fig. 14. Wax tree assembly

The wax patterns are assembled like a tree in order to reduce the casting time, as well as to reduce the metal consumption for the feeding network.

The wax tree is placed in the flask, which is covered with adhesive tape for preventing the flowing of the ceramic paste.

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The ceramic mold is made from powder and water, using a vacuum equipment, type KWS EB 20/70, existing within TUCN, Department of Manufacturing Engineering.

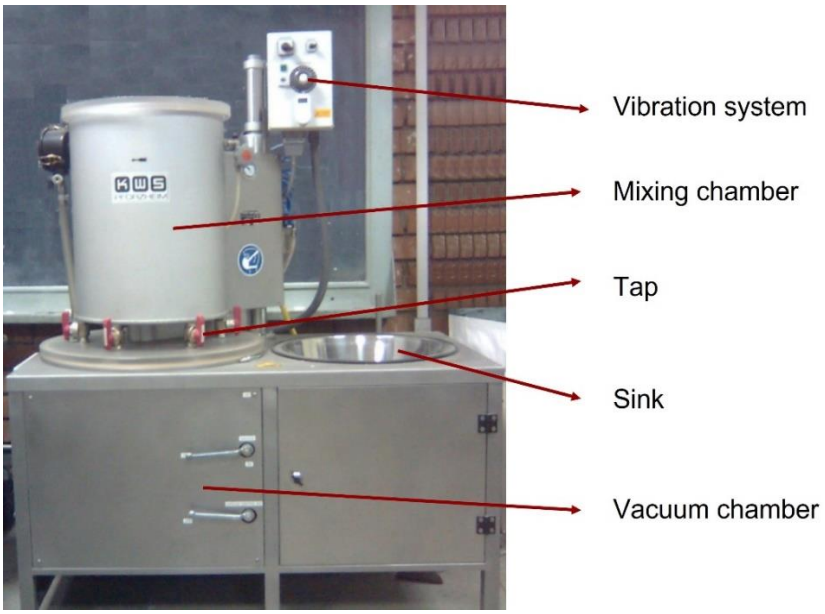


Fig. 15. KWS EB 20/70 mixing unit, for ceramic mold – TUCN

The mold is made of extremely fine-grained powder, a mixture of a special gypsum, refractory material and additives, a specific powder for casting non-ferrous metals.

The flask is placed in the lower chamber of the mixing equipment. The mixture between powder and water is made in the upper chamber of the equipment, and using the taps, this mixture is poured, under vacuum, in the flask.
The machine is equipped with a vibration system to be sure that all the shapes are filled with ceramic paste.

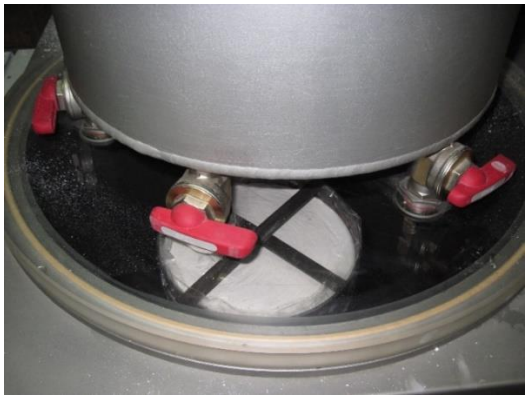


Fig. 16. Ceramic mold manufacturing

A post-processing process is required for the ceramic mold to be completely solidified and dried. The ceramic mold is placed in the oven for drying and for melting and removing wax. The transition from one temperature point to another must be done gradually and at a certain time interval, in order to avoid the appearance of cracks.

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The steps to be followed during this process are exemplified in the table from figure 17.

Step	Temperature increase rate	Temperature	Hold time
	[°C/h]	[°C]	[min]
0	Delay time		
1	20	170	120
2	30	550	120
3	50	680	180
4	-	250	-

Fig. 17. Steps for drying the ceramic form

Step 0 represents a postponement of the process (if it is necessary to start at a certain time).

In Step 1 the ceramic form is heated to 170° C, where it is kept for 120 minutes. The temperature increase rate is 20° C / h. Within this temperature level, the wax from the inside of ceramic mold is removed.

In Step 2, the temperature inside the oven reaches 550° C and is maintained for 120 minutes. The temperature increases gradually, the growth rate being 30° C / h.

Step 3 is to reach the maximum temperature point in the oven, 680° C.

The temperature decreases at Step 4, until 250° C. The entire drying cycle of the ceramic mold ends when the oven temperature reaches 250° C, which is the preheating temperature of the ceramic mold. The whole process of drying the ceramic form is represented in the diagram in figure 18.

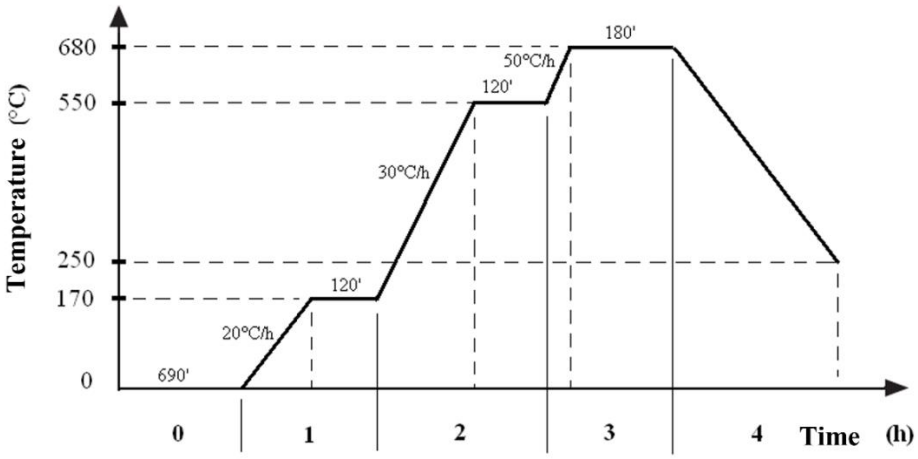


Fig. 18. Diagram for drying the ceramic mold

The working principle of the vacuum casting machine is to melt the material by induction until it reaches the melting point. The equipment has a software with a database with the

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main materials used and their characteristics, necessary for casting. During the casting process the working parameters must be set up: temperature, pressure, vacuum, and protector gas.

To avoid cracks or other defects on the surface of the ceramic mold, it must be preheated at 250-300ºC and after that it is introduced into the casting equipment chamber. The metal is

weighed and then inserted into the crucible. When the metal is melted, the vacuum is started inside the chamber and the casting takes place.

To complete the casting process, an overpressure is applied, which helps to completely fill the cavities.

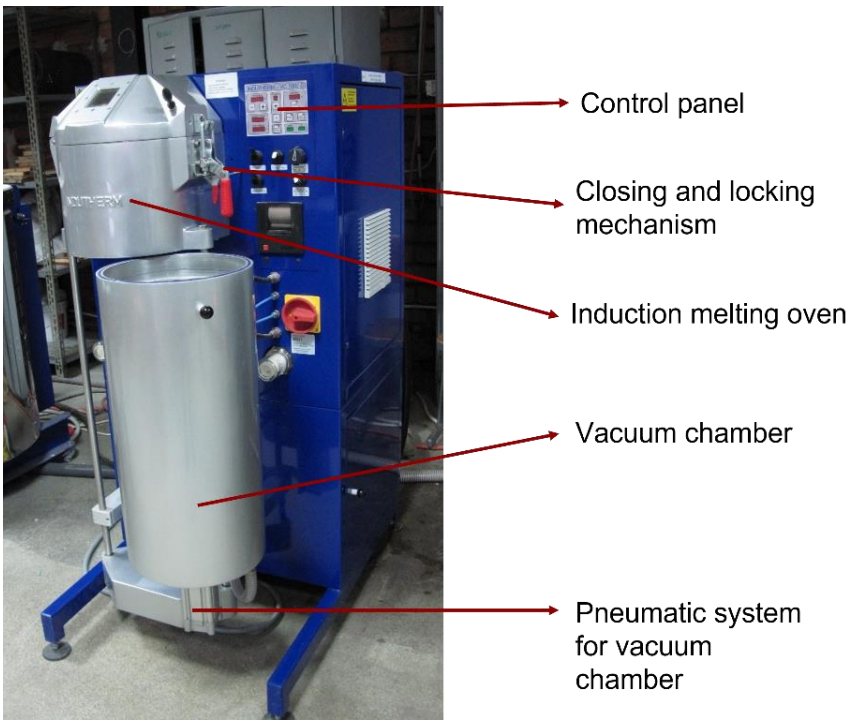


Fig. 19. Investment casting equipment Indutherm VC 1000D – TUCN

After solidification the ceramic mold is removed, using a water jet under pressure. Using a cutting tool, each metal part is removed from the tree. Depending on the technological and functional role of the parts, further finishing or other operations may be required. In figure 20 is presented an example of metal tree.

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Fig. 20. Metal tree





Fig. 21. Aluminum parts

IC is a modern technology for manufacturing complex parts, which could be efficient for new products development (prototypes or parts in small series production). The parts obtained using this technology are inexpensive compared to other technologies and are obtained in a short time and with a high accuracy.

The accuracy of the metal parts depends on master model and wax patterns accuracy.



Fig. 22. Example of master model - wax pattern - metal part

If there is a small defect or a fine scratch, these defects will also be found on the metal parts.

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3.3. Applications

The parts made using investment casting process are used in many industrial applications or in other fields such as: jewellery manufacturing, arts or even medicine.



Fig. 23. Wax pattern and metal jewellery

Source: www.3dsystems.com



Fig. 24. Wax pattern and metal jewellery

Source: www.indiamart.com

4. RAPID TOOLING BY SLM

4.1. Need and importance of SLM in producing fully dense metal parts

Selective Laser Melting (SLM) is a complex thermo-physical process that depends on material, laser, and process parameters. The SLM process occurred in 1994 at the Fraunhofer Institute (Aachen, Germany), patented by Dr. Fockele and Dr. Schwarze (DE19649865 patent). The basic component of SLM systems is the laser, which falls under the category of solid Nd:YAG lasers [Cosma'Acta]. It emits continuous light in the infrared spectrum with a wavelength of 1064 nm. SLM process in capable to produce directly metallic parts with 99.9% relative density. Most of the SLM research revolves around the following materials: tool steel and stainless steel, pure titanium, or titanium alloy (Ti6Al4V), Co-Cr, aluminum, and nickel (Inconel 625, Inconel 718) [Yap]. Besides these powders, other has been investigated by SLM such as copper, magnesium, tungsten, gold, alumina, silica (glass), zirconia or tri-calcium-phosphate [Fateri]. The main applications develop by SLM process are made of metallic powder because it provides a high degree of design freedom, the optimization and integration of functional features, the manufacture of small batch sizes at reasonable unit costs and a high degree of product customization even in serial production [3DHubs]. The ongoing transition to digital

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manufacturing prompts new possibilities of SLM process, especially in rapid tooling industry. The main benefits of SLM parts include [Aniwaa]:

- **On-demand production:** SLM manufacturing offers more flexibility and control over the production line.
- **Complex designs made possible:** With SLM technology, it is possible to create highly detailed and intricate parts that would have to be broken down into several pieces with conventional methods (examples CNC milling or turning; casting).
- **Waste reduction:** Compared to CNC milling, for example, SLM manufacturing produces less waste as it only consumes the material needed for a certain part. Moreover, it is possible to re-use the un-melted powder.
- **Lighter parts:** Whereas metal parts are usually completely solid infill-wise with other methods, SLM printing allows parts to be hollow without undermining their strength and resistance.
- **Cost-effectiveness:** All the above benefits of SLM manufacturing can inherently reduce costs per part.

An important aspect in SLM manufacturing is to fabricate 100% fully dense metal parts. The density of manufactured parts is influenced by SLM parameters such as: laser power, scanning speed, hatch space, and layer thickness. A systematic SLM optimization to reduce the porosity of SLM parts is presented in Figure 25, for titanium alloy. When the laser power ranged from 50W to 150W, the porous volume fraction had a gradually increasing trend with increasing scan speed [Wang]. In contrast, when the laser power increased to the power region of 200–250 W, the porosity was reduced below 1% if the scanning speed was configured between 850 mm/s to 1750 mm/s.

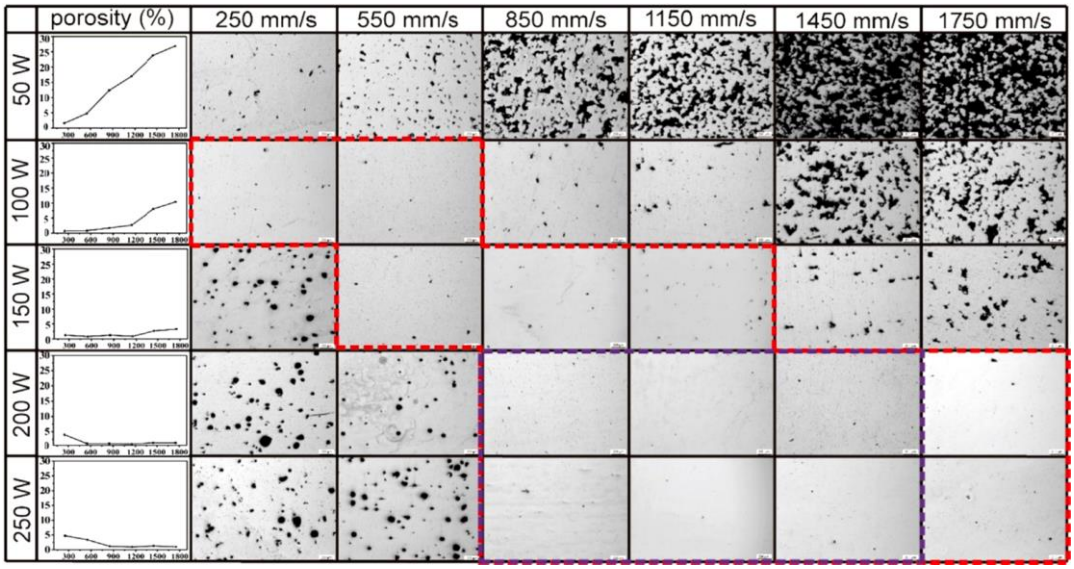


Fig. 25. The porosity of the specimens obtained varying the laser power and the scanning speed on titanium samples [Wang]

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Moreover, a current review shows that the porosity can be reduced using a laser power up to 300 W and adapting the scanning speed. A contour map of porosity arising from the combination of various laser scan speeds and laser powers can be seen in Figure 26 [*Majumdar*].

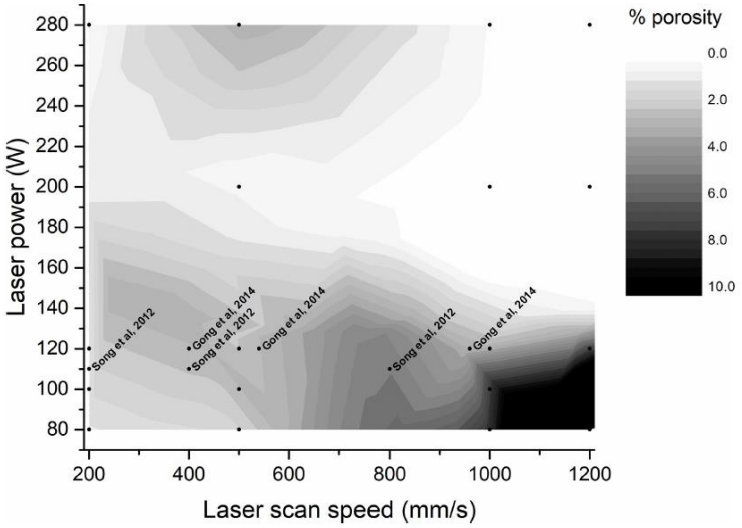


Fig. 26. Review of porosity map for Ti6Al4V alloy SLM-manufactured with different laser power and scan speed [*Majumdar*]

For each material the SLM parameters should be optimized to obtain 100% dense parts, high mechanical strength, reduced surface roughness, and limited manufacturing defects such as: macro- and microscopic cracks, gas voids, heat affected zones or a residual stress phenomenon. These technological defects are a consequence of rapid melting and cooling cycles, and the best SLM process parameters are needed to limit them [Cosma'Materials]. Figure 27 reveals the impact of porosity on hardness on 316L stainless steel SLM-manufactured.

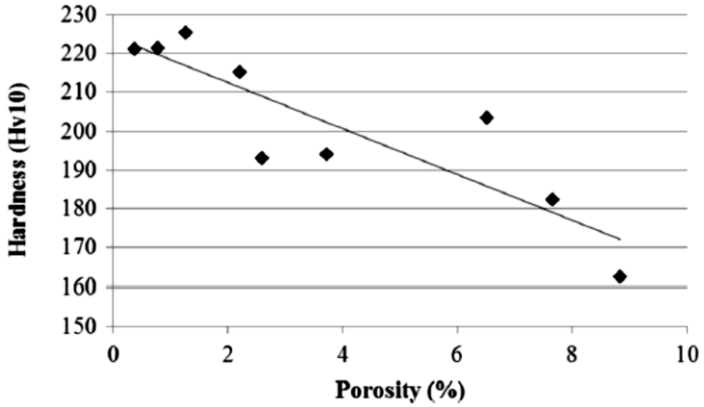


Fig. 27. Influence of porosity on surface hardness; Specimens made of 316L stainless steel SLM-manufactured [Cherry]

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Processability Rank		Laser Power (W)	Scanning Speed (mm/s)	Energy Density (J/mm^3)	YS (MPa)	UTS (MPa)	Elongation at Fracture (%)	Young Modulus (GPa)	Relative Density (ρ_{rel})
Relatively stable	R1	130	1034	44.98	630	672	6	182	98.3
	R2	170		58.82	654	689	8	173	98.5
	R3	160	400	142.85	590	648	7	178	99.6
Stable	S1	110	500	78.57	774	823	12	192	99.3
	S2	150	750	71.42	703	786	10	184	99.3
	S3	180	950	67.66	783	841	13	194	99.1

Fig. 28. Tensile test results of SLM-processed 316L samples; YS – Yield tensile strength; UTS – Ultimate tensile strength [Cosma'Materials]

The impact of SLM parameters on tensile properties are listed in Figure 28. The tensile tests were carried out on samples processed in relatively stable or stable processability using 316L steel powder. The following properties were determined such as: yield strength (YS), ultimate tensile strength (UTS), elongation at fracture, Young modulus, and relative density. The tensile tests showed the anisotropic behavior of SLM samples due to the generative production principle also observed in other studies [Cosma'Materials], [Wang].

4.2. Types of equipment / manufactures

The cost of SLM equipment's generally varies between 150,000 - 500,000 €, depending on the size of the work platform and the installed laser. The main manufacturers of SLM equipment's or similar technologies (like DMLS, EBM) are EOS (EOSINT M 280), Concept Laser (M1 Cusing), Realizer (SLM 250), Arcam (Q20plus), Sisma (MYSINT100), TRUMPF (TruPrint 1000 LMF), and Matsuura (LUMEX Avance-25) [Cosma'Acta]. Some of these systems are presented in Figure 29. In 2016, the FH Aachen and Fraunhofer Institute for Laser Technology develop a low-cost SLM machine for small and medium-sized businesses, with a cost of 30,000 €. On the other hand, DMG has developed a hybrid system that contains a 5-axis material deposition by a coaxial nozzle for homogeneous powder distribution and a full 5-axis milling machine. Combining the SLM process and CNC milling flexible systems were developed and new parts can be manufactured due to alternating material deposition and machining strategies. The price for this hybrid system is over 1,000,000 €.

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MYSINT100

By Sisma

Technology	Powder Bed Fusion > SLM/DMLS
Material	Metal
Topic	Metal 3D printing
Build size	ø 100 x 100 mm
Release date	2017
Country	Italy

From
$ 175,000



LASERTEC 30 DUAL SLM

By DMG Mori

Technology	Powder Bed Fusion > SLM/DMLS
Material	Metal
Topic	Metal 3D printing
Build size	300 × 300 × 300 mm
Release date	2020
Country	Germany

Price
upon request



TruPrint 1000

By TRUMPF

Technology	Powder Bed Fusion > SLM/DMLS
Material	Metal
Topic	Metal 3D printing
Build size	100 × 100 × 100 mm
Release date	2015
Country	Germany

From
$ 170,000



EOS M 100

By EOS

Technology	Powder Bed Fusion SLM/DMLS
Material	Metal
Topic	Metal 3D printing
Build size	100 × 100 × 95 mm
Release date	2015
Country	Germany

From
$ 350,000



HBD-100

Forming Size:	105mm×105mm×100mm
Laser Power:	200W
Layer Thickness:	10μm-40μm
Scanning Track Width:	40μm-80μm
Scanning Speed:	≤10000mm/s
Oxygen Content:	≤100PPM
Protective Atmosphere:	Integral sealed, automatic monitoring of oxygen content, recycling cleaning and collection coefficient ≥ 99%
Relative Density:	Nearly 100%
Typical Accuracy:	0.05-0.1mm
Metal Power:	Metal Power: Stainless steel, Cobalt-chrome alloy, Tool steel, Titanium alloy, High temperature alloy, Hastelloy, and some precious metals.

Fig. 29. Available on market SLM equipment's and manufactures [Aniwaa]

The manufacturing cost of typical SLM part is approximately $1,000 - $6,000 (including post-processing). In Figure 30 are presented the average costs of different manufacturing steps for SLM technology. Notice that the material cost, as well as the cost of post-processing, contribute considerably to the overall cost [Hubs].

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Production step	Operation	Cost
Manufacturing	Material cost	$200 - $500 per kilogram
	DMLS/SLM cost	$2,000 - $4,000 per build †
Post-processing	Stress relief	$500 - $600 per build †
	Part/supports removal	$100 - $200 per part
	Heat treatment / HIP	$500 - $2,000 per build †
	CNC machining	$500 - $2,000 per part
	Surface treatments	$200 - $500 per part

Fig. 30. Estimative costs of SLM manufacturing [Hubs]

On the other hand, the production rate of SLM systems varies between 10-40 cm^3/h. To provide an increased build rate, the latest SLM system are equipped with 2 or 4 laser sources up to 400 W. Practical, this technology allows lasers to work simultaneously but each one scan a different part from powder bed.

4.3. Steps and procedure in the SLM process

To achieve best outcome and reasonable cost the parts, models should always go through an optimization process. A general guideline for designing SLM-manufactured parts is shown in Figure 31.

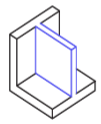
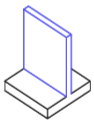
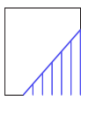
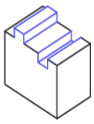
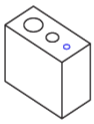
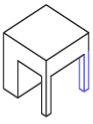
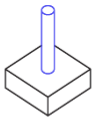
Supported walls	Unsupported walls	Support & overhangs	Embossed & engraved details	Horizontal bridges	Holes	Minimum features	Pin diameter	Tolerance
Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
								
0.4 mm	0.5 mm	45°	0.6 mm wide & 2 mm high	2 mm	Ø0.5 mm	0.6 mm	1 mm	±0.1 mm

Fig. 31. Design rules for SLM manufacturing [Hubs]

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The main steps and procedure in the SLM process are detailed in Figure 32 and Figure 33.

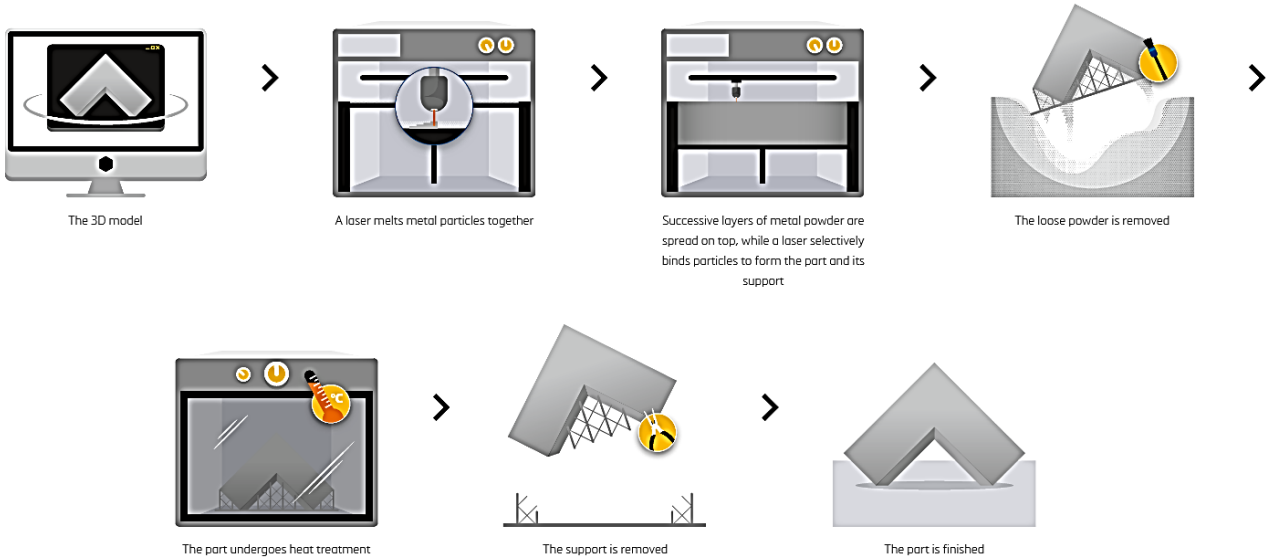


Fig. 32. Illustration of the main steps in SLM manufacturing.

Source: *www.materialise.com*

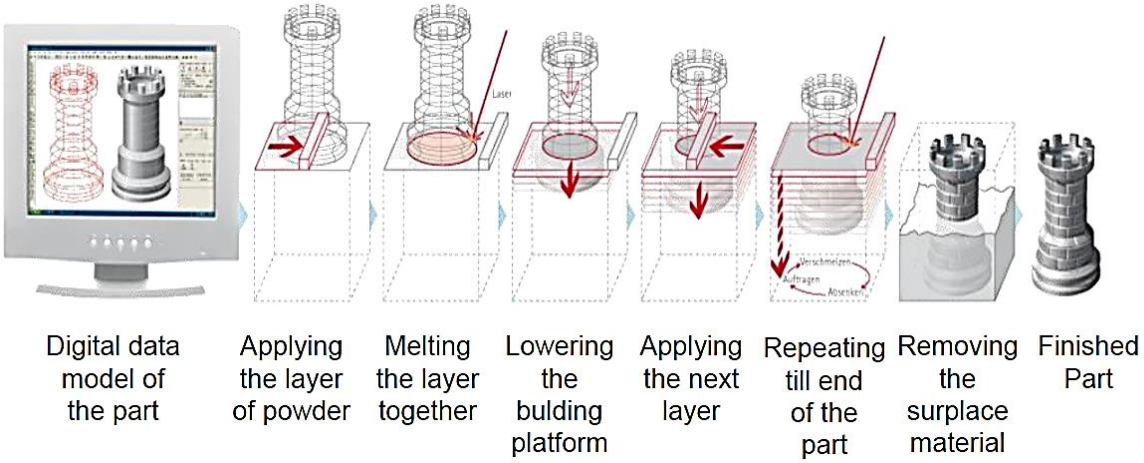


Fig. 33. SLM procedure to fabricate direct metal parts. Source: *www.eos.info*

A. Pre-processing of the STL file

Geometry preparation

In order to SLM manufacture the part, the 3D model should be saved into ".STL" format. The following function can be used for geometry preparation as following: measure details, repair defects (connecting unmatched edges, closing holes, aligning triangular normal, resolving overlapping areas), edit geometry, adjust mesh, and check the wall thickness. The TUCN SLM machine used the Realizer RDesign software.

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Part orientation

The orientation affects the economic production of parts as well as the surface quality of the parts [AutoFab]. To align the part within RDesign, the following steps are possible:

- Select the surface, which must be orientated towards the build platform.
- Rotate the part into the desired position.
- Define the distance between the part and the build platform (usually 2-3 mm).

The orientation of the part has a huge influence on the process stability. A recommendation is to have a small cross section because otherwise the so-called curling effect will occur, and the part could be destroyed due to thermal stresses [Schwarz]. A practical example is shown in Figure 34 where different orientations on SLM plate were tested.

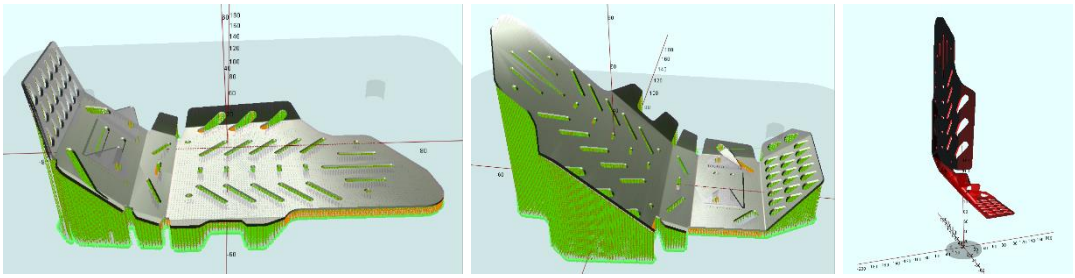


Fig. 34. Different part orientation on SLM plate

On the SLM platform, each part can be positioned and rotated. By orientating the part in different directions, the surface roughness is significant different, as can be seen in Figure 35. From this chart is evident that a vertical orientation of models can reduce the surface roughness, but it will increase the production time. Typical surface roughness Ra is between 10 - 15 µm on top surfaces, and between 8 - 10 µm on vertical surfaces (build-up angle 90°).

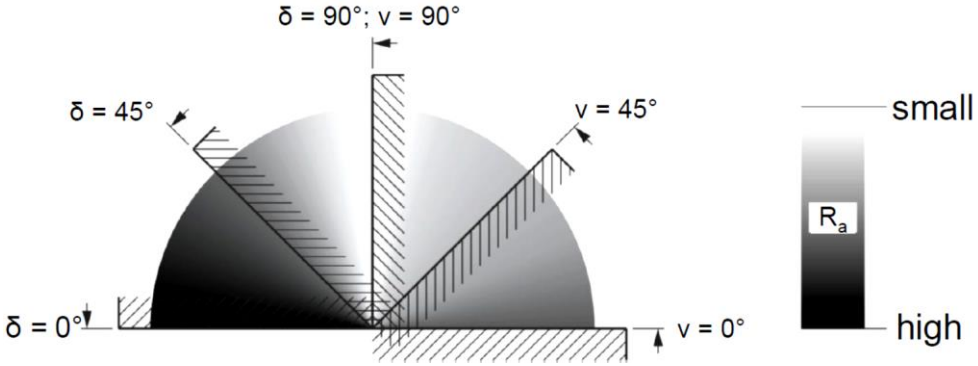


Fig. 35. Influence of build-up angle on the surface roughness (Ra). [Schwarz]

Parts are often oriented at an angle to minimize the likelihood of warping and maximize part strength in critical directions. However, this will increase the amount of required support, the build time, the material waste, and the total cost [Hub]. To reduce the build

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time, another method is to orientate the model to have a lower number of slices, but the volume of support structures will be high (e.g. Figure 34).

Beside SLM parameters, the build-up orientation influence also the ultimate tensile strength. Figure 36 shows that a higher value of ultimate tensile strength (Rm) can be expected if the direction of force is parallel to the layer structure. The less obtuse the angle between processing direction and direction of load, the more the strength characteristics decrease. Interestingly the tensile strength of horizontally generated parts (orientation b and c) is higher than the tensile strength of conventionally manufactured material [MEI].

a)

	reference material	orientation a)	b)	c)	d)	e)
R_m [N/mm²]	700	595 - 636	714 - 745	708 - 725	665 - 686	681 - 682

b)

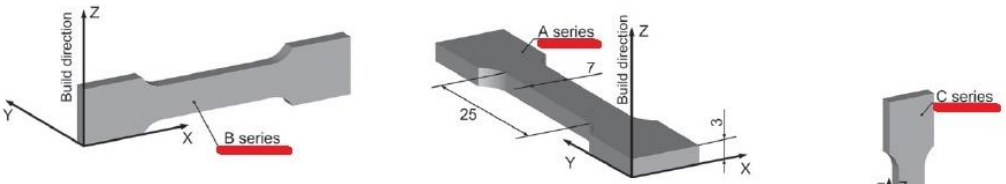


Table - Results of mechanical tests on the as-built Ti6Al—7Nb alloy.

Build direction	$\sigma_{0.2}$ MPa	σ_t MPa	E GPa
A series	1440±59	1515±60	88±2
B series	1360±30	1480±26	88±3
C series	–	776±40	121±14

Fig. 36. Influence of build-up orientation on ultimate tensile strength; Mechanical tensile tests elaborated on SLM samples made of:

a) 316L steel [MEI], b) Titanium alloy [CHE'11]

The part orientation is a critical aspect, and it should be adapted/optimized for each model according to user needs (example: reduced build time, low surface roughness, or high mechanical resistance on a specified direction).

Support structures

Support structures are required due to:

- Sustain the next layer built upon;
- Anchor the part on the build plate and to prevent the warping effect;
- Act as a heat sink drawing heat away from the part and allowing it to cool at a more controlled rate.

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They can be modeled using a lattice pattern. The lattice pattern can be configured in different ways, modifying the unit cell between 0.5 mm to 2.5 mm. This type of lattice support is illustrated in Figure 37 where the green lattice supports are the main ones and the orange ones just in areas with large section to prevent the part deformation. There is no systematic approach for configuring the support structures.

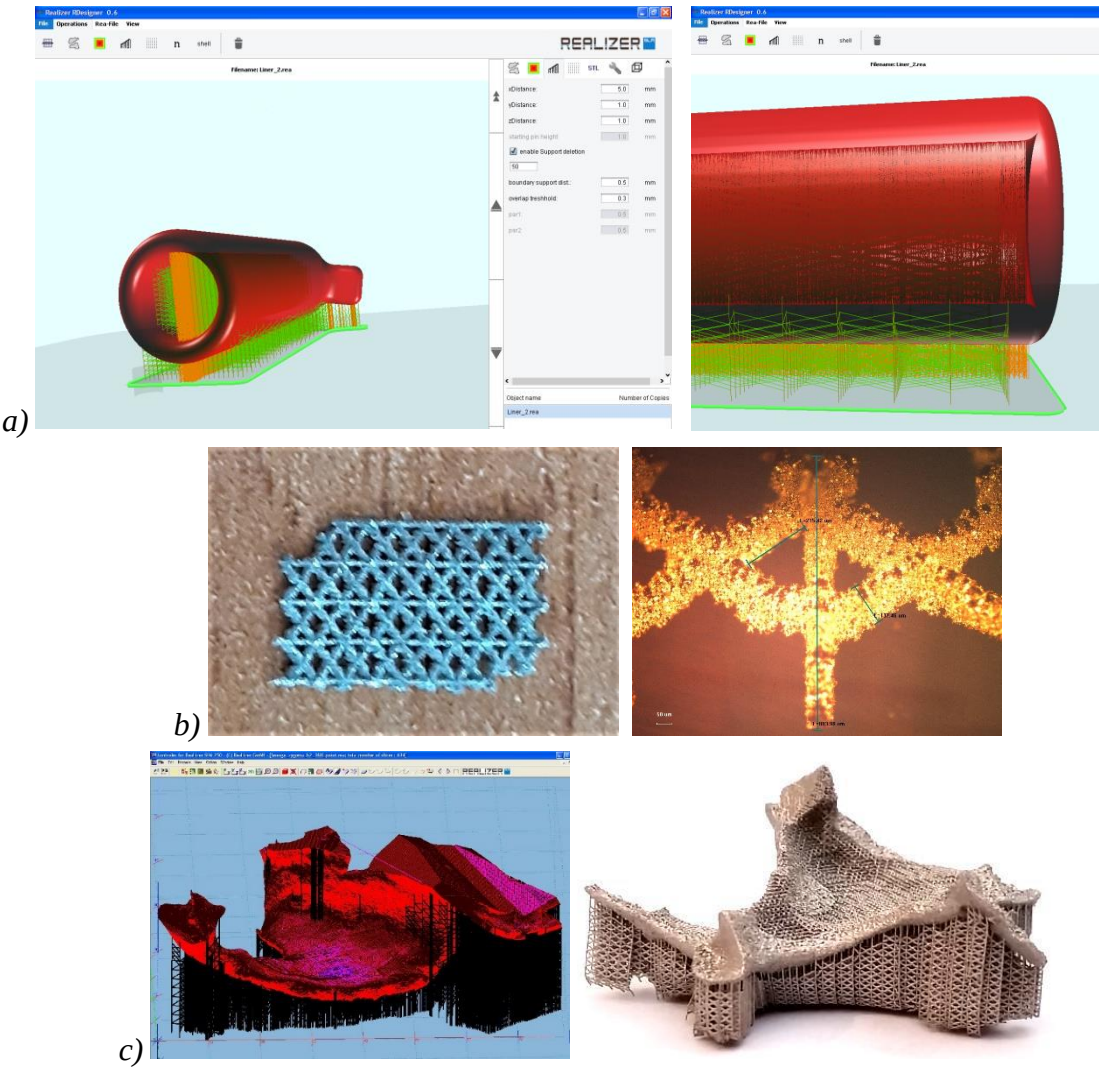


Fig. 37. Support structures type lattice: a) Modeled in RDesigner software, b) SLM manufactured, c) Virtual complex shape anchored with lattice supports (Realizer software) and SLM-manufactured

Angled surfaces more than 45° are possible to be built without supports structures according to multiples experimental studies [Additiva], [Cosma'2019] and German Standard VDI 3405 [VDI]. A self-supporting angle describes the feature's angle relative to the build platform (XY plane). A sketch of this principal is illustrated in Figure 38 where is presented a cross-section of a profile which has

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different δ angles between the surfaces and the SLM plate. This sketch demonstrates the importance of building orientation on SLM plate and how we can improve the design of parts.

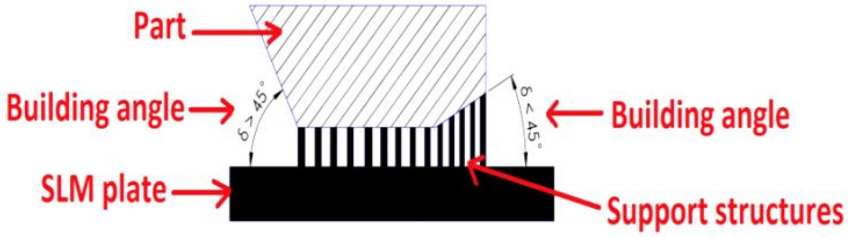


Fig. 38. Support structures needed to anchor surfaces. Surfaces with angles higher than 45° are possible to fabricate without supports [Cosma'2019]

The lower the angle, the less the likely it is to support itself. As the angle decreases, the downward facing surface becomes rougher and eventually the part will fail if the angle is reduced too far [Additiva]. We recommend avoiding designing self-supporting features that are less than 45° degrees relative to the horizontal plane (see Figure 38). Changing the gradient of the wall, the surface finish gets worse, even to compromise the wall melting as it can be seen in Figure 39.

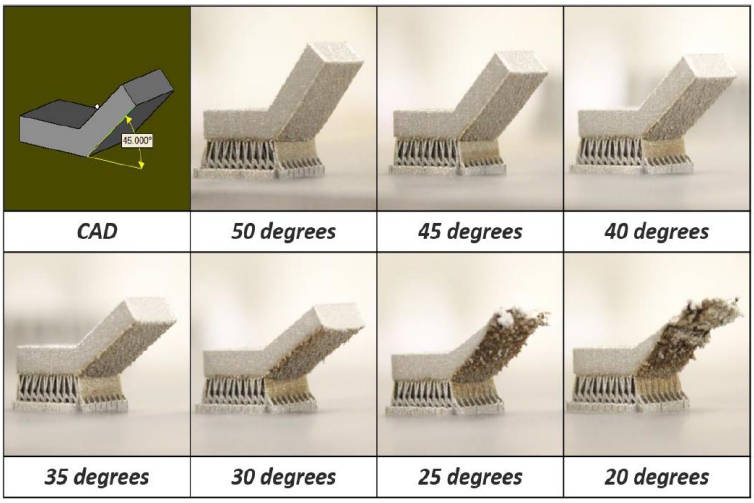


Fig. 39. Effect of built-up angle between 20°-50°; Surfaces SLM-manufactured with-out supports to test their limit [Additiva]

B. Set up the material file

Place all the parts in the virtual platform of SLM machine at minimum 1 mm distance between them without any intercalations using translate function. Setup the thickness of a layer powder (typically 50 μm) and slice all the models. By default, RDesigner saves build jobs in its own REA material file. In addition to the slice data and generated build paths for laser tracks, this REA file contains all the SLM process parameters (laser power, scanning

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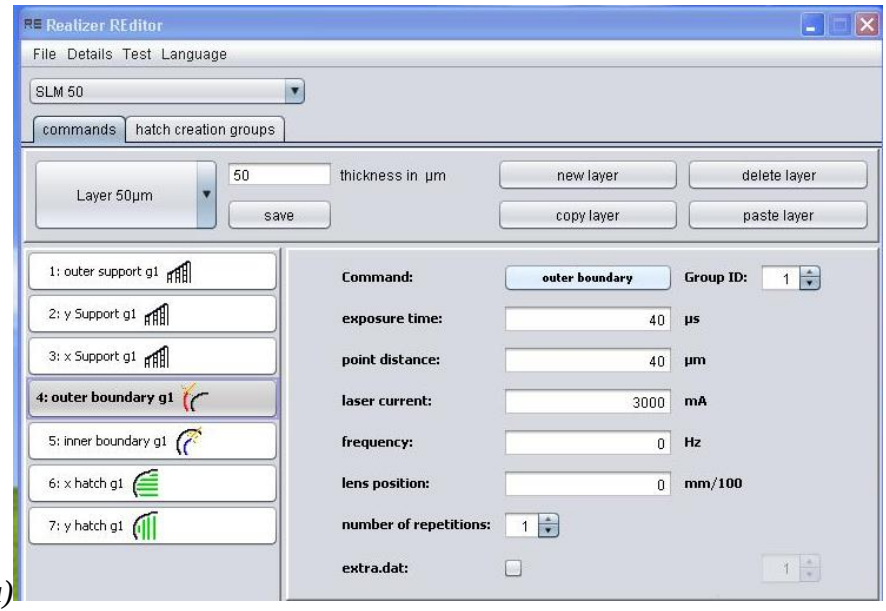
speed, hatch distance, etc.). To configure the SLM process parameters, REditor software is used. The REditor software tool is useful to optimize the SLM parameters, to define the scanning strategy, to organize the laser scanning steps (e.g., first scan the outer-boundary, after scan the hatch area, and in the end the inner-boundary), etc. An example is shown in Figure 40 where different functions are included as following: Outer-boundary, Inner-boundary, Hatch in X and Y direction. For a better understating of these laser functions used to scan the part, please see Figure 42. Beside these functions, the parameters for lattice support structures can be configured in the following function: X and Y Support, Outer Support, etc.

Each function should be configured, and the main parameters are:

- Laser power (10-200W), expressed in mA where 5000 mA = 200 W;
- Scanning speed (100-2000 mm/s), expressed by Exposure Time and Point Distance; Example: Scanning speed 1000 mm/s >> Exposure Time 40 µs, Point Distance 40 µm.

Moreover, the laser scanning strategy is another important aspect. Usually, we used an alternating X/Y strategy which allows a scanning in X direction of "n" layer and in Y direction of "n + 1" layer (rotating each hatch scan 90°, details in Figure 42). The advantage of this hatch pattern is that it can contribute to a high build rate compared with stripe hatch or chessboard pattern. On the other side, this scanning strategy can cause a rise of residual stress phenomena compared to the chessboard hatch pattern, and a special attention must be given to process parameters.

a)



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b)

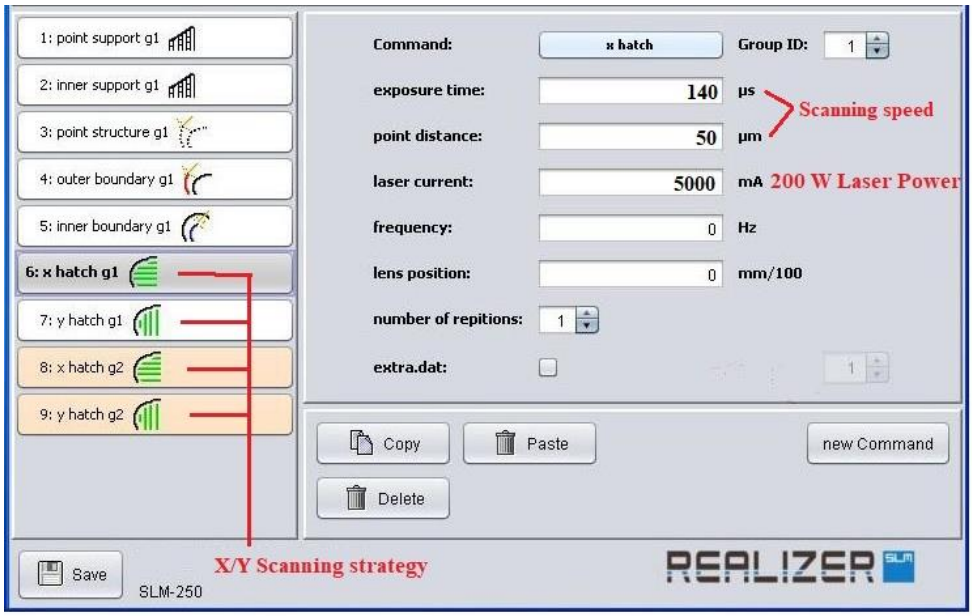


Fig. 40. Configure the SLM process parameters in REditor software:
a) Outer-boundary function, b) Hatch function for scanning in X direction

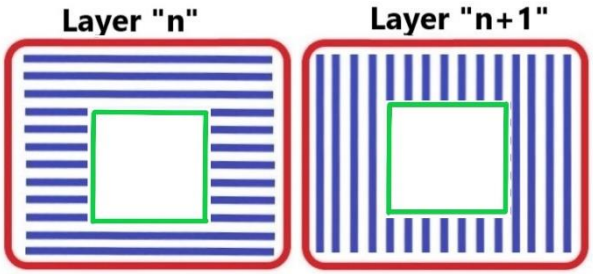


Fig. 41. X/Y alternating laser scanning strategies; Laser functions used to scan the part: Outer-boundary – Red, Inner-boundary – Green, Hatch area - Blue

Hatch distance represents the scan spacing between two consecutive laser tracks (see Figure 41 – blue tracks and details in Figure 42a). In general, this parameter is setup at maximum value of the spot laser diameter (Figure 42b). In this way, a reduced porosity and high mechanical resistance can be expected. If the spot laser diameter is 55 µm, the hatch distance could be 50 µm.

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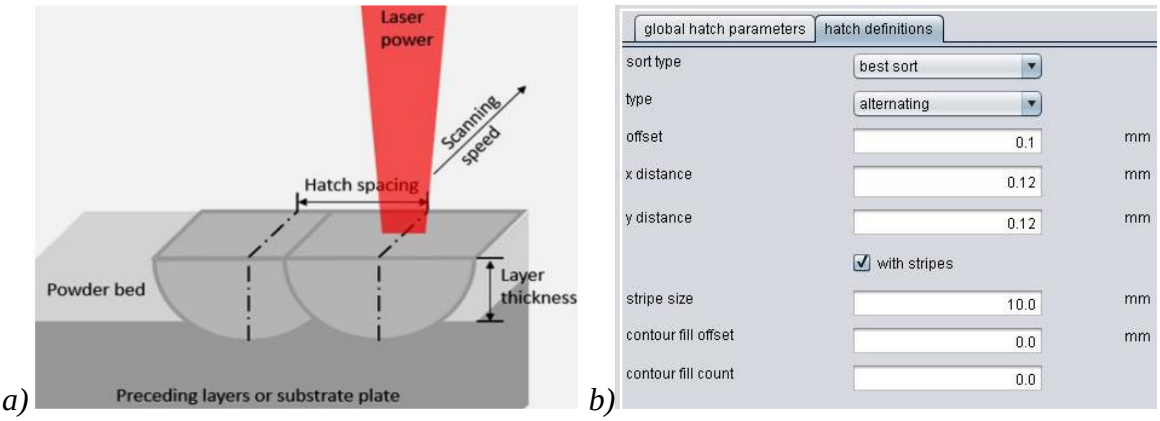


Fig. 42. a) SLM process parameters [Yap], b) Hatch distance setup in REdior

All these SLM parameters should be configured for each powder type and saved. The final REA file of the SLM job will contain the slice data and generated build paths for laser tracks, process parameters for each function, scanning strategy, etc. Annexa 1 details a typical file used to configure these the SLM parameters in REditor.

4.4. Simulation of SLM process

Since the cost of SLM fabrication is high, simulations are often used to predict the behavior of the part during processing. Figure 43 resume the SLM principle and main aspects which should be taken into consideration.

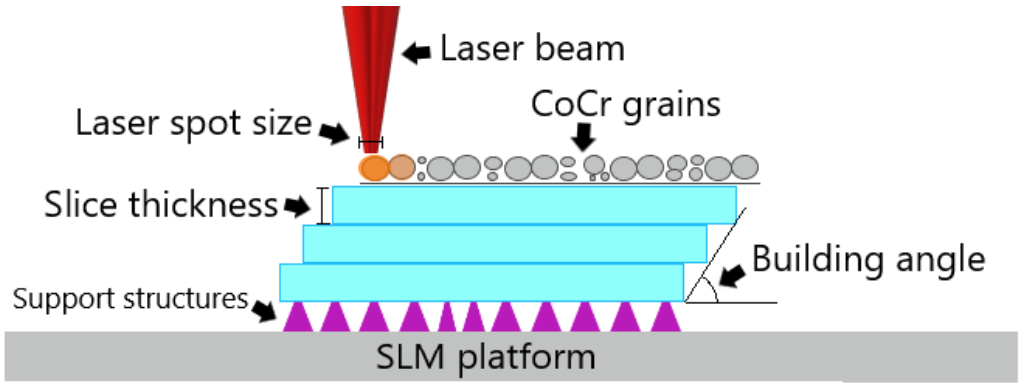


Fig. 43 Schematic illustration showing the SLM principle

Using created REA file of the SLM job, manufacturing simulation can be elaborated. Figure 44 shows a simulation of SLM manufacturing.

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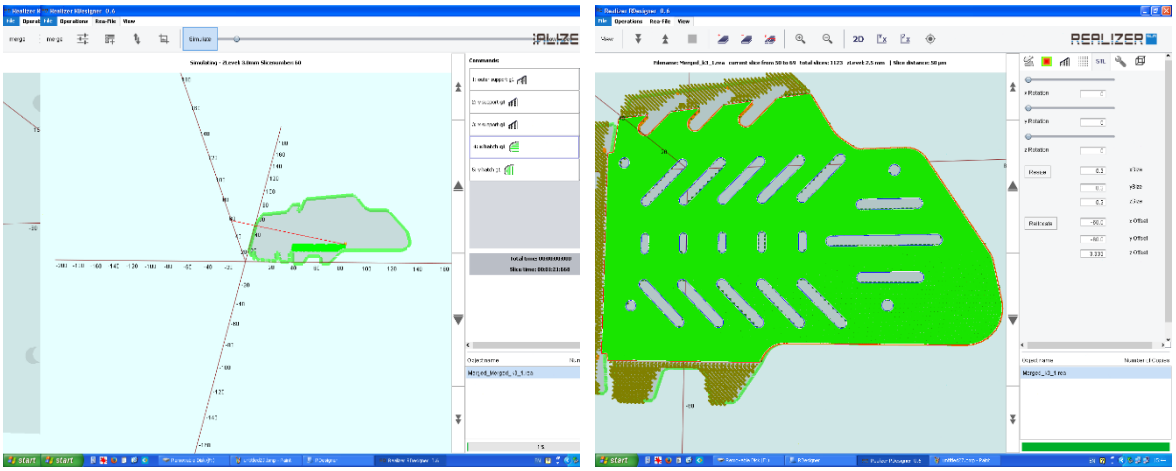


Fig. 44. Manufacturing simulation in RDesigner software

4.5. Realizer 250 equipment and working principle

Founded by Dr. Matthias Fockele, one of the two physicists that developed and patented the SLM (Figure 45), Realizer company was one of the leading producers of SLM machines. The SLM technology resulted from a German research project developed and patented in 1995 at the Fraunhofer Institute for Laser Technology (ILT, patent DE 19649865). The company manufactures four models (SLM 50, 100, 250 and 300) with different sized printing chambers. In 1999, the company delivered the world's first SLM machine for metals at the research centre in Karlsruhe [Realizer].

In 2017, DMG Mori announced the acquisition of the majority Realizer stake (50.1%). The two companies presented also the new LASERTEC 30 SLM metal 3D printer, a new machine for powder bed application based on Realizer's SLM300i model [Sher]. Now, the DMG company is thus following in the footsteps of other manufacturing giants such GE and Trumpf which have invested heavily in metal 3D printing. GE acquired Arcam and Concept Laser and has access to EBM (Electron Beam Melting) and SLM technology. Trumpf, just like DMG Mori, has access to SLM technology. Incidentally, all three groups currently record similar global revenues in the order of $4 billion yearly [Sher].

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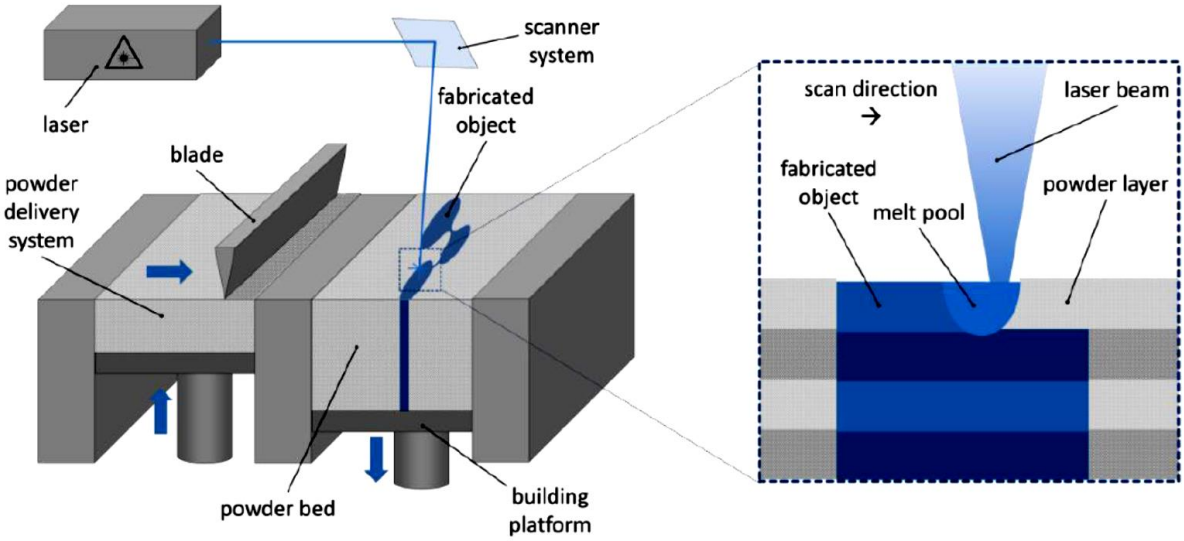


Fig. 45. Working principle of SLM. Source: *www.realizer.com*

SLM Realizer 250 machine

SLM technology is capable to produce a functional tool in a short time and in a direct mode. To complete such a task, in TUCN lab is available a SLM Realizer 250 machine (Realizer GmbH, Borchen, Germany). This SLM machine costs 0.5 mil. € and under slice-by-slice principle is capable to produce rapid tools. The Realizer 250 system is equipped with a 200 W solid fiber laser (type Nd:YAG) and emits continuous light in the infrared spectrum with a wavelength of 1064 nm. The main technical characteristics are presented in Figure 46. Other technical data are as following: ± 0.1 mm dimensional accuracy, 50 μm common layer thickness, less than 0.5% internal porosity, always required supports, inert gas argon or nitrogen depends on power type, heated platform up to 250°C, typical surface roughness Ra between 8 - 10 μm, and 100-1500 mm/s scanning speed.

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a)



System Parameters	
Bauraum in mm (x/y/z) Build Chamber in mm (x/y/z)	248 x248 x 250 (350)
Laserleistung Laser Power	200/400 W, YLR-Faser-Laser
Baugeschwindigkeitsrate* Build Speed Rate*	20 ccm/h
Prakt. Schichtdicke Pract. Layer thickness	20 µm - 75 µm (100 µm)
Min. Spurbreite / Wandstärke Min. Scan Line / Wall Thickness	150 µm
Operativer Strahlfocus frei wählbar Operational Beam Fokus variable	60 µm -100 µm (85 µm -130 µm)
Belichtungsgeschwindigkeit Scan Speed	20 m/s
Schutzgasverbrauch im Prozess Inert Gas Consumption in Operation	Ar/N_2, 1,5 l/min

b)



Fig. 46. SLM Realizer 250 machine: a) Technical data, b) Manufacturing chamber

This machine works with the following powders: tool steel and stainless steel, pure titanium, or titanium alloy (Ti6Al4V), Co-Cr, aluminum, and nickel (Inconel 625, 718). Information about particles shape and size are essential in controlling the SLM process. The shape of grains is almost spherical and have a diameter between 10-80 µm (Figure 47). The particle size distribution is described in percentiles, common is offer d90 value. This d-value indicate that 90% of particles are finer than this diameter according to laser diffraction result. It was observed that d90 value for normal SLM powder ranging from 30µm to 55µm. Moreover, the particle flowability can be measured using a hall flowmeter funnel with an orifice of 2.5 mm and is possible to calculate the flow rate (s/50g). The hall flow rate is expressed as the time required for a 50 g powder sample to be discharged by gravitational force through the flowmeter funnel (ASTM B213). Typical flow rate is

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between 17s to 34s per 50g of powder. The SLM powders are produced by gas atomization method.

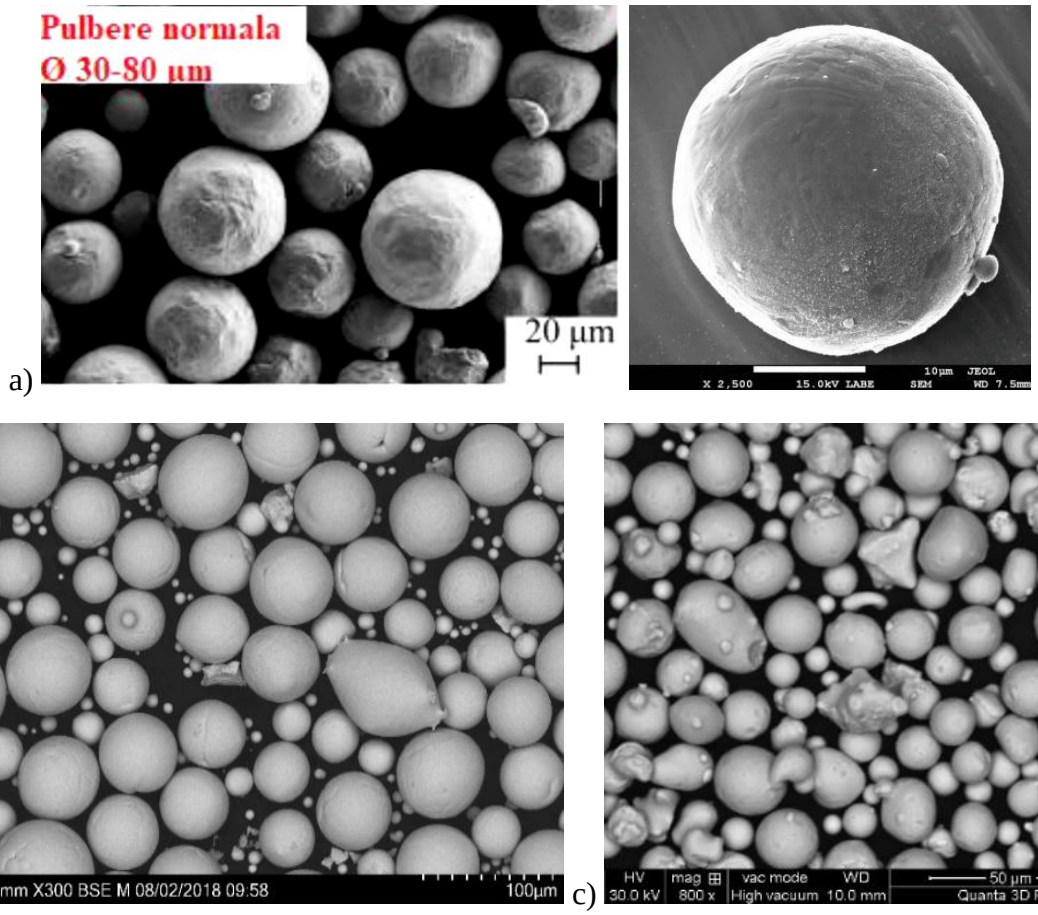


Fig. 47. SLM powders: a) Co-Cr alloy, b) pure Titanium, c) Stainless steel 316L

The most representative powder makers are:

- ►Arcast (www.arcastinc.com);
- ►Carpenter Additive (www.carpenteradditive.com);
- ►CNPC Powder (www.cnpcpowder.com);
- ►Constellium(www.constellium.com);
- ►Fehrmann Alloys (www.alloys.tech);
- ►GE Additive (www.ge.com/additive/fasterpath);
- ►Höganäs (www.hoganas.com);
- ►Hunan Hualiu New Materials (www.hlpowder.com);
- ►KBM Advanced Materials (www.kbmadvanced.com);

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- ►Kennametal (www.kennametal.com);
- ►Kymera International (www.kymerainternational.com);
- ►Material Technology Innovations (www.mt-innov.com);
- ►Metalpine (www.metalpine.at);
- ►Mimete (www.mimete.com);
- ►Oerlikon Additive (www.oerlikon.com/am);
- ►Osaka Titanium Techn. (www.osaka-ti.co.jp);
- ►Praxair Techn. (www.praxairsurfacetechnologies.com);
- ►PyroGenesis Canada (www.pyrogenesis.com);
- ►SAFINA (www.safina.cz);
- ►Sandvik Osprey (www.materials.sandvik);
- ►Sino-Euro Materials Tech. of Xi'an Co. (https://en.c-semt.com);
- ►TANIOBIS (www.taniobis.com);
- ►Tekna (www.tekna.com);
- ►Ultra Fine Specialty Products (www.ultrafinepowder.com);
- ►United States Metal Powders (www.usmetalpowders.com);
- ►VDM Metals (www.vdm-metals.com).

The powder material prices are subject to change weekly. Therefore, the below listed prices are just indications.

➢ Stainless Steel 316L (1.4404):	60 – 90 €/kg
➢ Tool Steel H13 (1.2344):	50 – 80 €/kg
➢ Tool Steel (1.2709):	90 – 130 €/kg
➢ Titanium Alloy TiAl6V4:	410 – 520 €/kg
➢ Titanium Alloy TiAl6Nb7:	530 – 680 €/kg
➢ Cobalt Chromium Alloy (CoCrWMo):	220 – 340 €/kg
➢ Aluminium Alloy AlSi10Mg:	70 – 90 €/kg
➢ Aluminium Alloy AlSi12:	60 – 95 €/kg
➢ Inconel 625:	120 – 170 €/kg
➢ Inconel 718:	165 – 190 €/kg

** Most used powders in SLM-manufacturing*

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4.6. Technological parameters

The basic steps of SLM process are:

- Configure the SLM parameters (Figure 48) and create the REA file;
- The build chamber is first filled with inert gas and then heated to the optimal print temperature.
- A thin layer of metal powder (typically 50 µm) is spread over the build platform.
- The laser scans the cross section of the part, selectively bonding the metal particles.
- When entire area is scanned, the build platform moves down a layer and the process repeat slice-by-slice until the whole build is complete.
- After printing, the build first needs to cool down and then the loose powder is extracted.

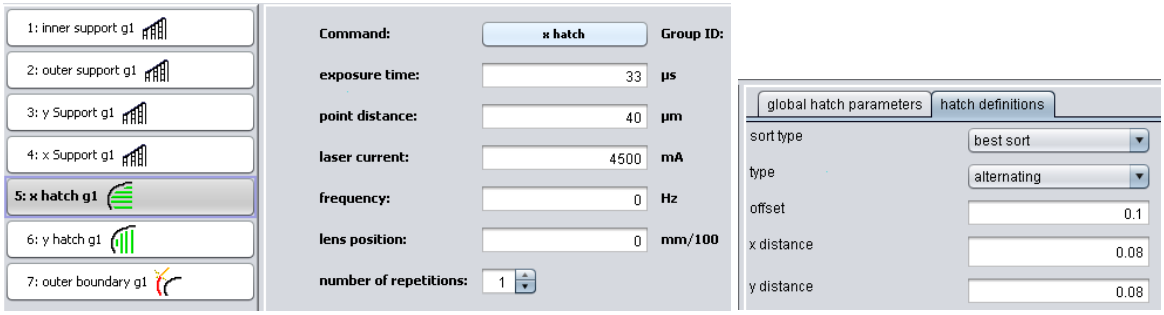


Fig.48. Technological SLM parameters setup for Hatch scanning: laser power, scanning speed, and space distance

The main process parameters which can be configured are laser power, scanning speed, hatch space, layer thickness and scanning strategy (Figure 48 and details in Section 2.2). From laser power point of view, there are systems which can generate a power of 100-400W or even 600-1000W. The trend is to use 2-4 lasers at the same time, to increase the productivity. The scanning speed may vary between 350-2000 mm/s, depending on the specific energy density that is needed for each material. The thickness of a layer is also important, and it can be set up between 20 - 100 µm. The spot diameter of Realizer SLM system is 80 µm. Before staring a job, the SLM platform is preheated at 250 °C and maintain constant until the fabrication is finish. Under a high-purity Ar-atmosphere and limited oxygen level (0.3–0.5%), the part can be SLM-manufactured.

Options like voxel size, number of considered neighbors, minimum and maximum applied laser power could be defined. If chess patterns are used, they are divided in sub heat patterns. After heat analysis the heat hatch groups must be calculated. A material file is generated automatically (generation of heat groups). The heat calculations can automatically adapt all the laser parameters for reduced surface roughness using advance simulations of mass distribution.

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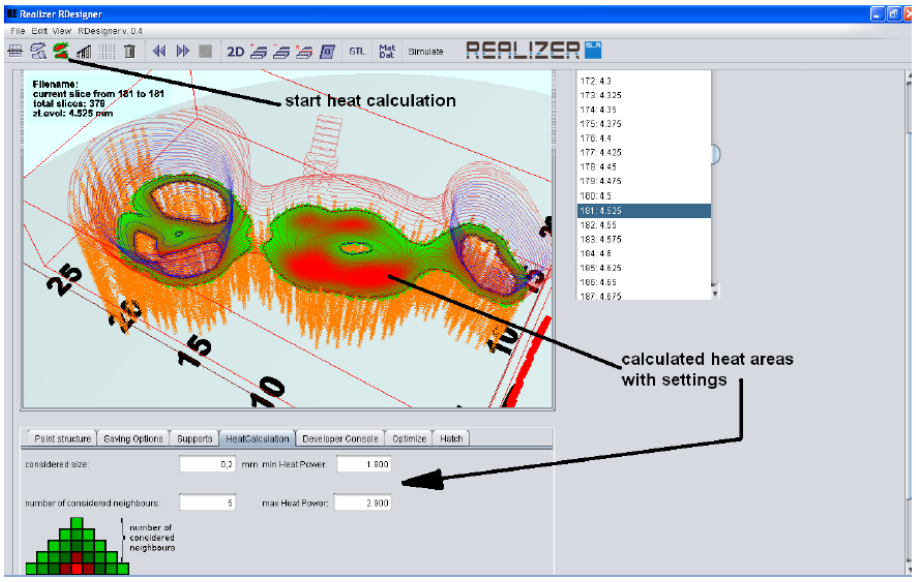


Fig.49. Heat map, RDesigner software

A soft recoater (wiper) made of dense carbon fibers with Ø 7.5 μm is used to spread the powder (Figure 50). This flexible recoater allows a continuation of the process when the metal was distorted and protruded out of the powder bed (e.g., small peaks). Hence, a collision which can de-calibrate the powder bed thickness was avoided. This technological issue cannot be managed by a hard recoater made of a stainless-steel blade or rubber wiper.

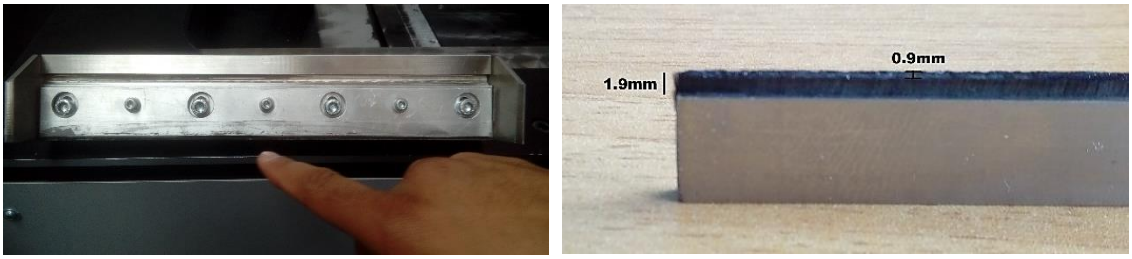


Fig. 50. Recoater (wiper) made of carbon fibers used to spread the powder on SLM plate

To prepare the Realizer machine (Figure 51), the following routine steps should be done [MCP]:

1. Mount the platform with a substrate plate.
2. Bring the platform in the right Z-height. This means that the substrate plate must be a little bit lower (0.5 mm) then the build chamber base. This height can be controlled with a spatula.
3. Clean the cover of the f-theta-lens with a soft and clean paper towel.
4. Close the build chamber and start flooding routine by pressing “flood on” in the Realizer software / motors page.
5. Turn the heating on if desired. A temperature of 240°C is all right.

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6. When the machine has reached an oxygen value lower than 1 % turn off the flooding routine by pressing “flood off” in the Realizer software / motors page.
7. Turn on the gas pump by pressing “gas pump on” and start the flooding routine (“flood on”) again till you have reached an oxygen value of 0.2%
8. If 0.2% or lower is reached turn of flooding routine (“flood off”) and press “Gas On”.
9. Now you must level the platform by driving the recoater to the front of the base plate, drop a little bit of powder by putting a value of 15.000 in the command box of the loader 2 in the Realizer software / motors page. Afterwards drive the recoater back to the end of the build chamber.
10. Raise platform by 0.1 mm and drive the recoater to the front and to the back.
11. Repeat point 11 till you can see the complete platform through the powder bed.
12. Press “Set Zero” for the elevator in the Realizer software / motors page to determine the actual position of the platform as zero position.
13. Open the data you want to build.
14. Start the job by pressing the yellow “GO” in the Realizer Software.
15. Then put in the slice you want to start from. First layer to be built is usually “0” and Press “OK”.
16. Now the machine starts the build.
17. During the fabrication, the oxygen concentration should be lower than 1% in a nitrogen/argon protection gas.

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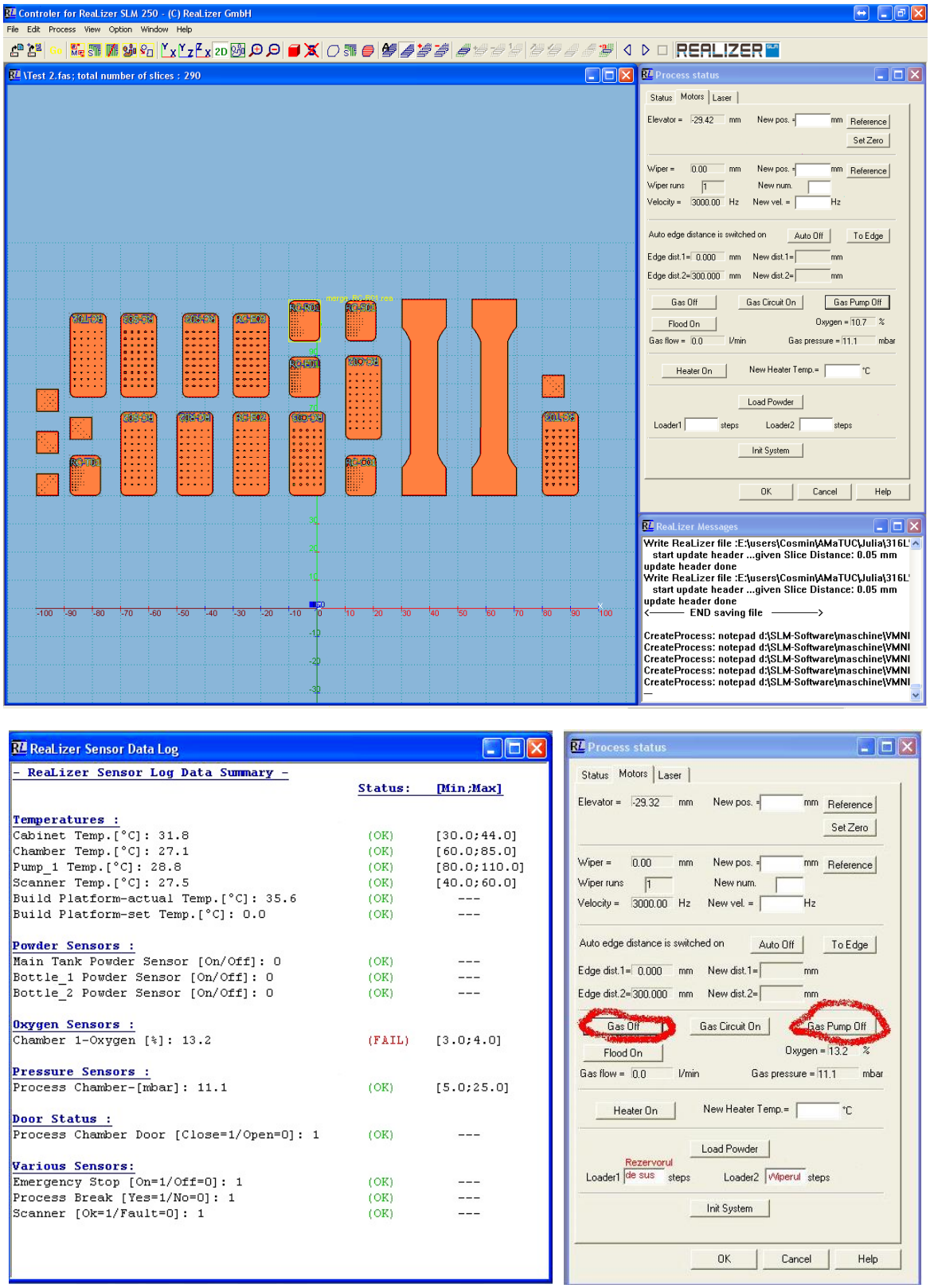


Fig. 51. Machine preparation (SLM Realizer 250)

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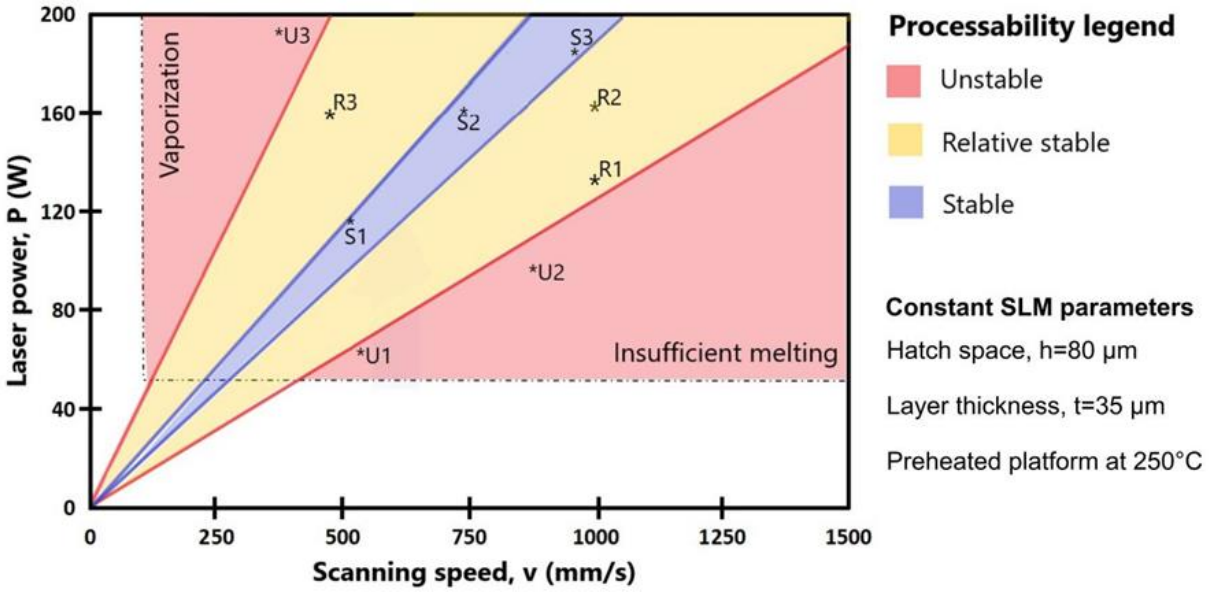


Fig. 52. Processability map of 316L powder via SLM technology [Cosma'Materials]

For each power, the SLM process parameters should be optimized to have a stable manufacturing and with-out defects in the manufactured parts. The main SLM defects for unstable SLM processability are cracks, severe warping, distortion, and vaporization. These defects may cause a premature failure in manufacturing. Based on temperature gradient mechanism, pre-solidified material underneath the melted layer is heated up rapidly upon laser irradiation, which readily expands, but is constricted by the cold and rigid portions of the solidified piece, repeated in multiple cycles [Cosma'Materials]. Figure 52 presents a processability evaluation which suggests that a stable SLM manufacturing can be expected using the parameters attributed to blue area.

4.7. Heat treatment for stress releasing

In general, the parts SLM-manufactured are exposed to a stress relief heat treatment in one or more cycles because the parts hold high thermal stress concentration. Before cutting the support structures, the SLM parts are exposed to a specific stress relief treatment. In TUCN lab, a Nabertherm furnace is used for thermal treatment (Figure 53). The furnace allows to configure specific heat treatment cycles, for each material. Technical details of furnace are listed in Figure 53.

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Technical specifications

Outer dimensions[1]	approx. 1010 x 1010 x 1340 mm (W x D x H)
Furnace chamber	approx. 350 x 350 x 250 mm (w x d x h)
Work space[2]	approx. 280 x 280 x 200 mm (w x d x h)
Furnace chamber volume	approx. 30 liters
Charging height	900 mm
Weight	approx. 210 kg
T_{max}	1280 °C
Temperature operating range	900°C – 1280°C
Temperature uniformity within temperature operating range	± 10 K according to DIN 17052-1 in the in the empty work space
Supply voltage	400 V 3/N/PE 50Hz, fuse protection without earth-leakage breaker, IT-net connection possible against surcharge
Power rating	approx. 15,0 kW
Max allowed charge weight	30 kg uniformly distributed load

Fig. 53. Nabertherm furnace type N 31/H with controller P 470 and protective gas box for heat treatments conducted under nitrogen or argon atmosphere

A practical example of stress relief treatment is listed below. This heat treatment is applied on Co-Cr parts, and it can be conducted using the following steps [Cosma'2021]:

- Heat up to 450°C within 60 minutes and hold for 45 minutes;
- Heat up to 880°C within 45 minutes and hold for 60 minutes;
- End heating process.
- The temperature is cooled down within 30-60 minutes to 300°C;
- After temperature decrease to 350°C stop argon/nitrogen supply;

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- Open furnace door after temperature has decreased to 300°C (or lower) and remove the SLM parts for further processing.

To avoid oxidation of parts, the stress-relief treatment is recommended to be conducted under nitrogen (for Co-Cr and steel) or argon atmosphere (for pure Ti and its alloys). Based on our internal studies, we found that this heat treatment is efficient even on large SLM components such as orthopedic prostheses or rapid tooling circular punch (Figure 54). The heat treatment limit significantly the residual stress and the deformations.

a)  b) 

Fig. 54. Rapid tooling application SLM manufactured from Co-Cr alloy (circular punch tool for automated stamping machine); a) After stress-relief treatment; b) After sandblasting with alumina

4.8. Supports removal and finishing the SLM parts

After heat relief treatment, the SLM parts are removed from machine plate and the support structures are cut using a metal bandsaw (Figure 4.31). To finish and clean SLM surfaces, a common method is to sandblast with aluminum oxide (approx. 110-150 μm) at 2-3 bar for 5-10 minutes (Figure 55). The recommend distance between the nozzle and the sample is 50 mm at an angle of 45°.

a)  *b)* 

Fig. 55. a) Metal bandsaw used to cut rapidly the support structures; b) Sandblasting tool

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To finish the surface where the support anchor the part, initially the peaks were removed manually. Then, the surface is cleaned with carbide/diamond burs suitable for CoCr/steel/Titanium alloys and by carborundum polishing (Figure 56).

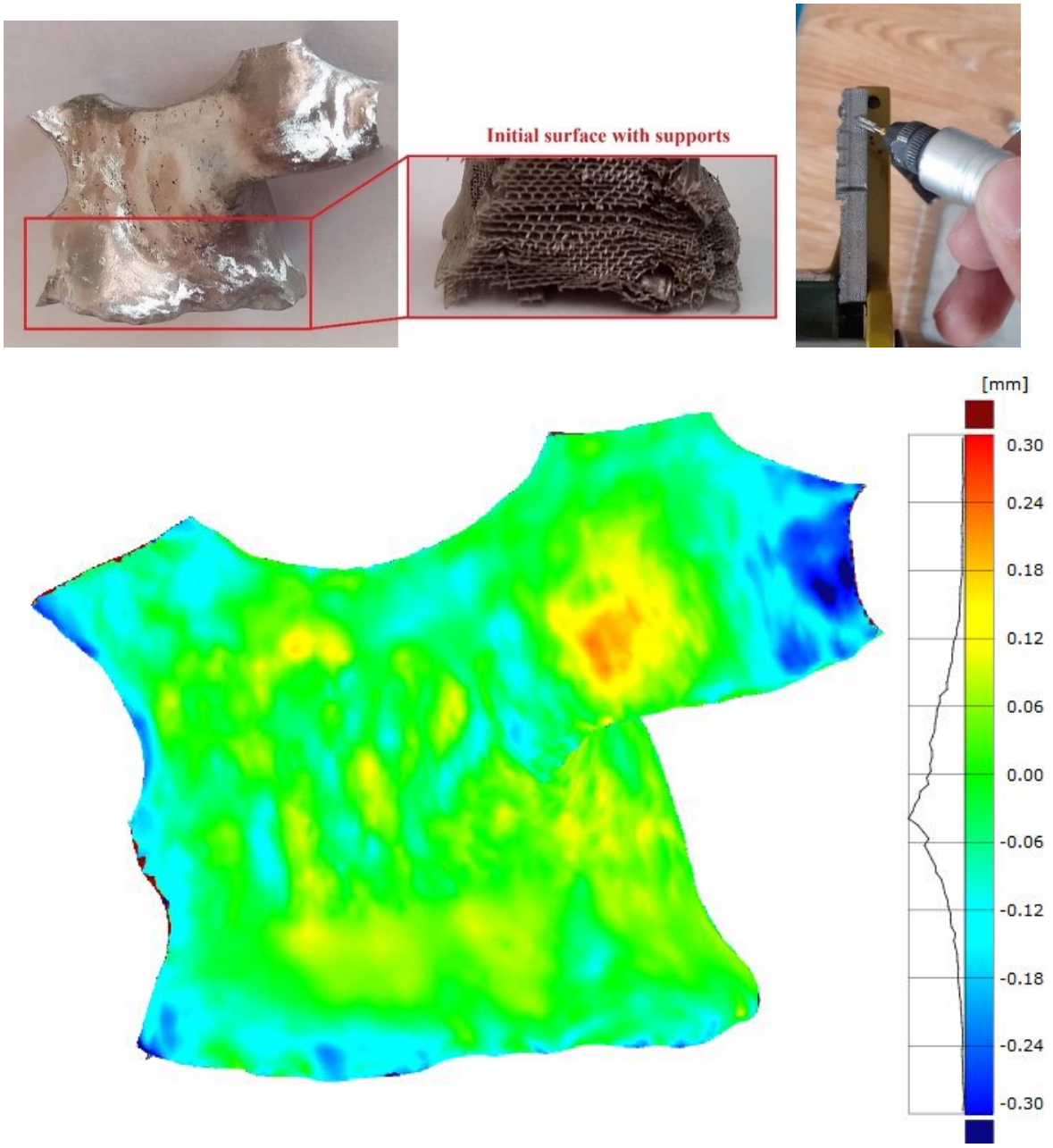


Fig. 56. Initial surface with support structures, after manual finishing, and map with dimensional deviations limited to ±0.3 mm

Certain application requires even a smoother surface and CNC machining, vibro or chemical polishing are all available solutions.

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One of the major advantages of SLM is the reusability of the un-melted powder. After a SLM job is finished, the un-melted powder is collected with a brush and recycled for future fabrication. To recycle the un-used powder, a vibratory sieve shaker is operated (type Retsch AS 200, Figure 57). During sieving procedure, the powder feedstock is subjected to vertical movement (vibratory sieving) or horizontal motion (horizontal sieving). Due to this combined motion, the particles are compared with the aperture sieve mesh which is commonly 45 µm or 63 µm. The probability of a particle passing through the sieve mesh is determined by the ratio of the particle size to the sieve openings, the orientation of the particle and the number of encounters between the particle and the mesh openings. The Retsch sieve have the following dimensions Ø200 x 50 mm. After fulfilling the sieve with powder, the amplitude is setup at 80% and the time at 15 minutes. One cycle is enough to recycle the powder and it is deposited in collection tray.



Fig. 57. Vibratory sieve shaker, type Retsch AS 200

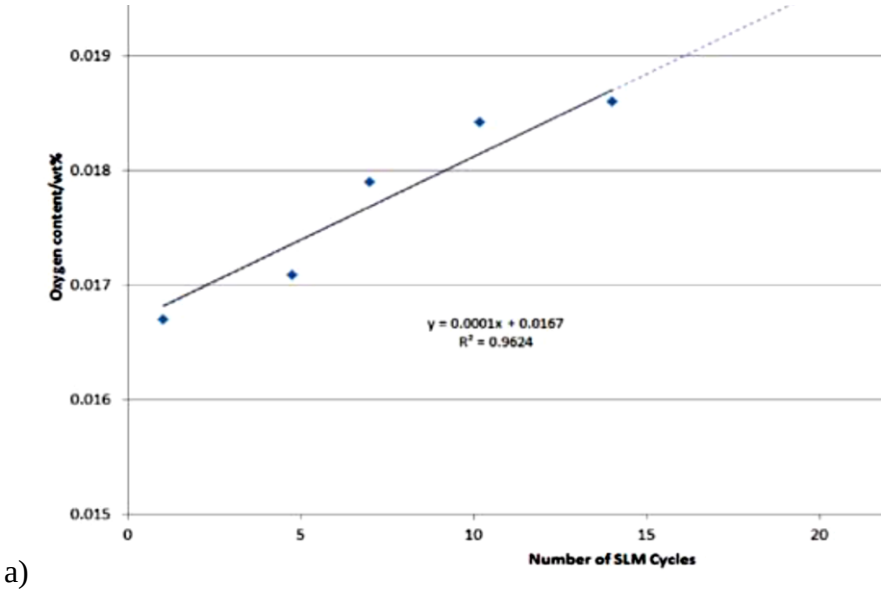
Generally, before starting a SLM job, into the recycled powder should be add 5% of virgin one. In this topic of powder recyclability, extended studies developed on Inconel 718 and Titanium (Ti6Al4V) reported the following results [LPW], [Strondl]:

- Disappearance of smaller particles and no change in particles morphology,
- Better flowability,
- No change in composition and in processed microstructure,
- No change in yield strength and ultimate tensile strength,
- Increase the oxygen content,
- Decrease in ductility and impact toughness (possibly connected to oxygen pick up),
- Slight porosity increase (possibly connected to oxygen pick up).

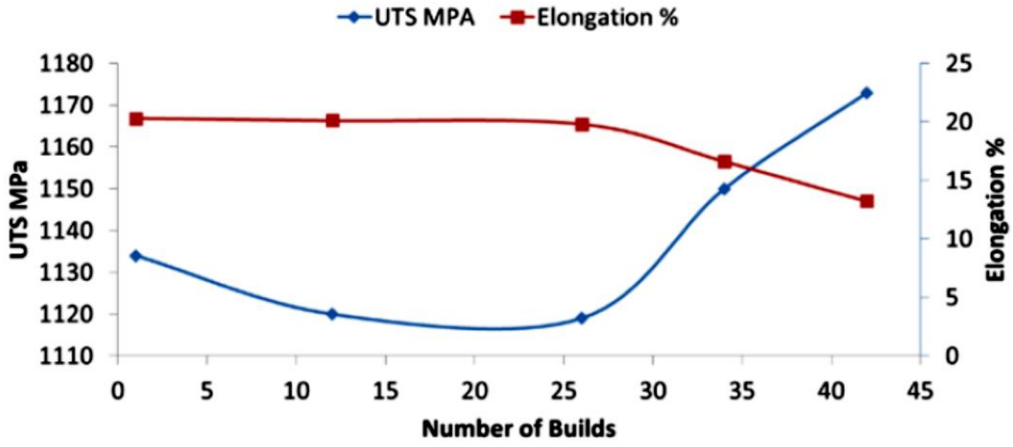
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Figure 58 details the results of LPW company after repeated use of Inconel 718 powder in SLM builds focused on oxygen content and ultimate tensile strength (UTS) [LPW].



a)



b)

Fig. 58. a) Oxygen content in In718 powder after repeated use in SLM builds, b) Effect of number of builds on mechanical properties of In718 specimens SLM-produced [LPW]

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INNOVATIVE MANUFACTURING AND QUALITY ENGINEERING

Lesson Material

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1. INNOVATIVE MANUFACTURING TO PRODUCE PARTS FROM COMPOSITE MATERIALS

1.1. Introduction

Polymer composites have a long and honorable history in the automotive industry, starting with hand lay-up bodies for limited production of sport cars (Ford 1940's). During World War II, in Britain, the material for fuselage of Spitfire aircraft was replaced from aluminum to flax fiber reinforced phenolic composites, (due to the insufficient supply of aluminum).

The major reasons for switching toward composite materials are due to their properties and performance that are comparable with conventional materials, such as metals, plastics, and woods while demonstrating their own advantages like light weight, corrosion resistance, and part consolidation.

In the recent years, there is a rapid growth in the development and use of composite materials due to the advantages that they offer, such as light weight and corrosion resistance. Composites comprise two or more phases where normally the constituent materials are processed separately and then bonded. The properties of the composites are different from the constituent materials acting alone. One of the constituents is reinforcing phase in the forms of fibers, particles, or sheets and are embedded in another constituent called matrix.

Composites are actually solid materials that are composed of a matrix that surrounds and binds together fibrous reinforcements. Composite materials are considered as today's materials because they are now being applied in various industries ranging from children toys to aircraft body. However, they can be regarded as tomorrow's materials due to their potentials that they can offer in the future, such as in the areas of nano-composites, functionally graded and smart materials. The most commonly used matrix is polymer or plastics (polymer matrix composite, PMC), and to a lesser extent ceramic (ceramic matrix composite, CMC) and metals (metal matrix composite, MMC) are also used. Composites are considered to demonstrate anisotropic behavior, that is, they have different properties along the axes in different directions. A wide range of matrices and reinforcements can be combined in various forms with virtually unlimited permutations (1).

There are many methods used to manufacture parts made from composite materials, depending on the size, the structure, or quantity of reinforcement fiber.

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1.2. Classical molding technology

Compression molding is among the oldest materials processing techniques. The basic process consists of heating a thermoset resin, under severe pressure, within a closed mold cavity until the resin cures through a chemical reaction of cross-linking polymeric chains. Under pressure the resin liquefies and flows, taking the shape of the mold cavity, and then hardens into the desired part or product. Once sufficiently cooled and strong, the part is removed from the mold and the cycle is complete although the curing reaction continues while cooling to ambient (room) conditions. Common resins include phenolic (phenol-formaldehyde), urea-formaldehyde, melamine-formaldehyde, epoxy, polyester, vinyl ester, silicone, alkyds, diallyl phthalate (allyls), and various rubbers and elastomers. This process is suitable for a wide range of industrial, commercial, and consumer parts and products ranging from very small to large automobile body panels. Product areas are lighting and electrical devices, closures, transportation, and appliances. Specific items are electrical wall switch plates and receptacles, circuit breakers, bottle caps, buttons, packaging, containers, covers, protective helmets, pump components, gears, brake parts, frames, pulleys, vehicle panels, dishware, and appliance housings, bases, handles, and knobs.

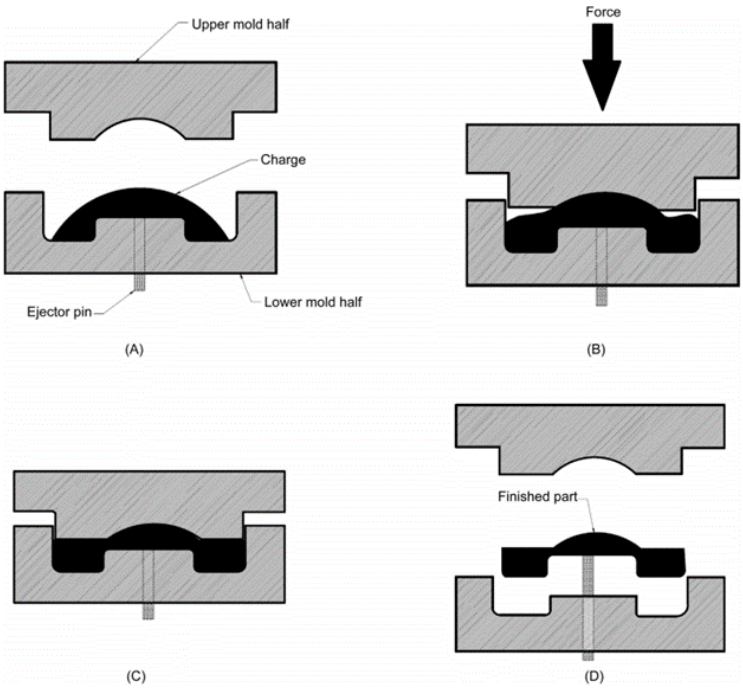


Fig. 1. The compression molding process as described by a simplified, four-step procedure [SIN17]

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The injection molding process in its simplest form has been in use for nearly 150 years. Compared with the injection molding machines of today, the early machines were, of course, primitive. Most advances have been made since the 1960s with the introduction of the reciprocating screw injection molding machine (IMM).

These are the machines that are in use today. The IMM can be considered to have two halves: the injection unit, where the material is prepared for injection into the mold, and the clamping unit, where the injected plastic is captured in the mold under conditions of temperature and pressure to form the finished product.

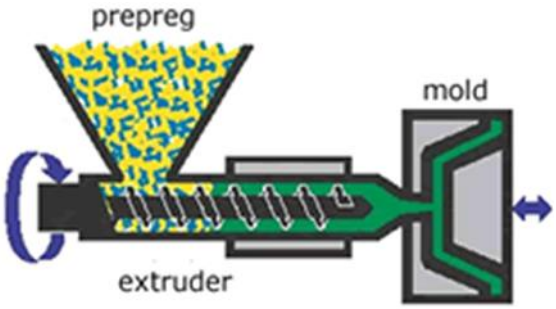


Fig. 2. Injection molding [MOL 17]

Liquid composite molding comprises all the composite manufacturing methods, where the liquid state matrix material (e.g. epoxy resin) is forced into the dry preformed reinforcing material (e.g. carbon fiber fabric). The main objective is to reach a full impregnation as the resin propagates between the fiber bundles and fibers. The impregnation driving force is usually resulting from pressure difference. Resin transfer molding (RTM) utilizes positive operating pressures, while in vacuum infusion the pressure is lower than the atmospheric pressure level. Vacuum assisted resin transfer molding (VARTM) operates with positive injection pressures, while the mold cavity is kept under vacuum. Positive operating pressure techniques require matched molding (two or more part molds), while vacuum infusion is usually done using a flexible membrane (e.g. polymer foil) on the mold.

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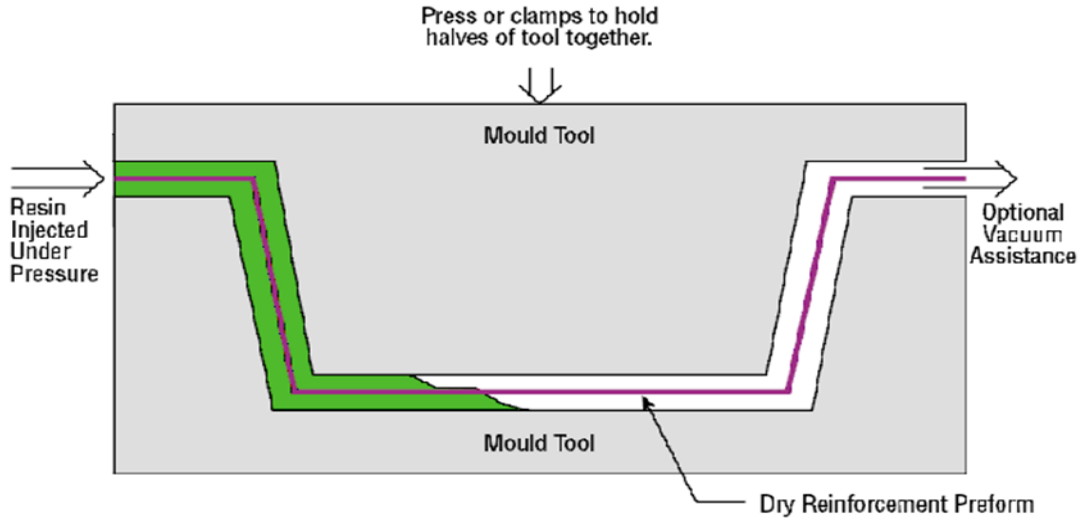


Fig. 3. Vacuum assisted resin transfer molding [MOL17]

1.3. 3D printing of the master models

Every process of creating a 3D master model for obtaining a mold, it starts with a virtual 3d model. This model can be obtained from a CAD program or from a 3D scan of an existent part. The technology used to obtain the master model can be: Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereolithography (SLA).

Selective Laser Sintering (SLS) or Laser Sintering, is one of the most established and widely used additive manufacturing techniques. In this process, an object is created layer-by-layer from heat-fusible powdered material with heat generated from a scanning laser beam. In principle, all materials that can be melted or fused can be used in the laser sintering process. The term 'selective laser sintering' is generally applied to the processing of polymers.

Thermoplastic polymer materials are well-suited for laser sintering because of their relatively low melting temperature. Theoretically, almost any polymer available in powder form can be laser sintered using optimized processing parameters. However, limitations exist with current laser sintering materials. Firstly, there is a very limited variety of polymers that can currently be processed. Polyamides 11 and 12 (PA11/PA12) are by far the most commonly used laser sintering materials at present, making up more than 95% of the current laser sintering materials market. Secondly, the polymers that are available at the moment cannot completely meet the needs of all applications. To further develop SLS process, there is a growing need to research and develop more materials which can meet the various requirements for different applications.

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Fig. 4. Car mirror holder printed by SLS

In **Fused Deposition Modeling** (FDM) process, as for many others 3D printing technologies, the model is built as a layer-by-layer deposition of a feedstock material. Initially, this is in the form of filament that is, successively, partially melted, extruded and deposited by a numerically guided heated nozzle onto the previously built model. After the deposition, the material cools, solidifies and sticks to the surrounding material. Once the entire model has been deposited, the FDM part shows orthotropic material properties with behavior similar to a laminate orthotropic structure.

Nowadays, besides the traditional FDM materials such as PLA (polylactic acid) and ABS (acrilonitrile-butadiene-stirene), many other materials have been employed and developed, e.g., short fiber composites, metals, bioresorbable polymers (PCL), ceramics and metal/polymers mixture materials. PLA has better thermo-mechanical characteristics than ABS, showing higher mechanical resistance and a lower coefficient of thermal expansion that improves the printability of PLA, reducing the warp effect during the printing phase.



Fig. 5. Video game lever case printed by FDM.

Stereolithography uses photopolymers that can be cured by UV laser. An UV-laser is controlled in a desired path to shoot in the resin reservoir, and the photocurable resin will polymerize into a 2D patterned layer. After each layer is cured, the platform lowers and another layer of uncured

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resin is ready to be patterned. Typical polymer materials used in SLA are acrylic and epoxy resins. Understanding the curing reactions occurring during polymerization is critical to control the quality of final printed parts. Intensity of laser power, scan speed and duration of exposure affect the curing time and printing resolution. Photoinitiators and UV absorbers can be added to the resin to control the depth of polymerization.

The main advantage of SLA printing technology is the ability to print parts with high resolution. Additionally, because SLA is a nozzle-free technique, the problem of nozzle clogging can be avoided. Despite these advantages, the high cost of this system is a main concern for industrial application. Possible cytotoxicity of residual photoinitiator and uncured resin is another concern.

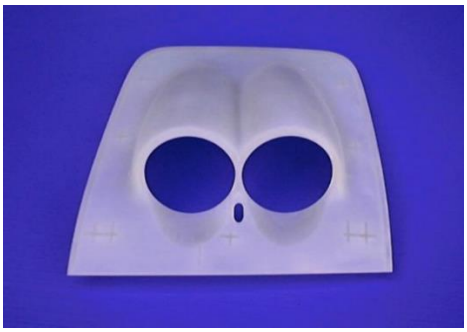


Fig. 6. 3D printed part using SLA technology

Source: http://www.solid-concepts.com.au/stereolithography.html

1.4. Mold building using metal spray technology

Using metal spray on the RP model, it is possible to create very quickly an injection mold that can be used to mold a limited number of prototype parts. The metal spray process is operated manually, with a hand-held gun. An electric arc is introduced between two wires, which melts the wires into tiny droplets. Compressed air blows out the droplets in small layers of approximately 0.5 mm of metal.

Metal spray gun



Fig. 7. Metal spray gun

The master pattern produced by any RP process is mounted onto a base and bolster, which are then layered with a release agent. A coating of metal particles using the spray is then applied to the master pattern to produce the female form cavity of the desired tool. Depending on the type of tooling application, a reinforcement backing is selected and applied to the shell.

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Types of backing materials include filled epoxy resin, low-melting point metal alloys and ceramics. This method of producing soft tooling is cost and lead-time saving. A typical metal spray process for creating an injection mold is shown in the next figures.

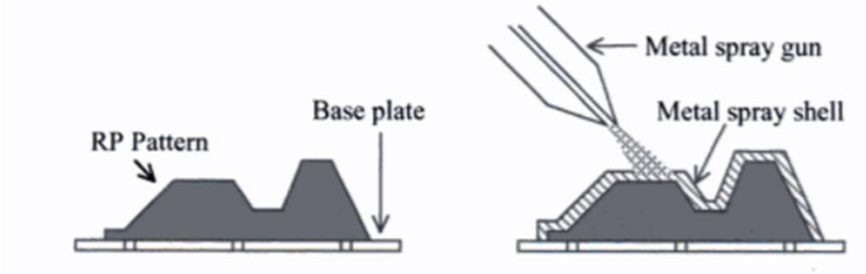


Fig. 8. RP pattern preparations and the metal spray shell building

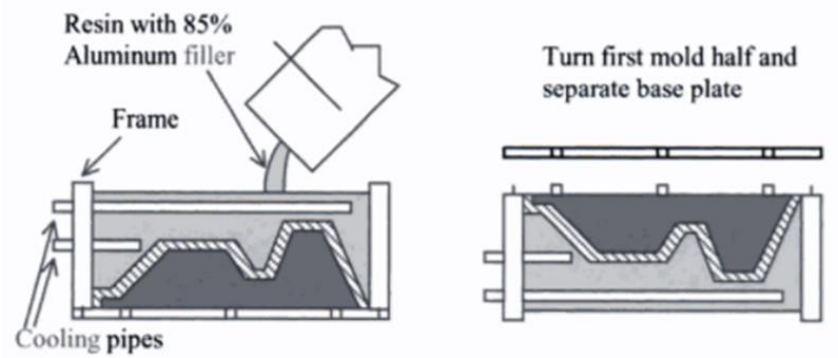


Fig. 9. The back reinforcement, the cooling pipes set-up and preparations for second semi-mold.

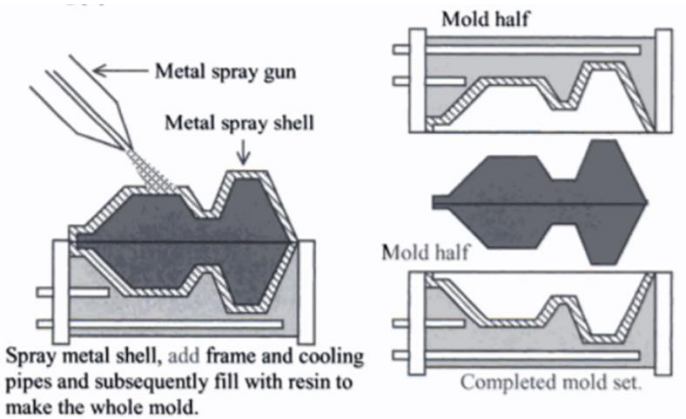


Fig. 10. Building second half of the mold and finishing the mold set. [MOL17]

Because the metal sprayed on the master model to form the metal shell is a material with a low melting point, the material does not have good wear resistance. The wear resistance is a very important characteristic of the active surface of the mold parts. The low wear resistance of the mold obtained by metal spray technology, recommends using this technology only if

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we intend to produce a small series of products or prototypes. An alternative for manufacturing molds for big series of products it can be the CNC manufacturing.

1.5. Vacuum bag technology

Hand lay-up is a simple method for composite production. The process consists of building up or placing layers of composite fiber in a sequenced layup using a matrix of resin and hardener.

Before starting with the lay up process an adequate mold preparation must be done. Mainly, this preparation consists of cleaning the mold and applying a release agent in the surface of it to avoid the resin to stick.

• Clean the mold with a clean cloth

• Apply and spread release agent in the surface of the mold

• Wait certain to set up the release agent

• Buff with clean cloth

Once all the materials are prepared, the workstation is ready, and the mold preparation done. The first step is to mix the resin and the hardener. The mixing is performed in the mixing containers with the mixing stick and should be done slowly so as to not entrain any excess air bubbles in the resin. It is best to use a "flat" stick- such as tongue depressor; a round stick does not work well as it does not 'paddle' the mixture to blend it properly. [51]

Next an adequate quantity of mixed resin & hardener is deposited in the mold and a brush or roller is used to spread it around all surface. It is important not to add too much resin, which will cause too thick of a layer, nor to add less than the necessary amount, which will cause holes in the surface of the part when it is cured. The first layer of fiber reinforcement is then laid. This layer must be wetted with resin and then softly pressing using a brush or a roller make the resin that was added in the previous step wick up through the fiberglass cloth.

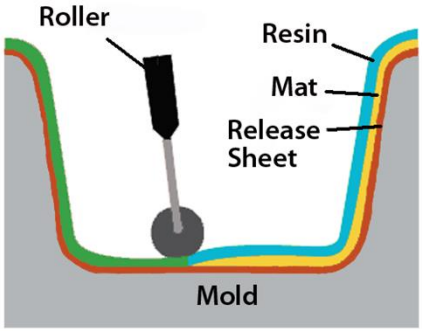


Fig. 11. Manual lay-up of composite material

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As the glass fiber layers are added to build laminates and total part thickness the individual layers may be oriented at varying angles to accomplish specific strength in the direction of the reinforcement weave- this is called ‘clocking’

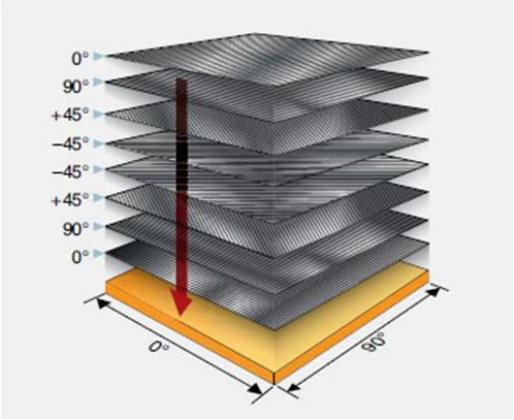


Fig. 12. Reinforcement fiber orientation

Vacuum bagging is a technique employed to create mechanical pressure on a laminate during its cure cycle. Pressurizing a composite lamination serves several functions:

- First, it removes trapped air between layers.
- Second, it compacts the fiber layers for efficient force transmission among fiber bundles and prevents shifting of fiber orientation during cure.
- Third, it reduces humidity.
- Finally, and most important, the vacuum bagging technique optimizes the fiber-to-resin ratio in the composite part.

These advantages have for years enabled aerospace and racing industries to maximize the physical properties of advanced composite materials such as carbon, aramid, and epoxy.

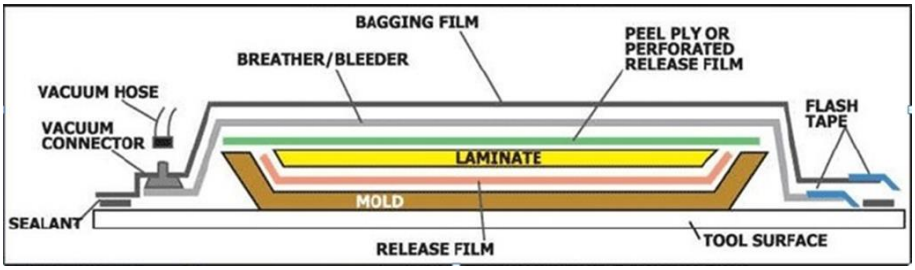


Fig. 13. Vacuum bagging lay-up

Source: http://www.nextcraft.com/vacuum_bagging_01.html

The reason that composites are used increasingly is the strength-to-weight advantages that they offer. The key to obtaining these advantages is maximizing the fiber-to-resin ratio. The reinforcement (fiberglass, aramid Kevlar, carbon, etc. is not particularly strong in the textile

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state. Also, thermosetting resins such as polyester and epoxy are quite brittle if cured without reinforcement. If excess resin exists in the laminate, the laminate will have more of the properties of resin only. If too little resin exists, places where the reinforcement is dry will cause weak spots. To optimize the resin content, the entire reinforcement must be saturated with resin with as little excess as possible. The technique of "squeezing out" excess resin to obtain a maximized fiber-to-resin content is the theory of vacuum bagging.

Vacuum bagging adds one atmosphere of pressure to a system. Often the people who insist on maximum fiber-to-resin content use autoclaves to both elevate the temperature and pressure surrounding the part and/or mold while curing these high performance parts. An autoclave can elevate the pressure on a laminate two to three atmospheres.

Many high-performance thermoset parts require heat and high consolidation pressure to cure conditions that require the use of an autoclave. Autoclaves, generally, are expensive to buy and operate. Manufacturers that are equipped with autoclaves usually cure a number of parts simultaneously. Computer systems monitor and control autoclave temperature, pressure, vacuum and inert atmosphere, which allows unattended and/or remote supervision of the cure process and maximizes efficient use of the technique.

Materials and equipment

There are two major groups of resins that make up what we call polymer materials-thermosets and thermoplastics. These resins are made of polymers (large molecules made up of long chains of smaller molecules or monomers).

Thermoset resins are used to make most composites. They’re converted from a liquid to a solid through a process called polymerization, or cross-linking. When used to produce finished goods, thermosetting resins are “cured” by the use of a catalyst, heat or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid form. Common thermosets are polyester, vinyl ester, epoxy, and polyurethane.

Polyester: Unsaturated polyester resins (UPR) are the workhorse of the composites industry and represent approximately 75% of the total resins used. A range of raw materials and processing techniques are available to achieve the desired properties in the formulated or processed polyester resin. Polyesters are versatile because of their capacity to be modified or tailored during the building of the polymer chains. They have been found to have almost unlimited usefulness in all segments of the composites industry. The principle advantage of these resins is a balance of properties (including mechanical, chemical, and electrical) dimensional stability, cost and ease of handling or processing. Polyester producers have proved willing and capable of supplying resins with the necessary properties to meet the

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requirements of specific end user applications. These resins can be formulated and chemically tailored to provide properties and process compatibility.

Epoxy: Epoxy resins have a well-established record in a wide range of composites parts, structures and concrete repair. The structure of the resin can be engineered to yield a number of different products with varying levels of performance. A major benefit of epoxy resins over unsaturated polyester resins is their lower shrinkage. Epoxy resins can also be formulated with different materials or blended with other epoxy resins to achieve specific performance features. Epoxies are used primarily for fabricating high performance composites with superior mechanical properties, resistance to corrosive liquids and environments, superior electrical properties, good performance at elevated temperatures, good adhesion to a substrate, or a combination of these benefits. Epoxy resins do not however, have particularly good UV resistance.

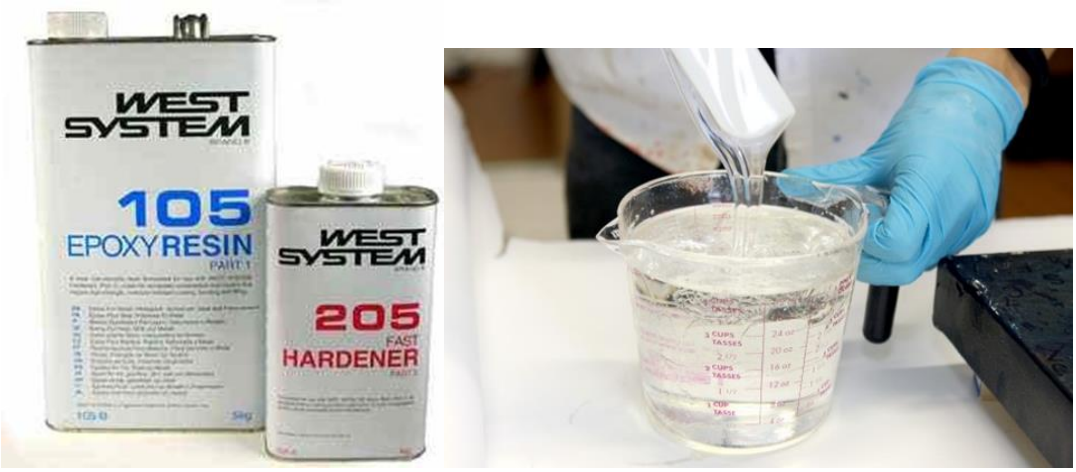


Fig. 14. The two components of the chemically activated resin and the gel phase of an epoxy resin.

A very important aspect of the resins that are used to make pieces of composite materials is gel phase time. Gel phase is the assembly time of mixed epoxy. It is the portion of the cure time, after mixing, that the epoxy will remain in a liquid state and be workable.

There are many different types of fibers that can be used to reinforce polymer matrix composites. The most common are carbon fibers (AS4, IM7, etc.), fiberglass (S-glass, E-glass, etc.), aramid fibers (kevlar, twaran) and boron fibers.

Carbon fiber is increasingly being utilized as a reinforcing material due to its high strength and high modulus, which is imparted into the properties of the final composite. Carbon fiber has been utilized in applications such as aerospace, sporting goods, marine, and infrastructure over the past several decades.

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Carbon fiber tensile strength is limited by the presence of defect structures, which can reside on the fiber surface or within the internal fiber structure. Some of the properties of the carbon fiber are:

- High Strength to weight ratio
- Rigidity
- Corrosion resistance
- Electrical Conductivity
- Fatigue Resistance
- Good tensile strength but Brittle
- Fire Resistance/Not flammable
- High Thermal Conductivity in some forms
- Low coefficient of thermal expansion
- Non poisonous
- Biologically inert
- X-Ray Permeable
- Self Lubricating

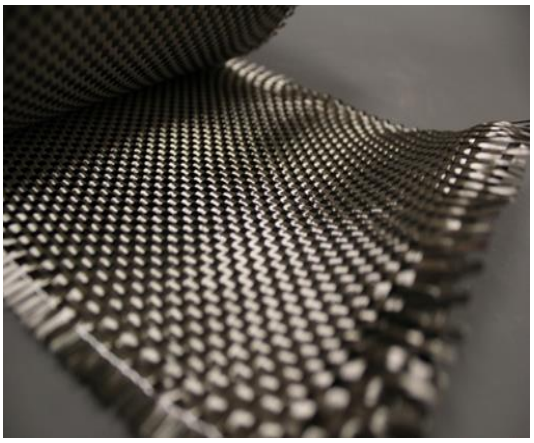


Fig. 15. Carbon fiber textile

Fiberglass is by far the most used fiber in reinforced plastic composites. In many industries, it represents over 90% of the reinforcements used. Its main advantages are:

- Low cost
- High strength
- Light weight (relative to steel)
- High chemical resistance

The main disadvantages are:

- Low modulus (relative to other reinforcing fibers)
- Low fatigue resistance (relative to carbon fibers)
- High weight (relative to other reinforcing fibers)
- Highly abrasive when machined
- Susceptibility to stress corrosion



Fig. 16. Chopped fiber glass

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Aramid fibers are highly crystalline aromatic polyamide manufactured by extruding an acidic solution of a proprietary precursor. Aramid fibers have very low density and high specific tensile strength when compared to commonly available reinforcing fibers. They are best known for their use in bullet proof vests, chainsaw pants, safety gloves and other applications where cut resistance and damage tolerance are required. The main advantages of aramid fibers are:

- Light weight
- High impact damage tolerance
- High tensile strength
- Moderately high tensile modulus (midway between E-glass & HS carbon)
- Excellent vibration damping
- Low (negative) longitudinal thermal expansion
- The main disadvantages of aramid are:
- Very low compressive strength
- Susceptibility to UV radiation
- Difficult to machine
- High moisture absorption
- Very high transverse thermal expansion



Fig. 17. Aramid fiber spool

Equipment

In order to obtain a higher degree of polymerization for the thermosetting resins used as matrix for the composite materials it is required a polymerization process.

The resins used for composite materials can be photo-activated resins. Ultraviolet light (UV)-activated composite resins serve a useful purpose. The depth of cure provided by the various UV systems has contributed to their acceptance.

Curing of thermosetting resins is usually carried out by conventional heating oven which involves a direct application of thermal energy from heaters to the resins. It has been evidenced that this thermal curing introduces a number of processing related problems such as long curing times and large temperature gradients

Microwave curing has been referred to as efficient alternative energy source for curing thermosetting resins and their composites because curing by the microwave can reduce the cure time and increase the crosslink rate

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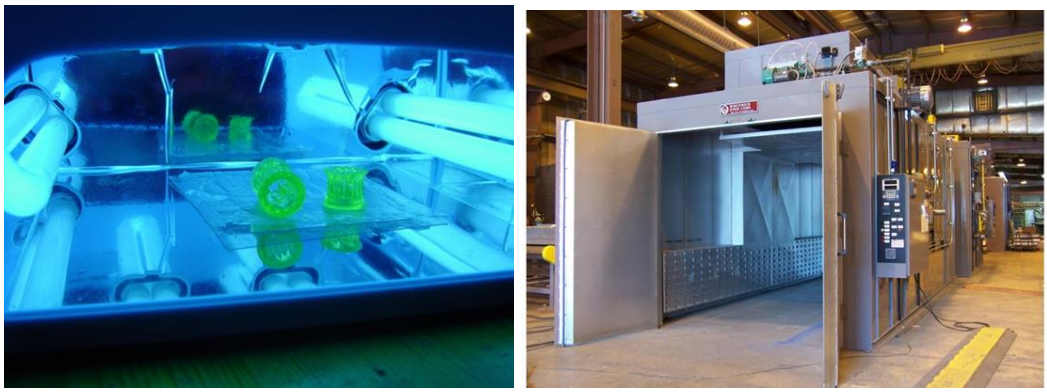


Fig. 18. Polymerization equipment for the resin curing

1.6. Direct 3D printing of the complex parts made from composite materials

Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA) are 3D printing processes that are used to create functional parts using carbon fiber-reinforced materials as feedstock. FDM is a process that builds plastic parts using layer-by-layer extrusion of heated filament materials. SLS is a process to fabricate parts by building successive layers made out of laser sintered powder materials. And SLA uses polymeric resins combined with reinforcing powder or short fiber to create the composite parts.

Between the three technologies presented above FDM is the most common used in direct printing of composite parts, and one major advantage over the other technologies is the capability of printing continuous fiber, which is it known for offering the final part better strength.

Fiber reinforcements can significantly enhance the properties of polymer matrix materials. For FDM processing, polymer pellets and fibers are mixed in a blender first and then delivered to extruder to be fabricated into filaments.

There are three configurations of FDM printers which can use composite materials.

The first one has an extruder head and prints parts using a composite filament that is pre-extruded with the reinforcement material included therein.

The second configuration has also an extrusion head, but the reinforcement process takes place inside the extruder (Fig. 19). The reinforcing fibre is covered with a layer of thermoplastic material at the time of extrusion being passed through the material bath formed inside the print head. In this configuration one of the problems that may arise is that of the non-uniform coating of the extruded fibre.

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The third construction of a 3D printer for composite materials possesses two deposition heads, one for the thermoplastic matrix and the other for the reinforcement fibre. This construction provides a better distribution of the thermoplastic material, so a better coverage of the reinforcement fibres than that in which the combination of the two materials takes place inside the extruder head. [MOL 18]

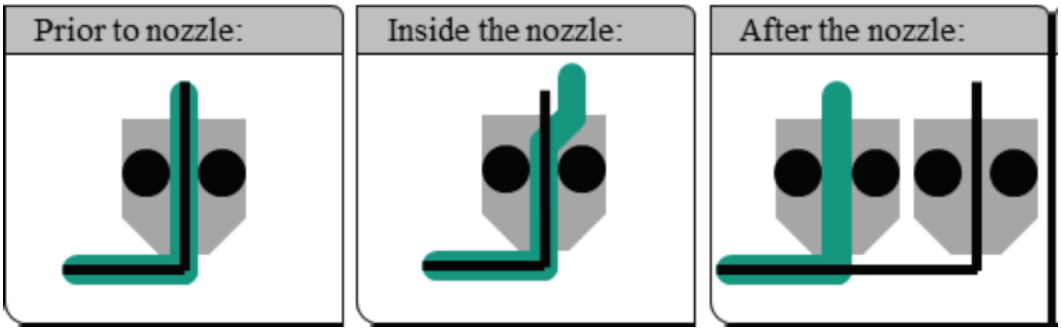


Fig. 19. The three structures of a composite FDM printing head [BAU 17]

Now on the market there are a wide variety of 3D printers that work with different types of materials such as resins, metal or plastic powders and wire of simple thermoplastic material or reinforced with different fibers or powders.

Among the manufacturers of equipment that print with composite materials are companies such as: anisoprint, continuous composite, ultimaker, CEAD, markforged.

Anisoprint

Composer A4 from Anisoprint has three printing nozzles, two for plastic and one for reinforcing fibers, unlike most printers that have one or two printheads. Another feature of this car is that it has a heated platform.



Fig. 20. Composer A4 3D printer

Characteristics:

- Working volume: 297 x 210 x 145 mm
- Plastic material: PLA, ABS, Nylon
- Reinforcement fibers: carbon fiber, fiberglass
- Maximum nozzle temperature: 270 °

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CEAD CFAM Prime

CFAM Prime is currently the printing equipment with the largest workspace (4x2x1.5m) in Europe.

It can use a wide range of thermoplastic materials such as PLA, ABS, Nylon, PET, including PEEK. High working temperature materials such as PEEK can be used due to the fact that the machine has a temperature controlled enclosure.

Currently, manufacturers recommend that carbon fiber be used as reinforcement materials.

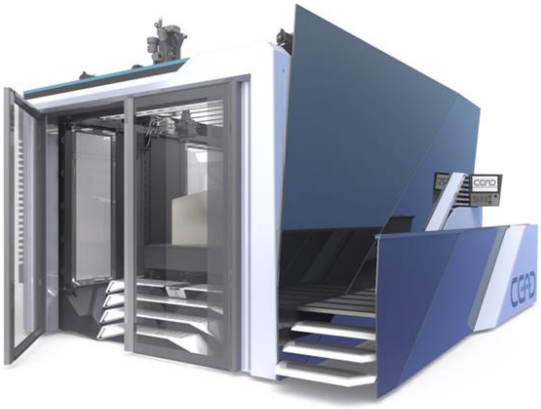


Fig. 21. CFAM Prime 3D printing equipment

Continuous composite

The continuous composite team thought of a 3D printing system based on a robotic arm, on which a printing head is mounted.

Due to the fact that this printing head is mounted on a robotic arm, it gives the system a lot of freedom. Also, the arm can be placed on a rail that offers the translation of the entire system and thus in a much larger workspace.



Fig. 22. Continuous composite equipment

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As the matrix material, a fast-solidifying resin is used which is impregnated in the reinforcing fiber. The reinforcement materials you can use are various such as:

- Carbon fiber
- Fiber glass
- Aramid (kevlar)
- Optical fiber
- Copper wire
- Fir NiCr

Markforged Mark Two

The Mark Two combines Markforged's unique continuous carbon fiber reinforcement with workhorse reliability for the strongest, most versatile parts in their portfolio. This printer as well as Onyx Pro, it has a second print head for continuous reinforcement fiber.



Characteristics:

- Build volume 320mm x 132mm x154mm
- Plastic material: Onyx
- Fiber materials: Carbon fiber, Kevlar, Fiberglass and HSHT Fiberglass (High-Strength High-Temperature Fiberglass)
- 2 layer resolution 100 micron

Fig. 23. Mark Two 3D printer

The reinforcement fibers that the manufacturer Markforged offers for this 3D printer are:

- Carbon fiber
- Aramid fiber (kevlar)
- Glass fiber
- HSHT (High Strength, High Temperature) glass fiber

MarkForged HSHT fiberglass is a material designed for users who need durable parts, for applications in environments with higher temperatures, above 105 ° C.

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1.7. Software for 3D printing

The Markforged manufacturer of 3D printers offers the Eiger program for their printers. This program require that the 3D model of the part that you want to print to be saved in .STL format so it can be processed.

After you uploaded the 3d model to the program, you can select the machine that you will use, the plastic material if you want to use reinforcement fiber and if you want to scale the part.

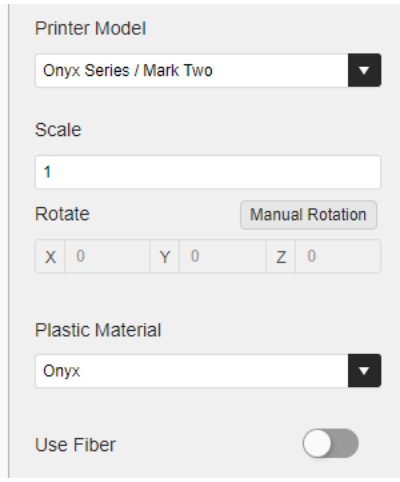


Fig. 24. General settings for the part

If using reinforcement fibers is needed the program offers the possibility to select the one that is necessary from a list. It can be also selected the number of fiber layers that will be printed in the part.

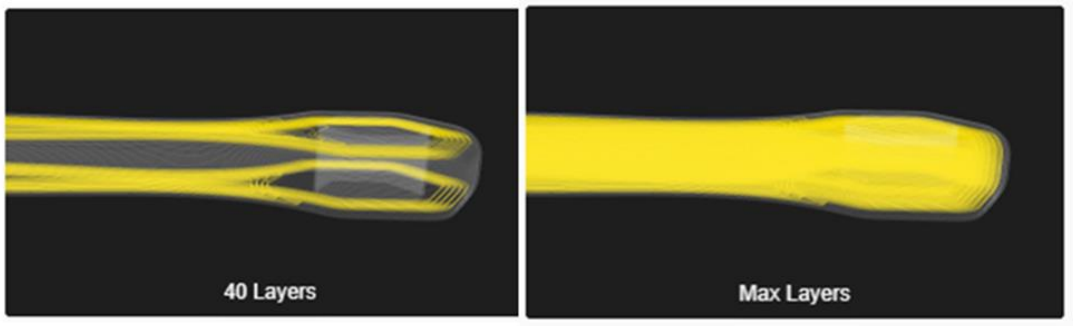


Fig. 25. Number of the reinforced layers and arrangement

The program offers the the possibility to select the fiber fill pattern which can be concentric or isotropic. For the isotropic it can be selected an angle for the fiber: 0°,45°, 90°, 135°.

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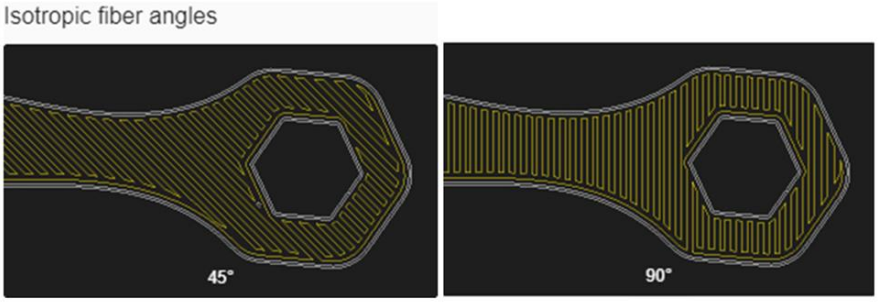


Fig. 26. Fiber fill pattern and angle

Another option in the program are the supports that can be used to help constructing the part. It is possible to turbo supports, which is an option to print the supports at twice the layer height and wider spacing to save time. The part can also be printed on 20 layers of supports if the supports printed on the bottom of the parts are too small to pill of. If the surface in contact with the print bed is small or during printing tends to warp, it can be used a brim. A brim is an anchor that holds the part to the print bed.

In the same menu it can be set also the height of the support layer, the infill pattern and infill density.

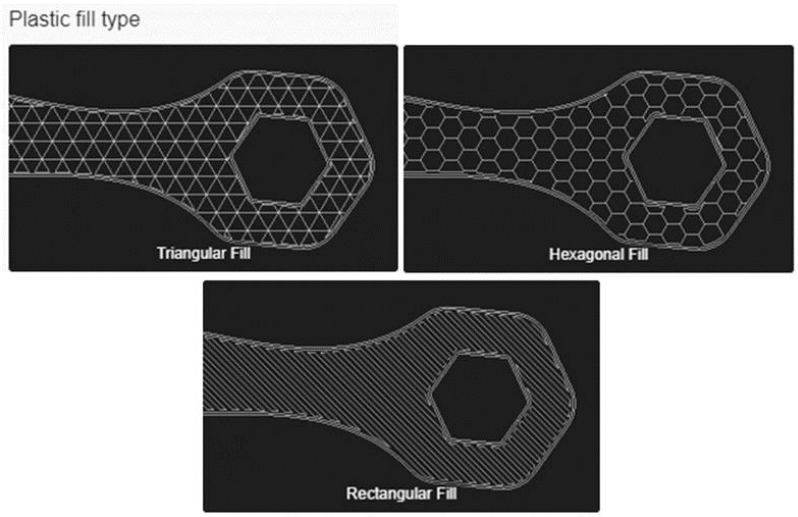


Fig. 27. Infill pattern and infill density in Eiger.

The program also offers the possibility to an internal view of the part so the structure can be very well controlled. The advantage is the fact that the structure of every single layer can be verified. It can be added or removed the reinforcing fiber from any layer, so it will result exactly the structure that we need.

Before printing the program will offer a final estimation of the cost and will give the user the data related to the printing time, material consumption and the weight of the part.

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There are many industries that use the 3D technologies to manufacture parts made out of composite materials:

In the medical field:

- Implants
- Proteases
- Operating devices



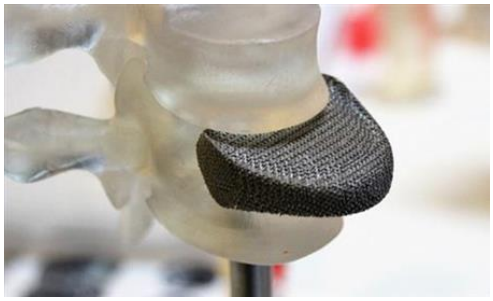




Fig. 28. Medical field applications of reinforced 3D printing

Automotive and motorsports

- Air intake manifolds
- Motorcycle handlebar component
- Motorcycle brake lever



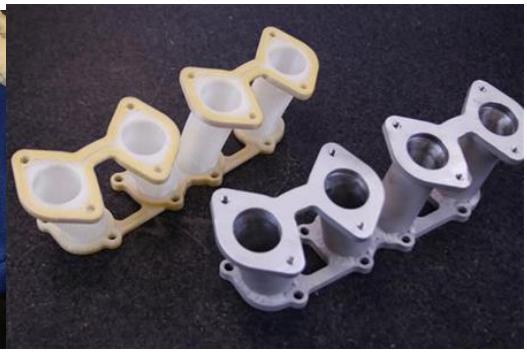


Fig. 29. Composite 3D printed parts for automotive

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Manufacturing industry:

- Vise jaws
- Claws for robotic arms
- Fixing devices, positioning



Fig. 30. Reinforced 3D printed, carbon fiber vise jaws and claws for robotic arms

In the industry the combination of shape freedom offered by 3D printing technologies and the good characteristics offered by fiber reinforcement, is the solution for many challenges that they are facing.

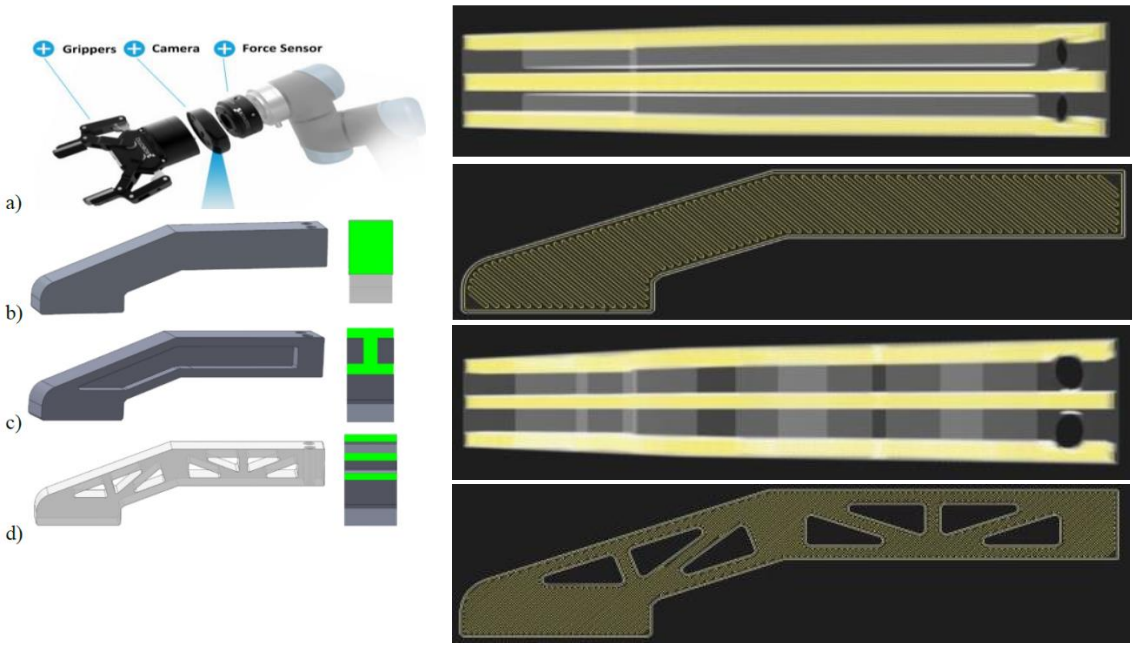


Fig. 31. Study case of a redesigned gripper claw for 3D printing with composite materials [MOL 21].

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2. WATER JET MACHINING

2.1. Introduction

Abrasive Water Jet (AWJ) is an innovative cutting tool, which uses an extremely high-pressure water jet for machining. This water jet can be used either by itself (Water Jet - WJ) or in connection with abrasive particles (Abrasive Water Jet - AWJ) [1], [2].

AWJ technology has demonstrated its capacity in machining of almost all kind of materials such as: food, paper, rubber, plastic, stone, ceramics, glass, composites, aluminium, steel, iron, titanium and much more [3]–[5]. It is capable to cut up to 150 mm of metals and up to 400 mm of other materials [4]. AWJ can process "difficult-to-cut" materials such as aerospace superalloys or even polycrystalline diamond [5].

A distinct advantage of the AWJ is that the materials can be processed without inducing thermal stress. By using water, the heat generated during the process is dissipated in the water and there are no heat-affected zones (HAZ) [3]. Low mechanical loading is another advantage of this technology.

AWJ is a high productivity process method, because of the reduced tooling and low complexity clamping system. Environmental friendliness is another characteristic of the process, it doesn't use lubricating or cooling and it generate little waste (abrasive material).

By using optimal process parameters, complex parts could be processed at a high dimensional accuracy and good surface quality. In a common AWJ cutting application the dimensional accuracy is ± 0.025 mm and the surface roughness can decrease up to Ra=0.4 μm.

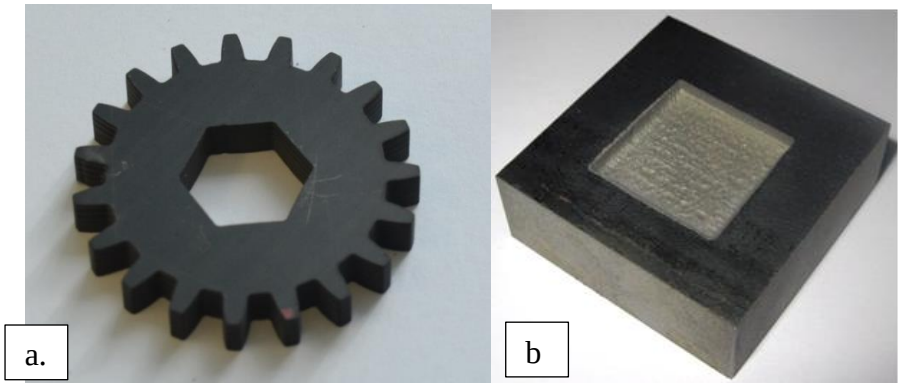


Fig. 32. AWJ parts examples: a. CFRP part cut with AWJ; b. Steel part process by AWJ cutting and milling.

AWJ technology is suitable for many processing applications. Figure 1.a shows an industrial part(gear) processed by AWJ cutting, from carbon fibre reinforced polymer (CFRP). Figure

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32.b presents a steel part processed by AWJ cutting (45x45 mm external contour) and milling (20x20x3 mm pocket).

2.2. Working principle for the AWJ technology

The AWJ process consists of a water jet (WJ) at high pressure mixed with abrasive particles, in order to process a variety of materials. Water is pumped at high pressure through a small orifice (d) to create a high speed WJ, that accelerates the abrasive particles at a high speed, generating kinetic energy. The WJ stream reaches the mixing chamber where abrasive particles are mixed in (M_a). The abrasive particles reach the mixing chamber through an inlet tube and are pulled in gravitationally and also by the suction generated by the WJ. The resulting AWJ is oriented towards the material through a focussing tube [2], [6], [7].

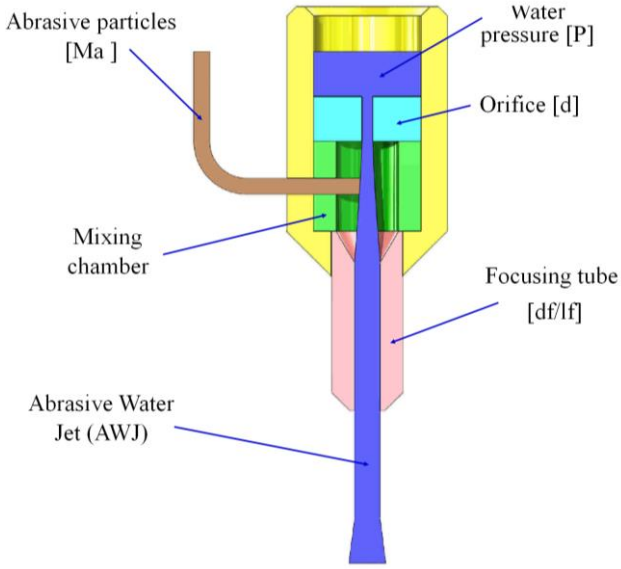


Fig. 33. Abrasive Water Jet (AWJ) process [7]

Figure 33. shows the cutting head working principle. The high-speed WJ stream is formed in a small oriffice. The WJ stream crosses the mixing chamber where abrasive particles are added. In the end, the abrasive water jet is created and focused in a carbide focussing tube, called nozzle.

Types of applications

AWJ is suitable for a variety of machining operations, like cutting, milling, drilling, turning, polishing, peening and surface cleaning [1], [2], [5]. The most common applications are

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AWJ cutting and AWJ milling. In figure 34.a is presented AWJ cutting working principle. This machining operation is using the WJ or AWJ in order to cut the entire thickness of the material. The jet is moved along the tool path with a traverse feed rate (V).

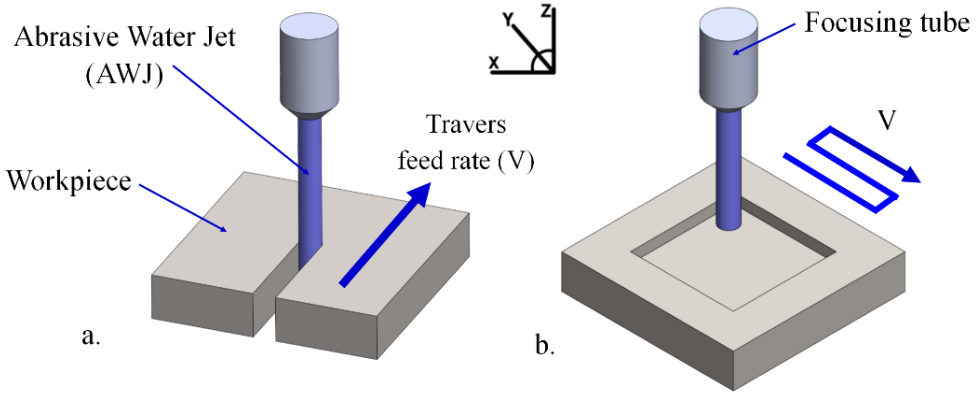


Fig. 34. The main AWJ processes: a. AWJ cutting and b. AWJ milling

The AWJ milling process consists of moving the jet, at such a speed, that the jet will not penetrate the entire thickness of the material (fig. 34.b). By moving the AWJ across the tool path, engravings, plane surfaces, slots, pockets and 3D shapes can be machined.

2.3. Types of equipment and manufactures

There are many machine tool manufacturers on the market that develop AWJ equipment for different applications. Analysing the size and precision of the manufactured parts, the following can be distinguished:

- AWJ equipment designed for high-precision machining of micro-parts. In some applications, micro parts (0.5-10 mm dimension) with +/- 10 µm tolerance could be manufactured [8]. In figure 35 is presented micro water jet C4. Similar equipment's are manufactured by: SMT (MicroCut Mj/V1), FINECUT (WMC 500II), Flow (NanoJet) or Omax (MICROMAX).

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Fig. 35. The AWJ equipment for micro machining micro water jet C4 [8]

- AWJ equipment designed for machining large parts. In some industrial applications, where large parts must be machined, heavy-duty AWJ equipment are used. In figure 36 is shown the AWJ equipment Flow Mach-700. This equipment has the working space up to 5 x 24 m and 0.03 mm positioning accuracy [9].

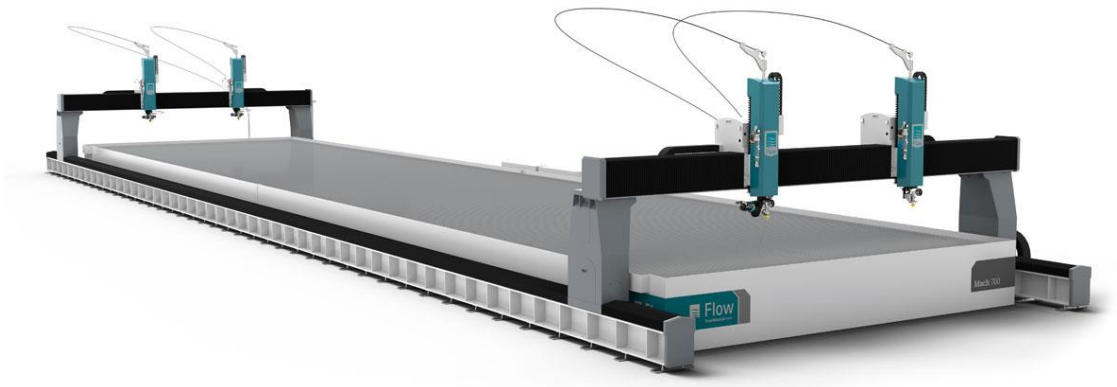


Fig. 36. The AWJ equipment for process large parts Flow Mach-700 [9]

- AWJ equipment designed for machining common parts. On this equipments are manufactured parts with dimensions between 3 and 3000 mm with ± 25 µm tolerance. In figure 37 is presented the OMAX 2626 JetMachining Center, an equipment designed for common applications. Similar equipment's are manufactured by: Flow (Mach 100-500 Series), TecnoCut (aquatec) or SMT.

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OMAX equipment and software

The OMAX 2626 JetMachining Center is a 3 axis CNC abrasive water jet equipment is designed for industrial application like: cutting, milling and turning. Parts with dimensions up to 660 x 660 x 200 mm can pe processed at a good accuracy (±0.025 mm).

The main component of this equipment is the EnduroMAX high-pressure pump with a work output pressure of 3.500 bar. The pump EnduroMAX 3060V is a direct-drive pump which uses an electric motor (22 kW) to generate up to 4,100 bar output pressure.

The cutting head used on Omax equipment is MAXJET 5i designed to obtain precision and durability (up to 500 hour). It contains diamond orifice (do=0.35 mm) and carbide focusing tube (Rotec 500 df =0.76 mm / lf =101 mm). For the exact supply of abrasive an electronic abrasive delivery system, controlled by the CNC, is used.



Fig. 37. The AWJ OMAX 2626 equipment

For controlling the AWJ equipment an OMAX CNC control system is involved in order to move the cutting head in 3 axis simultaneously. The system has ± 0.025 mm linear positional accuracy and max. 4,572 mm/min traverse feed rate [1]. The CAD/CAM software is integrated in CNC controller.

In case of the Omax equipment the CAD/CAM software is composed by two software: Omax Layout (CAD) and Omax Make (CAM). The CAD software Omax Layout has the

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following features: draw or load drawing, edit drawing and create the tool path. In figure 38.a the Omax Layout interface is presented.

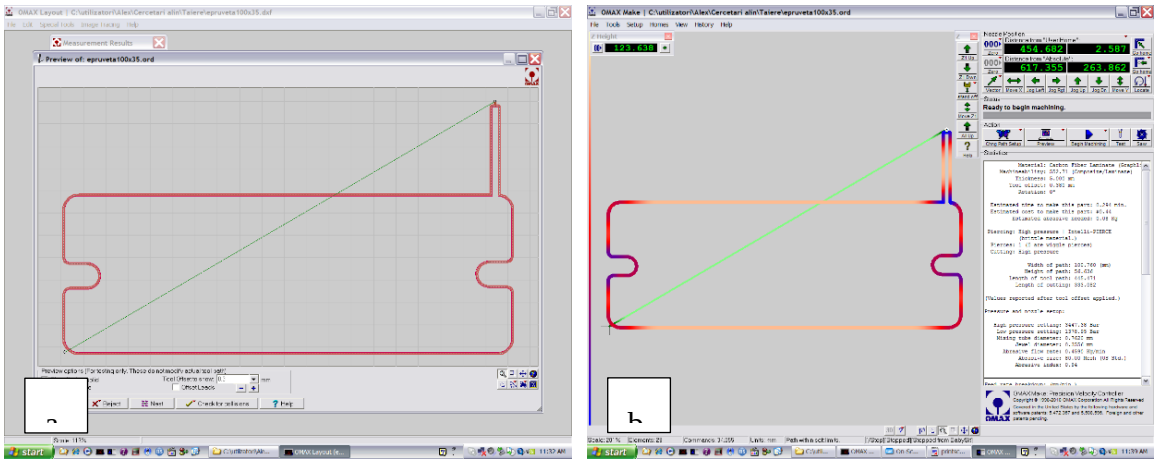


Fig. 38. CAD/CAM software used in AWJ process: a. Omax Layout CAD software b. Omax Make CAM software

The main features of the Omax Make CAM software are: controlling the AWJ equipment, process simulation and process parameters calculation. In figure 38.b is shown the Omax Make interface.

2.4. Technological parameters

The most important parameters of the AWJ cutting process are the following [1], [9]:

- Cutting: traverse feed rate V (1- 7000 mm/min), stand-off distance Sod (below 10 mm), impact angle φ.
- Hydraulic: orifice diameter d, water pressure P (500-6000 bar).
- Abrasive: abrasive mass flow Ma (0-0.8 kg/min), abrasive material (garnet sand, aluminium oxide, silica sand, carbide, steel grit), particle diameter (15-150 Mesh), mixing factors (focus diameter df, focus length, abrasive feeding direction).

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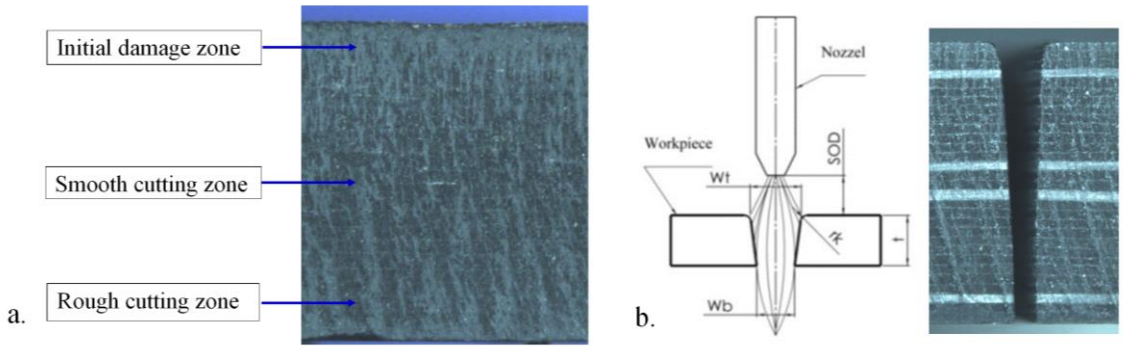


Fig. 39. The quality parameters: a. The surface cut, b. The kerf geometry

The quality parameters: surface characteristics (topography and roughness), cut material thickness (H), kerf geometry (kerf top width Wt, kerf bottom width Wb and kerf taper angle, edge radius rk), contour errors, cutting start and end errors (fig. 39.b).

The surface cut by AWJ is divided in three zones: initial damage zone, smooth cutting zone and rough cutting zone (fig. 39.a) [2].

To manufacturing precise parts with good surface quality, to use an optimal combination of the process parameters is required. One of the most accurate mathematical model used for calculating the traverse feed rate was proposed by Zeng J. in 1999 [11]:

$$V = \left(\frac{f_a \cdot M \cdot P^{1.594} \cdot d^{1.374} \cdot M_a^{0.343}}{163 \cdot Q \cdot H \cdot D_m^{0,618}} \right)^{1,15} \quad (1)$$

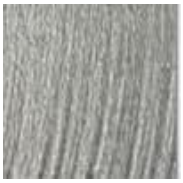
where: V - traverse feed rate (mm/min), M - material machinability, P - water pressure (bar), d - orifice diameter (mm), M_a - abrasive mass flow (Kg/min), Q - surface quality coefficient, H - material thickness (mm), f_a - abrasive material coefficient (1.0 garnet) and D_m - focus diameter (mm).

This mathematical model or cutting model is calculating the traverse feed rate V taking into account the flowing variables: process parameters, material thickness, cut surface quality coefficient Q and material machinability M [11]. In table 1 are shown the main characteristics of the surface quality coefficient Q.

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Table 1 Surface quality coefficient Q

Q=1	Q=2	Q=3	Q=4	Q=5
				
Very poor surface roughness	Poor surface roughness	Good surface roughness	Very good surface roughness	Excellent surface roughness

The material machinability M has values from 1 up to 1000, obtained experimentally (examples: Aluminium 6061 219.3, Stainless Steel 80.8, Titanium 6Al-4V 108.3).

2.5. Case study

The case study consists in manufacturing by AWJ cutting, a gear, with 70 mm diameter and 10 mm thickness out of aluminium. The case study was made by using the AWJ equipment, Omax 2626. The DXF file of the part was made by using SolidWorks software, based on the 3D model. The 2D contour was imported in Omax Layout software. The part origin was selected on the left top corner of the part, to be easy to setup the machine (figure 40.a). The lead In/Out of the AWJ from the contour is established automatically within the Omax Layout functions. In figure 40.a is shown the selected lead In/Out: length of lead In 3 mm and 1.5 mm for lead Out. The Omax Layout software offers the possibility to visualize the jet path and to simulate the cutting process.

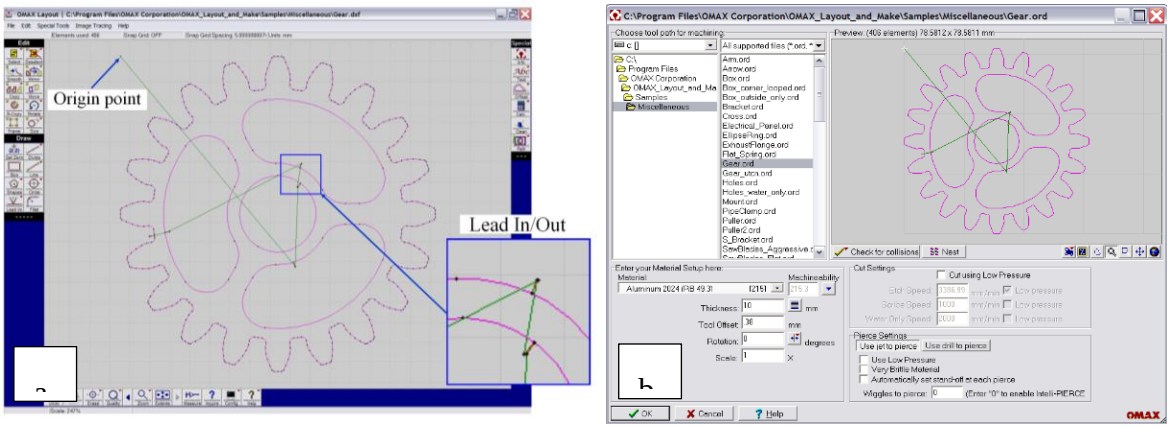


Fig. 40. CAD/CAM software used in AWJ process: a. Omax Layout drawing software b. Omax Make CAM software

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By using Omax Make software (figure 40.b) the material type was selected from the library (Aluminium 2024 with 215 Machinability) and material thickness (10 mm) was added, in order to calculate the cutting parameters (with equation 1). To process the part the following process parameters were used: water pressure: P= 3500 bar; feed rate V= 150 mm/min; abrasive flow rate: Ma=0.45 Kg/min, standoff distance: Sod= 1 mm abrasive size: 80 Mesh, nozzle diameter: 0.76 mm and orifice diameter (diamond): 0.35 mm.

The final simulation of the cutting process and equipment operation was made on Omax Make software, as shown on figure 41.a. In figure 41.b is shown the processed part by AWJ cutting. The surface roughness obtained is Ra= 3.3 μm and the maxim dimensional deviation from the nominal dimensions is +0.08 mm. In case of the kerf geometry an 0.73° taper angle and 0.2 mm top edge radius was measured.

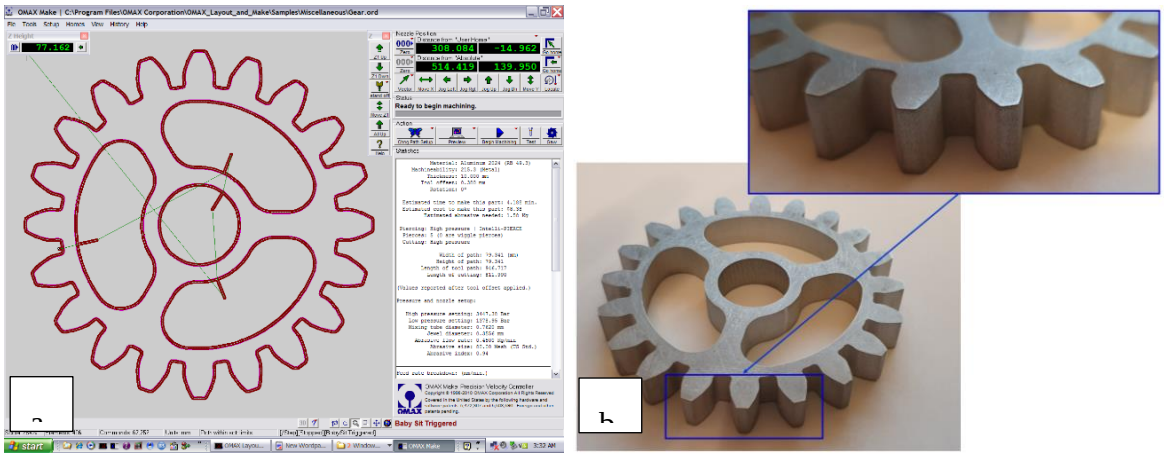


Fig. 41. CAD/CAM software used in AWJ process: a. Omax Layout drawing software b. Omax Make CAM software

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3. QUALITY ENGINEERING IN DIGITAL MANUFACTURING

3.1. Introduction

Digitalization of manufacturing is one of the integral parts of the fourth industrial revolution (Industry 4.0). Smart factories will link the physical world with the virtual world providing much more insight into the production process and its components. According to (Möller, 2016) managers/operators will be able to control manufacturing resources and steps in a context sensitive manner, which will allow them to "adopt the important role of quality assurance in the smart factory".

Quality management includes both quality assurance and quality control. The ISO 9000:2015 standard (ISO/TC 176/SC Technical Committee, n.d.) defines quality assurance

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as “the part of quality management focused on providing confidence that quality requirements will be fulfilled” and quality control as the “part of quality management focused on fulfilling quality requirements”. They are both an integral part of the Quality Management System. To control the quality of a product or service, one needs to perform inspections. According to the American Society for Quality (ASQ) “inspection is the process of measuring, examining, and testing to gauge one or more characteristics of a product or service and the comparison of these with specified requirements to determine conformity”(*Quality Assurance vs Quality Control: Definitions & Differences | ASQ*, n.d.).

The inspection process can be done with a variety of tools and equipment depending on the process, product or service being inspected. In the following chapter we will look at different equipment used in inspection and quality control, focusing on the ones specific to the manufacturing industry. We will also see some specific use-cases where this equipment is most appropriate.

After a broad view of inspection equipment used in manufacturing, we will narrow our focus on tactile and optical equipment and then specifically look at how to use optical scanners to evaluate the quality of parts.

Lastly, we will look at another application of 3D scanners, namely 3D object digitization for reverse engineering. Reverse engineering can be applied in many fields, but here we will look specifically look at the process of recreating a model or documentation from an existing part.

3.2. Inspection in quality control

Testing can be grouped into destructive and non-destructive methods. Destructive testing analyses the point at which a component, asset or material fails (Flyability, 2021a).On the other hand non-destructive inspection uses methods to collect data and evaluate a material system or component without permanently altering it (Flyability, 2021b, p.). Non-destructive methods include:

- Magnetic Particle Testing (MT)
- Liquid Penetrant Testing (PT)
- Radiographic Testing (RT)
- Ultrasonic Testing (UT)
- Electromagnetic Testing (ET)
- Visual Testing (VT)
- Acoustic Emission Testing (AE)
- Laser Testing Methods (LM)

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- Leak Testing (LT)
- Magnetic Flux Leakage (MFL)
- Neutron Radiographic Testing (NR)
- Thermal/Infrared Testing (IR)
- Vibration Analysis (VA)

Measuring equipment can be as simple as a caliper or a measuring tape or as complex as a CMM. Depending on the precision and time requirements of the measuring task, it is important to choose the measuring equipment appropriately. Over time the quality requirements of different industries have sent tolerances from millimeters to micrometers. The complexity of parts has also increased as injection moulded plastic parts have more complex geometries and nonconventional manufacturing technologies have become prevalent in leading industries such as automotive or aerospace. This creates the need for more complex and accurate measuring equipment such as tactile or optical Coordinate Measuring Machines (CMMs).

There is a very large variety of equipment used in manufacturing for quality control. We will not provide an exhaustive list in this chapter, but we will look at the main types of equipment used in manufacturing for quality control focusing mainly on CMMs. Coordinate measuring uses much more data points compared with classical measurement. As a result, a lot more information can be gathered from the inspected part.

The measuring of a part means comparing its ideal (nominal) characteristics that are specified in the part's documentation, with the real values of the part. To do this comparison, the real surface is analysed, and an associated surface is created of the same kind as the one being analysed usually through a point cloud (Figure 42).

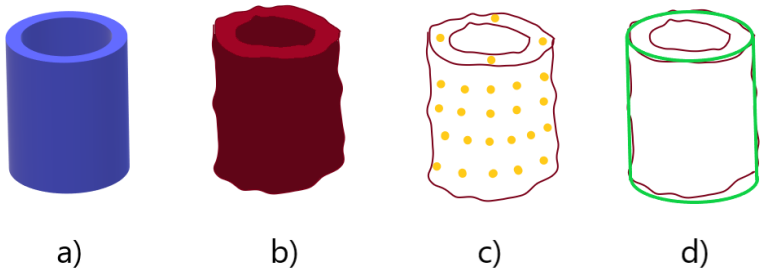


Fig. 42. The measurement process: a) the ideal (nominal) surface, b) the real surface, c) the point cloud d) the associated surface

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The digitization of the real surface, and the creation of the associated surface is usually done with a CMM. As they are the most widespread, we will be looking at tactile and optical measurement next.

3.3. Tactile measurement

Tactile CMMs use touch to get information from the real surface of a part. It touches the surface of the part using a touch-probe. It moves the probe along the X, Y and Z carriages of the machine to get to the part that is usually set on the machine's table (Figure 43). The movements in the work volume are controlled by a processing unit. As the probe touches the surface, the reaction force of the part is registered by a sensor and the encoders on the three axes register the position in space of the point of contact.

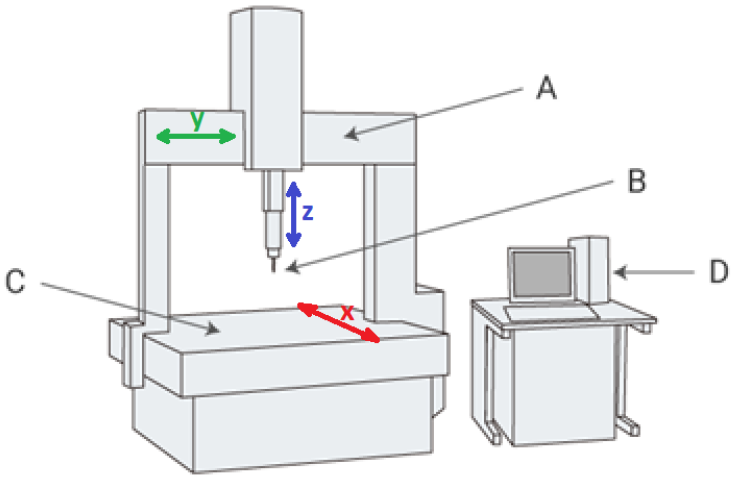


Fig. 43. Main components of a tactile CMM: A- mobile bridge, B – touch trigger probe, C – machine table (stage); D – CMM control and processing unit (Keyence, 2021)

There are different types of CMMs depending on their use case. The most common type of CMM is a bridge CMM that can either have a fixed or a mobile table. In the fixed bridge configuration, the X carriage moves the bridge where the Y carriage is mounted along with the ram that hold the Z carriage (Figure 42). The difference in the mobile table version is that the bridge is fixed, and the table moves along the X axis (Figure 43). This type of CMMs usually have the highest accuracy. It is used for most applications such as machined parts, molded parts, plastic parts etc. that fit in its measuring volume.

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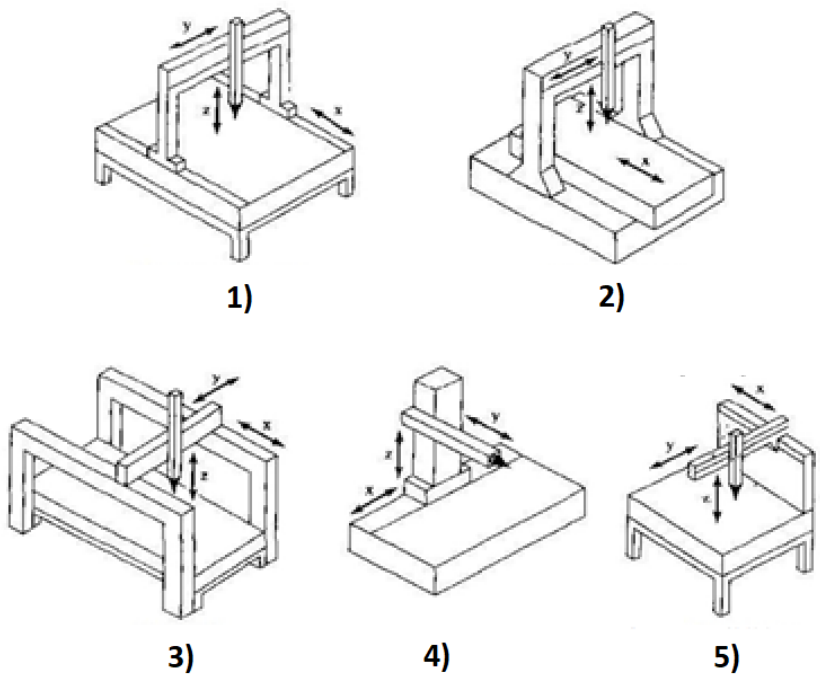


Fig. 44. Types of CMMs: Fixed table bridge CMM (1); Moving table bridge CMM (2); Gantry CMM (3); Horizontal arm CMM (4); Cantilever CMM (5). (Rosa, 2021)

Gantry CMMs are larger and are usually used for large or heavy parts (Figure 44). The larger size allows better access to the part. It is used for large parts such as casings, automotive or aerospace parts etc.

Horizontal arm CMMs offer the highest level of flexibility and access to the part (Figure 45.). It can be mounted on a plate or in combination with another horizontal arm CMM on runways. It allows the measurement of large parts and can reach difficult places.

Cantilever CMMs are used for measuring small parts with a high accuracy (Figure 46.). They allow access to the part from three sides and because of their size and robustness they are very fast.

To reach the surface of a part, a stylus system is used. A stylus system consists of an adapter plate that interfaces between the sensor and the stylus (Figure 45). Usually, an extension is used to allow a better reach and to increase the operator's visibility to the part. Different surfaces might be needed to be touched, so sometimes there's a need for more than one stylus. A cube allows the use of multiple styli.

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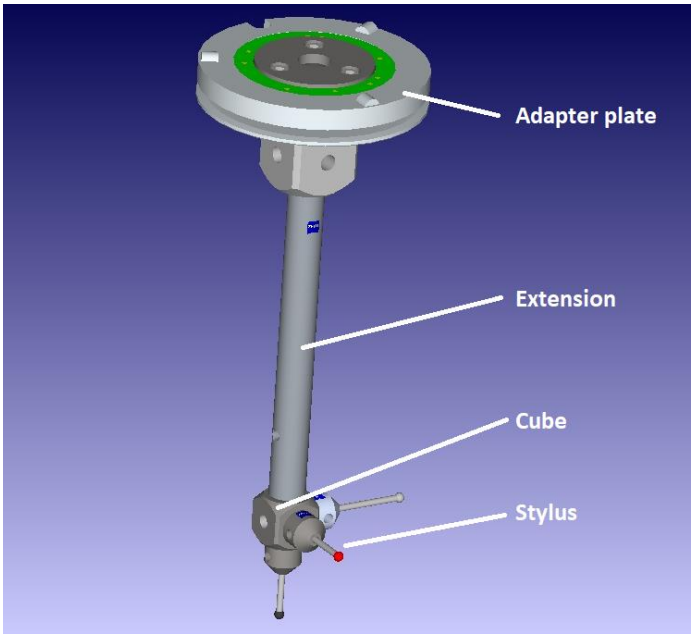


Fig. 45 A stylus system configuration example (Bocanet & Bulgaru, 2014)

To measure a part using a tactile CMM one needs to create a measuring program. An example of software used to program a CMM is Calypso, used on Zeiss equipment. Am example of the interface of Zeiss Calypso can be seen in Figure 46.

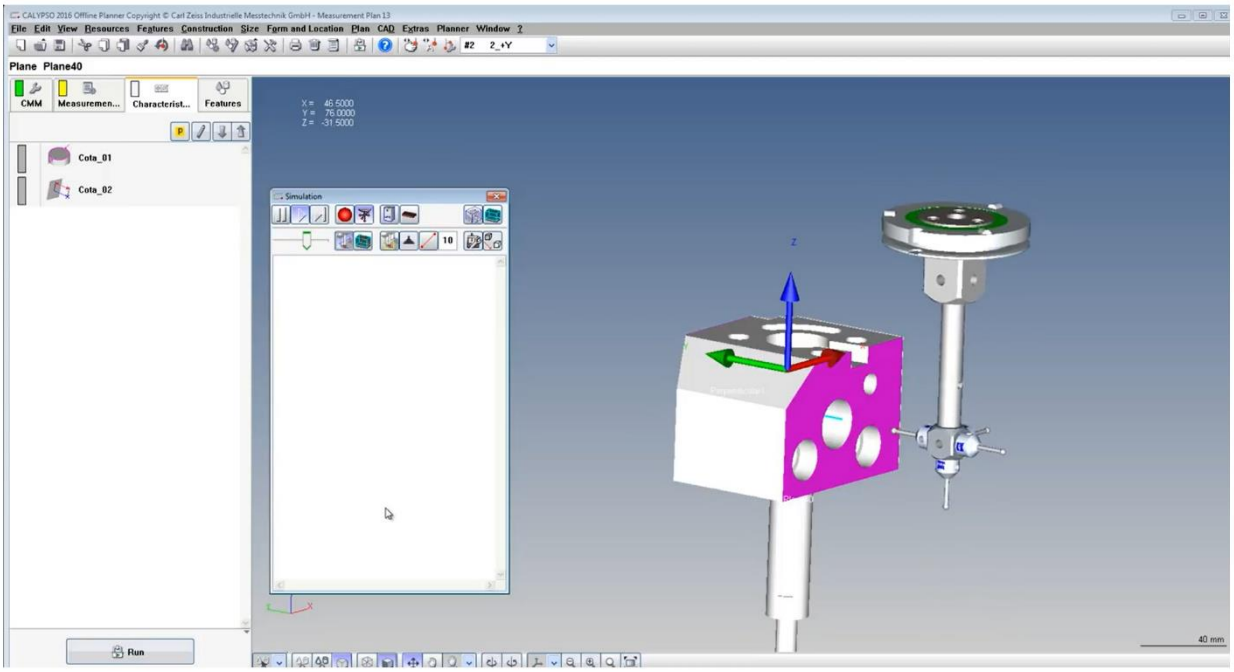


Fig. 46. The interface of the Zeiss Calypso software.

The steps needed to create a measuring program in Zeiss Calypso are:

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1. **Connect to the CMM**. After defining the type of machine, sensor panel type and other machine related parameters, we can connect to the machine.
2. **Create a new measurement program and stylus system**. After analyzing the part documentation and establishing the measurement tasks, a virtual stylus system can be created with the Stylus System Creator program. The components of the stylus system are assembled in a virtual environment where the user can see the resulting system. The physical stylus system needs to be identical to its digital twin.
3. **The stylus system is imported and qualified**. This process involves the use of a qualification sphere and a reference probe (also called a Master probe). The Master probe is a qualified stylus used only for qualifying other stylus systems. It is mounted on the machine, and the reference sphere on the machine table. The position of the reference sphere is determined using the Master probe. It is then released and the stylus system to be qualified is mounted. The stylus system touches the reference sphere with each stylus a predefined number of times until it is qualified.
4. **The CAD model of the part is imported, and its main features extracted**. The model is "decomposed" into elementary features (planes, cylinders, cones etc.).
5. **The alignment of the part is done** using the extracted features. The position of the part's coordinate system is determined.
6. **Clearance planes are set** around the CAD model to ensure there are no collisions with the part as the stylus system moves around it.
7. **Touch strategies are created** for all features that are of interest, starting with the ones used to define the coordinate system of the part. Strategies can be created using points, lines, circles, arcs, polyline paths etc. These determine where the stylus touches the part to digitize the feature being measured.
8. **Characteristics are determined** for the features being measured. The characteristics can be dimensional, form or position deviations. These will be presented in a report after the run of the program.
9. **The measurement program is simulated and run.** After all the strategies have been created, a simulation can be run to see if there are any collisions and if any improvements can be made to the strategy. When the operator is satisfied with the strategy, they can run the measurement program on the CMM.

Tactile CMMs have the advantage of high accuracy and are used in many measuring applications across industries.

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3.4. Optical measurement

As opposed to tactile CMMs, optical equipment doesn't physically interact with the part being measured. This has certain advantages especially when measuring flexible or soft parts. Other parts are too small to be able to be measured using a touch-probe.

Optical equipment include:

- Microscopes – used mostly for characterizing the material of a part or investigate phenomena at a microscopic scale.
- Profile projectors – are usually used for flat parts such as plates or parts made of sheet metal.
- Optical CMMs – are very versatile and are used for a wide variety of applications, from measuring electronic components to machined parts and plastic casings. They can use cameras or laser sensors to extract information or digitize surfaces.
- 3D scanning systems – can be used for digitizing parts for both measurement and reverse engineering.

In this section we will focus on 3D scanning systems with the example of the ATOS scanner manufactured by the company GOM. The ATOS scanner has two stereo cameras and one structured light projector (Figure 47). The projector uses blue structured light, to project a pattern of fringes onto the part. The deviations in the pattern as it is projected onto the part are captured by the two cameras. As the position and angle of the cameras is known, using triangulation, the position of the points in space are determined. Depending on the cameras that equip the scanner, there is a certain measurement volume. Only the surfaces inside the measurement volume are digitized.

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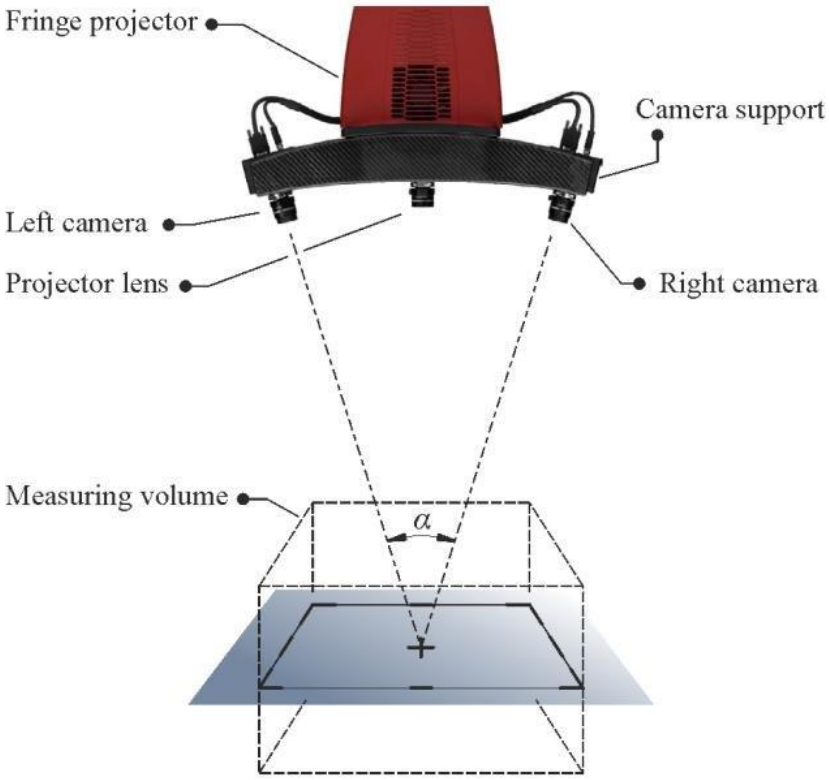


Fig. 47. The GOM ATOS 3D scanner with its measuring volume (Šafka et al., 2015)

The light conditions and the surface finish of the part have a great impact on the measurement result. Black, transparent, or shiny parts need to be covered using an antireflexive powder to be scanned. This powder is applied in a micrometric level on the surface and does not negatively impact the measurement results. The ambient lighting (such as fluorescent lights) is also important as it might interfere with the measurement. Newer models have a blue light projector that is less sensitive to ambient light.

Digitizing the whole surface of a part usually involves multiple scans, because only the surfaces visible to both cameras at the same will be acquired. The scans need to be aligned relative to each other and this can only be achieved by using markers (Figure 47). These markers are standardized with very precise dimensions and are recognized by the scanning software.

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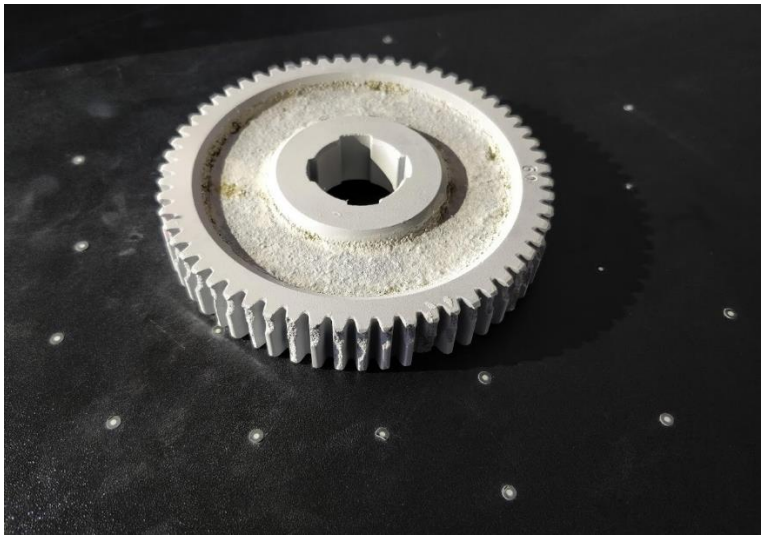


Fig. 47. Exampled of a part covered with antireflexive powder and surrounded by uncoded markers

Once a scan is performed, the markers that are visible to the cameras are given a code (Figure 48). At least three of these coded markers need to be visible in the next scan for the software to be able to align the scans.

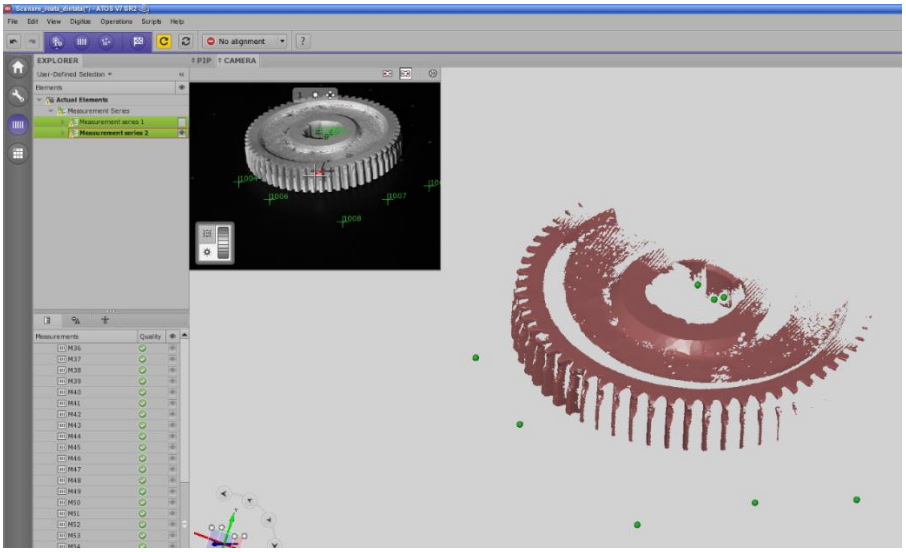


Fig. 48. The scan of the part: top left the camera view is visible with the coded markers in green; in the main window the point cloud is visible (in red) and the identified markers (green).

Once the part is completely scanned, the point cloud goes in the next stage, polygonization. The points of the point cloud are connected with tiny triangular surfaces, that approximate the scanned surface. This approximate surface is called a mesh. The mesh is saved in a STL format and can be used for measurements.

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The measuring process using GOM Inspect

The comparison between the nominal surface and the scanned surface is done in a software package called GOM Inspect (*GOM Inspect Pro*, 2021). This software package facilitates the inspection of parts and creation of measurement report. Let's look at the steps of a typical measurement task.

The first step is importing the CAD and the Mesh. It is done by dragging and dropping the files onto the program interface. The two objects are visible in the CAD window and in the list of the Explorer window to the left (Figure 49).

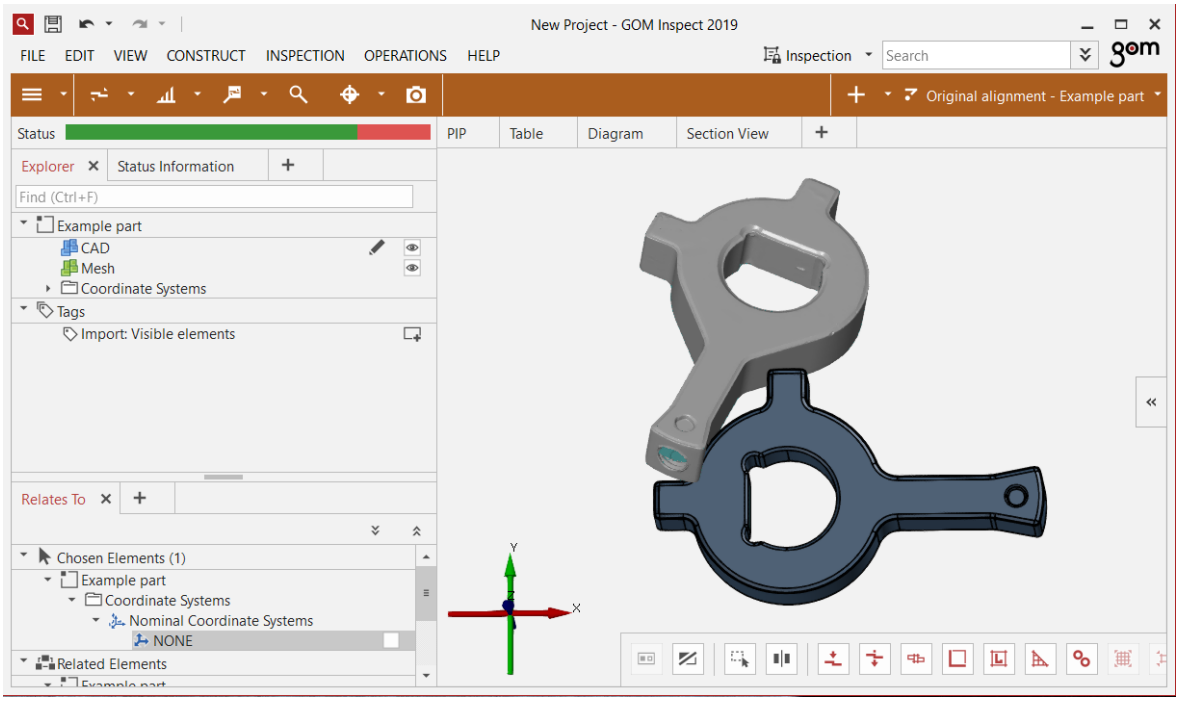


Fig. 49. Importing the CAD and Mesh.

As can be seen in Figure 49, the two objects are not aligned. The next step is to pre-align them. This is done by clicking on the plus sign  to the top right of the program, on the colored command bar (Figure 50) and choosing *Prealignment*. In the Prealignment window we observe the average deviation between the CAD and the Mesh and click *OK*.

We can evaluate the overall state of the part by comparing the two surfaces and observing the deviations.

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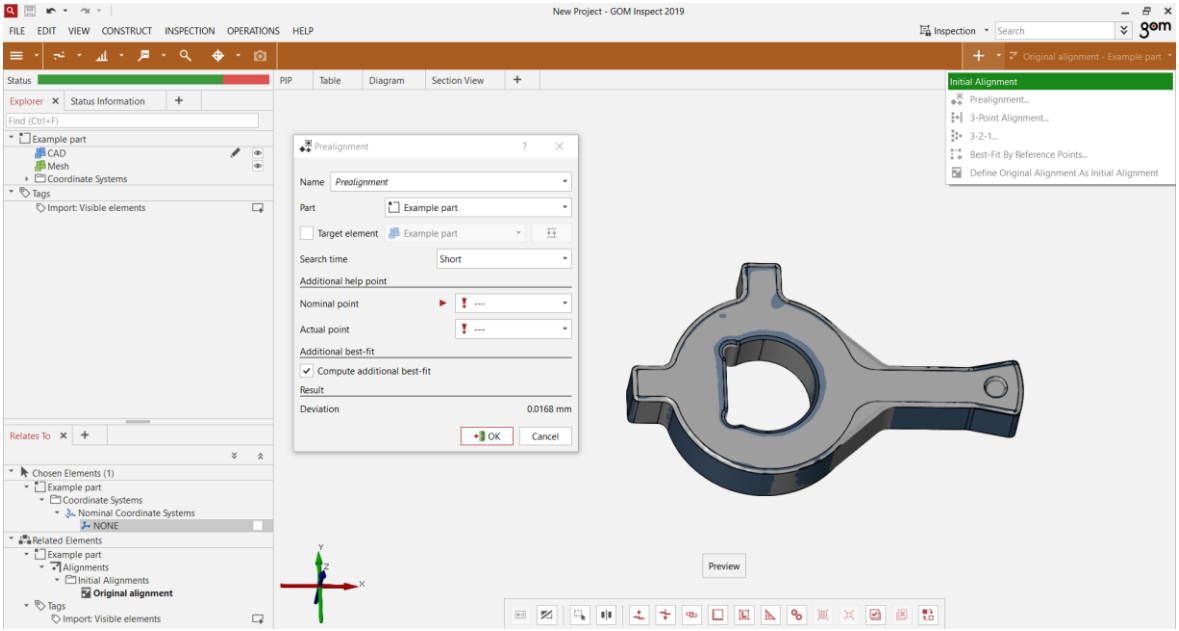


Fig. 50. Prealignment of the Mesh to the CAD.

For this, we click on the second icon on the command bar  and click on *Surface comparison on CAD*. In the window that opens, we define *Max distance* with 3 mm and click *OK*. This creates another object in the Explorer window under *Inspection* and *Surface comparison*.

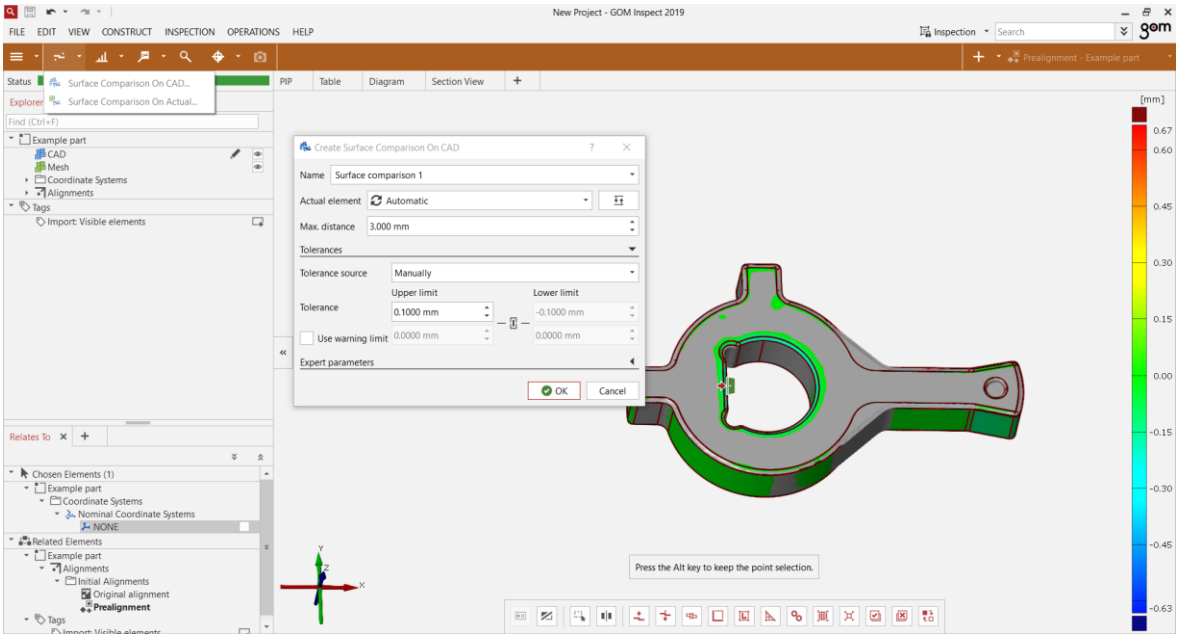


Fig. 51. Comparison between the CAD and the Mesh.

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We can see the surface comparison more clearly if we remove the other objects (CAD and Mesh) from view. To do this, we simply click on the  icons next to each in the Explorer window. Next, we have to adjust the scale of the deviations by choosing the ends of the color scale. Simply click on the top value of the scale and write another value (e.g. 0.30 mm). To ensure the tolerance field is symmetrical, click the button next to the editing field where you wrote the tolerance value (Figure 52).

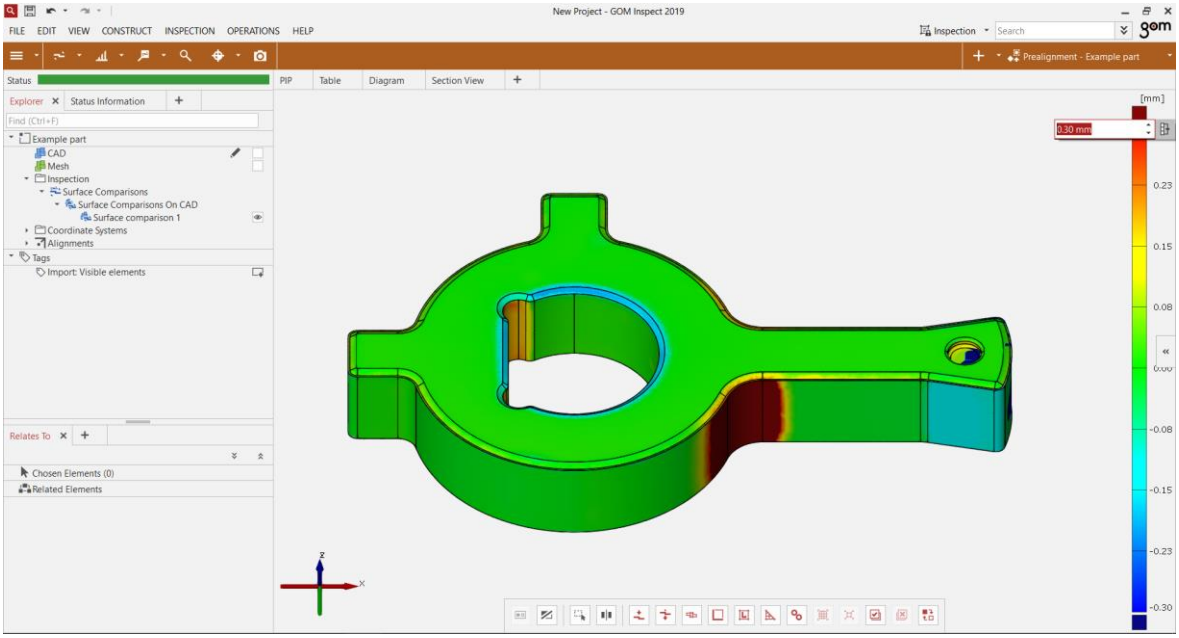


Fig. 52. Defining the tolerance field for the surface comparison between the CAD and the Mesh

The surface comparison can give us important insight into the problem areas of the part and even help us improve the manufacturing process of the part. Nevertheless, it would be helpful to get the numeric values of the deviations in points of interest. We can use Pointwise inspection to set deviation labels on the surface in regions of interest. Under *Pointwise inspection*  click on Deviation labels. While holding down the *CTRL* key, click on the regions of interest to add the label. When you are finished, you can hit the *Escape* key or simply *right click* (Figure 53).

Although we have prealigned the Mesh to the CAD, it is not properly aligned. The alignment of the part is done in accordance with the documentation of the part. The technical drawing should contain information about how to align the part, what are the datum systems used or define a coordinate system.

Although there are multiple ways to align a part, the most basic us using points. This is called a Reference Point System (RPS). To align a part with RPS, we need to construct 6 points on the part. In accordance with the 3-2-1 rule of alignment, we will place 3 points on the first

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datum (usually the largest surface), 2 on the second and 1 on the third. This way we completely define the position of the part in space by removing its six degrees of freedom.

Because we will place the points on the surface without any strict rule, we will construct surface points. The geometrical elements that we will construct, will always be placed on the CAD. We can make the CAD exclusively visible by selecting it in the *Explorer* window and taping the *E* key on the keyboard.

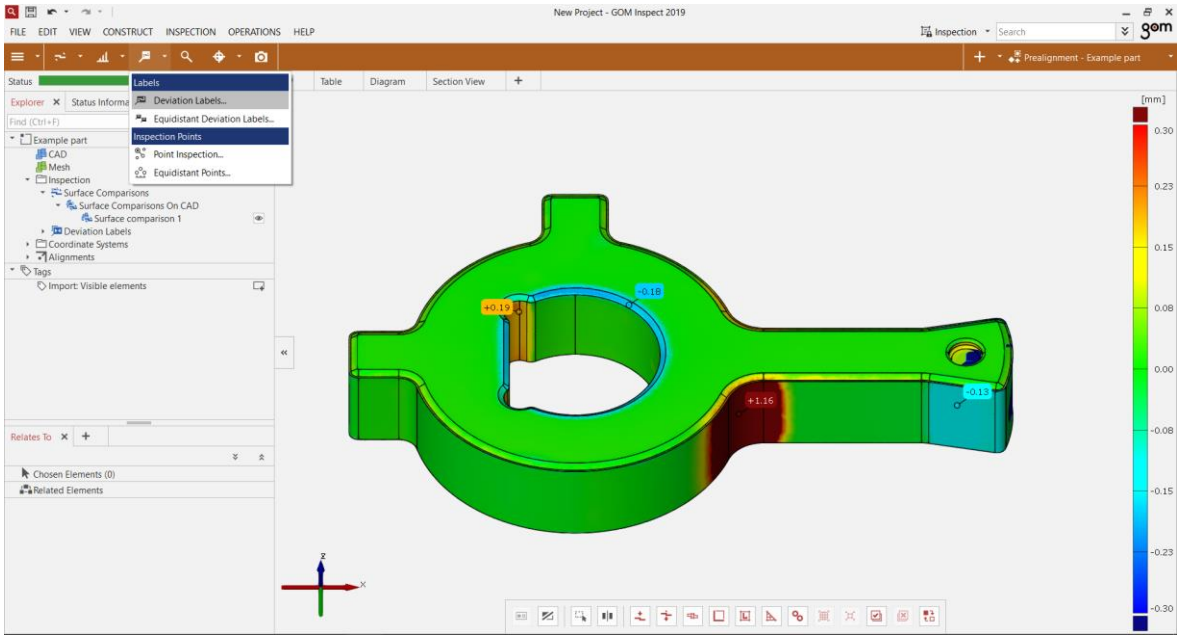


Fig. 53. Adding deviation labels to the surface comparison

To construct the surface points, we go to the *Construct* menu, select *Point* and *Surface point*. Holding down the *CTRL* key, we click on the top surface where we want the first point to be. After releasing the *CTRL* key we can click on the checkmark icon next to it. Repeat this process until you have placed the six points.

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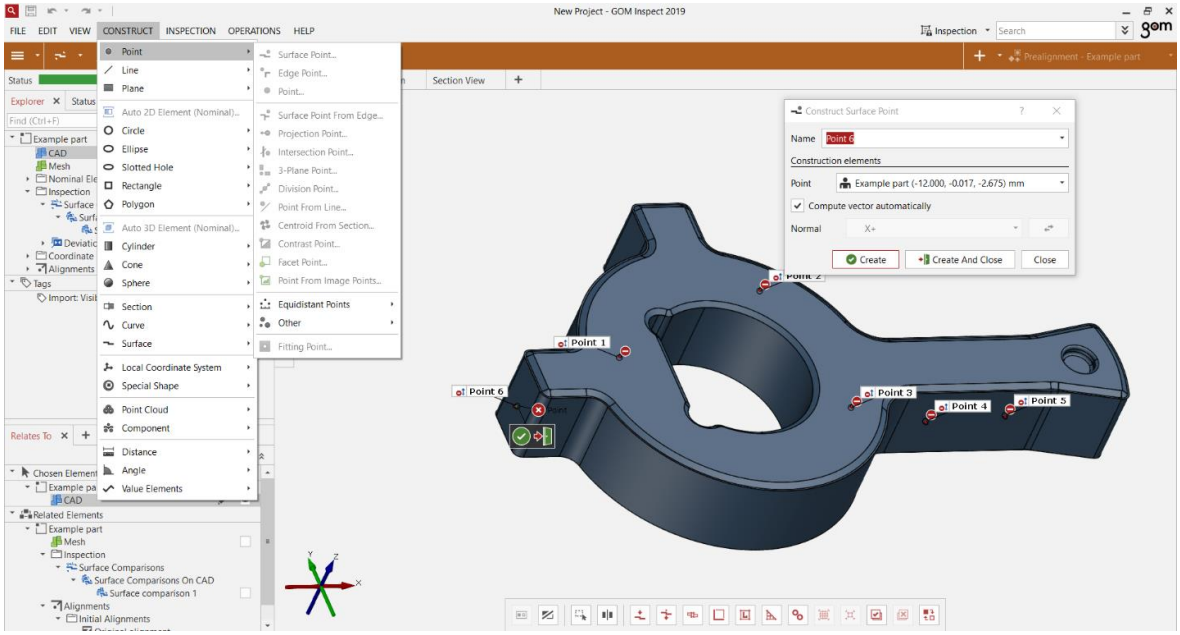


Fig. 54. Creating surface points

After we have created the points on the CAD, we need to find their equivalent on the Mesh. This is done by defining a measuring principle. To do this, we must make the I-Inspect palette visible. Click on the  icon in the command bar to make it visible and click on the  icon to define a measuring principle. For the surface points we will use the *Intersection with mesh* measuring principle. Be sure to have all the points selected to do this for all points. Notice that after defining the measuring principle, the red interdiction sign next to each point disappears.

We can now use the points to define the RPS alignment. Select the six points, go to the  sign to the top right and select *RPS*. In the window that opens we have an empty list. To add the points to the list we click on the  icon. We notice that the first three points define the direction Z, the next two, Y and the third one X. The deviation needs to be 0 for the two elements to be aligned (Figure 55). Once we click OK, the CAD and the Mesh are aligned using the defined points.

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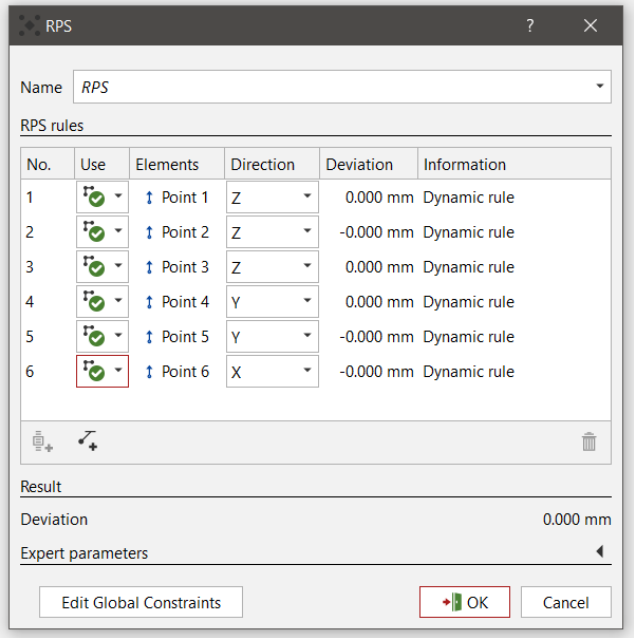


Fig. 55. The RPS alignment

If you drag and drop the surface comparison that we previously created from the Explorer window to the main CAD window, we will see that the deviation map is slightly different. You can compare the RPS alignment and the Prealignment by switching between them from the top right corner.

We can inspect the part further by creating sections through it. Although this is a simple part, we can create a section parallel with the Z plane. To do this, click on the  and select *Inspection section on CAD*. In the window that opens, we define the reference plane (Z) and the position of the plane (Figure 56). As the coordinate system is on the top face, the position will be negative. As the part is 5 mm thick, a section at -3 mm should be ok. Click on *Create* to create the section.

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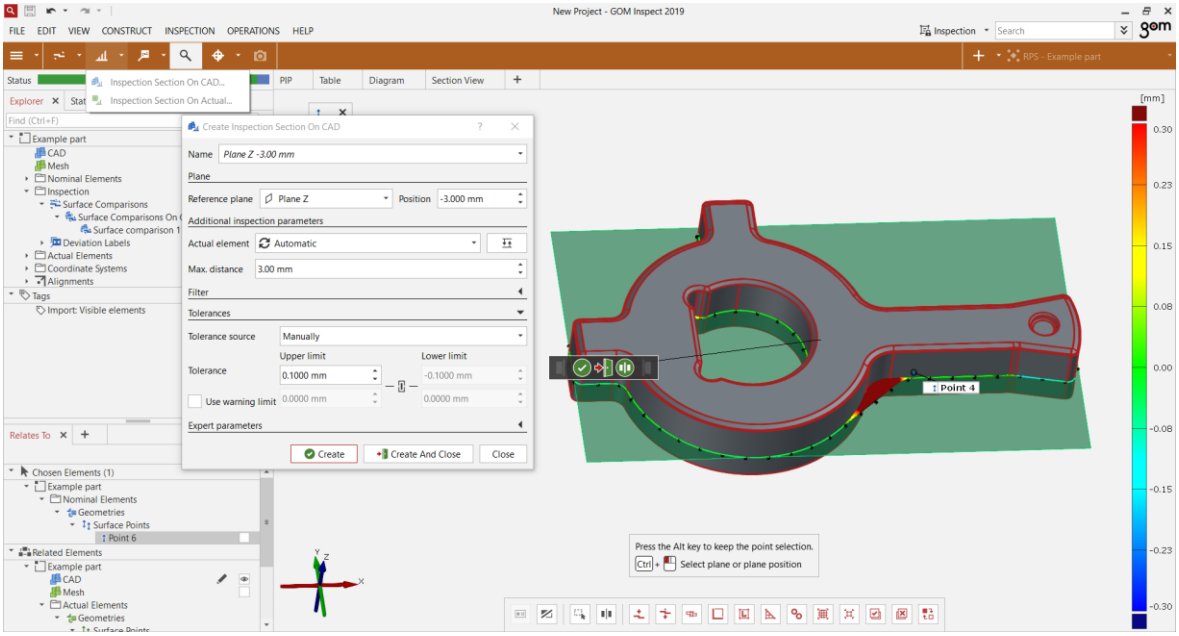


Fig. 56. Creating an inspection section

We can make the section exclusively visible from the Explorer window, under *Inspection> Curves>Inspection section on CAD*. As with the surface comparison, we can add deviation labels to check the deviations in areas of interest (Figure 57). As can be seen from the section, we have areas with very high deviations. These might be due to a design error or by using a different version of the CAD model.

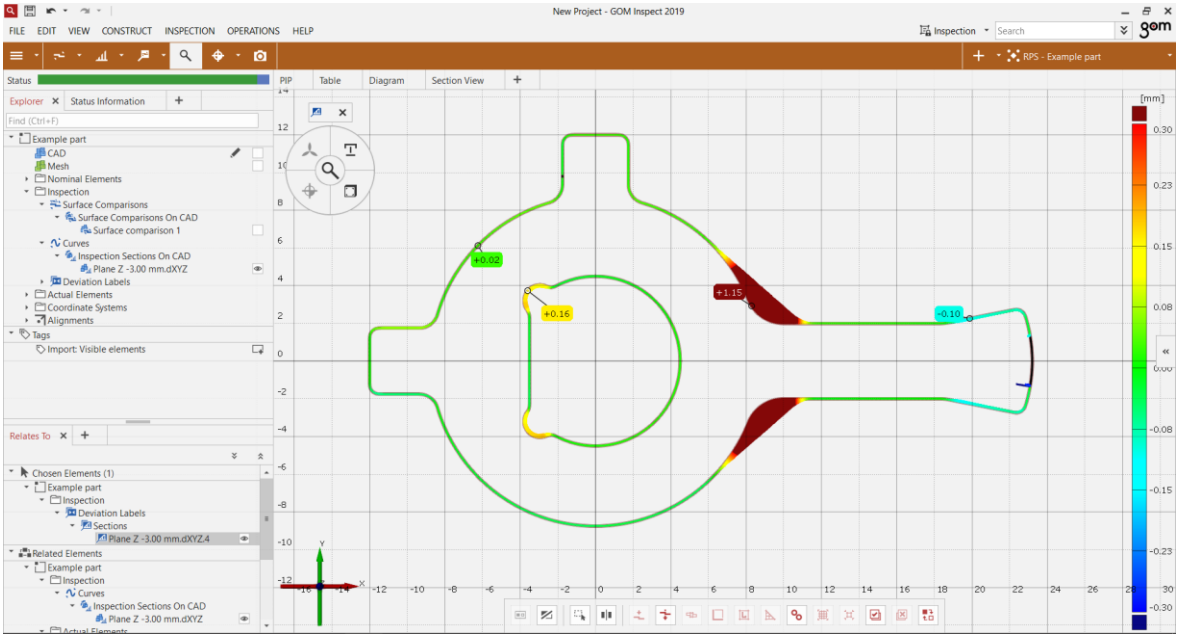


Fig. 57. Inspection section with deviation labels

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After generally evaluating the part, we can further inspect its features. For example, we can determine the dimensional, form and position deviation of the central hole. We first need to create the associated cylinder for our hole. We go to *Construct>Cylinder>Fitting cylinder*. Holding down the CTRL key we click on the cylindrical surface. Click *Create and close* to create the feature (Figure 58). We have defined the cylinder on the CAD but we still need to compare it with its counterpart on the Mesh. To do this, we define a measuring principle. Click on the  and then *Fitting element* as the element was created using a fitting method. You can find the associated feature in the Explorer window under *Actual elements> Fitting elements*.

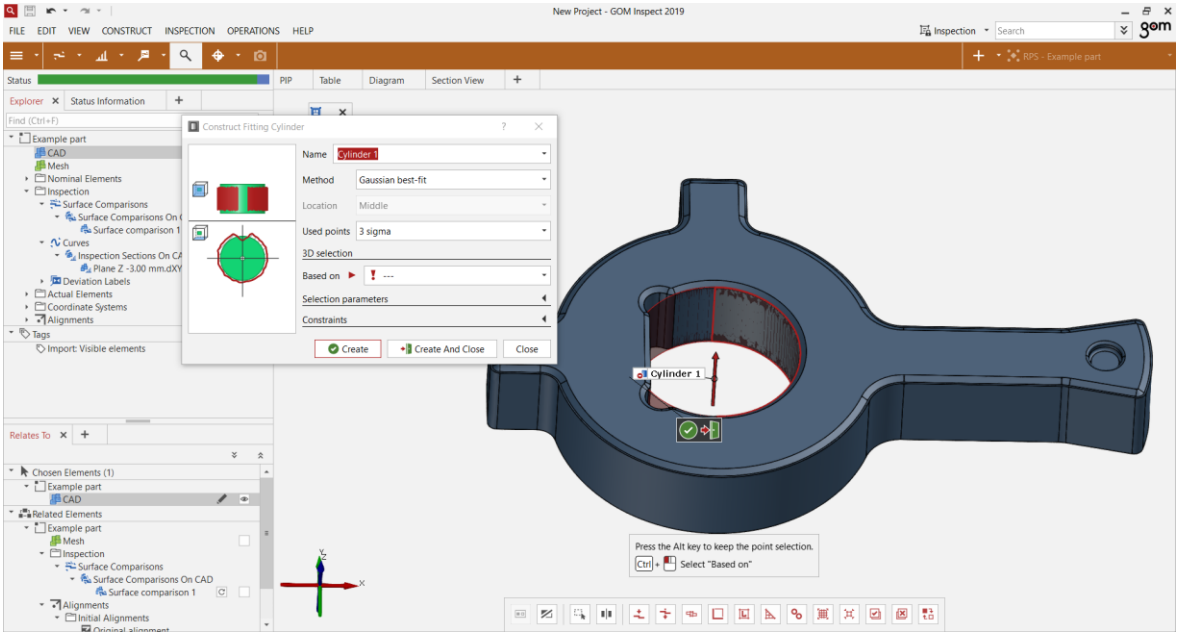


Fig. 58. Creating a fitting cylinder

To check the diameter, click on the  icon on the I-Inspect palette and select *Diameter*. You can rename the measurement as needed and establish the tolerances. By default, the tolerances are set to *No tolerances* but you can also define them manually or by using a tolerance table. The manual tolerances can be set either symmetrical or asymmetrical by checking or unchecking the box with the symbol .

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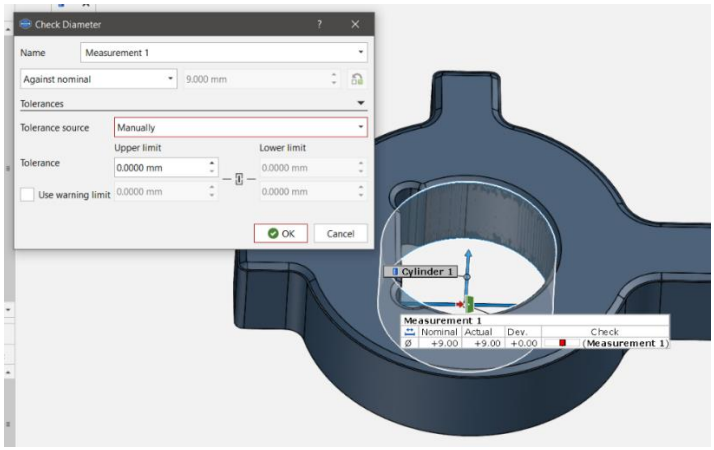


Fig. 59. Creating a fitting cylinder

To check the form or position deviations of this cylinder you can click on the  button on the I-Inspect palette. From the menu we can check the cylindricity for example and define the tolerance level.

For the position deviation we first need to define the datum system. For example, we define a datum system A|B using two planar sides of the part. First, we need to construct the two planes similar to how we constructed the cylinder. Go to *Construction* > *Plane* > *Fitting plane*, hold down *CTRL* and click on one plane, click *Create.* Repeat for the second plane. We again use *Fitting element* as the measuring principle.

To define the Datum system from the two planes, go to *Construct* > *Local Coordinate System* > *Create Datum System*. Select the two planes for Datum 1 and Datum 2 respectively (Figure 60). The order of the planes should be the order of the datums. Rename the feature and click *Create and close.* You will see your datum system appear on the screen.

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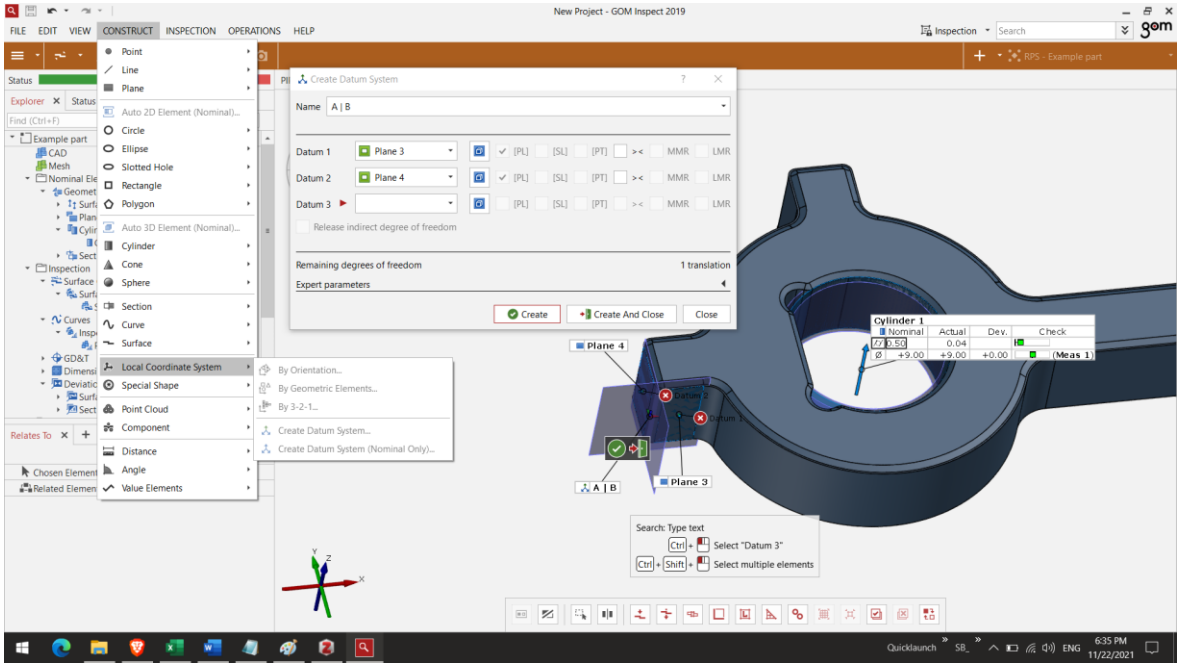


Fig. 60. Creating a datum system

In this section we looked at optical scanning of a part using a GOM ATOS 3D scanner. After looking at the steps necessary for acquiring the point cloud information from the part, we went over the steps to align and inspect the part. The main goal of this section was to give a broad overview of the workflow for such an operation. Digitizing and measuring a part can be a very complex process.

3.5. Reverse engineering a part using an optical scanner

Building on the knowledge gathered from the previous section, we will look at another application of optical scanning, namely reverse engineering. Let's assume that for the part we previously used as an example, we don't have a CAD or any type of documentation. Now, the goal is to get the necessary information to create the documentation for the part. Of course, we will not be able to create the documentation as accurately as its original, but we can get enough as to make a functional part.

The first thing you will notice after importing the part is that we don't have a CAD to prealign it to. As a result, the part and the coordinate system are misaligned. To overcome this, we can choose from a few alignment methods, but we will focus on one similar to RPS, namely 3-2-1 alignment. To use this alignment method, go to add an alignment ( ) and click on *3-2-1*. In the window that opens up we are prompted to select the points that define the three directions: 3 points for Z, 2 points for Y and 1 point for X. While holding down the

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CTRL key we click on the top surface (3x), the front surface (2x) and the side surface (1x) as shown in Figure 61. Notice the direction of the coordinate system in the bottom left corner. You can change the direction of the axis by checking or unchecking the *Plane/line positive* option. When you are satisfied with the alignment, click *OK*. Now the part is orthogonally aligned.

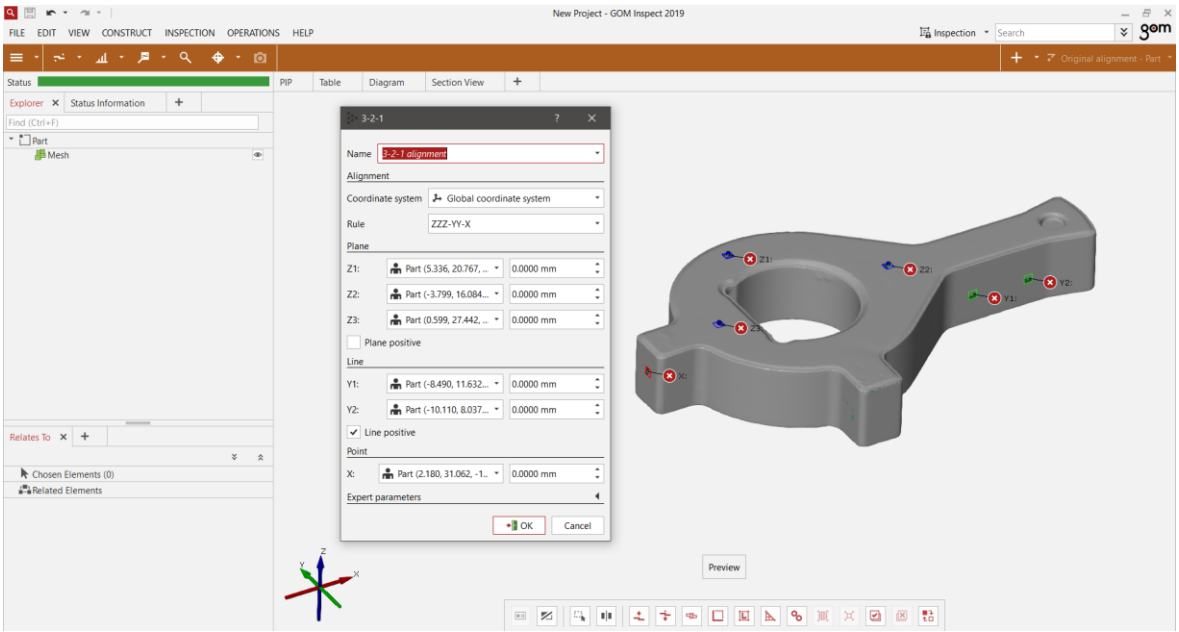


Fig. 61. Aligning the mesh using the 3-2-1 method

We can now construct different features like planes and cylinders and measure them like done in the previous section. The difference is that we will not be evaluating the deviations but observing the measured value and inferring the nominal value from it. Some expertise and functional know-how about the part's role in the assembly might be required for the reverse engineering process to be successful.

Another useful tool is being able to measure distances. To do this, we first construct a virtual caliper by going to *Construct* > *Distance* > *Outer disc caliper*. To get the distance between the two planes shown in Figure 62 for example, hold down the *CTRL* key and click on both sides. This creates the touch points of the caliper discs. By changing the radius of the disc, you can fit the size of the caliper to the surface being measured. As the part is aligned with the coordinate axes, we can measure along the Y direction. To finish the operation, right click on the mesh and use *Select all points of element* to select it. You can now click *Create and close*. Once the distance has been created, it can be evaluated using the *Check* section ( ) as any other feature.

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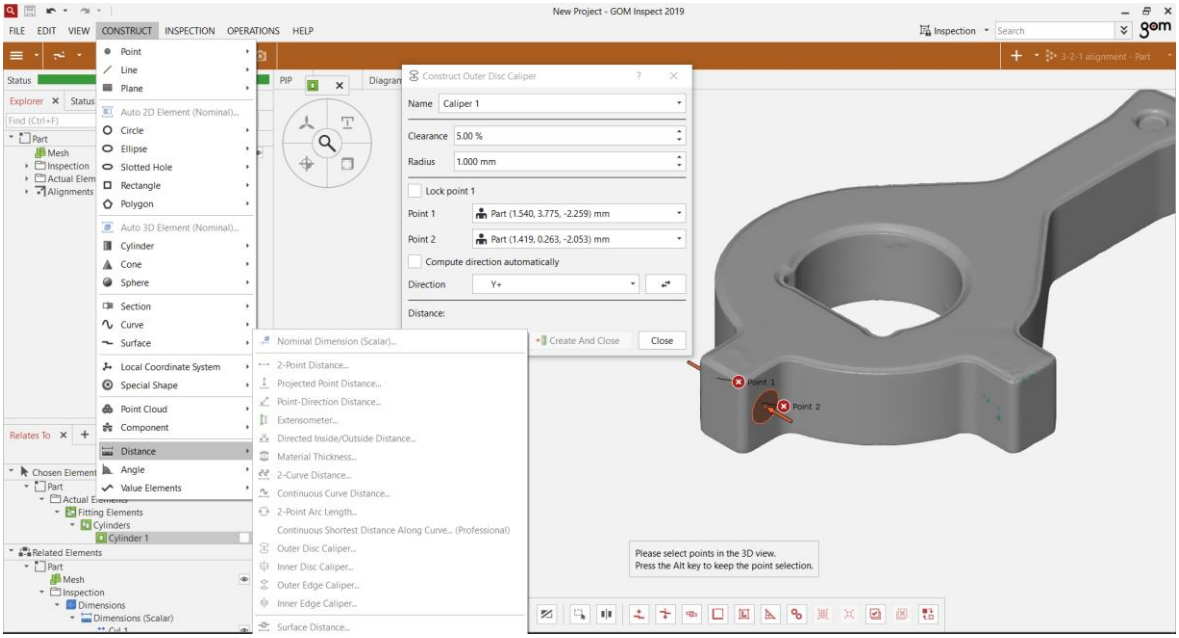


Fig. 62. Measuring a distance with an outer disc caliper

By reconstructing the different elements of the part through the scanned mesh and by determining their position relative to each other, we can recreate the whole part. Using these measurements, we can infer the drawing of the part and we can model it. Afterwards, we can import the created CAD and compare it with the original mesh to see if we haven't made any mistakes.

As digitization is an integral part of the digital manufacturing process and as quality requirements are more and more demanding, it is important to acknowledge the importance of measuring equipment. Both tactile and optical equipment can be used to increase the quality of products and processes and help design and manufacture products faster.

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VIRTUAL REALITY

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Virtual Reality

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UNIT NUMBER: Didactic Unit 1

Introduction to Virtual Reality

UNIT PRESENTATION

In this unit, you will find the introduction of Virtual Reality which is a technology that we previously only saw in science fiction movies but in 1957 it became a reality (Mihelj, Novak, & Begus, 2014).

OBJECTIVES

Get familiar with the concept of Virtual Reality, its background and applications.

CONTENTS DEVELOPMENT

When we talk about Virtual Reality (VR), one of the first things that comes to our minds are science fiction movies like Tron or Matrix. However, nowadays, this technology has been integrated into our daily lives in sectors such as video games, medicine, education, architecture, industry, culture, and military (Iberdrola, n.d.).

According to Bardi (2019), VR is the use of computer technology to create a simulated environment that allows users to immerse and interact with a virtual 3D world. In order to create a more realistic experience, this technology uses the senses of sight, hearing, touch and even smell.
With VR, it is possible to immerse ourselves not only in video games, or take guided tours of museums, but also to learn how to perform a heart surgery or dissect a muscle. VR allows us to cross frontiers that we consider unimaginable (Iberdrola, n.d.).

Even though it seems to be highly futuristic, the origin of VR is not as close as we think (Iberdrola, n.d.). The invention dates back to 1957, when Morton Heilig, considered the father of Virtual Reality, developed one of the first VR systems called Sensorama, in which the user experienced a virtual bike ride. When the user sat in the machine with a three-dimensional display of the city, he/she could hear the sounds, feel the wind and even smell some aromas (Mihelj et al., 2014).

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REMEMBER TIPS

According to (Bardi, 2019), VR is "the use of computer technology to create a simulated environment in which users are immersed and interact with virtual 3D worlds".
This technology can be applied in different sectors such as video games, medicine, education, architecture, industry, culture and military (Iberdrola, n.d.).
VR invention dates back to 1957 with a VR system called Sensorama (Mihelj et al., 2014).

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GLOSSARY

Immersion

Feeling that the user is part of a virtual environment. It can be achieved when the visualization, sound, atmosphere, etc., create in the user the sensation of being in the virtual world (Xymatic, 2021).

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UNIT NUMBER: Didactic Unit 2

Definition of Virtual Reality

UNIT PRESENTATION

When we talk about Virtual Reality (VR), one of the first things that comes to mind are science fiction movies like Tron or Matrix.
The concept of VR has changed over the years as more technologies have been integrated (Muhanna, 2015). In this unit, we will look at some definitions of VR and the concepts behind it.

OBJECTIVES

Get familiar with the definition of VR and the four key elements of a VR experience.

CONTENTS

2.1. Four key elements of Virtual Reality 9

CONTENTS DEVELOPMENT

Virtual Reality is…

"any experience in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint" (Brooks, 1999, p. 16)

"computer generated simulations of three-dimensional objects or environments with seemingly real, direct, or physical user interaction" (Dionisio, Burns III, & Gilbert, 2013, p. 34)

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2.1. Four key elements of Virtual Reality

From the previous definitions, it is possible to conclude that Virtual Reality is a combination of several elements, such as computers, worlds and environments, interactivity, immersion and the participants of VR experience (Muhanna, 2015).
According to Muhanna (2015), we can identify four basic elements of Virtual Reality:

Virtual environment: Artificial 3D world created by VR experts using computer rendering and simulation techniques. In the virtual world, the users are able to interact among themselves and with artificial objects. The objects and characters are displayed in various ways (visual, auditory and haptic), that are experienced by the user through vision, hearing and touch (Mihelj, Novak, & Begus, 2014) (Strohanova, 2019).

Immersion: The feeling of being physically present in a virtual environment. The more realistic the environment, the more natural sensations the user will experience (Strohanova, 2019).

Physical immersion: The physical way in which a user reacts to the virtual environment. It can be through movements, actions, visible emotions and interactions (Strohanova, 2019).

Mental immersion: It is the depth of the user's mental engagement in reaction to what they see (Strohanova, 2019). Users are so busy dealing with events in the virtual environment that they no longer doubt what they are experiencing (Mihelj et al., 2014).

Feedback: The user's ability to see the results (outputs) of his activities (inputs). For example, if the user looks to the left, the screen should adapt accordingly, in a realistic period of time and without delays (Muhanna, 2015).

Interactivity: The user has the ability to interact with the virtual environment and modify it. With the use of sensors and other devices, users can dynamically interact with virtual objects through different interaction styles such as navigation or direct manipulation (Muhanna, 2015).

REMEMBER TIPS

Virtual Reality is “any experience in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint” (Brooks, 1999, p. 16).
Four key elements of VR: Virtual environment, immersion, feedback and interactivity (Muhanna, 2015).

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UNIT NUMBER: Didactic Unit 3

Working of Virtual Reality

UNIT PRESENTATION

As described above, with VR technology it is possible to immerse yourself in a wide variety of activities, starting from video games, guided tours of museums, or even learn how to perform a heart operation or dissect a muscle (Iberdrola, n.d.).
However, have you ever wondered how it is possible to create such an experience? In this unit you will find out.

OBJECTIVES

Learn the three elements that differentiate VR from other digital media and become familiar with two VR visualization systems: CAVE and HMD.

CONTENTS

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CONTENTS DEVELOPMENT

According to Bassas (2018), the whole concept behind VR is to replace the current reality with a better one, through the use of a high-end user interface which involves real-time simulation and interaction. Using VR allows users to experience virtual environments in a way that makes the brain believe that they are somewhere else. In this way, users can navigate and interact with virtual simulations, by combining high-level graphics, position tracking and motion sensors.

3.1. Difference between VR and other digital media

VR experts say that any experience should involve the following points, which makes the difference between VR and other digital media:

- Dynamic point-of-view control. The system can update images whenever users look around. This is achieved through a built-in head-tracking device covered by sensors.
- 3D stereo vision. As if they were watching a 3D movie, users should be able to perceive depth and three-dimensional structures.
- An immersive experience. The more field of view the screen covers, the more immersed the user will feel. The screen size of the VR headsets might be tiny, but there is no escape. When the user looks around he/she sees images from the virtual world rather than the real world. (Bassas, 2018)

3.2. Main components of VR display systems and how do they work?

In the following section, we will compare two different VR display systems, the CAVE and the HMD and describe how they work.

3.2.1. CAVE

CAVE stands for “Cave Automatic Virtual Environment” (Pan & Gillies, 2021). It is a fully immersive room consisting of at least four display walls: three surrounding walls, plus the floor. The CAVE is equipped with projectors behind the walls to display high-resolution images (Pan & Gillies, 2021). In the following Figure 1 you can see a design for a four- wall CAVE, which includes three projectors for the walls and one for the floor.

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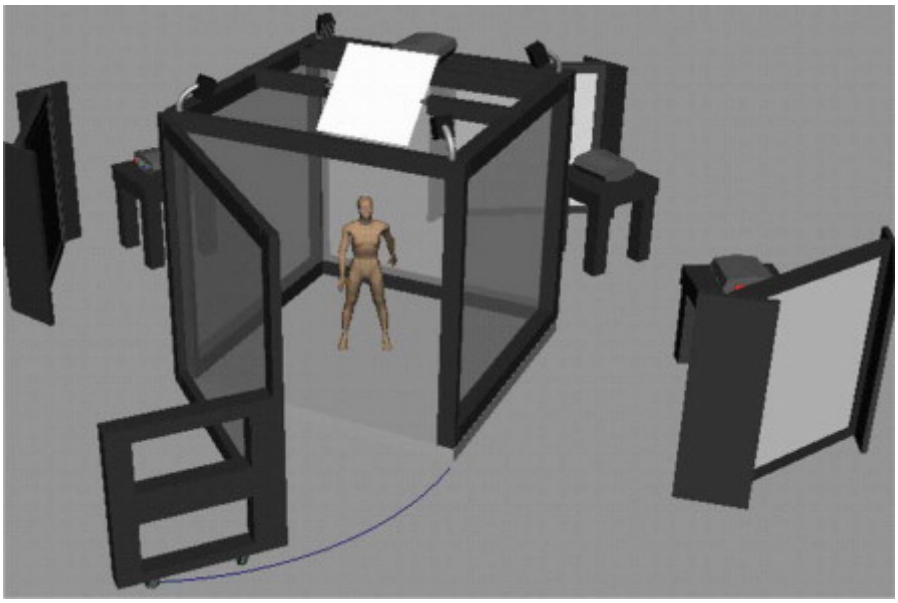


Figure 1: Four wall CAVE (Source: Muhanna (2015))

3.2.1.1. Stereoscopic 3D vision

In order to experience stereoscopic 3D vision, users have to wear a pair of shutter glasses. The displays are synchronized with the shutter glasses, delivering images to the correct eye at the right time. To produce the illusion of stereoscopic 3D vision, the images change at least 60 times per second (Pan & Gillies, 2021). The following Figure 2 shows a real CAVE system from the Desert Research Institute in Reno, Nevada. The participant is wearing shutter glasses for stereoscopic view, however, as an expectation without the glasses, you can see that the image of the CAVE is blurred (Muhanna, 2015).

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Figure 2: Participant wearing shutter glasses for a stereoscopic view at the Desert Research Institute's CAVE in Reno, Nevada (Source: Muhanna (2015))

3.2.1.2. Dynamic point-of view

In CAVE, dynamic point-of-view control by the user is also possible. This can be achieved by mounting the head-tracking device on top of the shutter glasses and updating in real time the display according to the user's point of view. Even though there could probably be more than one user in the room, each with a pair of shutter glasses, only one user could wear the head-tracking device that is synchronized with the graphics rendering machine. Therefore, only one person can have dynamic control of the viewpoint (Pan & Gillies, 2021).

In the following video you can see an example of a Virtual Reality Cave of the French Interdisciplinary Center of Virtual Reality (CIREVE) and the University of Caen Normandie in France:
https://www.youtube.com/watch?v=iik95LoBGxI&ab_channel=STEngineeringAntycip

3.2.2. Headsets

The most widely recognized VR displays are called head-mounted displays (HMD). It is a device that is attached to the head of the users and shows VR content directly in their eyes (IAB, 2018). No matter where the users look, the screen mounted in their face will follow them (Jiwani, 2018).
There are three types of HMDs:

1. Phone-based HMD: A smartphone is inserted into the headset and video is played from the phone, e.g. Google Daydream, Google Cardboard and Samsung Gear.

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2. Tethered HMD: The headset is connected to a console or computer so it can work, e.g. Oculus Rift and HTC Vive. This type of HMS offers the maximum VR quality.
3. Standalone HMD: a wireless headset that does not require a smartphone or a console/computer to work, because it has its own computer inside the headset along with the screen. Regarding quality, it is intermediate between phone and tethered HMDs. One example of this type of HMD is the Oculus Go. (Jiwani, 2018) (IAB, 2018)

In order to create a 3D environment, the headset has two displays for each eye and also lenses located between the displays and the user's eyes. The function of these lenses is to trick our brain and imitate the way our eyes see the real world. They focus and reshape the image displayed for each eye. They create the illusion that a 2D image is a 3D environment by showing two slightly different images for each eye (Jiwani, 2018).

The frame rate of VR headsets should be at least 60 frames per second (fps) to prevent the user from feeling nausea. Oculus Rift and HTC Vive frame rate is 90 fps and PlayStation VR at 120 fps (Jiwani, 2018) (Xymatic, 2021).

3.2.2.1. Head Tracking

As it was mentioned previously, one of the important features of VR is the dynamic point-of-view control, which means that if users move their head, the picture has to move accordingly. This is achieved because the headsets use a system called 6 degrees of freedom (6DoF) which tracks the position of the head when in the X,Y and Z axes. This system uses several sensors such as gyroscope, accelerometer and magnetometer for head tracking (Jiwani, 2018).

Head tracking technology requires low latency to be effective. According to Carmack (2013), it must be 50 milliseconds or less, otherwise our brain will perceive the delay between the moment when we move our head and the change in the VR environment. The Oculus Rift has an impressively low latency of only 30 milliseconds (Jiwani, 2018). Another important element that allows the user to be more immersed in the virtual experience is the binaural or 3D audio. Taking advantage of head tracking technology, the binaural technology provides the user with a complete audio-visual landscape of the virtual environment (Jiwani, 2018).

3.2.2.2. Motion Tracking

In order to create a more immersive and realistic environment for the user, there are some VR headsets such as the Oculus Rift and the HTC Vive that allow the user to control what happens in the VR simulation through a set of wireless controllers. Those controllers have

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certain buttons as well as a bunch of sensors that can detect gestures such as pointing and shaking (Jiwani, 2018).

3.2.2.3. Eye Tracking

In order to know where the user's eyes are looking in a Virtual Reality environment, an infrared sensor is used to monitor his/her eyes inside the headset. In standard VR headsets, all images are sharply focused, however, this is not how we are used to seeing in the real world. For example, if our eyes look at and focus on an object that is far, our brain blurs the foreground, on the contrary, if our eyes focus on a closer object the background is blurred. FOVE's headset graphics engine can simulate this in a VR 3D space by using eye tracking (Jiwani, 2018).

For a better understanding about how VR works, you can see the following videos:

MIT Explains: How Does Virtual Reality Work? (360° video):
https://www.youtube.com/watch?v=-Kovxf6g0mo&ab_channel=MITK12Videos
How Virtual Reality tricks your brain:
https://www.youtube.com/watch?v=ybyib5pAq7Y&ab_channel=Vox

REMEMBER TIPS

There are three key points that differentiate VR from other digital media: Dynamic point-of-view control, 3D stereo vision and an immersive experience (Bassas, 2018).
CAVE stands for "Cave Automatic Virtual Environment". It is a fully immersive room consisting of at least four display walls: three surrounding walls, plus the floor. With this technology the user can experience a stereoscopic 3D vision and a dynamic control of viewpoint (Pan & Gillies, 2021).
For HMD we have three main components: head tracking, motion tracking and eye tracking, which are supported by headsets, motion sensors and controllers (Jiwani, 2018).

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GLOSSARY

Degrees of Freedom (DoF)

According to IAB (2018), it refers to the user's ability to move in a space.

As you can see in Figure 3 3DoF headsets are able to track the rotational head movement (left and right, up and down or tilt to one side or another) while, the 6DoF headsets can track the position of the user within the room, as well as the direction in which the head of the user is pointing (Kovačević, 2018).

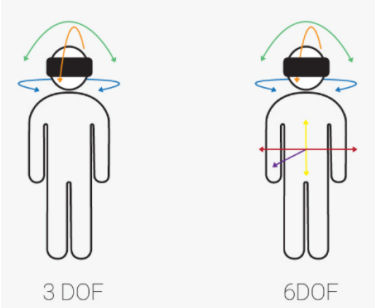


Figure 3: Degrees of Freedom (Source: Xymatic (2021))

Field of view (FOV)

The number of degrees that are visible from a given point of view at a given time. As it is shown in Figure 4, the FOV of most people is ~200°, approximately 120° of binocular vision (Xymatic, 2021).

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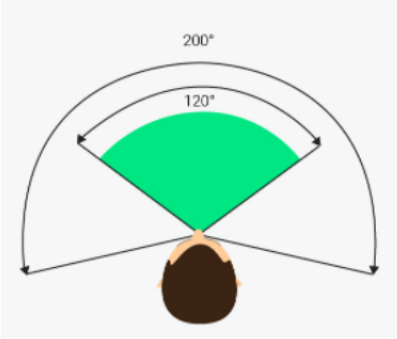


Figure 4: Field of view (Source: Xymatic (2021))

Frame rate

The frequency that an image/frame is replaced by another. In VR, it is very important to maintain at least 60 frames per second to allow user immersion and avoid nausea (Xymatic, 2021). The following Figure 5 shows the high frame rate (left side) vs low frame rate (right side).

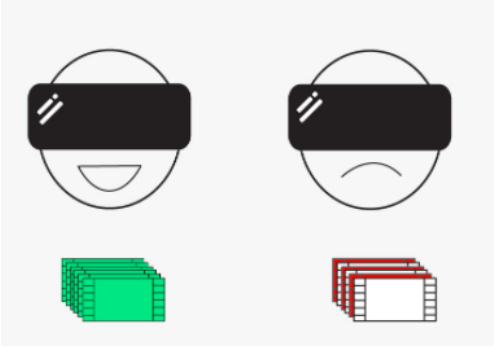


Figure 5: Frame rate (Source: Xymatic (2021))

Latency

The delay between user input, e.g. the user's movement, and the output, e.g. visual, haptic, positional, audio. It is measured in milliseconds.

High latency can cause motion sickness due to the unnatural sensation of the view going behind the motion (Xymatic, 2021).

Stereoscopic vision

The vision that humans and most animals have. It consists of the perception of two slightly different images, one for each eye, as a single image. As a result, depth perception helps us to see the world in 3D (Kovačević, 2018).

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UNIT NUMBER: Didactic Unit 4

History and Evolution of Virtual Reality

UNIT PRESENTATION

Virtual Reality goes back to the 1800s, nearly to the exceptionally starting of viable photography. The utilization of the term "Virtual Reality," first began in the mid-1980s when Jaron Lanier, author of VPL Research, started to develop the gears like goggles and gloves. Indeed some time before that, technologists were creating simulated environments. One point of reference was the Sensorama in 1956. Today's current Virtual Reality gear owes an obligation of appreciation to the pioneering innovators of the past six decades who cleared the way for low-cost, high-quality gadgets which are effectively accessible.

OBJECTIVES

In this unit you get to know the history and evolution of Virtual Reality from the early beginnings to the current state. You are able to see the development and different purposes behind a certain evolution.

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CONTENTS DEVELOPMENT

4.1. The Early Beginnings 1950s

In this first section, you will read information about the early beginnings of Virtual Reality from the 1950s. Furthermore, you will get to know the advancement of Virtual Reality over time.

1956 Sensorama: Morton Heilig, a cinematographer, designed the primary Virtual Reality machine named Sensorama. It was an expansive booth-like machine which had an arcade-style theater cabinet which would oblige 1-4 individuals. This would fortify all the senses and had multiple technologies included. Sensorama was considered the " Future of the Cinema" by Heilig (Barnard, 2019).

1960 Telesphere Mask: Morton Heilig invented the Telesphere Mask. There was no movement tracking in the headset, but it provided stereoscopic 3D images with stereo sound (Barnard, 2019). It was the first head-mounted display.

1961 Headsight: Two engineers Comeau and Bryan designed the Headsight. The gadget consisted of two video screens, one for each eye and a magnetic movement tracking framework. Headsight was not really created for Virtual Reality applications, but it was for the military (Virtual Reality Society, 2017). Headsight was considered as the first step in the advancement of the Virtual Reality head-mounted display which lacked the integration of the computer and picture era.

1965 The Ultimate display: Ivan Sutherland, a computer researcher, came up with a vision depicted as the “Ultimate Display” (Barnard, 2019). This vision was to simulate reality to the point where one might not tell the distinction of real reality by allowing the client to interact with objects. The paper composed by him is depicted as the basic outline for Virtual Reality.

1966 Flight Sim: A military designer, Thomas Furness was credited for the development of advanced flight simulator innovation since he made the primary flight simulator for the Air force (Barnard, 2019). He is considered as “the grandfather of VR” for his work in Human interface Innovation.

1968 Sword of Damocles: Sword of Damocles, the first Virtual Reality/Augmented Reality head mounted display that was associated with a computer and not a camera, was designed by Ivan Sutherland and his understudy Bounce Sproull. This was an

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overwhelming outline for any client to comfortably wear. Since the objects were shown against a genuine foundation, the innovation can be considered the birth of Augmented Reality (Pratt School of Information, 2021).

1969 Artificial Reality: Myron Kruegere developed a series of experiences and termed it "artificial reality". The projects named GLOWFLOW, METAPLAY, and PSYCHIC SPACE were progressions in his research which ultimately led to the development of VIDEOPLACE technology (Swag Soft, n.d.).

4.2. Virtual Reality in 1970s

1972 Digital Flight Sim

General Electric created a "computerized" flight test system. This had three screens encompassing the cockpit which were orchestrated in 180-degree configuration (Barnard, 2019).

1975 VIDEOPLACE: Krueger's VIDEOPLACE is regarded as the first interactive Virtual Reality system. It didn't feature any sort of headset. Computer graphics, projectors, video cameras, video displays and position-sensing technology were used for this. Large video screens were in dark rooms in order to surround the user in "Virtual Reality" (Virtual Reality Society, 2017). This allowed the users in different rooms to interact with other users as well. This encouraged the idea that people could communicate within a virtual world even if they weren't physically close.

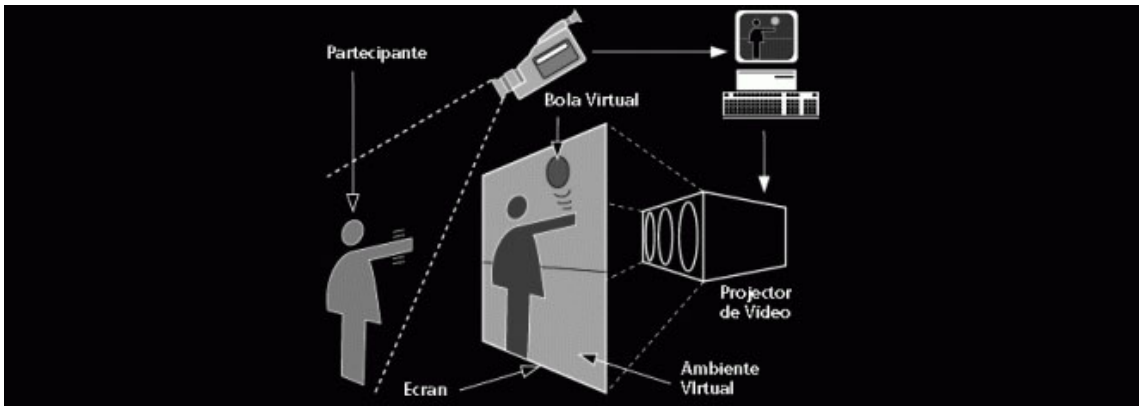


Figure 6: Videoplace (Source: https://virtualspeech.com/img/blog/VIDEOPLACE-vr-platform.jpg)

1977 MIT Movie Map: MIT created the Aspec movie outline. This framework let individuals wander through a virtual involvement of Aspen, Colorado to deliver watchers what they called a "Surrogate Travel" encounter. It was nearly like an antiquated antecedent of Google Street view (Virtual Reality Society, 2017).

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1979 McDonnel-Douglas HMD: The McDonnell-Douglas organization coordinates Virtual Reality into its head mounted display, the vital protective cap, for military use. The vital head protector is likely the primary legitimate illustration of a Virtual Reality head mounted display outside of the lab. Employing a head tracker, pilots may look at primitive computer-generated imagery (Virtual Reality Society, 2017).



Figure 7: Vital helmet (Source: https://virtualspeech.com/img/blog/VITAL-helmet-vr.jpg)

1982 Sayre Gloves: Finger-tracking gloves for Virtual Reality called "Sayre" gloves were designed by Daniel Sandin and Thomas DeFanti (Barnard, 2019). These gloves were the primary wired gloves and utilized optical sensors to distinguish finger development.

1986 Super Cockpit: Tom Furness created a flight test system known as the "super cockpit" (Pratt School of Information, 2021). The helmet's following framework and sensors permitted the pilot to control the airplane utilizing signals, discourse and eye developments.

4.3. The birth of the term "Virtual Reality"

1987 Virtual Reality - The name was born: Jaron Lanier, founder of the visual programming lab (VPL), coined the term "Virtual Reality". Through his company's visual programming lab investigation, Jaron made an extended Virtual Reality adaptation, tallying the data glove and the eyephone head mounted display.

1989 NASA Gets into Virtual Reality: NASA and VPL Research worked together to create a head mounted display that showed a CGI environment relayed from remote video cameras and utilized data glove and data suit innovation for the suit.

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Figure 8: NASA project (Source: https://virtualspeech.com/img/blog/virtual-environment-workstation-project-nasa.jpg)

1991 Arcade machines: The Virtuality Group released a series of games and arcade machines bringing Virtual Reality to the general public (Pratt School of Information, 2021). Players would wear a pair of Virtual Reality goggles and play immersive games in real-time. A few of these devices were even networked together for multi-player virtual gaming experiences.



Figure 9: Arcade machines (Source: https://commons.pratt.edu/virtualreality/wp-content/uploads/sites/362/2019/05/virtuality-arcade-games-300x169.jpg)

1992 The Lawnmower Man: The Lawnmower Man motion picture presented the concept of Virtual Reality to a more extensive gathering of people. It was based on the author of Virtual Reality Jaron Lanier and his early research days. Genuine Virtual Reality gear from VPL investigate labs was utilized within the film.

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1994 Sega VR-1: A VR-1 movement test system arcade machine was discharged by Sega. An arcade movement test system that moves in understanding of what's happening on-screen.

1995 Nintendo Virtual Boy: Nintendo launched the virtual boy comfort which played 3D monochrome video recreations (Pratt School of Information, 2021). It was the primary convenient way to show 3D design. But it was a commercial disappointment due to color design, software support and comfort to utilize.

1997 Landmark VR PTSD Treatment: Georgia Tech and Emory University analysts joined up to form virtual Vietnam. The gathering utilized Virtual Reality to reenact war zones to help in veterans' introductory treatment sessions treating PTSD.

1999 Matrix: In 1999 the Wachowski siblings' movie The Matrix hit the theaters (Swag Soft, n.d.). The film highlighted characters that are living in a completely recreated world. The Matrix encompasses a major social effect and brings the subject of simulated reality into the standard.

4.4. The Early 20s Advancements

In 2001 SAS cube was presented as the primary pc-based cubic room. In 2007 Google brought us street view. Google upgraded its maps benefit with street-level 360-degree pictures, captured by uncommon cars fitted with custom camera hardware. Nowadays you can "stand" close to any portion of the world and see around and appreciate this innovation (Barnard, 2019). In 2010 Palmer Luckey made the primary model of the Oculus Crack which he depicted as "the to begin with a genuinely immersive Virtual Reality headset for video games." (Virtual Reality Society, 2017).

4.5. The Present Advancements

2014 appeared as a promising year for present-day Virtual Reality advancement. It was at that point Facebook bought the Oculus VR company, Sony began working on Extend Morpheus (a Virtual Reality headset for PlayStation), Google discharged the cardboard, and Samsung declared its adaptation of Virtual Reality (Swag Soft, n.d.).

In 2015 Virtual Reality conceivable outcomes began getting to be broadly accessible to the common open, The Wall Street diary propelled a Virtual Reality roller coaster, The BBC made a 360-degree video, The Washington post discharged a Virtual Reality encounter of the Oval Office at the White House Correspondents' affiliation dinner. RYOT, a media company, showed a brief Virtual Reality film around solitary restriction in US jails (Barnard, 2019).

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By 2016 hundreds of companies were creating Virtual Reality items. Most of the headsets had energetic binaural sound. HTC discharged its HTC VIVE Steam Virtual Reality headset (Barnard, 2019). This was the primary commercial discharge of a headset with sensor-based tracking which permitted clients to move unreservedly in a space.

In 2018 Facebook F8, Oculus illustrated a headset model, the Half Dome. Usually a varifocal headset with a 140 degrees field of vision (Virtual Reality Society, 2017). We presently have both the Oculus Go and Oculus Journey. Portable Virtual Reality is declining quickly and standalone frameworks such as the Go are exceptionally affordable.

Today, the Virtual Reality industry sees frenzied competition among genuine players such as HTP, Google, Apple, Amazon, Sony. Virtual Reality has altogether advanced and is presently being utilized in an assortment of ways, from giving immersive gaming encounters, to making a difference treating mental disorders, to instructing unused aptitudes. Blended reality frameworks and advanced innovations are presently a portion of standalone Virtual Reality headsets (Swag Soft, n.d.). The cost of Virtual Reality headsets has dropped drastically and computer equipment competent to run these headsets is essentially standard. Numerous progressed headsets are on the skyline. Varifocal innovation, amazingly wide areas of see, hand scanning and eye following are but a couple of the key developments.

Major companies such as Apple are rumored to be working on Mixed Reality projects and at this point it seems as if Virtual Reality and Mixed Reality are likely to be inseparable in future (Swag Soft, n.d.).

REMEMBER TIPS

- The first idea of Virtual Reality was in 1950s
- Over the period of time Virtual Reality has seen a lot of advancements
- Now major companies are working on Virtual Reality and Mixed Reality

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UNIT NUMBER: Didactic Unit 5

Components of Virtual Reality systems

UNIT PRESENTATION

When you talk about VR it is equally important to talk about VR components to understand and enjoy VR technology in its entire sanctity

OBJECTIVES

This unit will throw some light on the various software as well as hardware components of the VR system.

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CONTENTS DEVELOPMENT

The components of VR are the tools, technologies and software required to access the VR system efficiently and they are further classified into below mentioned categories:

5.1. Hardware

5.1.1. Head Mounted Device (HMD)

First developed by Ivan Sutherland in 1968. An HMD is a helmet or goggles-like device. There are many types of VR HMD available in the market like 3DOF HMD (Oculus GO and Samsung Gear), 6DOF HMD like (Oculus Quest) and Computer-based VR HMD devices (Oculus Rift, Rift S). It is the most important and basic device required for a VR immersive experience.

Most HMD devices contain in-built memory, in-built gyroscope sensors for movement tracking, RAM, processing unit, screen, and sound capabilities that provide an immersive VR experience. There are various types of HMD devices available in the market. The below Figure 10 shows the HMD from Oculus (Quest).

(University of Calgary, n.d.)

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Figure 10: Oculus HMD (Source: https://scdn.slashgear.com/wp-content/uploads/2020/03/oculus_quest_headset_main-1280x720.jpg)

5.1.2. Sensors/Trackers

Sensors are in-built to HMD, attached with remote controllers/joysticks to track the movement (see Figure 12 for in-built sensors). There are also external stand-like sensors for PC-based VR systems like Oculus Rift and Rift S (see Figure 11 for external sensor). Sensors are one of the most important components of a VR system as they track the 3DOF or 6DOF user movement and help to create the immersive VR experience. Also, they are helpful to avoid collisions or prevent adverse consequences by tracking user movement in VR and nearby real environments and alerts the user to set the safe boundaries to access the VR experience. (University of Calgary, n.d.)

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Figure 11: Oculus Rift sensor package (Source: https://www.vrnerds.de/wp-content/uploads/2017/09/oculus-rift-kameras-room-scale.jpg)



Figure 12: Oculus Rift HMD sensors (Source: https://medium.com/@kenwang_57215/oculus-solution-to-room-scale-vr-37b2ff654dc9)

5.1.3. Hand-held device/Controller/Joystick

Controllers work as Mouse, they are helpful to point, touch, click, hold, throw away, get closer or to nudge something in the world of VR. Hand-held Controllers are well equipped with Sensors and powered by removable portable lithium-ion batteries. They are useful to play games in VR and act as gaming controllers for VR Games. Below image (Figure

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13) shows some of the hand-held controllers to interact with VR applications. (Strohanova, 2019)



Figure 13: Different Hand-held devices Source: (https://vrsource.com/wp-content/uploads/2016/11/VR-Controllers-1-of-24-1024x578.jpg)

5.1.4. Cables for PC-based VR

Cord wire or cable are required to experience the immersive world of VR. They work as a link to attach the HMD with highly capable PCs and External sensors. Oculus Rift and Rift S are the best examples to understand it.

5.1.5. Charging cable and Adapter

USB type C cables and Adapters are being employed to charge most of the recent and advanced VR devices.

5.1.6. Gloves

It looks almost like normal gloves. It also contains sensors to track the hand movement. It synchronizes the hand movements with the media being played on VR devices. Gloves can let users perform the functions of Hand-held controller like click, touch or grab something in the world of VR. Latency can be observed in hand tracking compared to physical Hand-held controllers. (Strohanova, 2019)

5.1.7. Head Strap

Adjustable head straps to adjust the screen/lens to the comfort level of our eyes. They help to fit our head size as well.

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5.2. Software

VR requires Software support for its functioning and this section talks about the Software components required for VR systems. Below Figure 14 shows the working of the VR system.

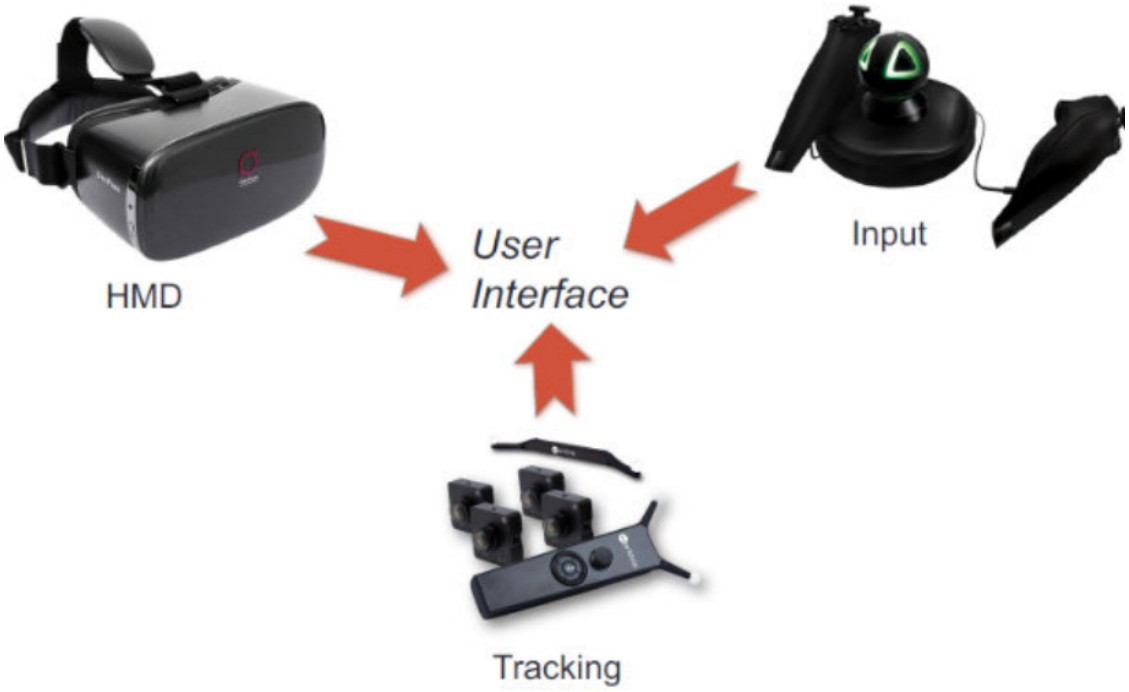


Figure 14: Connection of HMD, Input devices and Tracking (Source: https://www.researchgate.net/publication/337265640/figure/fig1/AS:825340259745792@1573787860131/Typical-immersive-VR-system-components.png)

5.2.1. Companion apps for Stand-alone HMD

The Companion App is an essential component to register, login, connect and access VR HMD devices. It connects and creates a synchronous link between a particular HMD device and respective controllers. It works as a bridge between all the components of a VR system. Oculus Quest is a standalone VR system which requires a dedicated companion app called Oculus app by Oculus.

5.2.2. Simulation Software

Simulation Software is responsible for providing an immersive experience to the VR system. Simulation software processes the input received from the input devices like Controllers and produces the reflection on the user screen with maximum consistency. Internal database of all the objects in the VR world gets generated, maintained and continually monitored by the Simulation software. It also notifies the VR system when

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any changes are identified in the internal database. (Human Interface Technology Laboratory, n.d.)

5.2.3. 3D Modelling Software

In order to achieve immersive media and effect for the real objects, 3D modelling software is used that specifies the actual shape, size and dimensions of the real-world objects in the world of Virtual Reality. (Human Interface Technology Laboratory, n.d.)

5.2.4. 2D Graphics Software

2D graphics software is responsible for making the real-world objects look more detailed and interesting in the Virtual world. This is achieved by employing the process called Texture Mapping or Paint programs. The images processed or edited by 2D graphics software must pass through the 3D modelling software as well, after the 2D model adds more detail to the surface of the objects for the Virtual world. (Human Interface Technology Laboratory, n.d.)

5.2.5. Digital Sound Editing software

Sound synchronization with the matching virtual effects gives the immersive VR experience. 3D graphics in VR are aesthetically very attractive but not very real without the high-resolution synchronous sound effect of the objects and actions in the VR environment.

5.2.6. Virtual Reality Game Engine

VR Game Engine facilitates the game developers with the framework to build games in VR. SDKs ease the work for developers to design, develop and test their VR Games and App. Unity, Unreal, Maya, CryEngine are a few of the VR game engines.

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UNIT NUMBER: Didactic Unit 6

Types and brands of VR systems and devices

UNIT PRESENTATION

This unit will cover types of VR systems and brands that manufacture VR technology.

OBJECTIVES

You will get to know all about various types of VR systems.

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6.2. Semi-Immersive Virtual Reality 35
6.3. Immersive Virtual Reality 36
6.3.1. Mobile based Virtual Reality 37
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CONTENTS DEVELOPMENT

Non-Immersive, Semi-Immersive and Full-Immersive are the three primary types of VR systems.

6.1. Non-Immersive Virtual Reality

It is the most basic, common and known VR type, but hardly considered in the list of VR technology. It gives the least VR experience among the three. To experience the Non-Immersive VR one needs a computer or video game console, display, and input devices like a gaming remote controller, mouse and keyboard as shown in Figure 15. Consider it as an advantage or disadvantage, the user stays aware about the surroundings while experiencing the Non-Immersive VR. The prime example for Non-Immersive VR is Video game. (Poetker, 2019)



Figure 15: Video Game (Source: https://learn.g2.com/virtual-reality)

6.2. Semi-Immersive Virtual Reality

Semi-Immersive VR resembles the AR system and provides a high level of immersion, it provides a partially virtual environment through Virtual Reality depth. It uses

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projectors/display and synchronous sound effects to the visuals for a rich VR experience as shown in Figure 16.

In a Semi-Immersive VR system, the visual graphics quality, sound and physical environment plays an important role in providing a better immersive experience. The detailed visual graphics, sounds, and environment quality results in a better VR experience. The scope of Semi-Immersive VR systems ranges from Education and Training purpose to Entertainment purpose. The Driving Simulator and Flight Deck Simulator perfectly define the scope of Semi-Immersive VR systems. (Poetker, 2019)



Figure 16: Semi-Immersive Racing Game (Source: https://cyberpulse.info/what-is-semi-immersive-virtual-reality/)

6.3. Immersive Virtual Reality

Immersive VR or Full-Immersive VR provides the maximum level of VR experience. The immersive VR system consists of VR HMD (Head Mounted Display), Handheld Controllers, Trackers, Sensors, batteries, mobile device or computer system among various other components, which makes this VR system the most expensive VR and that can be seen in Figure 17.

It gives the real-life experience virtually in the HMD device. The immersive experience is so rich that users get carried away in the virtual world. User's movement and control are based on the scenarios in the HMD of the user. User loses control while using a fully Immersive VR device as the user cannot see the physical real world surrounding and may cause damage if the see-through option fails to enable it whenever the user approaches any physical entity from the real world.

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It has numerous scopes like it can be used for Tourism industry, Medical, Education and awareness, entertainment industry, professional or business purpose, Research and Development, real life like long distance communication and mainly for Gaming purposes as well. Immersive VR evolved tremendously in the recent past and is still growing rapidly. (Poetker, 2019)



Figure 17: Full-Immersive Flying Simulation (Source: https://learn.g2.com/virtual-reality)

Immersive VR can further be classified as follows:

6.3.1. Mobile based Virtual Reality

Mobile based VR is on the verge of extinction. It requires a specific mobile device to be mounted on the VR HMD to access the VR system as it can be seen in the below image (Figure 18) where a user has mounted a mobile device with VR HMD. The Mobile based VR are 3DOF (Degree of Freedom) which makes the VR experience less interactive in comparison with 6DOF VR headset. The other drawback was that it requires the specific mobile device to gain the VR experience. The Mobile based HMD are not having any inbuilt capabilities of their own, they are mostly dependent on the Mobile phones to perform almost all the VR operations. All they have is a chip connector to connect mobile phones with HMD and optics. Samsung Gear VR is the early day Mobile based VR HMD.

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Figure 18: VR with mobile Device (Source: https://medium.com/@aismobileapps/virtual-reality-in-mobile-app-for-business-857fa19a6bcb)

6.3.2. Standalone Virtual Reality

Standalone VR are the most popular and most exciting among all other VR types. Standalone VR does not require any wired connection to PC or any other device.

Standalone VR are portable, easy to access and it only requires to pair with the android or iOS based companion app. Standalone VR are available in 3DOF as well as 6DOF. The 3DOF VR headset is Oculus GO and the 6DOF VR headset are HTC Vive Focus and Oculus Quest (see Figure 19 for Oculus Quest which is a prime example of Standalone VR). Oculus Quest 2 is unique among all the VR headset, it is an All-in-one VR headset, which means it can work Standalone using VR companion app and it can also connect with PC using Oculus Link and it will work as PC based VR like Oculus Rift and Rift S

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Figure 19: Oculus Quest (Source: https://www.forbes.com/sites/solrogers/2019/05/03/oculus-quest-the-best-standalone-vr-headset/?sh=7cb0a4548ed8)

6.3.3. PC based Virtual Reality

PC-based VR requires safe and sufficient vacant physical space to experience the world of VR. PC based VR has great capabilities to provide amazing immersive experiences as they are fully equipped with specialized hardware like high caliber Computer system, dedicated external sensors unlike any of its hierarchical siblings.

It is not a portable VR HMD and is linked to the computer system with a lot of wires or cords and also the specialized hardware makes this type of VR more expensive one than the rest of the VR systems. Oculus Rift, Rift S and HTC Vive are examples of PC based VR systems. Below described Figure 20 shows the PC based VR from Acer.

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Figure 20: PC based VR with HMD (Source: https://mspoweruser.com/acer-windows-mixed-reality-headset-compared-to-oculus-rift-htc-vive-and-psvr-by-vr-expert-video/)

6.2. Brands of Virtual Reality systems

There are numerous international VR manufacturers among them, few are very popular such as Oculus VR, HTC, Sony Playstation VR, HP, and Valve. (Dexter A, 2021)

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UNIT NUMBER: Didactic Unit 7

Scope of Virtual Reality

UNIT PRESENTATION

The application fields of VR have expanded a lot and this unit will take us through the scope of VR

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CONTENTS DEVELOPMENT

The VR industry as a whole is growing very rapidly, the current global market size of the VR industry in 2021 is approximately around $ 4.8bn and estimated to reach more than $12bn by 2024. Currently, the VR headset unit sale is around 6bn, which is also estimated to grow rapidly in the near future. (Alsop, 2021)

7.1. Defense

Virtual Reality can help to train armed forces for war-like situations and also to survive at the toughest geological location by creating such virtual environments around them. Using VR technology, armed forces can get trained pro efficiently without putting their lives in any danger. (Bhatia, 2016)

7.2. Virtual Events

Virtual Reality is a prominent option in the days of Corona to organize and attend events like Concerts or Seminars virtually. VR can be one of the safest ways during times like pandemic to join the event without really stepping out of our homes. (Bhatia, 2016)

7.3. Entertainment

Virtual Reality has positively impacted the entertainment industry. VR provides an immersive experience to the Gamers and also provides a great movie watching experience. (Bhatia, 2016)

7.4. Medical & Healthcare

Virtual Reality can play the most prominent role in improving medical efficiency by providing guidance to understand the human body complexities to students of medical and science. Also, VR can help surgeons to execute or to prepare for surgeries. (Bhatia, 2016)

7.5. Sport

Players of various sports teams can be trained efficiently using VR technology by providing them with an environment where they can play against their real-world opponents, having the same venue set up and crowd to cheer and motivate them. (Bhatia, 2016)

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7.6. Tourism

Using Virtual Reality and Immersive 360 Video, one can have a glimpse of the world's historic sites, monuments and wonders of the world like the Great Wall of China or Taj Mahal without having to pay a single cent or without stepping out of their home. (Bhatia, 2016)

7.7. Fashion

Fashion industry can employ VR technology to try out their designs on virtual models, can organize virtual fashion shows and also can put their creativity on display for sale in virtual fashion stores or virtual exhibitions. (Bhatia, 2016)

7.8. Construction and Architecture

Builders and architects can examine the construction site, finalize construction design and suggest changes accordingly with the help of Virtual Reality. Also, Builders can show the prototypes to customers using this impressive immersive VR technology. (Bhatia, 2016)

7.9. Journalism

The journalism piece of work-'Project Syria' shows the very minute details and conditions about the war-torn Syria in VR. Hence it paves a way forward for the journalism sector to employ Virtual Reality in order to showcase their report in a way that attracts the world. (Bhatia, 2016)
(Additional Material: https://www.youtube.com/watch?v=jN_nbHnHDi4)

7.10. Civil Aviation

Various national and multinational firms do provide training to their newly joined employees and also provide on-job training to their existing employees via VR system.
Using VR, employers can create real life scenarios for their employees and train them accordingly. Sometimes it is difficult to provide training for various tasks and requires a lot of effort, technological advancements and finance, for such scenarios VR plays an important role in providing critical training to the employees and new recruits. RampVR project by IATA (International Air Transport Association) fits as the best example which provides Virtual Reality training solutions for Airport and Runway ground operations which combines highly configured VR hardware and software to train Airport Ground operation professionals. (Bhatia, 2016)
(Additional Material: https://www.youtube.com/watch?v=WKKTJmiChSk)

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7.11. Business & Marketing

Product models are being developed in VR technology to provide an immersive experience to the customers about product and related services, that can help customers to decide whether to buy or not and also benefits businesses to not invest more on developing real products for customer demonstration. Here, VR plays a WIN-WIN role for both the parties involved in the business. (Bhatia, 2016)

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UNIT NUMBER: Didactic Unit 8

Problems and Challenges using Virtual Reality

UNIT PRESENTATION

Problems and Challenges are just the other side of the coin for every technology and the VR system is no different. This unit will take you through a few such problems and challenges of using VR.

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8.3. Potential addiction 48
8.4. Price 48
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CONTENTS DEVELOPMENT

8.1. Sweating

Whenever users play highly Intensive games Like Creed, they tend to sweat a lot. Which makes the cushion area of HMD (Head Mounted Display) stingy and wet. This problem cannot be rectified, but to let the HMD rest until it gets dry. One Solution to it is to place the tissue papers between our face and HMD cushion area while using HMD for highly intensive games or activities.

8.2. Health-related issues

When naive and new users wear HMD they feel uneasiness and motion- sickness. Symptoms of motion-sickness or cybersickness like headaches, vomiting, eye strain and tiredness. Users enjoy the clarity of sound in noise-cancelling headphones but also have a strange sensation in their ears. People might experience headache and neck pain caused by the heavy weight of VR devices. Some cybersickness cases keep going such as when the real gravity is in contrast with the seen environment. For example, when the user is flying in an airplane in VR. The behavior of particular users (such as the consumption of alcohol and certain medications before or simultaneously with the use of HMD) may exacerbate cybersickness during VR use. (Thompson, 2020); (Trescak, 2019)

The graph in Figure 21 was taken from a survey report. This survey was conducted by VR heaven. They asked some people about their VR experiences through Discord and Reddit groups. Around 300 people were given responses, then they recorded those results and made this VR motion sickness survey. This may skew the data a bit, because it consists of people who are more technology savvy. All responders were under 50. It seems the older generation are more prone to motion sickness than younger generation. (VR heaven, 2021)

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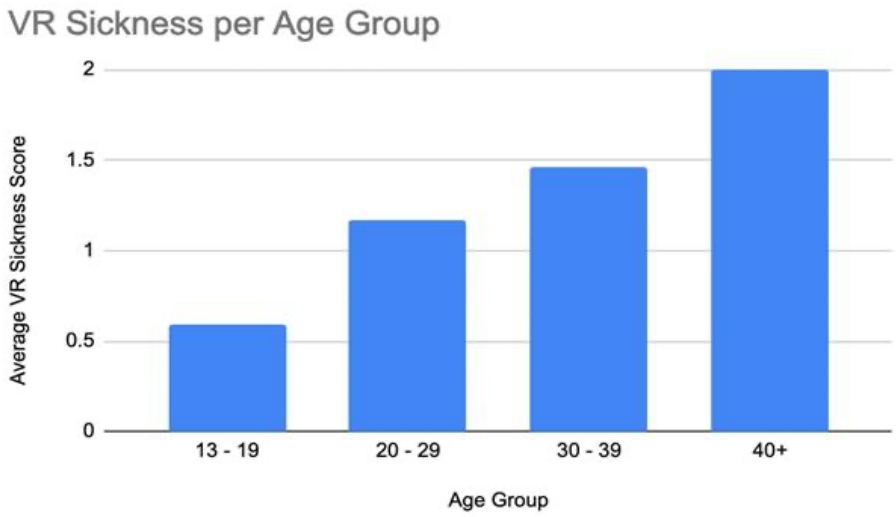
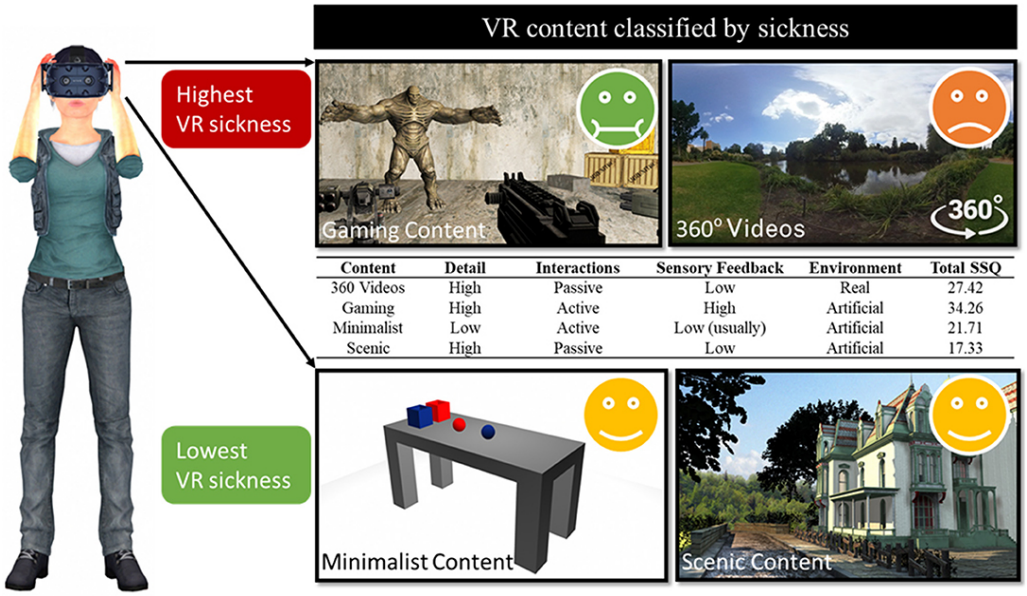


Figure 21: VR Sickness score vs Age Group (Source: https://www.youtube.com/watch?v=jN_nbHnHDi4)

In Figure 22, there are four types of content categorized in studies including analysis: Gaming content, 360 videos, minimalist content and scenic content. User interaction and environmental features differed for each category. The 360 videos included content captured with a 360 camera or video taken that allowed a 360 view of the virtual environment. Gaming included high detailed content where the user could actively interact and perform tasks in the virtual environment including off-the-shelf games and content developed by researchers. Minimalist content consisted of basic shapes or minimal textures, with typically simple interactions. Scenic content included detailed environments, for example, a landscape or cityscape with no or simple interaction by the user.

All studies were categorized based on the amount of visual movement within the content regardless of user-directed movement, such as locomotion (Locomotion refers to how a user navigates in the virtual environment) and head movement. Low visual stimulation included content with slow visual changes, while high visual stimulation included content with fast visual changes. (Saredakis et al., 2020)

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Content	Detail	Interactions	Sensory Feedback	Environment	Total SSQ
360 Videos	High	Passive	Low	Real	27.42
Gaming	High	Active	High	Artificial	34.26
Minimalist	Low	Active	Low (usually)	Artificial	21.71
Scenic	High	Passive	Low	Artificial	17.33

Figure 22: VR Content Types vs Probability of Motion Sickness (Source: https://www.frontiersin.org/files/Articles/512264/fnhum-14-00096-HTML/image_m/fnhum-14-00096-g002.jpg)

8.3. Potential addiction

It might be an obstacle that many psychologists predicted when talking about VR. VR is capable of taking people out of reality. And that can be a huge drawback. Users who spend a lot of time using VR, might experience anxiety. This feeling of anxiety might take time due to the realistic aspect of VR. (Baniasadi, Ayyoubzadeh, & Mohammadzadeh, 2020)

8.4. Price

As with new technology, the initial costs are extremely high. Even mediocre VR devices are priced fairly high. Price is one of the major setbacks the industry is facing recently. At this price point everyone cannot afford VR gear. Google and Facebook have invested a lot for VR and they allow some powerful hardware Oculus Rift to hit the market in the last years. But Customers were not satisfied. (Wiltz, 2017)

8.5. Lack of good content

Due to content lacking, users are unable to maximize the use of their devices.
VR requires these major things to create content: (Wiltz, 2017)

100% computer generated: simulation in which a person can interact within an artificial three-dimensional environment using electronic devices, such as special goggles with a screen or gloves fitted with sensors. (Numerati Partners, 2021)

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360° fully immersive: spherical video recordings where a view in every direction is recorded simultaneously.

8.6. Size of VR software

Software of VR requires a large amount of memory. VR devices involve more programming for their immersive experience. VR software takes up a lot of space and requires a lot of computing power compared to other devices.

8.7. Movement in Virtual Reality

At times, user wants to move beyond certain boundaries while accessing few applications or games, but they are unable to move beyond certain limits because PC-based VR HMD requires the HMD to be remain connected to the VR compatible PCs using various chords/wires and external sensors hence it makes it difficult for the users to move more than the length of the linked chords/wires. These difficulties can be faced mainly in PC-based VR like HTC VIVE, Oculus Rift and Rift S. (Mealy, 2021)

8.8. Need 5G speed

When the rendering is done in the cloud and not on a mobile device, there is a need for a fast and reliable 5G connection to deliver the final experience to the user. Both AR and VR use cases require stringent network requirements such as low latency, high reliability and high bandwidth. (Ethirajulu, 2020); (Wiltz, 2017)

8.9. Lack of vision of the surroundings

When users use VR devices, they cannot see around. Use of HMD at home or at critical places like near lakes, rivers or any such place and the lack of vision can cause near tragic accidents.

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UNIT NUMBER: Didactic Unit 9

Future of Virtual Reality

UNIT PRESENTATION

It's always fascinating to unfold what the future holds and the future of VR is no different, it is filled with excitement. Let's see what the future holds for VR in this section.

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CONTENTS DEVELOPMENT

9.1. Virtual Reality System

Many big tech firms are developing standalone headsets which will be able to show HD images. Also they are working on VR headsets in 8K with more powerful processors. There are some possibilities in upcoming years that they could merge AI (Artificial Intelligence). The latest 5G standard can be useful in the advancement of VR. This standard will allow more devices and user communities to be connected (see Figure 23). (PUSJV, 2021)

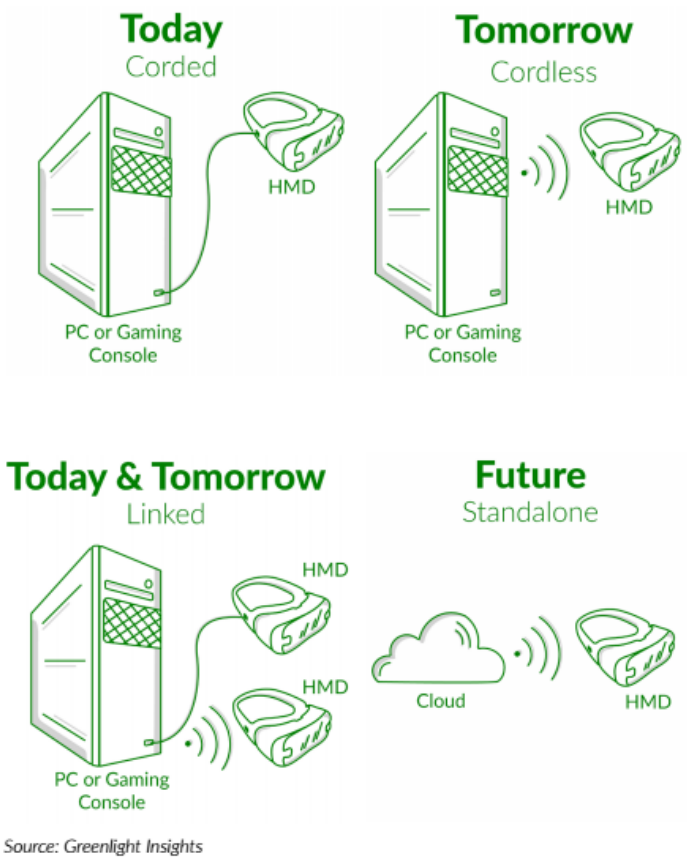


Figure 23: Future of VR (Source: https://www.ge.com/news/sites/default/files/Reports/uploads/2017/02/03100048/GreenlightUntetheredIllustration.png)

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9.1.1. Interaction with Virtual Reality to be through handheld devices

In the future VR technologies will be able to make smartphones smarter and other smart devices like VR goggles, VR devices will be popular in the market. Handheld devices will be the main way users interact with VR, as controllers give users a tactile feel and experience rather than using motion sensing devices.

9.1.2. Virtual Reality headsets will look like sunglasses

VR headsets will become sleeker as users see headsets downsize to a similar size style to sunglasses.

9.1.3. Help resolve phobias or fears

In medicine, VR will help resolve phobias or fears by transporting the patient into a comfortable situation.

9.1.4. Replacing high street shopping

People will make all of their purchases from home, trying on clothes in a Virtual Reality changing room and getting advice from AI shop assistants that know exactly how to cater for their taste.

9.1.5. Human senses

Most probably in 2050 users would have a Virtual Reality with a perfect emulation of sight, sounds and smells. They will also have good haptics and taste emulation.

9.2. 5G Technology will be used in Virtual Reality

5G will also have larger implications as the Internet of Things (IoT) expands. Other companies like Qualcomm and T-Mobile are also investing heavily into 5G development and National Instruments recently announced a channel sounder system, created in collaboration with AT&T, for scientists and engineers working to develop 5G technologies.

5G will enable cloud computing to hold and process more data at a faster rate. This will also mean that VR devices will connect directly to the cloud without the need for additional computing devices to power them (see Figure 24). (Wiltz, 2017); (Blouin, 2020)

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Figure 24: Connection of 5G with VR (Source: https://www.mccourier.com/5g-in-virtual-reality-market-to-perceive-biggest-trend-and-opportunity-with-key-players-facebook-huawei-technologies-zte-corporation-samsung-electronics-qualcomm/)

9.3. Virtual Reality technology will be used for real 3D Movies and Videos

The Real 3D format is natively digital. This means that movies have to be produced in a digital 3D format for projection on film-less digital projectors. Real 3D cinemas also use a passive circular polarizing technique to achieve 3D which allows viewers a clear image even when turning or tilting their heads.

Users can Experience 3D for now. But real 3D will be based on VR technology. In real 3D, users can see themselves as a part of the movie. Users can feel the film from their choice of angle, not from the camera's choice. Users can feel colors and can get a better view. (Clifford, 2020); (Vivian, 2018)

9.4. Learning purpose

The quality of learning will improve with the use of VR. Virtual Reality can be used to enhance student learning and engagement. VR education can transform the way educational content is delivered; it works on the premise of creating a virtual world - real or imagined and allows users not only to see it but also interact with it. Being immersed in what users are learning motivates them to fully understand it. It'll require less cognitive load to process the information. (Clifford, 2020); (Marr); (Almaida, 2020)

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9.5. Travelling

With the use of VR users will be able to travel over the space from Earth and that will also be in 3D. With the use of 3D Virtual Reality, users would be able to view and feel the place before the actual arrival. Users would judge the feel of the place before actually going there.

VR has become a new form of showrooming, an incredible 3D taste of a destination that will make travelers long to experience the real thing. Haptic technologies will also influence the way users book travel and how they prepare for it. Through clever technologies, Users will be able to feel the sand on the beach before they actually get there or the mossy ground under our feet in a virtual rainforest. (Clifford, 2020)

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UNIT NUMBER: Didactic Unit 10

Exercises: Virtual Reality with Unity

UNIT PRESENTATION

The practical usage of VR has increased over the last years and more and more VR applications are emerging. Therefore it is important to have knowledge about the topic “Development with VR”.
In this unit we will take a practical approach towards the field of VR. Therefore we will create a small and well understandable example application to demonstrate basic principles of developing with VR. The following exercises will give you a basic overview over the important points when working with VR and also let you understand the basic principles.

OBJECTIVES

The goal of this unit is to demonstrate an easy way of developing an application that contains VR. Furthermore we want to show how to use the Virtual Reality Toolkit inside the Unity Engine and build a small VR application. This VR application serves as a starting point for students who want to start developing VR applications or want to go deeper into the topic of creating VR content with Unity.

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CONTENTS DEVELOPMENT

10.1. Introduction

In this section we will create a simple example project to demonstrate how you can include VR into an application. For this we use the Unity Engine (https://unity.com/) and the Virtual Reality Toolkit (VRTK) (https://vrtoolkit.readme.io/).

The Unity Engine is a games engine that provides us with an environment to develop our exercises. Furthermore it is free for noncommercial projects and has a large community as well as a rich ecosystem around it. This makes it the ideal environment for our exercises.

VRTK is a toolkit for easy development of VR-applications in Unity. It provides various useful scripts to work with VR and to simplify the whole development process. Furthermore it provides a VR-simulator for testing VR-apps inside Unity without the need for a VR-device and also allows easy development for multiple VR-devices. These characteristics make VRTK ideal for our project.

The exercise section is structured in the following way: First we provide you information for setting up your environment for the exercises. After that we continue with the exercise itself.

10.2. Set Up

First of all, you have to get Unity. Therefore go to https://store.unity.com/download-nuo where you can download the Unity Hub under “Get Started”. Be sure to read and understand the license information for the underlying “Personal”-license. Install the Unity Hub after the download has finished.

Furthermore you have to create an Unity-account on the same page by clicking on the person-icon. After that select “Create a Unity ID” and follow the steps.

After installing the Hub and creating your Unity-account start the Unity Hub and log in with your credentials. Then you click on your username and select the tab “License Management”. There you select “Activate new license” to add a license for working with Unity. Select the Unity Personal license and verify that you are under the given license conditions or select another paid license if it suits your current situation. Finish this step by clicking on done.

With your activated license you are now able to download the Unity Engine. Therefore you have to go back to the main screen, click on “Installs” and select “Add”. In the pop up you can select a Unity version of your choice (LTS is preferred) but keep in mind that these exercises were made with Unity version 2019.4. With the “Next button” you can install

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additional components for Unity like Visual Studio for coding or Android Build Support (see chapter X). Select all components that you need and click on “Done”. After that Unity will be downloaded to your device. Be aware that this process may take some time.
When Unity is installed, you can create a new project through the Hub by clicking “New” in the projects section.
VRTK can be obtained through the Unity Asset Store (https://assetstore.unity.com/packages/tools/integration/vrtk-virtual-reality-toolkit-vr-toolkit-64131). There you have to log in with your Unity account. After that you are able to add VRTK to your assets by clicking on “Add to my Assets”. Then you can import VRTK by opening your desired Unity project and then opening the package manager under “Window” → “Package Manager”. Inside the package manager you have to select “My Assets”. After that you can import VRTK by selecting VRTK in the list and clicking “Import”.

10.3. Exercise

For the VR-exercise we want to build a small indoor scene where a player can walk around and has to place a cube on a pressure switch to open a door.

10.3.1. 3D Models

For this scene we need some 3D-objects, mainly a room with a door, a cube and a pressure switch. For the cube we will be using the default standard cube already built in Unity. The indoor room with its door and the pressure switch were modeled using blender (https://www.blender.org/) but you can also use ProBuilder which is a tool for 3D-prototyping which is already included in Unity (see https://blog.unity.com/technology/probuilder-joins-unity-offering-integrated-in-editor-advanced-level-design). Since the creation of the 3D-models is a topic in itself it will not be covered in this exercise. When you create your models in an external program (like blender) you have to export them in a supported format (FBX is recommended) and then drag and drop your model file into the “Assets” tab in your project (see https://docs.unity3d.com/2020.2/Documentation/Manual/ImportingModelFiles.html for more information). The cube can be added by right clicking on the “Hierarchy” tab and selecting “Cube” under “3D Object”. After that you need to arrange your objects in a meaningful way (see Figure 25).

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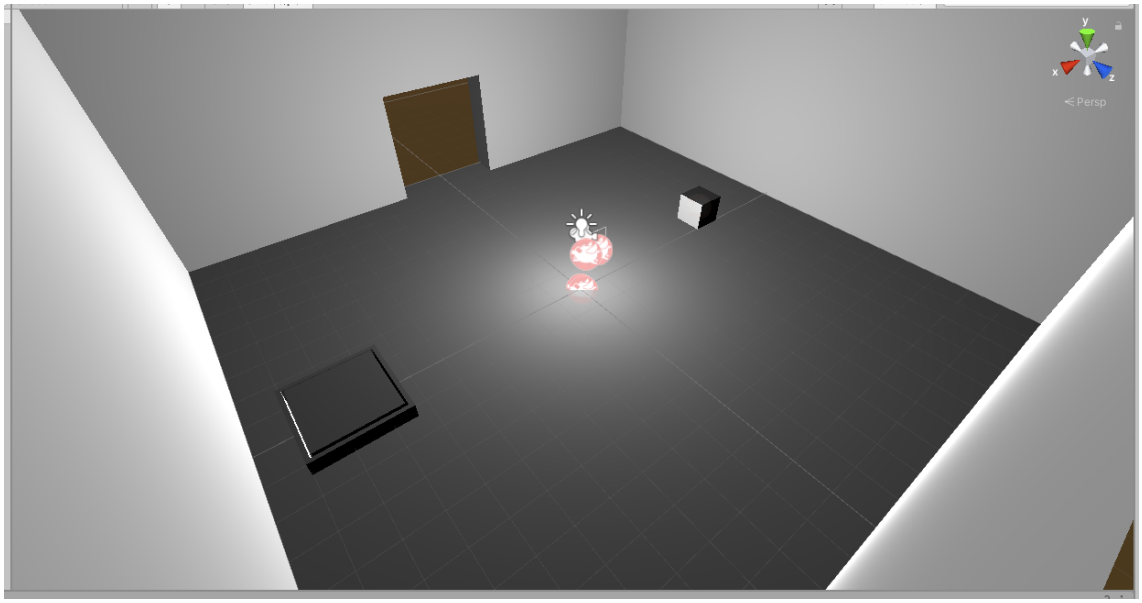


Figure 25: Basic object set up for VR example application

10.3.2. VRTK Player Set Up

After we successfully imported and arranged our objects, we need to enable VR by adding VRTK scripts to our objects. Therefore we start by adding the player to our scene. The player object has a special role in VRTK because it defines with which device the game will be used.

For this exercise we use the so called “VRSimulator” which can be used to build VR applications and test them inside Unity without the need to have a VR device on hand. If you want to build your game for multiple devices or test the app with the simulator and build it for a specific device, you may have a look into the sample scenes provided by VRTK under VRTK → Examples in the “Assets” tab. There VRTK shows the usage of the “SDKSetupSwitcher” which can be used to achieve the mentioned cross device development.

To add the player object, we first have to create an empty GameObject by right clicking on the “Hierarchy” tab and selecting “Create Empty”. We rename this GameObject to SDK Manager. Inside the SDK Manager we add the “VRTK_SDK Manager” script by clicking “Add Component” inside the “Inspector” tab after we select our SDK Manager. Inside the component selection we add the name of the script to the search bar and add the correct script by clicking on it.

After that we create a new empty GameObject, rename it to Simulator and drag and drop it to our SDK Simulator so that it’s placed indented under the SDK Manager. With this process the Simulator becomes a child object of the SDK Manager which is important for VRTK to work.

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The following step is to add the VR simulator as a child of the Simulator GameObject. Therefore we navigate to VRTK→ Source→ SDK→ Simulator in the "Assets" tab. There you can find the [VRSimulator_CameraRig] which is a prefab provided by VRTK that contains all necessary scripts and objects for the simulator object. Drag and drop the VRSimulator_CameraRig from the "Assets" tab to our "Hierarchy" tab and make it a child of the Simulator.
The final step for setting up the player is to connect the nested GameObjects. Therefore we select the Simulator and select the Simulator SDK in the SDK Selection section. After that press on "Populate Now" to add the Simulator Camera Rig. Then select the SDK Manager and click on "Autopopulate". This step adds the Simulator to the list of Setups in the VRTK_SDK Manager script. After that the player set up is almost completed.

10.3.3. Hands

To interact with objects, we need hands for our player. To create these, we first create another empty GameObject and rename it to hands. After that we create two more empty GameObjects, make them children of Hands and rename them to left respectively right hand. Then we add the VRTK_Pointer and VRTK_StraightPointerRenderer scripts to enable a pointer for our hands, the VRTK_ControllerEvents script to enable different kinds of interactions for our hands and the VRTK_InteractTouch and VRTK_InteractGrab scripts to enable touch and grab interaction for both hands. The last step is to select the SDK Manager and to drag and drop the corresponding hand into the field for Left respectively Right Controller.

10.3.4. Interactable Objects

To enable objects for interactions with our player we have to make them interactable. This step is pretty complicated if you want to do it manually, but VRTK offers an automatic way of doing that. For this you just select the object you want to become interactable (e.g., the cube we added recently) and click Window→ VRTK → Setup Interactable Object in the upper menu in the Unity editor. After that you have the possibility to customize the basic behavior of your interactable object in a pop up, although the standard settings are sufficient for this exercise. To finish the process just click "Setup selected object(s)" in the pop up and close the pop up. The last step then is to add the Left/Right Hand object to their corresponding fields inside the VRTK_ChildOfControllerGrab script of your interactable object.

10.3.5. Additional Scripts

To give our exercise the last finishing touch we add some C# scripts to provide some functionality to our VR application. These scripts do not interact with VR and therefore we will not explain them in detail. The used scripts are shown in Figure 26 and Figure 27.

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```
{
    public float speed = 1;

    public MoveWith[] attached;

    Coroutine moveC = null;

    0 Verweise
    private void OnCollisionEnter(Collision collision)
    {
        GameObject other = collision.gameObject;
        if(other.tag == "Placeable")
        {
            movePlatte(false);
        }
    }

    0 Verweise
    private void OnCollisionExit(Collision collision)
    {
        GameObject other = collision.gameObject;
        if (other.tag == "Placeable")
        {
            movePlatte(true);
        }
    }

    2 Verweise
    private void movePlatte(bool up)
    {
        Debug.Log("moving " + (up ? "up" : "down"));
        if (moveC == null)
        {
            moveC = StartCoroutine(move(up));
        }
    }

    1-Verweis
    private IEnumerator move(bool up)
    {
        float increase = 0.005f;
        float waitingTime = increase / speed;
        yield return new WaitForSeconds(0.1f);
        for(float i = 0; i < 1; i += increase)
        {
            foreach(MoveWith other in attached)
            {
                other.move(up, i);
            }
            yield return new WaitForSecondsRealtime(waitingTime);
        }
        moveC = null;
    }
}
```

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Figure 26: PressureSwitch Code

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

2 Verweise
public class MoveWith : MonoBehaviour
{
    public Vector3 offset;

    public bool invert;

    private Vector3 startPos;

    private Vector3 targetPos;

    0 Verweise
    private void Start()
    {
        startPos = transform.position;
        targetPos = startPos + offset;
    }

    1-Verweis
    public void move(bool toStartPos, float position)
    {
        if(toStartPos ^ invert)
        {
            moveTransform(targetPos, startPos, position);
        }
        else
        {
            moveTransform(startPos, targetPos, position);
        }
    }

    2 Verweise
    private void moveTransform(Vector3 Start, Vector3 End, float Position)
    {
        transform.position = Vector3.Slerp(Start, End, Position);
    }
}
```

Figure 27: MoveWith Code

The main purpose of the PressureSwitch script is to detect if the cube is currently placed on the switch or got removed from the pressed switch. This is done by checking if there is a collision between an object that has been tagged with “Placeable” and the inner part of the pressure switch. If that is the case the script will continuously count a variable from zero to one. Furthermore the script recognizes whether the other object was placed on the switch or removed from the switch. This information, together with the current value of the variable will then be transmitted to all attached MoveWith scripts.

The purpose of the MoveWith script is to move an attached object between its initial starting position and a defined end position depending on a passed parameter and a Boolean that

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describes whether the object should move to the starting or the target position. The script uses these parameters to interpolate the position of the object and to change its current position.

10.3.6. Testing & Further Information

To test your application just click the “Play” button in the middle upper part of the Unity editor and follow the instructions given by VRTK to move the player and its hands. To grab an object, hold down CTRL-key, place the appearing cross on the object and press the left or right mouse button depending with which hand you want to grab the object. To release the object just press the same mouse button you used for grabbing it. To move the grabbed object switch to hand, move mode and move the hand that grabs the object.
For further information on how to work with VRTK and on how to build for real VR devices consult the VRTK documentation available under https://vrtoolkit.readme.io/ or the VRTK YouTube channel under https://www.youtube.com/channel/UCWRk-LEMUNoZxUmY1wO7DBQ. If you need more information regarding Unity, take a look into the Unity documentation available under https://docs.unity3d.com/Manual/index.html

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AUGMENTED REALITY

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Augmented and Mixed Reality

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UNIT NUMBER: Didactic Unit 11

Introduction to Augmented Reality / Mixed Reality

UNIT PRESENTATION

This unit serves as an introduction for the terms Augmented Reality (AR) and Mixed Reality (MR). Whereas Virtual Reality (VR) works purely digital, AR and MR work in union with the physical, real world.

OBJECTIVES

After this section students know the basic ideas and concepts of both of these terms. The main focus here is to distinguish AR and MR and to give a broader understanding on why there are two different terms that describe similar conditions and what the specifics are that distinguish them.

CONTENTS DEVELOPMENT

Augmented Reality (AR) is a technology that lets the user experience a version of reality that has been augmented to stimulate different human senses. These senses can be:

- Visual (see something)
- Auditory (hear something)
- Haptic (grasp something)
- Somatosensory (feel something)
- Olfactory (smell something)

Visual: The visual stimulation happens through the eyes. Since AR mainly focuses on creating a visually enhancing experience this is the main sense that will be interacted with.

Auditory: The next most common human sense in terms of triggering or stimulation is hearing which can be interacted with, with sounds of all kinds.

Haptic: The ability to grasp objects that are virtual is important since grasping in augmented environments or scenes can sometimes either enhance the situation greatly or at least make the experience more convenient.

Somatosensory: Being able to feel in an augmented scenario can be very beneficial since it goes even further than just the basic haptic feedback when grasping something. It expands the possibilities and use cases and enables more sophisticated scenarios to be more immersive.

Olfactory: While all senses are generally important for the best experience possible, the olfactory sense can be ranked as the lowest of priorities in most AR scenarios (Craig, 2013).

AR can be described as interactive since it usually features the option for the user to interact with the environment. This defines the need for 3 mandatory features that have to be implemented into an AR-environment. For AR to work properly real-time-interaction, a visual representation of the real world and the augmented parts, as well as a 3D registration of where the user and where objects are, are needed. In contrast to Virtual Reality (VR) Augmented Reality only changes or enhances the environment it does not replace it fully. AR is used to enhance real world scenarios and situations by offering the enhancement of the surrounding environment through computer supported data acquisition (e.g. sensory data, that can be visually displayed in the world for the user). The beginnings of AR can be traced back to the early 1960s where it was conceptualized for a military context by the US-Army. Today AR can be used in several different fields. These fields include amongst others:

- Entertainment
- Commerce
- Industrial Manufacturing
- Education

Mixed Reality (MR) on the other hand is described as the space in between the extremes of VR and AR. Accordingly MR describes the whole spectrum between physical reality and pure virtuality (Milgram (1994), p. 283). MR measures the whole continuum, excluding both extremes on each side (AR and VR), and combines all possible variations of real and virtual objects. All three of these terms AR, MR, and VR can sometimes be difficult to distinguish, especially MR and AR. That is why the general idea to specify MR is to state that in MR, physical and virtual objects are being combined. Important is the degree of virtuality which means at which state of virtuality it still can be called expanded reality (Augmented Reality) or whether it is already augmented virtuality (tekla, n.d.).

- MR based on the virtual world (augmented virtuality) means that primarily real elements (persons or physical objects) are displayed in a virtual world.
- MR based on the real world (Augmented Reality) states that the real world is the main focus and is expanded to include virtual elements e.g., projecting graphs or videos into the real world (tekla, n.d.).

REMEMBER TIPS

AR is an interactive technology which enables a user to interact with the environment.
AR requires real-time-interaction, a visual representation of the real world and 3D registration.
Compared to VR, AR only changes the visualization through enhancement; it does not replace it fully.
MR describes the space between VR and AR.

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UNIT NUMBER: Didactic Unit 12

Definition of Augmented Reality / Mixed Reality

UNIT PRESENTATION

In this section the definitions of the term AR and MR are described.

OBJECTIVES

Clarify the terms and provide clear definitions.

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CONTENTS DEVELOPMENT

12.1. Definition of Augmented Reality

AR describes a computer-aided perception or presentation, which expands the real world with virtual aspects (Markgraf, 2018).

Augmented Reality (AR) is an enhanced version of the real physical world that is achieved through the use of digital visual elements, sound, or other sensory stimuli delivered via technology. It is a growing trend among companies involved in mobile computing and business applications in particular (Hayes, 2020).

12.2. Definition of Mixed Reality

When talking about Virtual- or Augmented Reality the term Mixed Reality (MR) has to be explained as well. According to Microsoft, Mixed Reality is a spectrum whereas Augmented Reality enhances the real world with information, while Virtual Reality completely creates a new virtual world (Ronsdorf, 2020).

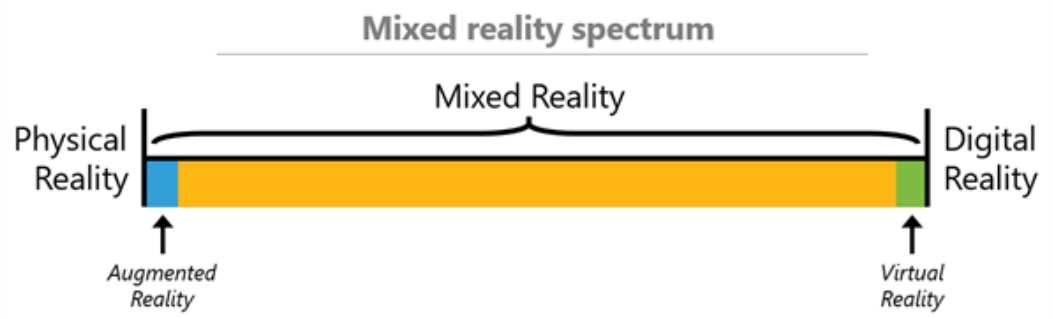


Figure 1: Mixed Reality spectrum (Source: https://news.microsoft.com/de-de/microsoft-erklaert-was-ist-mixed-reality-definition-funktionen/)

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UNIT NUMBER: Didactic Unit 13

Working of Augmented Reality / Mixed Reality

UNIT PRESENTATION

This section contains information about how AR and MR work and what the difference between them is.

OBJECTIVES

The objective of this section is to explain the functionality of AR and MR in a more detailed scope.

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13.2. Working of Mixed Reality 11

CONTENTS DEVELOPMENT

13.1. Working of Augmented Reality

According to Craig (2013) two things need to happen for every step in an AR application for AR to work:

1. The application needs to keep track of the current state of the physical world and the current state of the virtual world
2. The application needs to display elements of the virtual world in a way that they are intuitively recognized by the participant and blend in with the physical world

For AR to work there are three major components needed (Craig, 2013):

1. Sensor(s) to determine the current state of the physical world
2. Processor(s) to evaluate sensor data according to the rules and settings of the virtual world
3. A display that is able to transmit the complete result creating the impression of the virtual and physical world coexisting together

For AR applications to work properly they must gather information about the physical world in real time. For this the already mentioned sensors are usually split up into three different categories:

1. Sensors for tracking
2. Sensors for gathering information about the environment
3. Sensors for user input

- Sensors responsible for tracking are generally implemented through the use of a camera. This camera, also sometimes called computer vision, enables the application to realize where its position currently in the real world is. This includes location and rotation. While gathering visual information with the help of a camera is necessary there is usually also an advanced software supporting this step since just getting the visual information is not enough to determine spatial distances, rotation and location (Craig, 2013).
- Sensors that are responsible to gather information about the environment provide the user additional information that might be interesting in the current use case. Environmental information might be surface temperatures that are examined by temperature sensors of the device which then can be visualized showing "hot spots" on surfaces of objects (Craig, 2013).
- The sensors responsible for gathering user input are e.g., keyboards, touchscreens or other displays that allow for user input.

Processors in AR applications must be able to calculate the necessary information which include all the different inputs from every sensor in real time. Depending on the context and scope of the AR application a handheld device might be sufficient. This does not always apply though. In some cases, workstation or powerful distributed systems are necessary to provide the required computing power.

Displays can be categorized into what sense they stimulate. In most cases displays provide feedback to the user in an audiovisual form which means they provide visual information in form of a video stream and auditory information in the form of sound (Craig, 2013).

13.2. Working of Mixed Reality

The concept of Mixed Reality is driven and endorsed by Microsoft since they own and developed their in-house product the Microsoft HoloLens. With MR it is possible to place holograms in the real world (XR Today, 2021).

Since MR is defined as a spectrum it is harder to narrow it down and clearly define where it begins. Mixed Reality is a mixture of the physical and digital world and enables the intuitive 3D-interaction between humans, computers and the environment. Whereas both

extremes on the spectrum have their benefits and restrictions, MR being the space between AR and VR it can try to combine the benefits of both (XR Today, 2021).

REMEMBER TIPS

Multiple steps that are necessary to get AR to work:

- Videorecording
- Tracking
- Registration
- Representation
- Output.

Mixed Reality applications:

- Spatial mapping
- Hand tracking
- Eye tracking
- Voice input.

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UNIT NUMBER: Didactic Unit 14

History and Evolution of Augmented Reality

UNIT PRESENTATION

Augmented Reality has had a great and fast development in recent years. You may have seen or even played Pokémon Go or read some news about the Microsoft HoloLens. But the history of AR began back in the 1960s where the first ideas of combining the real world with computer-generated objects appeared (Schmalstieg & Höllerer, 2016). After the first steps of AR and its usage in a cockpit of an army pilot the evolution of AR began, like the "Studierstube" by Schmalstieg & Höllerer (2016) in 1996, until Augmented Reality has developed to the state you know (Billinghurst, Clark, & Lee, 2015).

OBJECTIVES

In this unit, you get to know the history and evolution of Augmented Reality from the early beginnings to the current state. You are able to see the development and different purposes behind a certain evolution.

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14.1. The early beginnings 13
14.2. The birth of the term "Augmented Reality" and further development 15
14.3. After 2000 and the development in mobile computing AR 18

CONTENTS DEVELOPMENT

14.1. The early beginnings

In this first section, you will read information about the early beginnings of Augmented Reality in the 1960s from the first ideas and the first usage of AR. Furthermore, you will get to know the "Videoplace" which was one of the first interactive collaborative graphical overlays.

1960s: The first ideas of combining the physical world with computer-generated information appeared (Schmalstieg & Höllerer, 2016).

1965: Ivan Sutherland, started an investigation in the field that would develop into VR and AR. He wrote in his essay “ultimate display”:

”The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming, such a display could literally be the Wonderland into which Alice walked.” (Schmalstieg & Höllerer, 2016, p. 4)
Furthermore, he said: “The user of one of today’s visual displays can easily make solid objects transparent—he can “see through matter!” (Schmalstieg & Höllerer, 2016, p. 4) which refers to AR (Schmalstieg & Höllerer, 2016).

1969: Tom Furness and others worked on the Super-Cockpit program for the US Air Force to create new ways to present more complex flight details to the pilots (Billinghurst et al., 2015). They prototyped an HMD which overlays computer graphics over the pilot’s view of the real world. Additionally, during bad weather and night computer graphics could be used as substitutes for the real world (Billinghurst et al., 2015). You can see this in Figure 2.

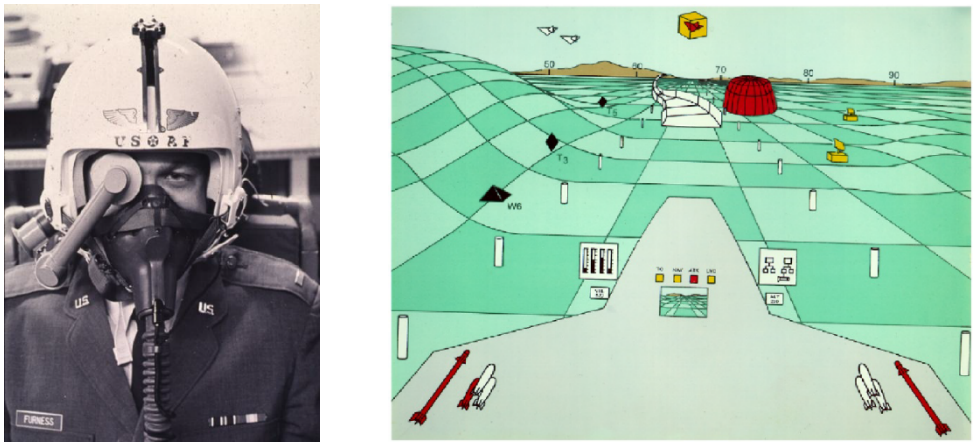


Figure 2: Pilot wearing the head-mounted display (left), artist drawing of the view of the Super-Cockpit (right) (Source: Billinghurst et al. (2015))

1970s-1980s: Myron Krueger, Dan Sandin, Scott Fisher, and others investigated with multiple “concepts of mixing human interaction with computer-generated overlays on video for an interactive art experience” (Schmalstieg & Höllerer, 2016, p. 5). Around 1974 Krueger presented his Videoplace installations, which contain collaborative interactive graphical overlays among participants’ silhouettes (Poetker, 2019); (Schmalstieg & Höllerer, 2016). You can also see Kruegers Videoplace here: https://www.youtube.com/watch?v=d4DUIeXSEpk&t=161s

1980s-1990s: Improvements in computing performance made it possible for AR to arise as an independent field of research (Schmalstieg & Höllerer, 2016).

14.2. The birth of the term "Augmented Reality" and further development

In this section, you will get to know a lot of different developments about Augmented Reality between 1990 till 2000. AR experienced great evolutions during this time span, like the usage of AR in medicine to observe a foetus, the "Studierstube" – a first collaborative AR system, or the development of AR in television.

1992: Birth of the term "Augmented Reality". AR was first mentioned in the work of Caudell and Mizell at Boeing. They developed a see-through HMD, which should help workers in an airplane factory and show the wire bundle assembly schematics (see Figure 3) (Schmalstieg & Höllerer, 2016).



Figure 3: HMD used at Boeing to show the wire bundle assembly schematics (Source: Schmalstieg & Höllerer (2016))

1993: Feiner, MacIntyre, Haupt, and Solomon (1993) presented KARMA. This system incorporated knowledge-based AR and was able to automatically derive instruction sequences for repairing and maintaining (Schmalstieg & Höllerer, 2016).

1993: Fitzmaurice built "the first handheld spatially aware display" (Schmalstieg & Höllerer, 2016, p. 6), which served as a forerunner for handheld AR. The Chameleon contains a tethered handheld liquid-crystal display (LCD) screen (Schmalstieg & Höllerer, 2016).

"The screen showed the video output of an SGI graphics workstation of the time and was spatially tracked using a magnetic tracking device. This system was capable of showing contextual information as the user moved the device around—for example, giving detailed information about a location on a wall-mounted map." (Schmalstieg & Höllerer, 2016, p. 6).

1994: State et al. introduced a medical AR application for physicians to see a fetus inside a pregnant patient (see Figure 4). That application shows the usage and importance of AR in medicine (Schmalstieg & Höllerer, 2016).



Figure 4: Using AR in medicine to observe a fetus (Source: Schmalstieg & Höllerer (2016))

Mid 1990s: Steve Mann developed "a "reality mediator" – a waist-bag with a video see-through HMD that enabled the user to augment, alter or diminish visual reality" (Schmalstieg & Höllerer, 2016, p. 8). This research led to the establishment of the academic field of wearable computing and mediated reality, which had similarities and synergies with AR (Schmalstieg & Höllerer, 2016).

1995: Rekimoto and Nagao built first handheld AR display (tethered), called NaviCam. It was connected to a workstation and was equipped with a forward-facing camera. It could "detect color-coded markers in the camera image and display information on a video see-through view" from the video feed (Schmalstieg & Höllerer, 2016, p. 8).

1996: Schmalstieg & Höllerer (2016) built the first collaborative AR system, called "Studierstube". Many users were able to sense the virtual objects in the same shared area (see Figure 5). "Each user had a tracked HMD and could see perspectival correct stereoscopic images from an individual viewpoint." (Schmalstieg & Höllerer, 2016, p. 9). In contrast to multi-user VR, communication cues like "voice or body posture" were not affected in this application because "the virtual content was added to a conventional collaborative situation" (Schmalstieg & Höllerer, 2016, p. 9).

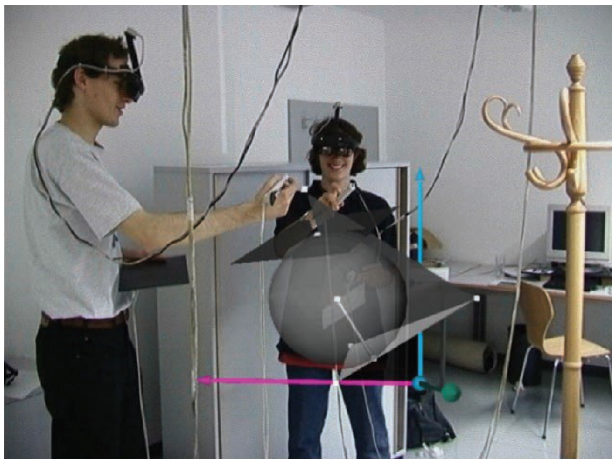


Figure 5: Using AR to experience virtual objects in the same shared space: The "Studierstube" (Source: Schmalstieg & Höllerer (2016))

1997-2001: Japanese government and Canon Inc. funded the Mixed Reality Systems Laboratory. It was the largest research facility for Mixed Reality. They designed the first coaxial stereo video see-through HMD, called COASTAR (Schmalstieg & Höllerer, 2016).

1997: MacIntyre, Höllerer, Feiner, and Webster (1997) build the first outdoor AR system, called "Touring Machine". It uses a "see-through HMD with GPS and orientation tracking" (Schmalstieg & Höllerer, 2016, p. 9). Furthermore, it required a "backpack holding a computer, various sensors, and an early tablet computer for input" for delivering mobile 3D graphics via this system (Schmalstieg & Höllerer, 2016, p. 9).

1998: Thomas, Demczuk, Piekarski, Hepworth, and Gunther (1998) introduced an outdoor AR system as well, called Map-in-the-Hat. Thereafter, Tinmith (an acronym for "This is not map in the hat") developed into a well-known experimental platform for outdoor AR. It was used for advanced applications like 3D surveying, or the first outdoor AR game, called ARQuake (Schmalstieg & Höllerer, 2016).

1998: Raskar, Welch, and Fuchs (1998) build a telepresence system with the idea of structured light-scanning and projector-camera systems. It was presented as the Office of the Future. But it was not very practical for everyday use at the time (Schmalstieg & Höllerer, 2016).

1998: First usage of Augmented Reality in Sports television in a live NFL game showing the 1st & Ten markers. It shows a yellow line marker where the next first down is achieved. This technology is still used today with further information and graphics (Poetker, 2019).

If you want to see how that looks like, you can watch this YouTube video: https://www.youtube.com/watch?v=1Oqm6eO6deU&t=3s

1999: Kato and Billinghurst released ARToolKit, which was the first open-source software that was available outside of specialized research labs. It offered a 3D tracking library that uses fiducials, which could be printed with a laser printer (Billinghurst et al., 2015); (Schmalstieg & Höllerer, 2016).

1999: Germany's Federal Ministry for Education and Research started a €21 million program for using AR in industry, called ARVIKA (Schmalstieg & Höllerer, 2016). Over 20 research groups from industry and research worked on developing advanced AR systems for industrial application, especially for the automotive industry. The project raised worldwide awareness of AR (Schmalstieg & Höllerer, 2016).

1999: IBM researcher Spohrer published an essay on Worldboard, "a scalable networked infrastructure for hyperlinked spatially registered information" (Schmalstieg & Höllerer, 2016, p. 12). This was the first concept of an AR browser (Schmalstieg & Höllerer, 2016).

14.3. After 2000 and the development in mobile computing AR

In this section, you will learn about the evolution of AR in the time between 2000 till today. During this time the development of Augmented Reality in the field of mobile computing experienced great attention: the first handheld AR system running on a personal digital assistant was developed, the first AR Sony PlayStation 3 game was published, Pokémon Go and other AR games and apps were created.

After 2000: Fast development in mobile computing and usage of AR in this area (Schmalstieg & Höllerer, 2016).

2003: Wagner and Schmalstieg developed the first handheld AR system running autonomously on a "personal digital assistant" (short PDA), a forerunner of the smartphones (Schmalstieg & Höllerer, 2016).

2005: Pintaric et al. published the multiplayer handheld AR game "Invisible Train" (Schmalstieg & Höllerer, 2016).

2007: The Sony PlayStation 3 game "The Eye of Judgement" was released, which is one of the first games that made AR available for the masses. It was a card-based battle game, which uses the PS3 camera to show the AR video game characters on the physical cards (Billinghurst et al., 2015).

2008: Wagner et al. presented the first truly usable natural feature tracking system for smartphones. This work is known as “the ancestor of the Vuforia toolkit for AR developers” (Schmalstieg & Höllerer, 2016, p. 13).

2011: Newcombe et al. build the KinectFusion system, which builds detailed 3D models from an inexpensive depth sensor (Schmalstieg & Höllerer, 2016).

2013: Volkswagen presented the MARTA app (Mobile Augmented Reality Technical Assistance) to help technicians with step-by-step instruction (Poetker, 2019).
Watch this video if you want to get an impression of how this looks like: https://www.youtube.com/watch?v=H7RzyjNJH6c

2014: Debut of Google Glasses: it is a pair of Augmented Reality glasses. The user could achieve further information of their environment shown as digital graphics on their glasses. They could communicate with the Internet via natural language processing commands (Poetker, 2019).

2016: Microsoft’s HoloLens is introduced. It is more advanced than the Google Glasses. It is a wearable computer and allows the user to create their own AR experience in their environment (Poetker, 2019).

2016: Pokémon Go made AR available and popular for the masses of the people (Poetker, 2019).

2017: IKEA presented the IKEA Place AR app. The users can experience virtually how it would look like to have specific furniture e.g. in their living room (Poetker, 2019). This link provides you a video how the IKEA Place AR app looks like: https://www.youtube.com/watch?v=UudV1VdFtuQ

Today: AR is used in many different areas. A lot of retailers use AR for their shops and offer a virtual fitting room, which is a great opportunity for customers, especially during the pandemic. AR is also used for indoor navigation, f.eg., to guide people to the correct room (Makarov, 2021). In this video, you can get an impression of how this looks like: https://www.youtube.com/watch?v=VmROm6nbElA. Furthermore, it is used for remote assistance and virtual manuals, in the military, entertainment or gaming, and a lot of other areas, which will be discussed in more detail in chapter “Scope of AR”.

REMEMBER TIPS

- The first idea of Augmented Reality was in the 1960s
- During the time of 1990-2000 there was a great development of AR in various areas especially for AR as a collaborative system
- After 2000 the development of AR in the field of mobile computing and gaming arose

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UNIT NUMBER: Didactic Unit 15

Components of Augmented Reality systems

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CONTENTS DEVELOPMENT

An Augmented Reality system is more than just a pair of glasses with digital lenses. It is much more than that. First and foremost, the main components are divided into three categories. Hardware, software, and the application are all involved. These three topics will be discussed in greater depth below (Craig, 2013).

15.1. Hardware

The hardware section is subdivided into three major sections. It consists of sensors, processors, and displays. These are the three areas where hardware is required for the purpose of data capture, calculation, or visualization (Craig, 2013).

15.1.1. Sensor

Sensors provide information about our real world and send it to the AR application. The important values are the location and the orientation of the participant. These values are either gained through the glasses or from the cell phone. Furthermore, sensors provide

much more information, such as the temperature, lightness, darkness and some more types of values about the environment (Craig, 2013).
With the tracking of the location and orientation it is possible for the AR application to determine different factors in the real world. One example connected to this is the determination of the participant's location at the moment of his usage of the application.
Optical tracking can also be used through accessing the camera. It is the most used technique because by using the camera you get a lot of different information about the environment. Through optical tracking you can detect the location and orientation of the user from a handheld device (Craig, 2013).

15.1.2. Processor

The processor is a heart element in the entire AR system. Multiple processes can be handled by the processor at the same time. Firstly the processor processes the sensor data. Secondly the processor runs as a typical CPU and sometimes supports the GPU. The processor can be used in different ways. Additionally it is different where the processor is located. The most common options according to Craig (2013, p. 82 f.), are listed below:

- Application run on handheld system such as a smartphone
- Application run on handheld system connected to remote server(s)
- Application run on desktop/laptop computer
- Application run on desktop/laptop computer connected to remote server(s)
- Application run as a web application
- Application run on a cloud with a thin client
- Other combinations of local and remote systems

(Craig, 2013, p. 82 f.)

There are a lot of variations and combinations for an AR setup. Ultimately you should find a way that fits your application best.

15.1.3. Display

A display can provide information to the user of AR glasses in a variety of ways. This can be accomplished through visualization and audio signals. Audio and visual information are frequently combined. An audio signal, for example, can indicate that there is new information that is visualized. The visualization can be done in two dimensions or three dimensions. Measured values or more complex content, such as the content from applications designed for targeted interaction with the user, can be displayed. An example of this is that the user could use his hand to touch the displayed content, and the application would respond accordingly. (Craig, 2013)

15.2. Software

The software of AR glasses is divided into three major categories. The software on the AR device, the AR Application and some Libraries you can use for your own Application. (Craig, 2013)

15.2.1. Significant Components

The AR Software combines three main parts. As you can see in Figure 6 there is a software part that is running on the AR Device itself. It is a part of the device. To run an application, it needs software to create an application and finally there is a need to create content in an application. (Craig, 2013)

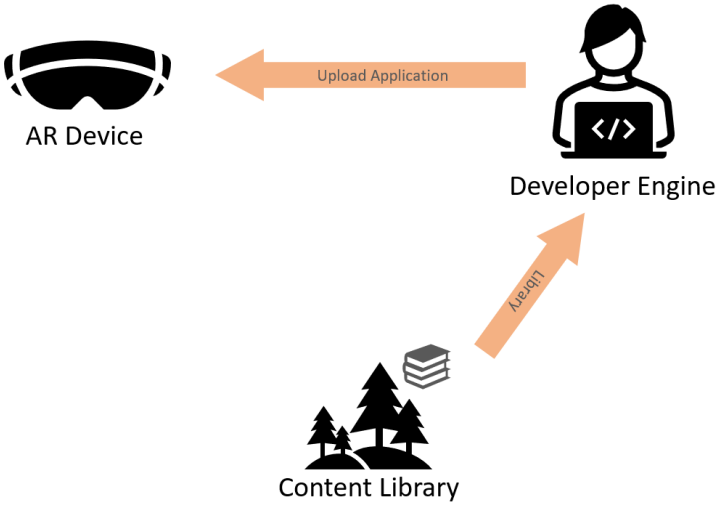


Figure 6: Main components of AR software

15.2.2. Software in the AR Device

The internal Software is working in different ways. The Software stays in contact with the environmental sensors, the application engine, other sensors and rendered visual and audio information. That is the basic work for this software in the AR Device (Craig, 2013). Figure 7 visualizes this part.



Figure 7: Basic layout of AR software (Image Rebuilt from Craig (2013, p. 128))

The software which interacts with the environmental sensors is working to get information on how the environment looks around the user. It uses the camera and analyses the image (Craig, 2013). The sensor integration is necessary to read the sensor values and prepare it into a piece of information for the app engine (Craig, 2013). The Application Engine is the heartbeat for the AR Device. It is listening to sensor, audio and the video data and provides some information for the participant. For example the App Engine shows some information about the environment (Craig, 2013). The Rendering Software takes care that all information is being made visible to the participant. It renders all information and sends it to the display devices (Craig, 2013).

15.2.3. Content Library

Libraries for AR Devices are accessible in a free and commercial way. Every library has specific capabilities and its own way of thinking about how an application has to be developed. Therefore it is important to think about the libraries before buying or starting to develop an application. Craig (2013, p. 133) gives some simple exemplary questions to think about what the application needs.

- What platform or platforms am I developing for?
- What sensors do I need to integrate?
- How many markers do I need to track simultaneously?
- What kind of graphics and audio are supported?
- How much can I afford to invest in development time vs cost to purchase a higher end AR library?"

(Craig, 2013, p. 133)

It is possible that it becomes necessary to compare libraries. Especially now that the AR field is growing, the choice of libraries is getting bigger and more diverse. For example, if two libraries are suitable for an application on their first impression, they should be compared. The next list shows some important questions by Craig (2013, p. 135) that help us compare libraries.

- What is the licensing arrangement? (Free?, Free for education? Fee?, etc. One-time purchase or ongoing license?, etc.)
- What is the level of support? (Commercial support? Open source community? None?, etc.)
- What platforms does it support? (Windows? MacOS? iOS? Android? Linux?, etc.)
- How difficult is it to use?
- Is training available for how to use it?
- What is its performance level?
- What input and output devices does it support?

- What types of content does it support?
- What kinds of interaction does it support?
- How widely is it used by other developers?

(Craig, 2013, p. 135)

15.2.4. Application

The development of an AR application is, for the most part, similar to the development of other applications. The Eclipse development environment, for example, can be used to create an AR application (Java-based). The speed of development is especially important in the development of an application. Waiting times are not an option for real-time applications. As a result, there are also special and recommended AR application environments that can be used to develop an application. It should be noted that certain license costs and development environments must be used depending on the target platform of an application. To develop an application with the Xcode IDE, for example, Apple requires a license (Craig, 2013).

As a result, the development of an application must be carefully considered. The libraries which are available are also affected by the environment and hardware. Even though AR application development involves content such as 2D, 3D, and audio, there are also individual specialization tools that can be used to create content in these areas (Craig, 2013).

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CONTENTS DEVELOPMENT

There are still no clear guidelines for determining which category a sort of AR system belongs in. It is, however, clear whether the device is a portable, smart glass, or helmet (Peddie, 2017).

16.1. Helmet

When a device covers most of the head, it is referred to as a helmet. As though it were a regular helmet. The helmet frequently covers the ears, head, and a large portion of the face (Peddie, 2017).

16.2. Head Up Display

Cars are frequently associated with a Head Up Display. The speed, fuel consumption, and a variety of other data can be presented here. The display can be projected three-dimensionally for the eye in the windshield, among other things. It's unknown when or if this will become a reality and be available for purchase. Of course, Head Up Displays are also available in buses, vehicles, and airplanes (Peddie, 2017).

16.3. Smart Glasses

In terms of size, the wearable smart glasses are similar to regular glasses. The lens serves as a display and can be used to create visualizations, or it can be used in conjunction with another visualization component. When it comes to glasses, it's important to note that they can be used both inside and outside. It has something to do with the illumination.

There's also the option of wearing sunglasses, which are obviously only appropriate for use outside (Peddie, 2017).

16.4. Handheld

We're probably most familiar with the portable version. It could be a phone, a computer, or a tablet. Objects that we use on a daily basis. Pokémon Go or a QR code scanner are two well-known AR applications for this.

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UNIT NUMBER: Didactic Unit 17

Scope of Augmented Reality

UNIT PRESENTATION

I am sure most of you have heard of Pokémon Go or even played it. Or may have recognized that during sports television further information and statistics are displayed. All of these are applications of Augmented Reality. But there is a lot more, like medicine, manufacturing and maintenance, shopping and so on. During this learning unit, you will get to know some of these.

OBJECTIVES

In this unit, you get to know different application areas for Augmented Reality. Furthermore, you have a look at these usages in more detail and get some impressions of them. There are a lot of links included in the sections. So have a look at them.
You are able to understand what possible application areas for AR are and can think of possible new ones.

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CONTENTS DEVELOPMENT

17.1. Training & Maintenance

Training and maintenance can be really stressful or exhausting. In this section, you will get to know how Augmented Reality can support training and maintenance and improve these processes.

As mentioned in the history section of AR, the usage for training and guiding workers in the aircraft industry with wire bundle assembly schematics was one of the first applications for AR in training. Instructions, hints, or support can be offered via AR to the trainee or worker (Dörner, Broll, Grimm, & Jung, 2013).

There are a lot of machines around the world with unique technology to maintain. It is very expensive or even not possible to train employees for maintaining every single variation of these machines. AR can be used to show how to maintain a specific machine (Dörner et al., 2013).

Additionally, studying the whole documentation is time-consuming and it cannot be ensured that the employee remembers every detail from the maintenance manuals. Using AR to show the instructions next to the maintained machine in the field of view of the employee is a more efficient way of training (Schmalstieg & Höllerer, 2016). Furthermore, higher accuracy for maintenance can be achieved with less training (Schmalstieg & Höllerer, 2016).

But AR can also be used for giving instructions or explain a user manual to make it more understandable for the user (Makarov, 2021). If you want to see, how this can look like, here are two YouTube videos of it:

https://www.youtube.com/watch?v=11NiyGoKOrk

https://www.youtube.com/watch?v=6ceN7YgSEdU

17.2. Entertainment

One of the first things that may come into your mind when thinking of applications of AR may be entertainment and gaming. In this section, you will learn how Augmented Reality is used for entertainment. Therefore, the usage in television and AR games are presented.

17.2.1. Television

AR is used in sports for displaying supporting information, f.eg. showing the distance to beat in ski jumping, or “down and distance” information in American football, or showing information in football, like player stats (Dörner et al., 2013). You can have a look at various examples in Figure 8, Figure 9, Figure 10 and Figure 11

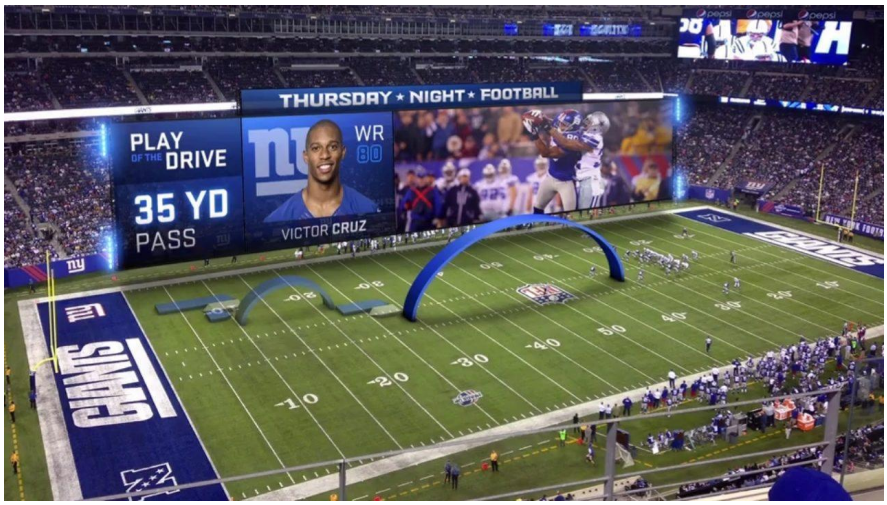


Figure 8: Using AR to show further information and statistics in an NFL football game (Source: https://vrscout.com/news/cbs-sports-super-bowl-liii-ar/)



Figure 9: Using AR to show the "down and distance" information in an NFL football game (Source: https://www.arcweb.com/blog/augmented-reality-digital-enterprise)



Figure 10: Another example of using AR to show additional information and statistics to a specific football player (Source: https://www.wtvision.com/en/augmented-reality-solution-for-football/)

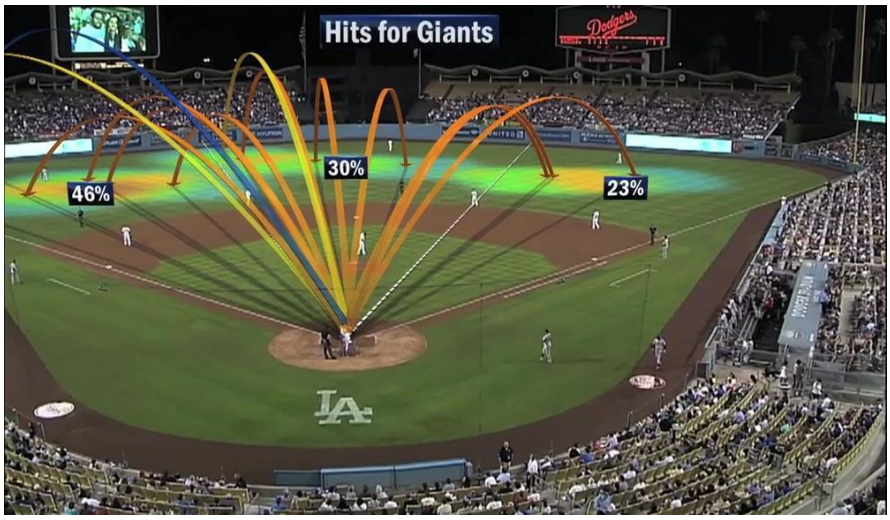


Figure 11: Using AR to show additional statistics in baseball (Source: https://www.queppelin.com/augmented-reality-in-sports/)

17.2.2. Games

As already mentioned in the history section, the usage of AR in the gaming area has developed (Dörner et al., 2013); (Makarov, 2021); (Poetker, 2019). With AR the user can have a greater gaming experience, while AR combines digital in-game objects with the real world (Von Itzstein, Billinghurst, Smith, & Thomas, 2017).

One of the most favourite AR games in the last couple of years was Pokémon Go, which was released in July 2016 (Niantic, 2016). In this game, you have to catch wild Pokémon which appear in your surroundings. While catching a Pokémon you can turn on your camera to see the digital Pokémon standing in your real environment. But there are a lot of other popular Augmented Reality games, like Angry Birds AR, Jurassic World Alive, Neyon Clash, or Harry Potter: Wizzards Unite (Farouk, 2021). Especially Neyon Clash is a relatively new idea for AR gaming. It is like a digital paintball game, which uses the real world as the room in which the different game modes take place. But the game extends the real world with digital objects, like targets, spawn areas, flags to capture, borders or statistics. If you want to see more about these games, here are some videos:

For Angry Birds AR: https://www.youtube.com/watch?v=0mxfWQL3K5A

For Jurassic World Evolution AR: https://www.youtube.com/watch?v=cHW1Py5xqTA

For Neyon Clash: https://www.youtube.com/watch?v=8PAdSot3urY

For Harry Potter: Wizards Unite: https://www.youtube.com/watch?v=ngHLSmAvCMQ

Furthermore, Simao & Bernardino (2017) developed an AR system, which is used in elderly institutions to offer active exercises as gamification. They try to fight the sedentary lifestyle. The digital objects are projected on the floor and the users can play the games while moving sideways, sitting, or moving their arms to interact with the system.

AR games are also used in different fields of education. Lehto, Luostarinen, and Kostia (2020) discuss an AR system, which should enhance the user experience of cultural

heritage locations. The game leads the user to various, not-so-popular, historical locations and will present information about it. But something essential is missing in every location. So, the user has to go around the place and look for codes to scan with the app of the game. Digital persons from different eras will appear and explain something about this place, give hints about the missing key, and provide challenges until the user has found the missing key (Lehto et al., 2020).

17.3. Shopping & Retailers

Augmented Reality is more and more used in shopping or retailer apps. In this section, you will learn how AR can support retailers and improve the shopping experience for customers.

In the last couple of years, AR is used more and more in shops (Makarov, 2021). For example, IKEA uses AR to give the customer the opportunity to see how some furniture would fit into their room, before buying it (see Figure 12) (Steuerwald, 2019).

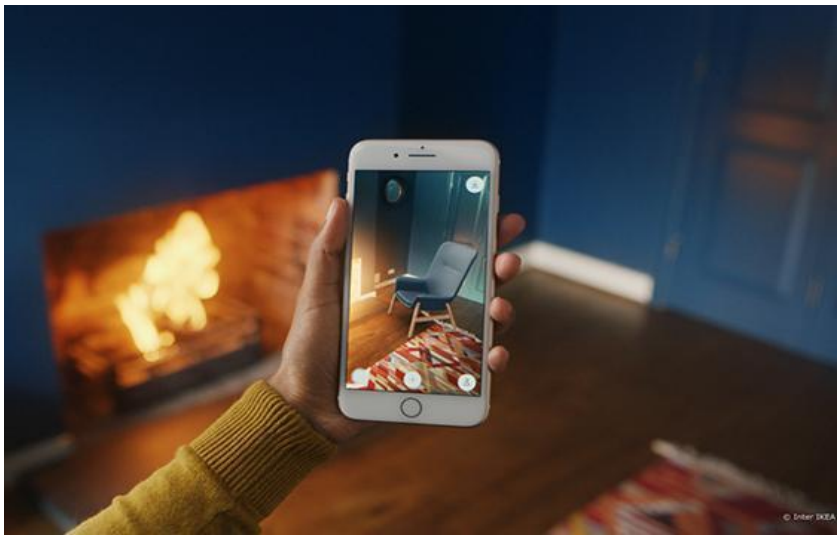


Figure 12: Using AR to improve the shopping experience for customers. Here you can see an example of the IKEA app (Source: Steuerwald (2019))

Using this technology can increase the customer's satisfaction, because they can decide which chair or table, for example, will fit into their room and then buy it, instead of buying a chair, noting that it actually does not fit and returning it back to IKEA. Other companies, like Lacoste or Sephora, offer virtual fitting rooms. The customer can see how it would look like to wear specific clothing. There are also AR shoe fitting and measuring tools (Dacko, 2016). Especially during the Covid-19 pandemic, this was a great opportunity for customers because they cannot wear the clothes in the shop to try them out (Makarov, 2021).

Furthermore, using AR technology has also a lot of advantages for the retailers (Dacko, 2016). With AR technology they can achieve a deeper level of customer satisfaction and increase the revenue (Dacko, 2016). Personalized digital content, discounts, and recommendations can help to increase customer satisfaction and loyalty. This personalized digital information is only available in the AR app of the shop and the retailer can provide this information for the customer in and outside of the store. So, therefore, the retailer can gain a competitive advantage over other competitors without using AR technologies (Dacko, 2016).
Such personalized information could be:

- Recommending a cooking receipt or what other products a customer could buy, regarding the products the customer bought before
- Show the way to the next product on the shopping list
- Show ingredients of a product that are important for the customer (f.eg. vegan, or lactose-free food)

With this information, the customer can build a connection to the product and associate it with the retailer (Dacko, 2016).
With the mentioned virtual fitting room, the retailers can improve the conversion rates. With other features, f.eg. by placing objects in your room, like in the IKEA app, the return rates can get reduced. Because the customer can have a first glance if this furniture or any other object would fit (Dacko, 2016). So, more people will just buy the object that will probably fit in their room. With the reduction of the return rate, the retailers can save a lot of money, because of the reduced transport costs (Dacko, 2016).

17.4. Education

AR has a very broad scope. Maybe you do not have thought of using AR for education, but there are a lot of opportunities for AR to support learning and understanding new things or to make learning more interesting.

AR can also be used for educational purposes, especially in school. Instead of just showing the information on pictures or maybe videos, using AR can make the representation more vivid. E.g., special experiments in science courses might not be possible in school due to lack of material and equipment. But with AR such experiments could be presented and enhance the understanding of this experiment and the underlying scientific concept (Sinha, 2021). AR can also be used for design or art courses. The students can create the digital object and have a look at it in AR to see the object from other perspectives in order to analyze, evaluate and improve it (Bower, Howe, McCredie, Robinson, & Grover, 2014).
Additionally, AR can increase the motivation of the students and affect the learning attitude in a positive way (Bower et al., 2014). AR can also enhance the enjoyment in learning and raise the level of engagement (Akcayir & Akcayir, 2016).

Especially during the Covid-19 pandemic, the usage of AR could really support education. AR provides a more diverse presentation of the teaching content by showing more information. And the students have the opportunity to look at the virtual object from different perspectives or rotate it in space to gain a greater understanding of it (Makarov, 2021).
Wikitude, e.g., developed an app called Ai.R-Cord, which should assist elementary students in Japan learning various subjects, but especially programming. If you want to read more about it:
https://www.wikitude.com/showcase/teaching-programming-with-ar/

Museums benefit from AR as well. They can make use of Augmented Reality in multiple ways. The simplest way is just to add further information next to the object. But they could also display the artist as a digital person, which explains something about their work. Or another version of the object is presented, e.g., there are dinosaur skeletons in the museum and the visitor can see what the dinosaurs looked like as a digital 3D object (Coates, 2020). If you like to read more about it or get an idea how this could look like, use this link:
https://www.museumnext.com/article/how-museums-are-using-augmented-reality/.
There are examples from multiple museums and art galleries, like the national museum of Singapore, the Smithsonian Institute, or the art gallery of Ontario.

17.5. Medicine

The use of MR/AR in medicine can be seen as a multidimensional domain, which has long been expected to be a disruptive technology. Medical MR/AR has potential uses in applications like medical education/training, treatment, rehabilitation, surgery planning, intraoperative navigation, and guided surgery. Therefore, a crossover of many technologies can be used, e.g., visual displays, camera tracking, computer graphics, computer vision, and robotic vision (Chen, Day, Tang, & John, 2017). In the following, we will provide a deeper look into the fields of treatment, surgical guidance, and medical education.

Treatment: One commercial system in the field of treatment guidance using AR is the Vein Viewer Vision, which assists with vascular access procedures. Hereby, near-infrared light is projected directly onto the skin of the patient to use the data to view an image of the vascular network (map of patient's blood vessel pattern, see Figure 13) (Chen et al., 2017).

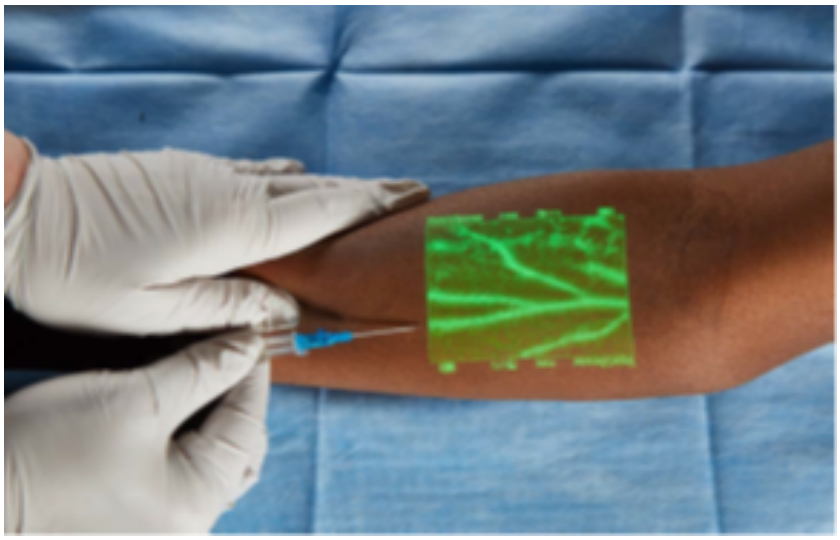


Figure 13: Vein Viewer Vision system helps with needle injection through the projection of patient's vascular network onto the skin (Source: Chen et al. (2017))

Surgical guidance: AR can benefit surgical guidance by providing information from medical scan images intuitively and conveniently to the surgeon. Two main processes are useful to improve the visual capabilities of a surgeon with AR technologies: Visualization of patient data in 3D; visualization of data onto the patient (e.g., during surgery, as depicted in Figure 14) (Chen et al., 2017).



Figure 14: Usage of medical AR during surgery or for education and training purposes by registration of the visualization onto the patient. (Source: https://wear-studio.com/wp-content/uploads/2018/07/Screenshot-2017-02-27-08.01.16.png)

Medical education: Related to medical education it is very common to use health care simulators or teaching programs that consist of life-or-death scenarios or very high-risk industries. Those methods are used to train healthcare providers like surgeons on a

complicated procedure before being prepared for the surgery on actual patients. (Sunthara, 2021)

To get a visualized overview of AR in the medical field, this 1-minute video can be recommended: Explaining Augmented Reality in Medicine In One Minute! - The Medical Futurist - YouTube (https://www.youtube.com/watch?v=wVZ2oFm4B3w)

If you want to get even more information considering the future of AR in the field of healthcare, have a look at: The Future of Augmented Reality - AR in Healthcare - YouTube (https://www.youtube.com/watch?v=w9mXtVHSIv4)

17.6. Manufacturing

The goal in the manufacturing field is to design and implement AR systems that could enhance manufacturing and product development processes, reduce cost, reduce product lead-time, and improve quality (Thomas & David, 1992).

The application areas of *Training & Maintenance* (section 17.1. Training & Maintenance) have already been described for other use cases and its approach can be transferred to the field of manufacturing. Independently of this, other areas benefit from the use of AR/MR, which will be explained in the following.

Improving Design: AR/MR enables the user to make decisions upon life-like presentations of the product very early in the development process. This approach was used by Ford to design and improve car prototypes in 1:1 ratio, which reduces costs and time. (WE'AR', 2021) In this context Figure 15 shows a real-life related design process for a motorcycle using AR to view a 3D model, here not in 1:1 ratio.



Figure 15: Design process with AR using a realistic model of a motorcycle (Source: WE'AR' (2021))

Operation, maintenance, and quality control instructions: Machine operators, service technicians, and staff that are responsible for quality assurance can be guided to perform a certain task using AR/MR that visualizes information needed in the correct real-word context (Tamburini, 2018). Figure 16 depicts a hands-on car manufacturing process where information is overlaid on the workers view field using AR, to depict the component that needs to be mounted and additionally the necessary tool for this task.



Figure 16: Overlayed information during a manufacturing process (Source: WE'AR' (2021))

3D models: With the opportunity to preview 3D-modeled assets and equipment, it can be tested if they fit in the building without heavy lifting (Tamburini, 2018). Related to this topic, Figure 17 shows how a 3D model of a machine is viewed within the designated location of the working area.

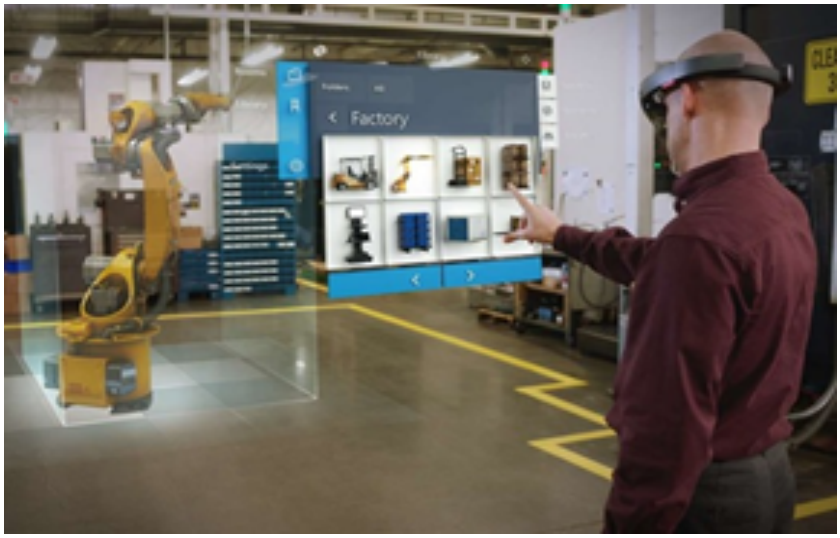


Figure 17: 3D-modeling of a machine in the designated environment (Source: Tamburini (2018))

Remote expert assistance: AR/MR enables technicians to remotely collaborate with an expert to get help for troubleshooting and problem fixing. Herby, they can even communicate with hands-free and heads-up video calling as well as image sharing, and Mixed Reality annotations. (Tamburini, 2018) As an example, Figure 18 shows how a worker can use the remote expert assistance based on AR to fulfill an electrical task.



Figure 18: Remote expert assistance for problem fixing during a manufacturing process (Source: Tamburini (2018))

A short overview of AR in the usage of industry 4.0 and building technology can be seen in those two videos:

Augmented Reality in use for industry 4.0 and building technology - YouTube (https://www.youtube.com/watch?v=UhW12bILH7U)

Augmented Reality: Enhancing the Manufacturing Workforce - YouTube (https://www.youtube.com/watch?v=af78eYuONuc)

17.7. Architecture and Construction

AR benefits the whole construction team: designers, architects, engineers, project managers, and service providers. The main goal of the usage is the combination of virtual architectural designs with the construction site reality in order to increase efficiency, accuracy, and creativity, as well as to reduce the occurrence of errors and save time, money, and resources. (Souza, 2019)

The interaction between the architect and the customers gets on a new level and enables the customer to understand more deeply the design and the vision. Therefore, most architects already use AR to transit from creating solely 2D plans to interactive 3D models of their designs, as depicted in Figure 19.



Figure 19: 3D-modeling of architectural design (Source: Gallagher (2018))

To get an even more accurate view of what will be built, clients can use applications like AR Sketchwalk on their phone or tablet to dive into their construction and get a truer sense of the space (see Figure 20) (Souza, 2019). When using AR, clients can move inside the building at full scale. Upon Gallagher (2018) this represents the ultimate customer experience for a low price".

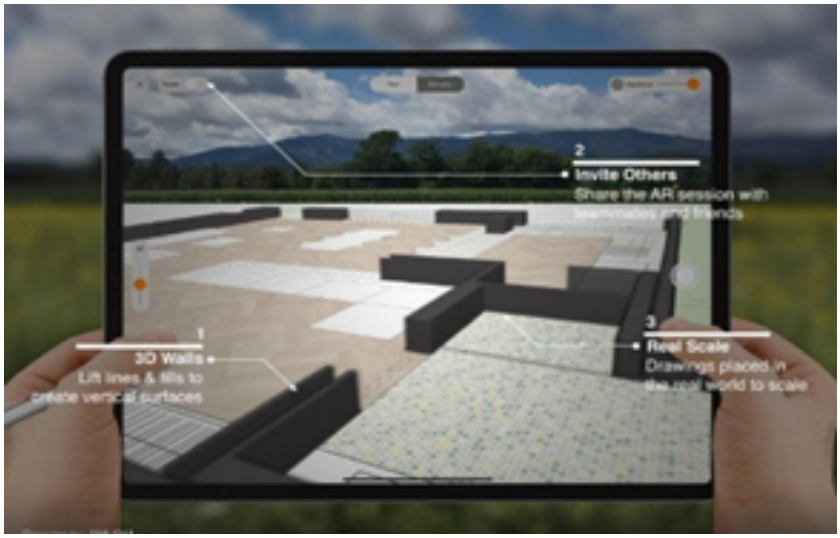


Figure 20: Virtual walkthrough planned building using AR Sketchwalk application on a tablet (Source: Souza (2019))

AR devices can additionally be used to effectively view inside walls on construction sites, which allows workers to identify spatial relationships more accurately and detect mechanical, electrical, and plumbing clashes sooner (Corke, 2021).

The following video gives an overview of opportunities and benefits for construction professionals using VR, AR, and MR: Applying AR, VR, and Mixed Reality in Construction - YouTube (https://www.youtube.com/watch?v=sBglJdIp52o)

REMEMBER TIPS

- Augmented Reality can be used in a lot of different areas
- AR can improve maintenance and lower training costs and time
- AR is used a lot for entertainment (showing further information in sports television or providing new user experience in games)
- AR can help retailers to improve their business by lowering refund rate and increase customer satisfaction
- AR can improve shopping experience for users
- AR is used in education to support understanding of new information
- Medical AR has potential uses in applications like medical education/training, treatment, rehabilitation, surgery planning, intraoperative navigation, and guided surgery.
- AR systems can enhance manufacturing and product development processes, reduce cost, reduce product lead-time, and improve quality.
- The combination of virtual architectural designs with the construction site reality can increase efficiency, accuracy, and creativity, as well as it can reduce the occurrence of errors and save time, money, and resources.

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UNIT NUMBER: Didactic Unit 18

Problems and Challenges using Augmented Reality

UNIT PRESENTATION

We already got to know the different applications and the opportunities of AR in the previous chapters. But it is still early days with AR. The promise of how these devices and how this technology will change our lives is profound. But there are a number of barriers that we have to push through before we can make this vision a reality. This chapter will provide a look at what these barriers are.

OBJECTIVES

In this chapter, we review some of the challenges of AR in the areas of Technology, Cyber sickness, Perception/Neuroscience, Collaboration/Interaction as well as Social/Ethical aspect. The goal is to give an overview of possible problems and input for deeper research.

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CONTENTS DEVELOPMENT

The development of AR and its introduction to the market is still facing grand challenges through aspects according to fundamental technologies, cyber sickness, perception/neuroscience, collaboration/interaction as well as social and ethical aspects (depicted in Figure 21).

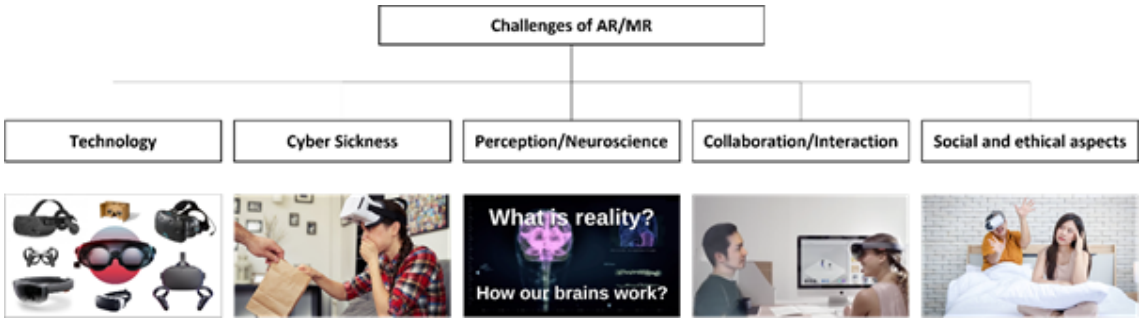


Figure 21: Overview – Challenges of AR/MR (Sources of subfigures from left to right: Future of Education & Online Teaching with Spatial Networks | by Andy Fidel | AR/VR Journey: Augmented & Virtual Reality Magazine (arvrjourney.com); Why people get sick in Virtual Reality | UNSW Newsroom; Neuroscience and perception Archives - Quantum Mind (quantum-mind.co.uk); Augmented Reality Collaboration Is Real. Avoid It Like the Plague (dice.com); Top 5 Virtual Reality Challenges - From Pricing to Ethical Issues and Health Effects - Skywell Software)

These topics will be addressed in this chapter to define obstacles for AR and MR to reach their full potential as transformative technology.

18.1. Technology

The technology of the AR/MR systems forms the basis for a user-friendly and high-quality end device. Some technology challenges in the field of mobility, tracking, visualization, and performance will be explained in more detail.

Mobility: Mobility challenges relate to the portability of Augmented Reality systems. The ideal Augmented Reality system would be mobile outside a controlled system (Rabbi & Ullah, 2013). This requires hardware that is light, small, and in general easily portable but still fast enough to display high-quality graphics. The battery life of complex AR devices is an additional limitation for the use of AR systems (Mekni & Lemieux, 2014).

Tracking: In terms of tracking, the precise location of a user's position in any location is required for an AR system (Billinghurst, 2021). This can be explained by the fact that even small tracking errors can cause a significant offset between virtual and real objects. When a user is changing location or viewing angle, the virtual objects must remain aligned with the location and orientation of the real objects. Therefore, to align real-world objects and virtual objects an accurate tracking of the viewing position in relation to the real environment and annotation of objects is required. The analysis of different sensor-based and vision-based tracking techniques proved that no tracking technique itself provides the ideal solution for pose tracking and orientation in an outdoor unprepared environment. For example, vision-based tracking provides accurate registration of virtual information without delay, but the technique is not robust and has high computational costs. Instead, hybrid tracking provides accurate and robust tracking but is costly and computationally difficult. (Rabbi & Ullah, 2013)

Visualization: The visualization for AR/MR systems requires that the illumination of virtual objects and real-world objects are of the same quality (Rabbi & Ullah, 2013). The

current systems still face issues to create a 3D image of high quality and resolution. Additionally, the HMDs should be designed in a socially acceptable form, e.g., in the form of sunglasses. The goal hereby is a see-through display with a wide field of view and high resolution that provides sufficient contrast and brightness. Furthermore, the addressing of eyestrain and the possibility for the users to see each other's eyes are also factors to make the HMD socially acceptable. (Rabbi & Ullah, 2013); (Billinghurst, 2021)

Performance: The performance of AR/MR applications can be decreased by the requirement of real-time processing and computationally expensive visual recognition (Rabbi & Ullah, 2013).

18.2. Cyber sickness

Cyber sickness occurs when the camera motion is inconsistent with the head motion, e.g., a person does not move, but a compelling sense of movement is evoked by the alternation of visual images (Corke, 2021). The problem of cyber sickness is more known to occur while using VR devices and has been intensively researched for decades. While VR users experience more symptoms at the disorientation to nausea end of the scale, cyber sickness occurring in AR is more associated with everyday ailments like eyestrain and headaches. The feeling might be compared with how you feel after wearing glasses with the wrong prescriptions for a long period of time. Because the symptoms seem mild to the users, they may tend to ignore them. However, long-term AR use with these symptoms may cause potentially longer-lasting effects after exposure (e.g., blurred vision, altered depth perception). (Hughes, 2021)

18.3. Perception/Neuroscience

AR systems are used to create an illusion for the brain that virtual content really exists in the real-world (Billinghurst, 2021). According to Billinghurst (2021) different perceptual problems can occur in AR, which can be classified into environmental, capturing, augmentation, display device, and user issues. Therefore, digital objects need to be created with a strong "Object Presence" (Mojo Vision, 2021). In this term, it should be analyzed how virtual lighting, shadow, real object occlusion, and similar techniques can be used to create the AR content according to real objects (Billinghurst, 2021).

18.4. Collaboration/Interaction

In the area of remote collaboration or interaction in virtual teams, research is going on to enable people to work together as easily as if they would work together face to face. The goal is that the users can share rich communication cues on a virtual basis, e.g., what they are hearing, seeing, or feeling. (Billinghurst, 2021)

18.5. Social and ethical aspects

Besides the technical issues, the social and ethical aspects can be seen as one of the biggest challenges when AR devices become more widely used. Reasonable questions might occur, like: "Who should be allowed to place AR content in the view of a person and what are the ethics around AR advertising?" or "What is the consequence of people having different views of the same real environment?" (Billinghurst (2021), p. 3). Pase (2012) mentioned the questionable ethical uses of AR in terms of deception, surveillance, behavior modification, and punishment. Additionally, privacy issues of AR are becoming a topic when we think about users capturing and sharing their surroundings (Billinghurst, 2021).

This video depicts AR challenges and solutions in terms of privacy, security, and physical aspects: Augmented Reality: Challenges and Solutions - YouTube (https://www.youtube.com/watch?v=S21XaUffheQ)

REMEMBER TIPS

- The challenges of AR can be classified in technology, cyber sickness, perception/neuroscience, collaboration/interaction, and social & ethical aspects
- Technology faces barriers in AR development in terms of mobility, tracking, visualization, and performance
- Although cyber sickness is more commonly associated with VR, long-term exposure to AR with mild symptoms such as eyestrain and headaches can lead to long-term consequences
- The visualization of digital objects with a strong "Object Presence" requires further research in the field of neuroscience
- AR enables remote collaboration with rich cues comparable with face to face communication
- One of the main challenges for AR are social and ethical aspects

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UNIT NUMBER: Didactic Unit 19

Future of Augmented Reality

UNIT PRESENTATION

Nowadays, we always carry our smartphone with us, whether for communication, entertainment, research or navigation purposes. Hard to imagine, but in the future AR eyewear could almost completely replace the use of smartphones, tablets or in general keyboards and mouse cursors. A few technical approaches and further future visions for the use of AR are mentioned in this chapter.

OBJECTIVES

As we already could have gained a good overview of the possible areas for use of AR, a future vision for those areas is already established. This chapter aims to complete this view by naming a few examples in very interesting fields like smart lenses, brain computer interaction and combining AI with AR.

CONTENTS

19.1. Smart lenses 49

19.2. Brain computer interaction 49

19.3. Combination of Artificial Intelligence and Augmented, Virtual and Mixed Reality 49

CONTENTS DEVELOPMENT

Many topics relevant to the future of AR/MR have already been covered in chapter “Scope of Augmented Reality” and chapter “**Error! Reference source not found.**”. The application of AR/MR is currently being intensively researched, developed, and tested in various areas. However, until the use of most AR/MR technologies can become commonplace, many challenges must be overcome, and further research must be done. The picture of the future can therefore be derived from the previous chapters for many areas, considering that the challenges are solved, and the mentioned use case is established.

In the following, only a few areas or interesting applications will be mentioned additionally.

19.1. Smart lenses

The future use of AR or MR devices like socially suitable HMDs might replace smartphones when they overcome certain challenges. Additional research is ongoing on AR-enabled contact lenses. One example is Mojo Lens (Mojo Vision, 2021) which is a smart contact lens using a built-in display that delivers timely information without interrupting your focus on the real world. Smart lenses enable the user to get information like a street number of the next appointment, the latest sales projections, or what work order to complete first without burying the face in a screen or getting distracted from the real world by mobile devices. (Mojo Vision, 2021) In 2021 Apple also released, that they plan to offer lenses with AR within 10 years, which would work as a miniature of Google Glass (see Figure *22*) (Adwaith, 2021).



Figure 22: Smart lenses using AR technology (Source: *Adwaith (2021)*)

19.2. Brain computer interaction

In the future, users of wearable hardware will be able to work hands-free when future devices work on voice commands or gestures. This could be the end of physical controllers such as a keyboard or a mouse cursor (Bharadwaj, 2021). Additionally, research is going on for brain computer interaction methods that enable AR content selection via brain activity (Si-Mohammed et al., 2018) or other physiological sensors that enable AR devices to react upon the heart rate or emotional state of the user (Billinghurst, 2021).

19.3. Combination of Artificial Intelligence and Augmented, Virtual and Mixed Reality

Different sources claim that with the combination of AI, AR, VR and MR the transfer between the virtual and the real world will become easier and quicker. Recent developments in the field of AI, specifically deep learning, that support real-time image and speech recognition have helped to combine VR and AI for new applications. Apple's Animoji is a perfect example of a perfect combination of AI and AR (see Figure 23). Apple Animoji is used to create custom animated messages that use the voice and facial expressions of the user as a reference to reflect on. (Bharadwaj, 2021)

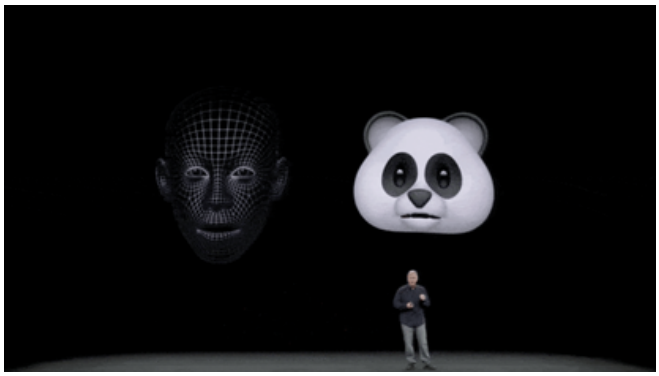


Figure 23: Apple Animoji demonstration (Source: *Adwaith (2021)*)

REMEMBER TIPS

- AR devices like HMDs or smart lenses might replace smartphones in the future
- Research is ongoing for brain computer interaction methods that enable AR content selection via brain activity
- Researchers see potential in a combination of AI, AR, VR and MR to transit between the virtual and real world easier and quicker

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UNIT NUMBER: Didactic Unit 20

Exercises: Augmented Reality with Unity

UNIT PRESENTATION

Since the appearance of Pokémon Go the usage of AR in different forms of applications is increasing. Therefore, it is good to know how to integrate AR into an existing application or how to, generally speaking, develop an AR application. This unit will take a practical approach towards this question and provide you with an easy to follow and easy to understand approach to the integration of AR into an Unity application.

OBJECTIVES

The objective of this unit is to show how to integrate AR into an Unity application. Therefore this unit shows how to add different types of targets for AR content into an application. This exercise serves as a starting point for further AR development as well as for deepening the students' knowledge about the practical usage of AR.

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CONTENTS DEVELOPMENT

20.1. Introduction

In this section we will create a simple example project to demonstrate how you can include AR into an application. For this we use the Unity Engine (https://unity.com/) and Vuforia (https://www.ptc.com/en/products/vuforia).
Vuforia is a tool mainly for recognising images and objects. We will use Vuforia to recognise various images or objects(targets) and to react to the recognition of a target. For this purpose Vuforia provides free licenses for developers and projects under development.

The Unity Engine is a games engine that provides us with an environment to develop our exercises. Furthermore it is free for noncommercial projects and has a large community as well as a rich ecosystem around it. This makes it the ideal environment for our exercises

The exercise section is structured in the following way: First we provide you information for setting up your environment for the exercises. After that we have a look at Image Targets which are the simplest types of targets in our exercises. At the end we have a look at simple Model Targets which are more advanced targets and provide a way to interact with 3D geometry.

20.2. Set Up

First of all you have to get Unity. Therefore go to https://store.unity.com/download-nuo where you can download the Unity Hub under “Get Started”. Be sure to read and understand the license information for the underlying “Personal”-license. Install the Unity Hub after the download has finished.

Furthermore you have to create an Unity-account on the same page by clicking on the person-icon. After that select “Create a Unity ID” and follow the steps.
After installing the Hub and creating your Unity-account start the Unity Hub and log in with your credentials. Then you click on your username and select the tab “License Management”. There you select “Activate new license” to add a license for working with Unity. Select the Unity Personal license and verify that you are under the given license conditions or select another paid license if it suits your current situation. Finish this step by clicking on done.

With your activated license you are now able to download the Unity Engine. Therefore you have to go back to the main screen, click on “Installs” and select “Add”. In the pop up you can select a Unity version of your choice (LTS is preferred) but keep in mind that these exercises were made with Unity version 2019.4. With the “Next button” you can install additional components for Unity like Visual Studio for coding or Android Build Support (see subsection 11.2.1. Using Android Devices). Select all components that you need and click on “Done”. After that Unity will be downloaded to your device. Be aware that this process may take some time.
When Unity is installed, you can create a new project through the Hub by clicking “New” in the projects section.

Vuforia can be downloaded from https://developer.vuforia.com/downloads/sdk. There select the download for Unity and download it.
Furthermore you have to create a Vuforia account which can be done on the same site by clicking “Register”.

To add Vuforia to a project you have to either create a new project or open an existing project. Then you have to drag and drop the downloaded .unitypackage file into the Assets tab in Unity. After that just follow the prompted steps and import Vuforia into your project.

After that you have to obtain a license key for your project. This can be done in the Vuforia Developer Portal under https://developer.vuforia.com/. Log in on the page and go to “License Manager”. There you select “Get development key” to obtain a license for developing with Unity. Follow the steps and copy the license key to your clipboard. After that go back to your Unity project and navigate to the VuforiaConfiguration-Script under Assets/Resources. Open the script in the inspector and paste your license into the field “App License Key”. Activate your license by clicking “Add License”.
Now you are ready for the following exercises.

!!ATTENTION!!
Never upload any kind of Unity project with your personal Vuforia license key to any publicly available space (e.g. public git repository)!

20.2.1. Using Android Devices
If you want to use android devices in your development process you have to follow the following steps.
If you haven’t added “Android Build Support” during the installation of our Unity version, you have to add it manually. To do this close all your open Unity projects and open the Unity Hub. Navigate to “Installs” and click on the three gray dots on the version

where you would like to add the build support. Click on “Add Modules” on the opening menu and select “Android Build Support” under “Platforms”. Finish the process by clicking “Done”.
Furthermore you have to activate developer mode on the device you want to use. To do this you have to go to “About your device” part of your device’s settings. There should be a build number at the bottom of the corresponding page. Tap ten times on this number to activate developer mode.
After completing these steps, you are now able to connect your device via USB with your computer and build and run your application directly on your device.

20.3. Image Targets

Our first exercise will be about using images as targets for virtual content. Using Image Targets is the simplest way of including AR into your application and therefore it is our first exercise.

20.3.1. Creating Image Target Database

The first step to use Image Targets in with vuforia is to create a database for the used images. This step is necessary because vuforia analyses your image(s) and identifies parts that can be used to identify the whole image. This information is stored in a database and can be used to add Image Targets to your Unity project.

To create an image target database, you have to log in into the vuforia developer portal (https://developer.vuforia.com). In the Target Manager tab (see Figure 24), you can create a new image target database by clicking “Add Database”. In the following dialog you have to provide a name for your new database as well as specifying the type. For this exercise we will be only using the type “device” which means that all data will be stored on the target device and the recognition will also be performed on the target device. Keep in mind that other types may cause costs. After successfully creating the database, we add a new target by clicking on the newly created database and clicking on “Add Target”. In the following pop up you can select different types of images and upload your own image. For this example, we will be using the HHN logo, which is a “Single Image” and has a width of 0.135 meters. Please keep in mind that this process does not support transparency with RGBA images.

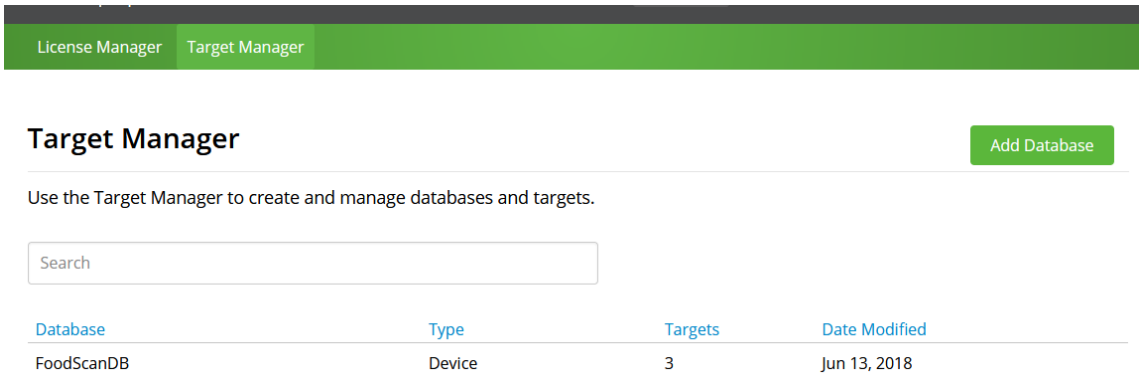


Figure 24: Target Manager View

After you imported your pictures, you can click on the newly imported picture and select "Show features" to see the points vuforia uses for recognizing this image (see Figure 25).

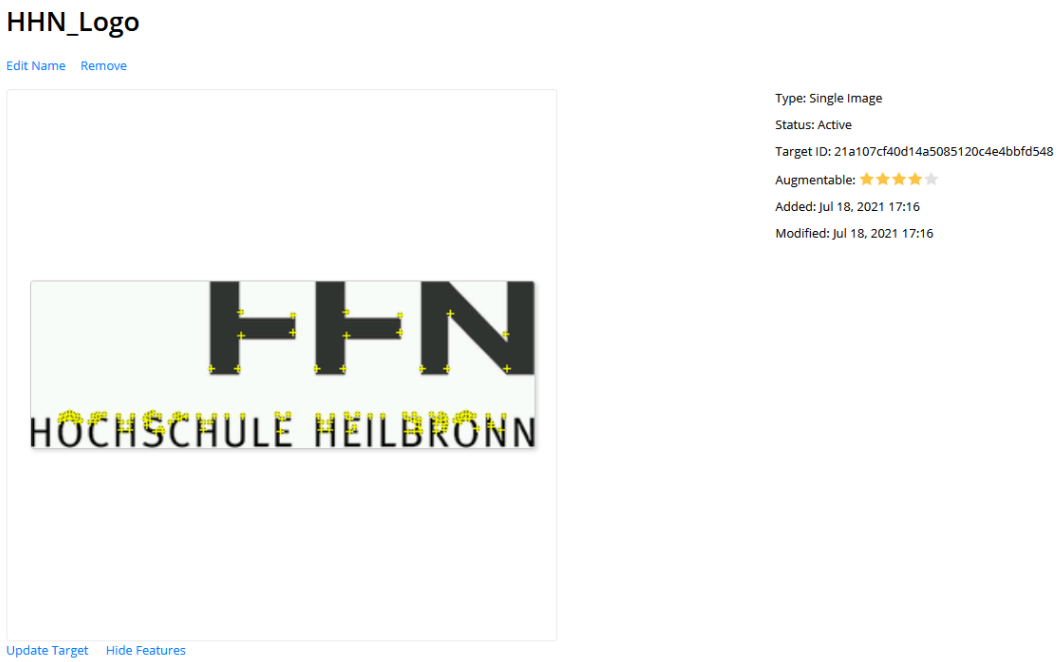


Figure 25: Recognized Features of HHN Logo

To download your database just click "Download Database" and select "Unity Editor" as development platform. After the download has finished just drag and drop the unitypackage into the "Assets" tab in your Unity project.

20.3.2. Creating Image Target

To add your Image Target to your Unity project after you imported the previous image target database you have to follow the following steps. First of all make sure that you imported vuforia and added a valid license key in the VuforiaConfiguration script in the Resources directory. After that remove the default camera and add an ARCamera by right

clicking on the “Hierarchy” tab and selecting ARCamera under Vuforia Engine (see Figure 26). The ARCamera is needed to enhance the default camera with the vuforia functionalities. Then we are ready to add Image Targets. To do that right click on the “Hierarchy” tab and select Image Target under Vuforia Engine. Then select the Image Target and take a look at the Image Target Behaviour script in the “Inspector” tab. There you have to change the type to “From Database”, select your database in the database section and select the concrete image in the “Image Target” section.

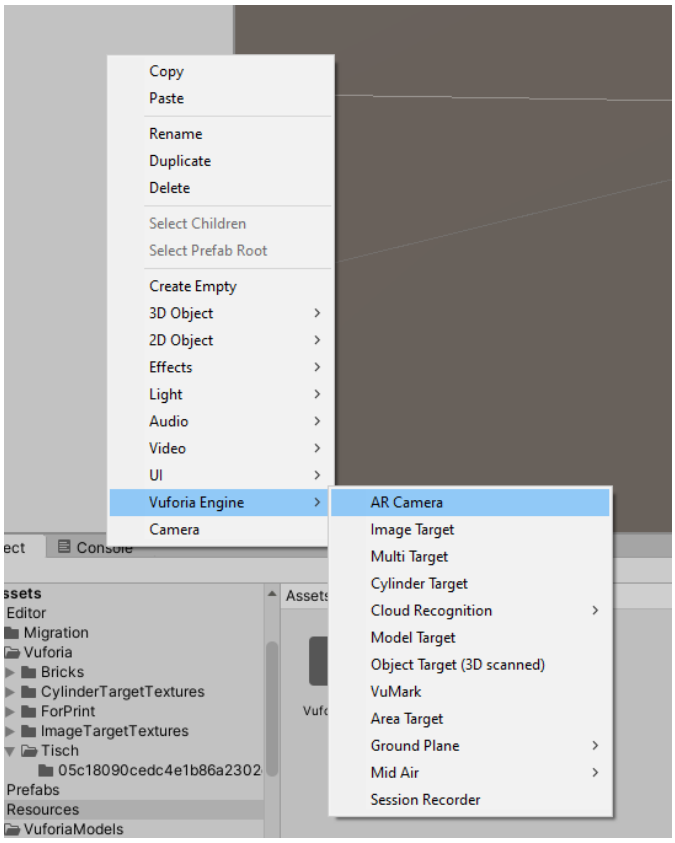


Figure 26: Creation of AR Camera

20.3.3. React to Image target Recognition

There are two basic ways of reacting to the recognition of an image target. In the first way you just add a GameObject as a child of an Image Target (see Figure 27). When the Image Target gets recognized, all child objects will be displayed in relation to the image target (see Figure 28).

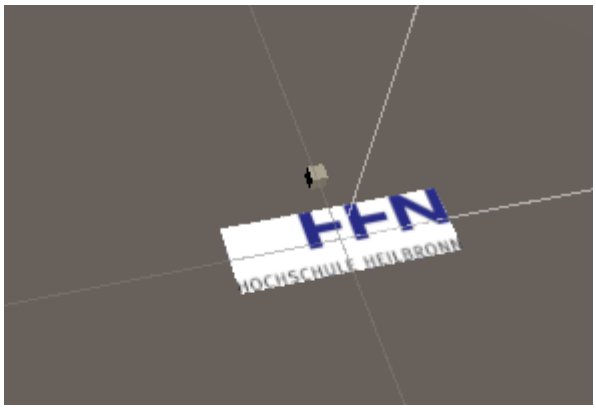


Figure 27: Cube placed as Child of Image Target



Figure 28: AR Webcam Image with added virtual Cube

The second way works programmatically. At this approach you add methods as event listeners for the events when a target has been found or lost. This can be done in the "Inspector" view of an image target. In the Default Trackable Event Handler you will find the two sections "Event(s) when target found" and "Event(s) when target lost". By clicking on plus you can add custom action to these events. By dragging and dropping a specific GameObject into the empty Object field you assign this GameObject to the corresponding event and therefore you are able to use its public methods. A specific method can be selected in the list on the top right side next to the assigned GameObject. There you have the ability to browse through all assigned scripts and select a public method. If this method has additional properties, fields for them will be prompted underneath the selected method.

The assigned methods will then be executed when the corresponding target has been found or lost. To demonstrate that we wrote a little script that displays the current status of our image target (see Figure 29 and Figure 30)



Figure 29: Programmatic Reaction to recognize Image Target

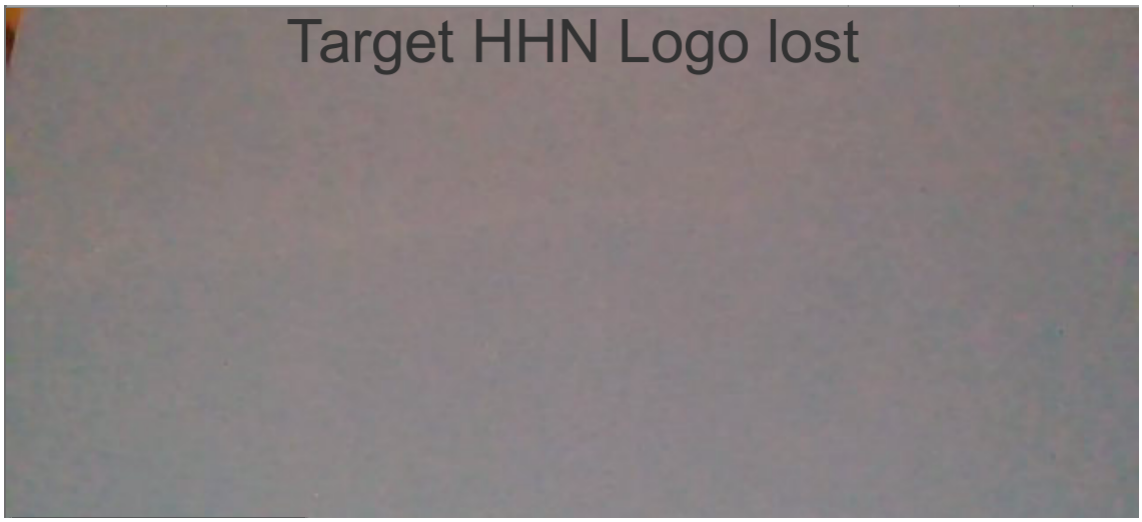


Figure 30: Programmatic Reaction to lost Image Target

20.4. Model Targets

Our second exercise will be about using 3D models as targets for virtual content. Using Model Targets is a more advanced way of including AR into your application and offers some advantages over Image Targets. Due to the fact that reacting to the recognition of a Model Target works the same way as it does for Image Targets we will not cover this topic again in this section.

20.4.1. Additional Software

The recognition of 3D models is more complicated than the recognition of images. Therefore we additionally need the Model Target Generator (MTG) from vuforia which can be downloaded from https://developer.vuforia.com/downloads/tool. Be aware that the software needs an active vuforia developer account and only provides 20 targets for free. The MTG is used to translate 3D (CAT) models into Model Target Database which can be used to generate Model Targets.

20.4.2. Creating Model Target Database

To generate Model Target Databases using the MTG you need a 3D representation of your real world object that matches the criteria mentioned under https://library.vuforia.com/articles/Solution/model-target-generator-user-guide.html. For this exercise we use a brick model (see Figure 31) that we remodeled as a 3D model using blender (https://www.blender.org/). This approach was chosen because the model contains many edges that provide more features for the vuforia recognition process. Furthermore it is easy to build and easy to remodel in blender.

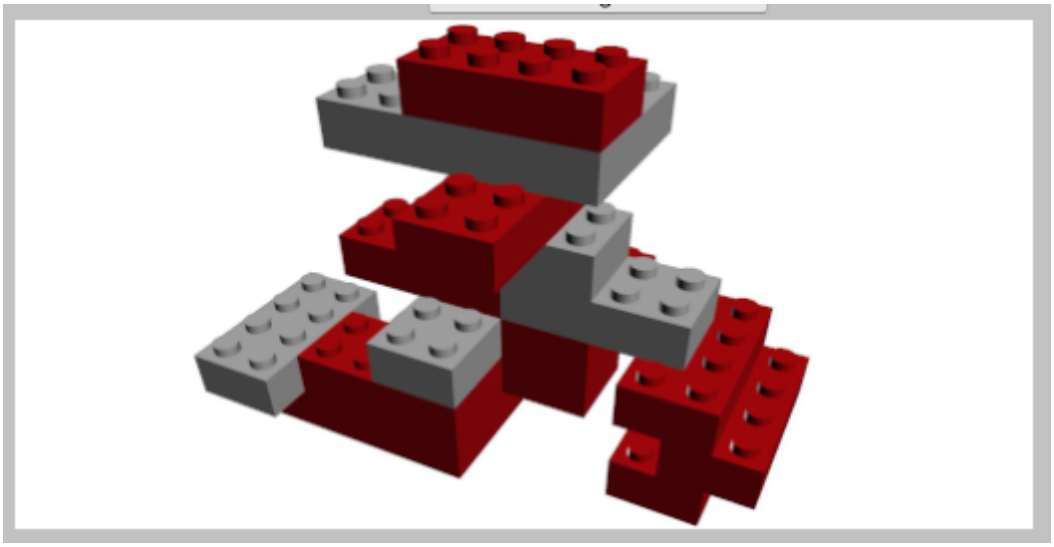


Figure 31: Used Brick Model

To generate a model target database open the MTG, log in and select “Create New Model Target”. In the following pop up you have to specify the location of our 3D model file and a location where the generated database shall be saved (see Figure 32).

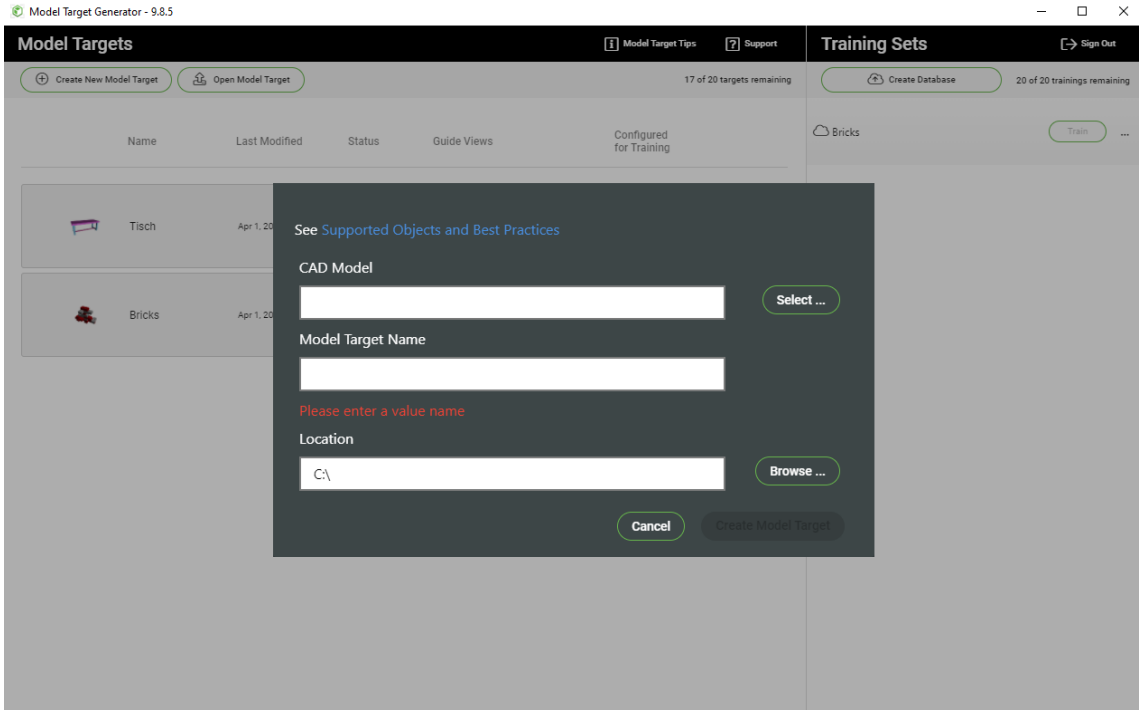


Figure 32: Model Target Database Creation Screen

After that you have to select the correct up axis, the model units, additional coloring and the model type. Normally you can use the default values for these selections. Be careful when it comes to the model units because they have a larger influence on the recognition process and therefore should match the size of the real-world object. After the mentioned selections you are asked to specify a Motion Hint. Select Static for static objects and Adaptive for moving objects. After that you will be asked to specify Guide Views. These views are images of your model and will be used to detect your model. There is also an option to create Advanced Views that work with machine learning and allow the recognition of the object without the need for separate images, but this is an advanced topic which will not be covered in this exercise.

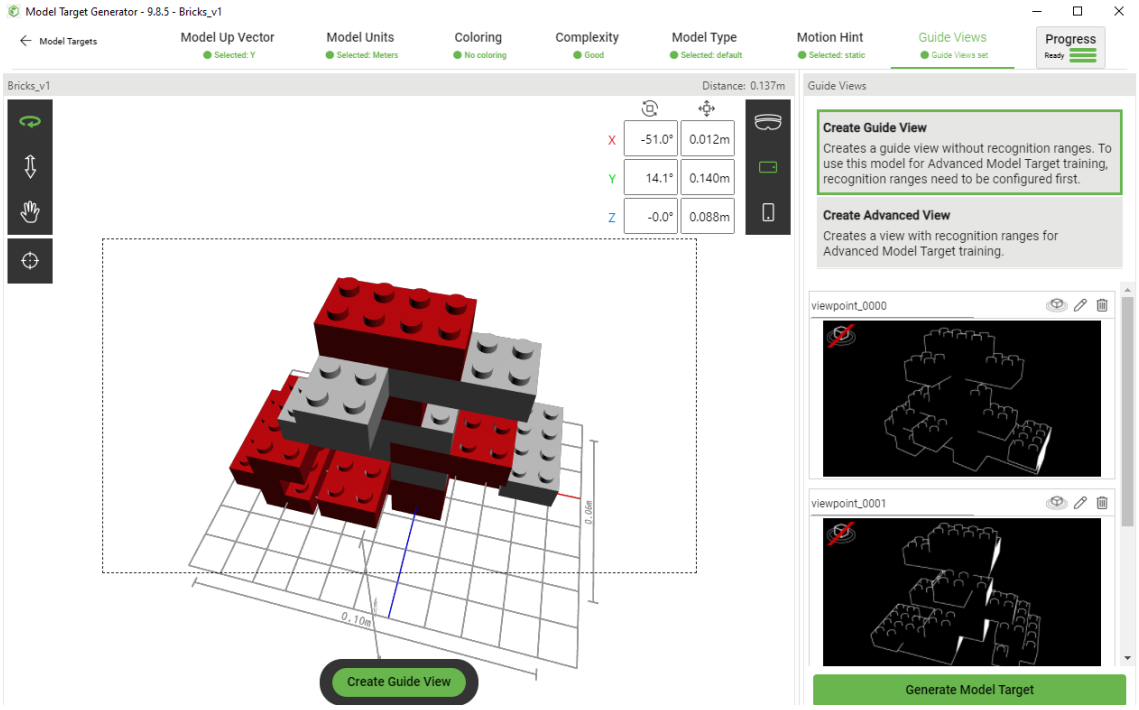


Figure 33: MTG Guide View Selection View

To create your Guide View select “Create Guide View” and press “Next Step”. Then you can select the type of target device you want to create the Guide View for. After that you can adjust your model by rotating, panning and zooming until your model shows enough detail and fits into the dotted rectangle (see Figure 33). Then press “Create Guide View” and repeat the whole process for different perspectives. When you have enough Guide Views press “Generate Model Target” to finish the whole process. When the model target has been created there will be a link to the generated data. Click it to have a look at the generated data in your explorer.

20.4.3. Creating Model Target in Unity

The first step to create a Model Target is to import our newly created Model Target Database. Therefore open the directory where the data for the Model Target Database has been saved. There should be a unitypackage file which you have to drag and drop into the “Assets” tab of your Unity project. After you have completed the import process you can create a Model Target by right clicking on the “Hierarchy” tab and selecting Model Target under Vuforia Engine. Then select the newly created Model Target and open its “Inspector” view. In the Model Targets Model Target Behavior script, you have to specify a Database and a Model Target (see Figure 34). Furthermore you can adjust the Physical size of your real world object (see Figure 34). Also you have to select a Guiding View for the Model Target (see Figure 34). After you have made your adjustments your Model Target is ready. You can now use it like the Image Target we worked on before.

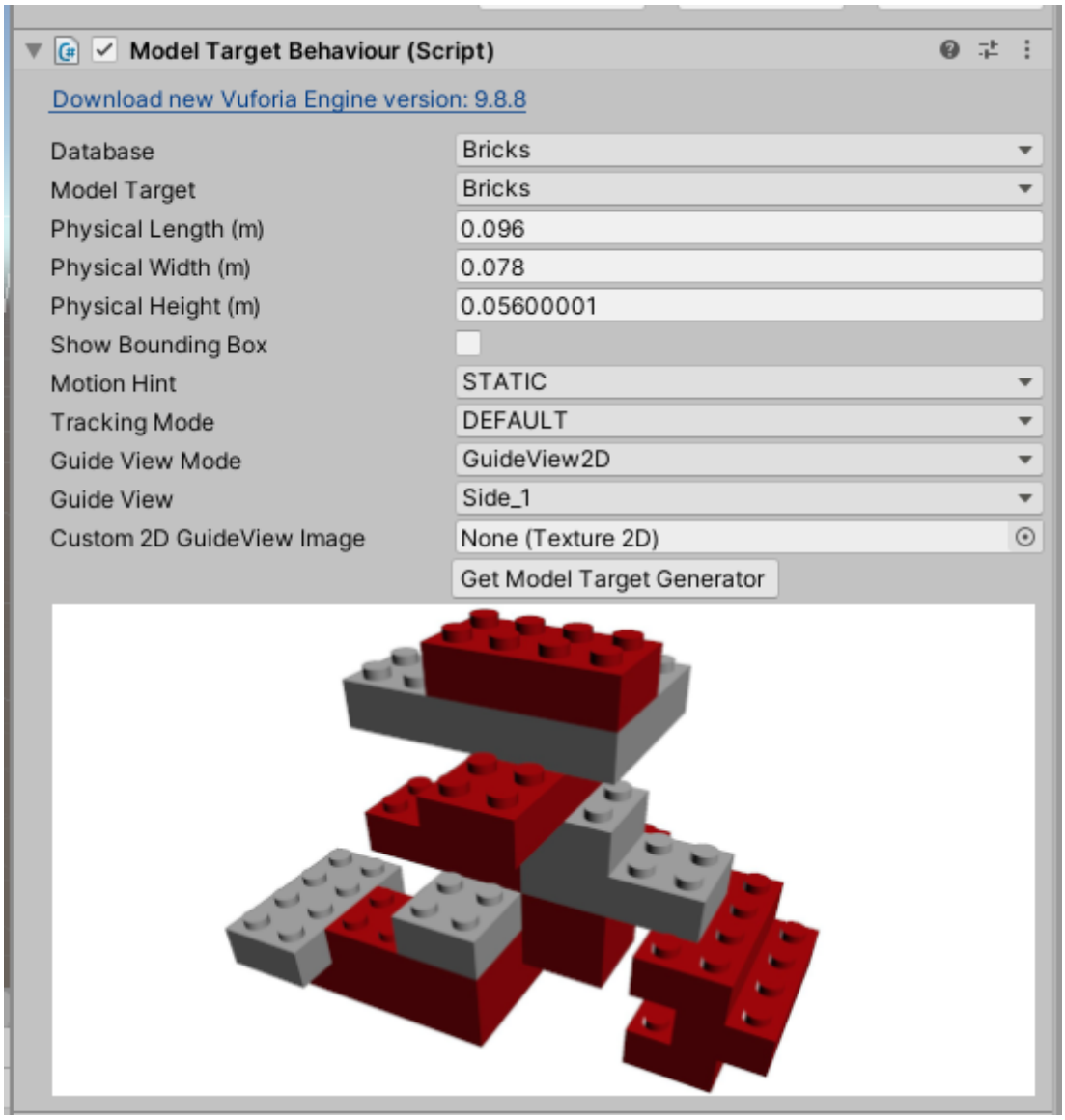


Figure 34: Properties of example Model Target

20.5. Testing & Further Reading

Testing of vuforia AR applications is straight forward. If your device has a camera just start your application by pressing the play button in the upper middle menu inside the Unity Editor. Then place your real-world model in front of your camera (see Figure 35).

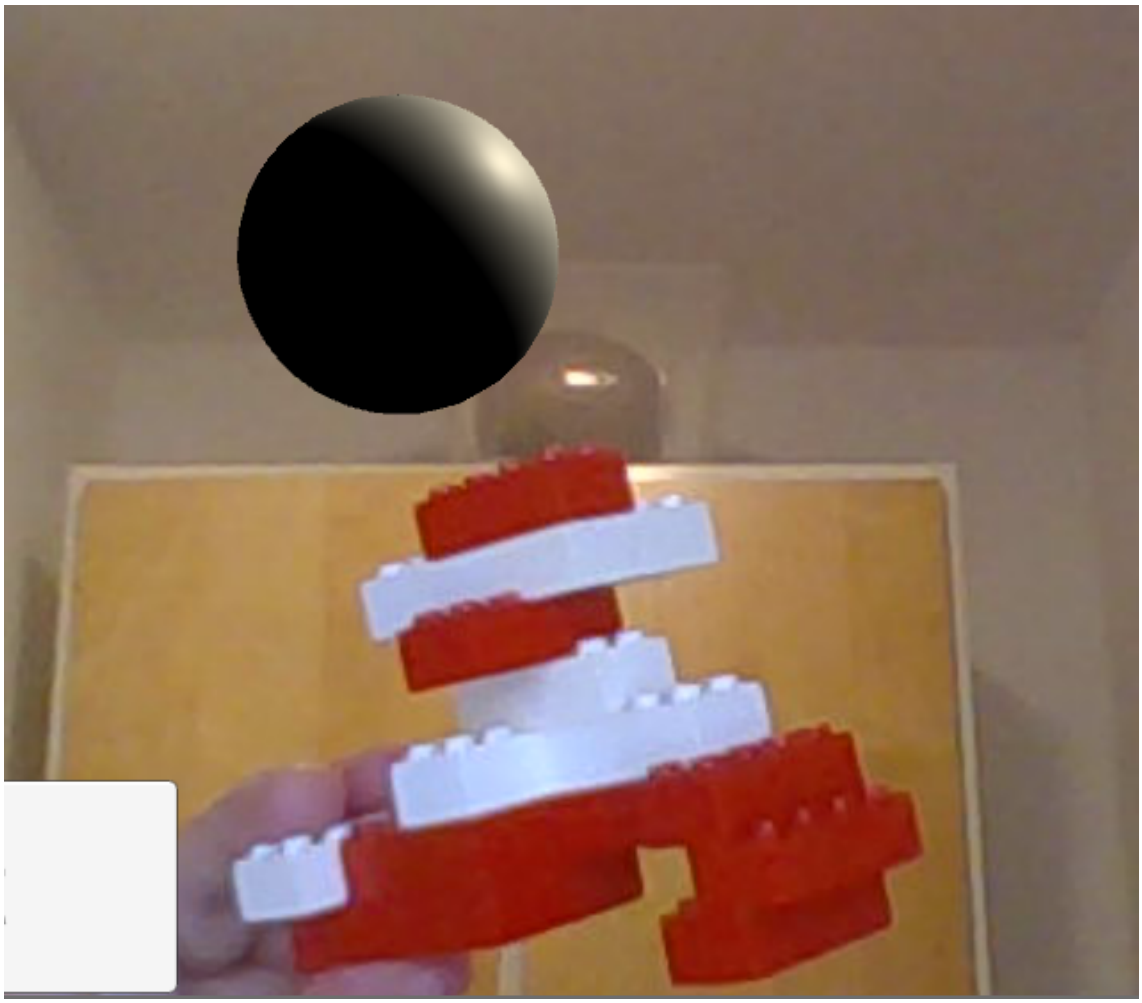


Figure 35: Recognized Model Target with virtual Sphere

If your device has no camera you can try to build and run your application on an Android smartphone (see subsection 20.2.1. Using Android Devices).
Further information regarding vuforia can be obtained from the vuforia developer library under https://library.vauforia.com/.

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Digital **Man**ufacturing Master Degree to set specialists for the dawn of the Industry 4.0



Design of Digital Manufacturing

Lesson Material

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1. INTRODUCTION IN DIGITAL MANUFACTURING

1.1 History of digital manufacturing

Currently, industrial manufacturing is in the era of Industry 4.0. However, before industry 4.0 the first (1.0), second (2.0), and the third (3.0) industrial revolutions had to take place. In order to understand the basic concept in Industry 4.0, we look back and briefly summarize the previous industrial revolutions which led industrial manufacturing to where it is today.

1.1.1 Industry 1.0

The first industrial revolution took place from the middle of the 18th century to the middle of the 19th century. During this period the manufacturing transformed from hand production methods to machines, with the help of the increasing use of steam and water power systems and by using scientific achievements for example in chemistry, which led to new ways of higher quality steel making processes. The higher quality of steels led to the improvement in machinery and mechanized factory systems. The first industrial revolution started from Great Britain, as this country was the world's leading commercial nation at the middle of the 18th century. One of the reasons for this was the significant British control over the maritime trade routes due to the empire's colonies (Figure 1.).

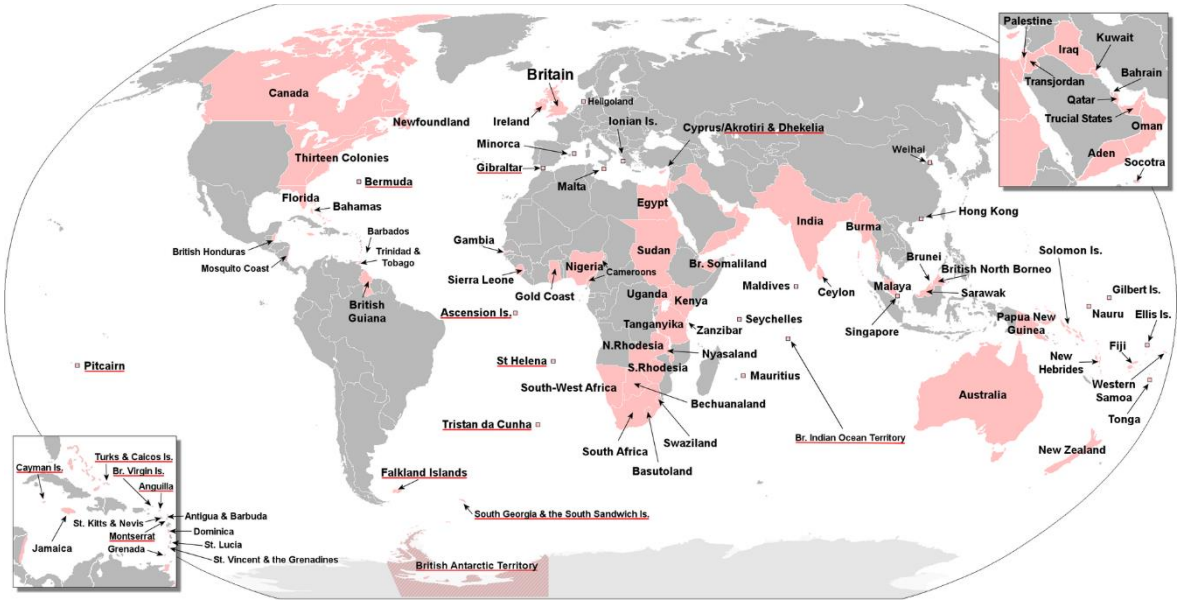


Figure 1. The territories that were at one time or another part of the British Empire. The United Kingdom and its accompanying British Overseas Territories are underlined in red [1].

Among the first achievements of the first industrial revolution the textile production was mechanized (Figure 2.). This mechanized textile production then spread to continental Europe and the United States.

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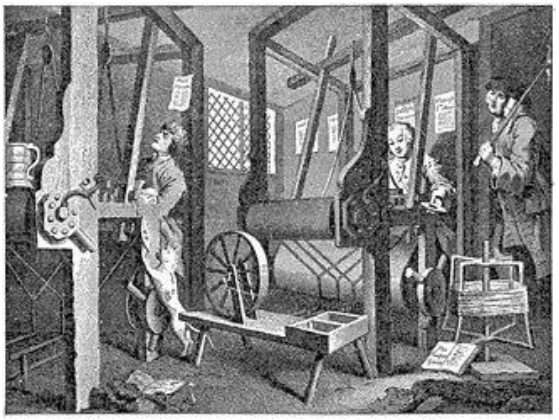
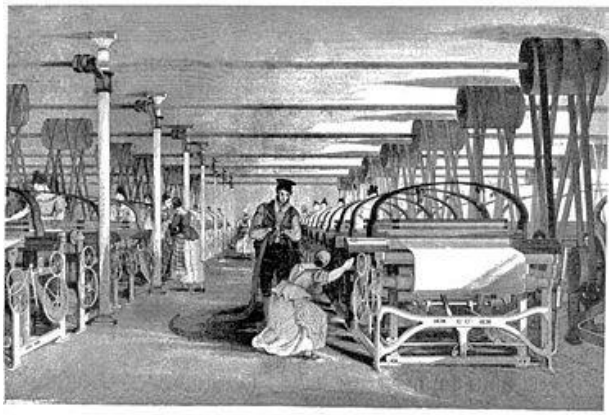



Figure 2. Handloom weaving in 1747, from William Hogarth's Industry and Idleness (left) [2]*, and a Roberts loom in a weaving shed in 1835 (right)* [3].

Beside textile industry, iron production also started to bloom at the era. During the first industrial revolution first coal and then coke was used in the reduction process of iron ores, which meant greater efficiency and lower content if impurity elements such as sulfur and phosphorous in pig iron. With the invention of puddling processes the high carbon content could also have been decreased by slow oxidation, which made possibly using cast iron product as machine parts.
For machineries sufficient power supply was needed. During the first industrial revolution a fundamental change was introduced in the steam engines by James Watt. With the higher power and efficiency higher quality of machine tools could have been manufactured leading to the improvement in industries like glass making, paper machines, agriculture, mining, transportation, etc.

1.1.2 Industry 2.0

The second industrial revolution is also known as the technological revolution. During this phase standardization and industrialization was significantly improved from the late 19th to the beginning of the 20th century (beginning of the first world war). The second industrial revolution started form the United Kingdom, continental Europe and the United States. The second revolution's main characteristics were build-out railroads, large-scale iron and steel production, the use of the telegraph, and the beginning of electrification.
In steel making the Bessemer process was invented during this era. With the usage of Bessemer converters (Figure 3.) the carbon content and impurity contents of pig iron could further be decreased by blowing air into the molten iron.

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Figure 3. Bessemer converter, Kelham Island Museum, Sheffield, England (2010) [4].

Following Bessemer converters, Siemens-Martin furnaces were invented, further reducing the impurity elements in steels by using basic type and oxidating slags. The newly developed steel making processes made it possible to increase better quality steel production, which lead to railway manufacturing more competitive.

The other significant element in the second industrial revolution was the electrification. Electrification made it possible to improve telecommunications and also to manufacture much more efficient engines and turbines than before.

1.1.3 Industry 3.0

The third industrial revolution took place in the latter half of the 20th century. This industrial revolution is also called the digital revolution, as it is mainly characterized by the digitalization of previously mechanical and analogue technologies.

The first stage of the industrial revolution was led by the improvement and development of digital communication. Digital communication become personal and economical widespread. Digitalization led to the invention of the internet.

While the internet became widespread, firstly home computers, then laptops, and smart phones became available for each individual. Digitalization also took place in the manufacturing industry, using computer-based algorithms, monitoring systems, sensors, etc. which gave

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access to globalized mass production with safer and much more efficient technologies, including automation (Figure 4.).

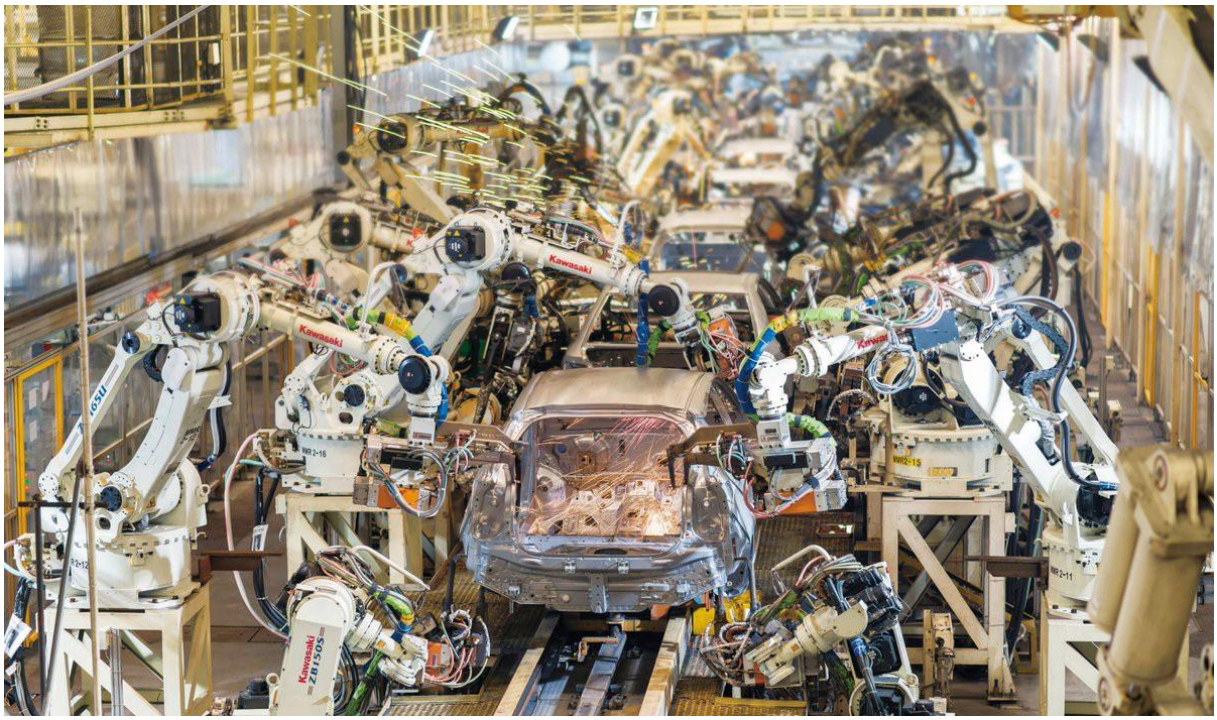


Figure 4. Automated car production at Toyota [5].

1.2 Introduction to Industry 4.0.

The fourth industrial revolution is currently ongoing. Its characteristics are automation using modern smart technologies, machine-to-tool communications and the internet of things. Smart machines can improve and take place in production processes with or without human interventions.

The term Industry 4.0 stem from its German equivalent “Industrie 4.0” which was introduced in 2011 at the Hannover Fair. Industry 4.0 immediately became the focus of the government in Germany and many other European countries. In general, Industry 4.0 is interpreted as the application of the cyber-physical systems within industrial production systems [6].

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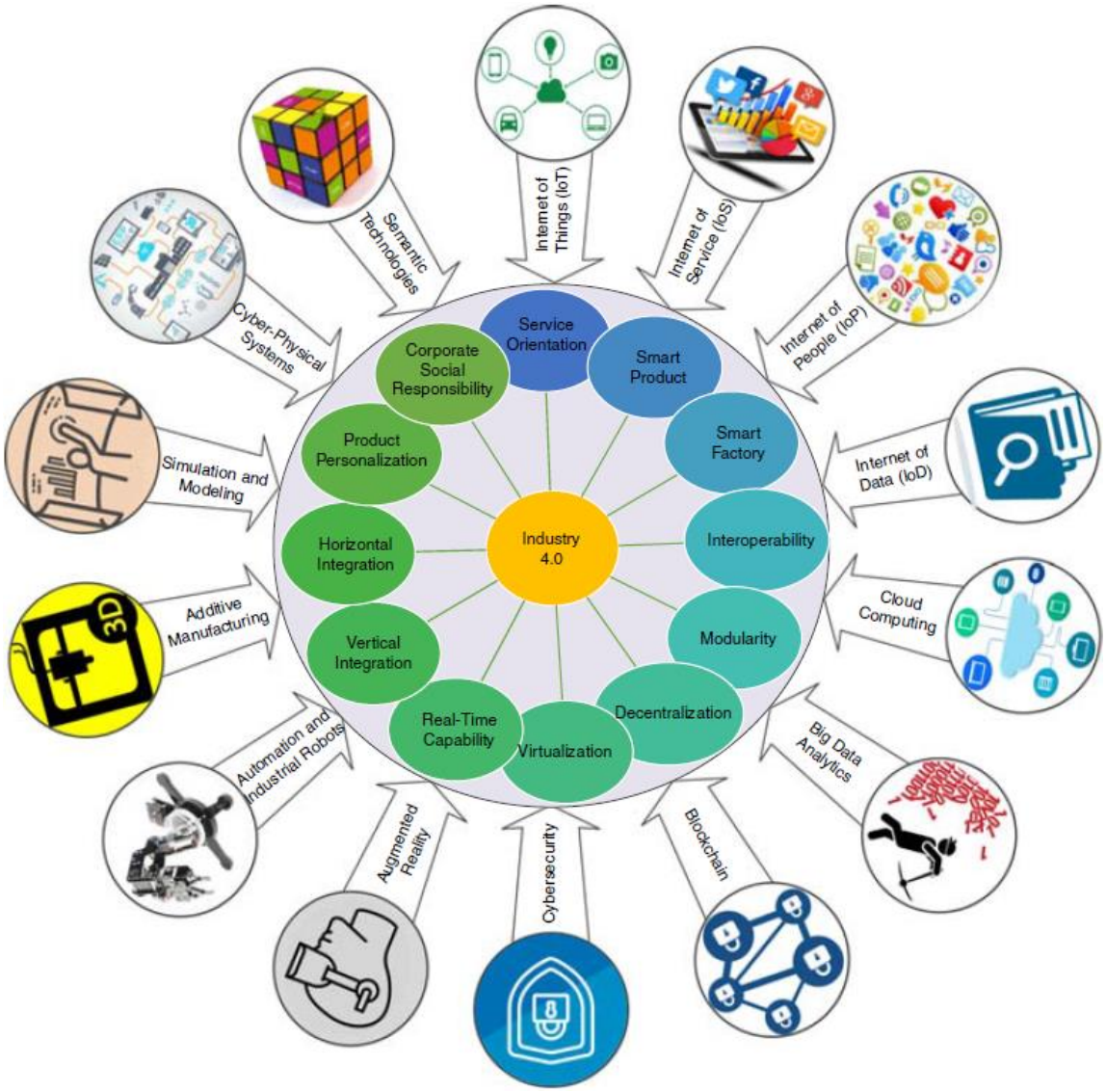


Figure 5. Design principles and technology trends of Industry 4.0 [6].

In the Industry 4.0 era, manufacturing systems can monitor physical processes, create a so-called "digital twin" (or "cyber twin") of the physical world, and make smart decisions through real-time communication and cooperation with humans, machines, sensors, and so forth [7]. Industry 4.0 combines embedded production system technologies with intelligent production processes to pave the way for a new technological age that will fundamentally transform industry value chains, production value chains, and business models [8].

Various technologies or techniques can be used for implementing Industry 4.0. The internet of things (IoT) is a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual 'Things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network [9].

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The foundation of IoT can be considered as a global network infrastructure composed of numerous connected devices that rely on sensory, communication, networking and information processing technologies [10].
The second main characteristics of Industry 4.0 is the application of cloud-based date bases. Virtualization technology provides cloud computing with resource sharing, dynamic allocation, flexible extension, and numerous other advantages. A large volume of data can be uploaded to a cloud computing center for storage and computation, which facilitates manufacturing and production. Cloud-based manufacturing is a rising technology which can contribute significantly to the realization of Industry 4.0 that enables modularization and service-orientation in the context of manufacturing, in which systems orchestration and sharing of services and components are important considerations. A modern enterprise's operation involves numerous decision-making activities, requiring a large amount of information and intensive computation. At one point, manufacturing enterprises required multiple computing resources such as servers for databases and decision-making units. This caused inefficient data exchange and sharing, low productivity and less optimal utilization of manufacturing resources. Cloud computing provides an effective solution to such problems. All data can be stored in private or public cloud servers, and in this way, complex decision-making tasks can be supported by cloud computing [10].
The third main pillar of Industry 4.0 is the cyber-physical systems (CPS). In CPS, physical and software components are deeply intertwined, each operating on different spatial and temporal scales and interacting with each other in a myriad of ways that change with context. CPS are engineered systems that are built from, and depend upon the seamless integration of computational algorithms and physical components. Advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security and usability that will far exceed the simple embedded systems of today. New smart CPS will drive innovations in sectors such as manufacturing, energy, transportation, agriculture, automation and healthcare [10].
Future research perspectives for intelligent manufacturing in the Industry 4.0 era are believed to be in the following areas: a generic framework for intelligent manufacturing, data-driven intelligent manufacturing models, IMSs, human-machine collaboration, and the application of intelligent manufacturing. Intelligent manufacturing systems are characterized by the following components [8].

Smart design

It is expected that traditional design methods will be updated to digitalized, smart forms. With the extensive spread of virtual and augmented reality techniques design can be correlated to manufacturing processes e.g., during additive manufacturing. By using augmented reality in the design (Figure 6.) process the manufacturing of prototypes can be more economical, leading to new design attitudes.

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Figure 6. Smart design, using augmented reality [11].

Smart machines

Smart machines mean industrial robots or any machinery that take place in he manufacturing process and can interact with each other and learn, using real-time sensing. Machines can be asked to do simple tasks or can decide themselves what would be the next step in an industrial manufacturing process.

Smart monitoring

Smart monitoring systems using several sensors, which gather data on various manufacturing features. These features can be temperatures, pressures, vibration etc. which all collected to a cloud-based database. The collected data is then evaluated by smart machines, improving the manufacturing processes according to the previous process parameters, or helping predictive maintenance.

Smart control

With the development of cyber-physical production control systems smart machines can be controlled using digital technologies. Cloud-based platforms make it possible to in-situ control several manufacturing processes at the same time.

Smart scheduling

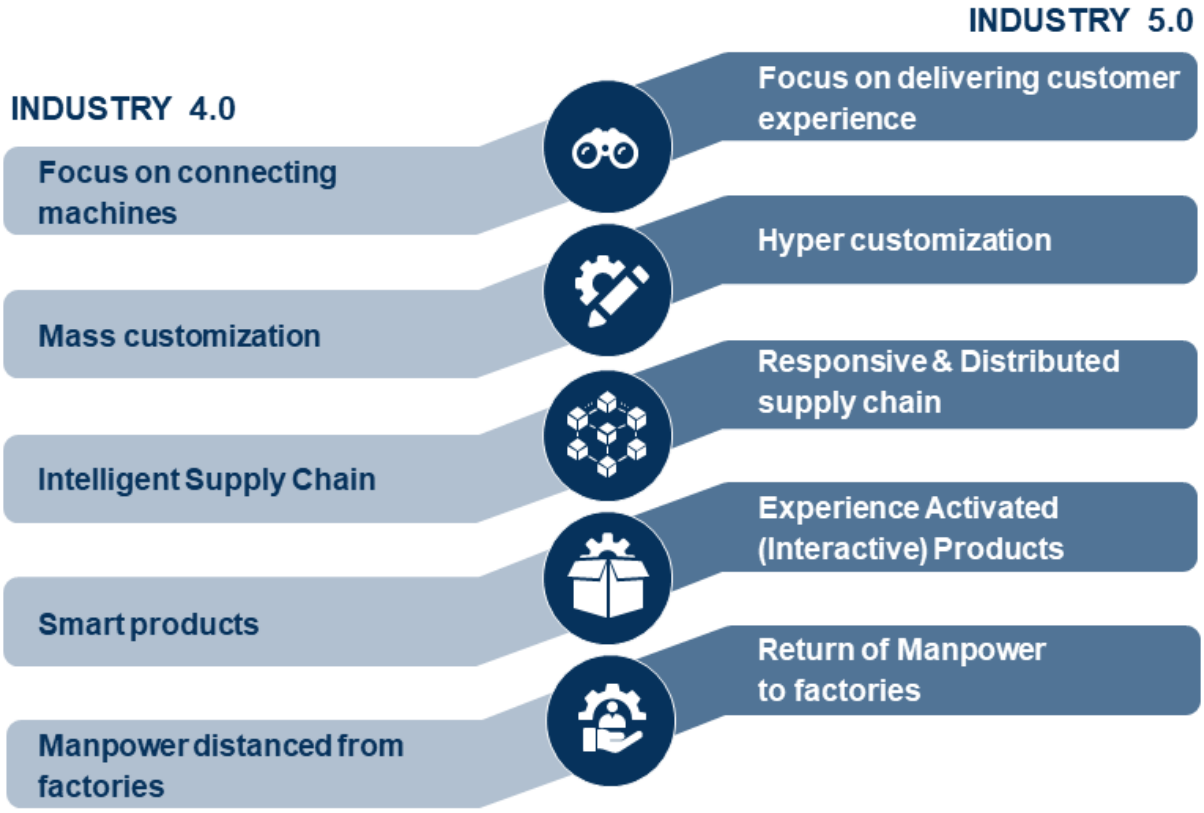
In smart scheduling decision architectures and data collected form the smart sensing technologies can be used in order to make decisions in the manufacturing processes.

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1.3 Industry 5.0

Recently, industrial research and innovation have already started to introduce Industry 5.0 as a definition. In Industry 5.0 the main focus will be on sustainability and the human-centric manufacturing processes. Industry 5.0 will be based on the achievements of the fourth industrial revolution in the near future [12]. The term Industry 5.0 refers to people working alongside robots and smart machines. It's about robots helping humans work better and faster by leveraging advanced technologies like the Internet of Things (IoT) and big data. It adds a personal human touch to the Industry 4.0 pillars of automation and efficiency. s machines in the workplace get smarter and more connected, Industry 5.0 is aimed at merging those cognitive computing capabilities with human intelligence and resourcefulness in collaborative operations [13].

The EU sees Industry 5.0 as a complement to Industry 4.0 and has placed it high on its agenda. The research and consulting firms and experts who started talking about the need for an Industry 5.0 (also elsewhere) all 'invented' the term for more or less the same reasons the EU embraced it. Industry 5.0 is a model of the next level of industrialization characterized by the return of manpower to factories, distributed production, intelligent supply chains and hyper customization, all aimed to deliver a tailored customer experience time after time (Figure 7.) [14].



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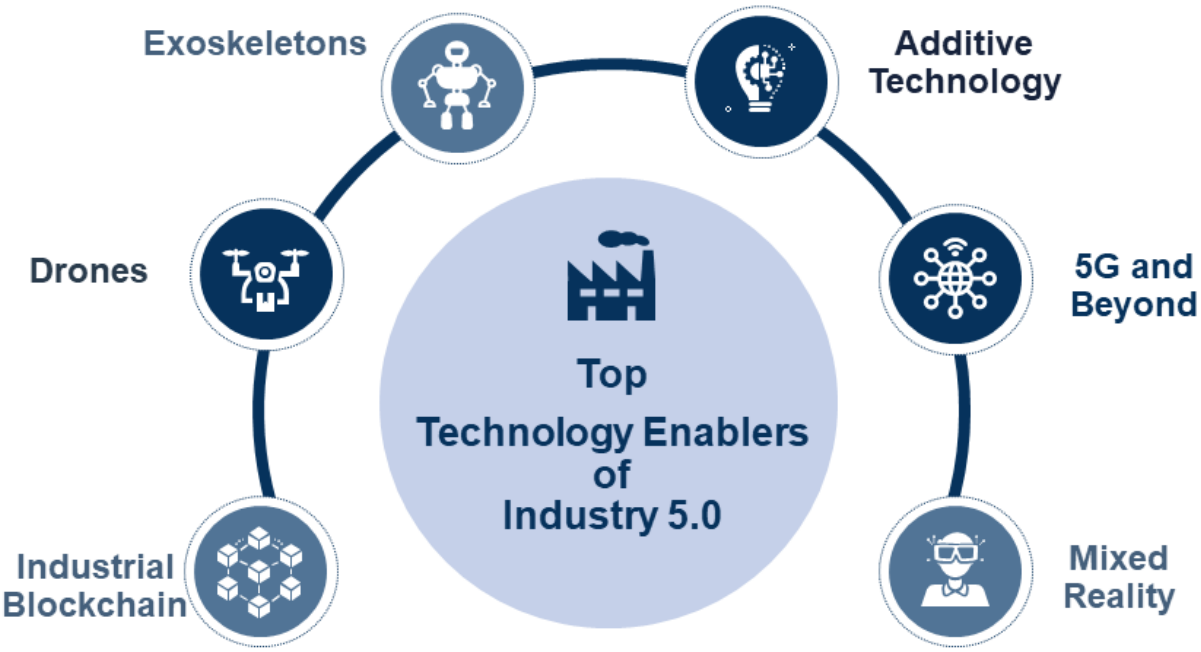


Figure 7. Highlights of Industry 5.0 (top) and its technology enablers (bottom) [15].

Design using digital instruments

In most cases, engineering enterprises employ traditional technologies, such as computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE). However, enterprises are not yet ready to introduce such latest digital technologies as real-time big data analysis, electronic data exchange, cloud manufacturing. Also, most employed technologies come from different vendors, and can only be partially integrated with each other, or even are not compatible at all. The basic concept that became the standard for foreign developers and manufacturers of high-tech products, is cross-cutting modelling as properties (in the early stages of design), and processes for the preparation of production and product release. This ensures the achievement of the required production (cost, time, exit products to market) and operational parameters. The complex solution of this problem may be reached by the introduction of digital technologies which allow modelling of alternative scenarios at all stages of the product life cycle: designing, process planning, manufacturing, operation and aftermarket servicing [16].

Project management using digital instruments

Online databases and the world wide web can help in project management. This concept is often called a web-based project management system (WPMS). The system is only accessible by a project team, but team members can be located in different organizations. It basically provides a centralized, commonly accessible, reliable means of transmitting and storing project information. Project information is stored on the server and a standard Web browser is used as a gateway to exchange this information, eliminating geographic and boundary hardware platform differences [17].

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2. DIGITAL MANUFACTURING VS TRADITIONAL MANUFACTURING

The definition for Industry 4.0 was first introduced in 2011 at the Hannover Messe trade fair and was the subject of an Industry 4.0 working group set up by the German federal government. Germany Trade and Invest (GTAI) defines Industry 4.0 as *A change of paradigm. . . possible through technological advances that constitute a reversal of the conventional logic of the production process. Simply put, this means that industrial production machines no longer simply "process" the product, but that the product communicates with the machines to tell them exactly what to do* [18].

To shed light on the concept of Industry 4.0, GTAI invokes the concept of cyber-physical systems (CPS) - technologies that combine the digital and physical worlds [18], usually through sensors attached to physical devices and network technologies that collect the resulting data [19]. The concept is remarkably similar to the most commonly referred IoT.

At the same time, increased connectivity and increasing data collection, as well as analytical capabilities enabled on the Internet of Things (IoT), have led to a shift towards an information-based economy [20,21].

Manufacturing is a constantly evolving industry, and data show that the industry contributes a significant amount of revenue to any country. That being said, industry leaders have begun to shift their focus from traditional to smart production using Industry 4.0 solutions, as it offers a multitude of benefits to operators, managers and executives in companies in this sector. In addition, partnering with a successful IoT application development company cannot be ruled out [22].

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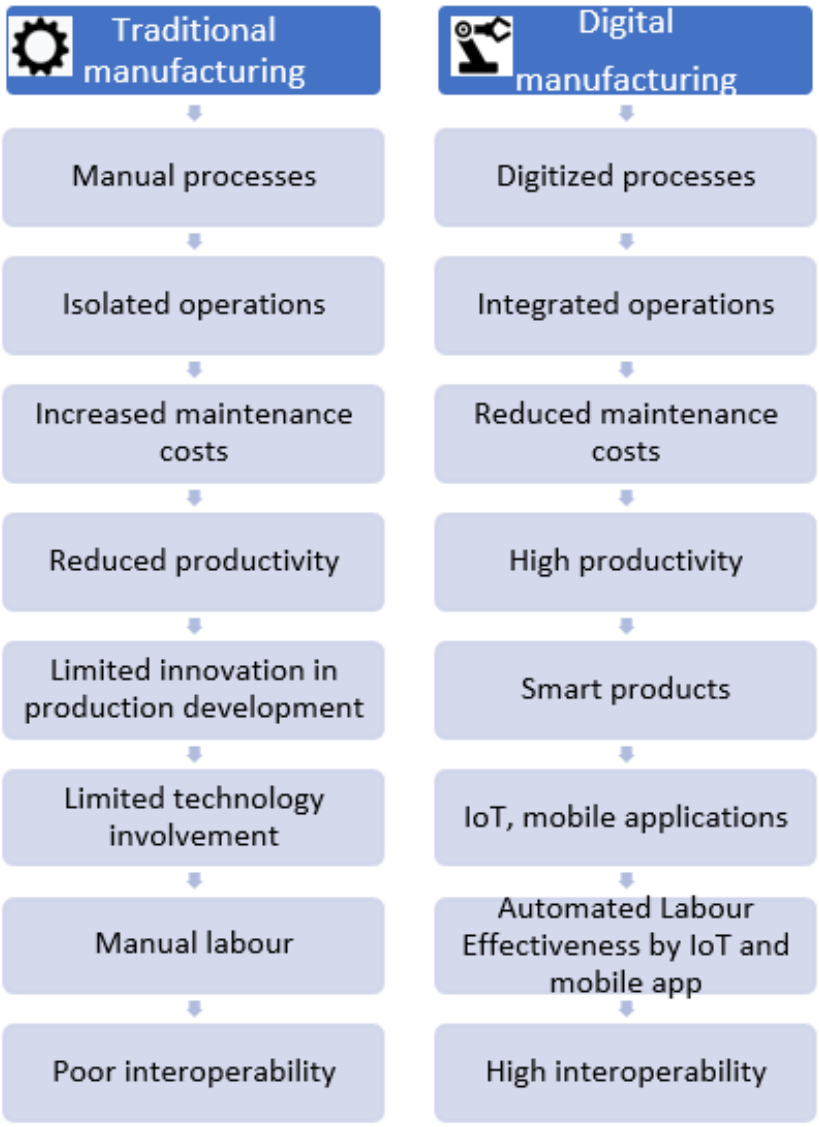


Figure 8. Traditional vs digital manufacturing features

The integration of information technology (IT) and operations technology (OT) to form a stronger production organization is a state that is commonly referred to as Industry 4.0. Also known as SMART manufacturing or Manufacturing 4.0, Industry 4.0 is marked by a transition from physical to digital and vice versa connection [23]. The benefits of Industry 4.0 can be better understood by clarifying the influence of the technologies facilitating physically heavy routine tasks and moving them from the human workers to machines through software.

A design is created by drawing, CAD software or scanning a physical file object and in this way creating data.15 This data is then communicated to the executing machine's design, bringing it from the digital environment to the physical one [24].

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Another concept that Industry 4.0 introduces is the one called the "smart factory". This concept refers to cyber-physical systems monitoring the physical processes of the factory and making reasoned decisions. Physical systems become in this way the Internet of Things, communicating and cooperating both with each other and with a human operator in real-time using a wireless network [25].
Under these circumstances, a „smart factory" faces both requirements and challenges.

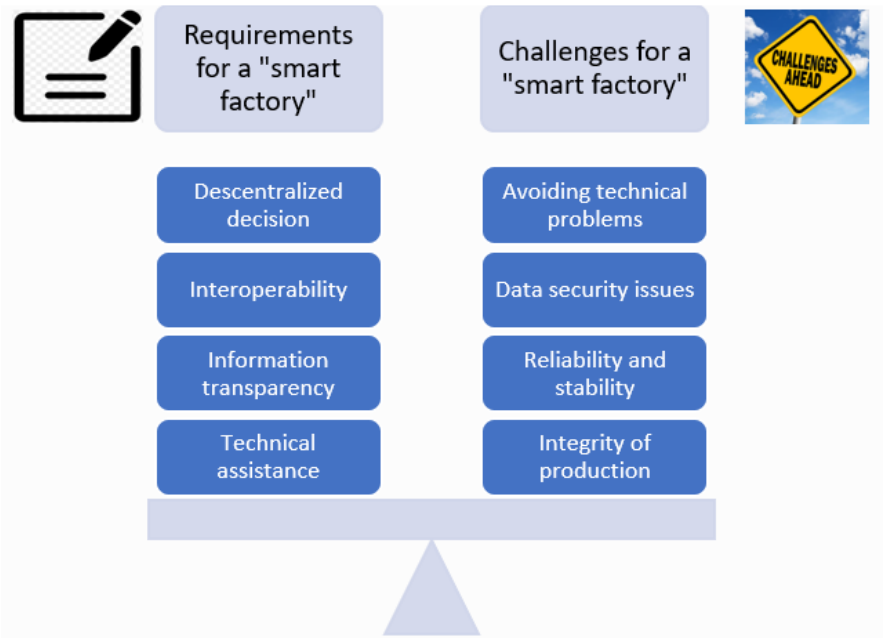


Figure 9. Requirements and challenges for a "smart factory"

The smart factory is a concept used to describe the application of different combinations of modern technologies to create a hyperflexible, self-adaptive production capacity. Smart factories are an opportunity to create new forms of efficiency and flexibility by connecting different processes, information flows and stakeholders (front-line workers, planners, etc.) efficiently. Smart factory initiatives can also be called a "digital factory" or a "smart factory" [26].
Some companies built tool kits for assessing the capacity of a manufacturing company to move from „traditional" to „digital". They start by evaluating the performance of the current environment and the digital maturity of the organization. The digital transformation is based on certain criteria such as: social media environment, cloud computing, big data, internet of things, cybersecurity and mobility. These criteria are considered the 6 core technologies that make possible a digital transformation.

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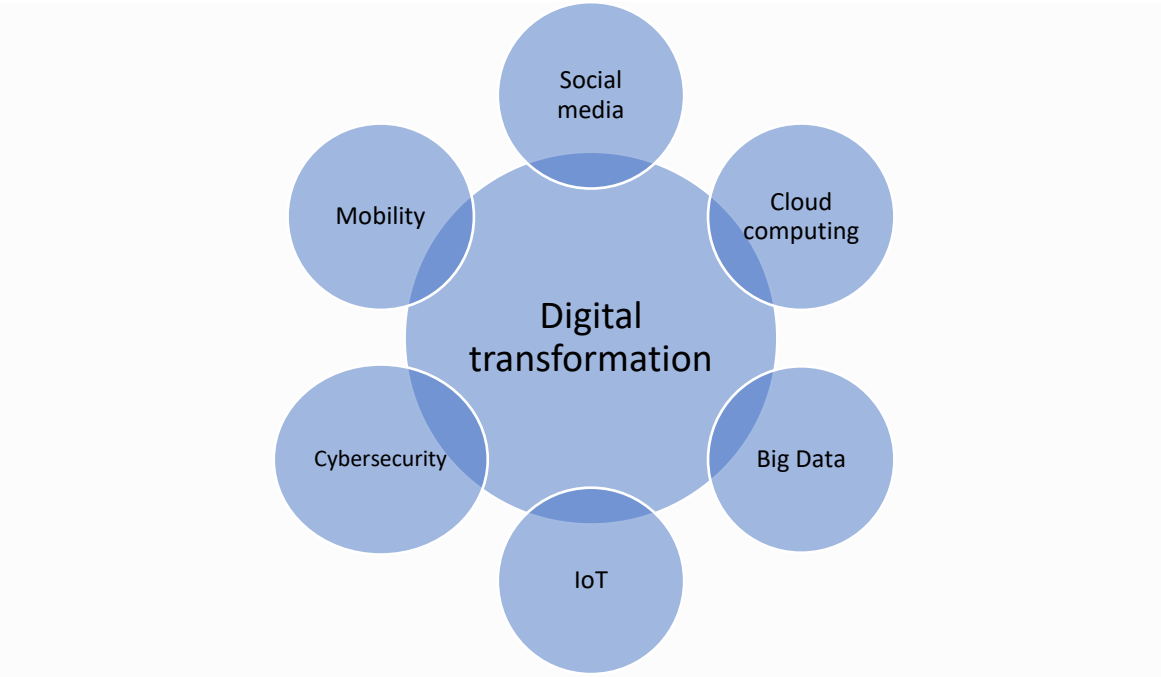


Figure 10. The main technologies leading towards digital transformation

- Social media – a mix of networks and applications enabling the users to create and share content (Facebook, LinkedIn, Twiter, Youtube, Instagram, etc);
- Cloud computing - is based on remote servers hosted on the internet able to store, and process data from a different location;
- Big data – extremely large data sets that can be analyzed computationally to reveal patterns, trends, connections between different parameters
- Internet of Things – a characteristic of the internet that allows different objects to get connected and share information in both directions
- Cybersecurity – a set of technologies able to protect computers, networks and programmes from unauthorized access
- Mobility – the use of mobile devices which changed human interaction providing new opportunities to interact, collaborate and work

3. DESIGN FOR MANUFACTURING

3.1 Introduction

Manufacture is defined as, the process of converting raw materials into products. The word manufacturing is derived from the Latin word *manu factus* meaning made by hand.

It usually involves activities in which the manufactured product is used to manufacture other products.

Products are seldomly made of just a single part, such as a nail or bolt.

Most objects are constructed by assembling several single parts, and these components can be made from a variety of materials.

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In the past, products have been designed that could not be produced. Products have been released for production that could only be made to work in the model shop when prototypes were built and adjusted by highly skilled technicians.

Effective product development must go beyond the traditional steps of acquiring and implementing product and process design technology as the solution. It must address management practices to consider customer needs, design those requirements into the product, and then ensure that both the factory and the virtual factory (the company's suppliers) can effectively produce the product.

Products are initially conceptualized to provide a particular capability and meet identified performance objectives and specifications. Given these specifications, a product can be designed in many different ways. The designer's objective must be to optimize the product design with the production system.

A company's production system includes its suppliers, material handling systems, manufacturing processes, labour force capabilities and distribution systems.

Generally, the designer works within the context of an existing production system that can only be minimally modified. However, in some cases, the production system will be designed or redesigned in conjunction with the design of the product. When design engineers and manufacturing engineers work together to design and rationalize both the product and production and support processes, it is known as integrated product and process design.

The designer's consideration of design for manufacturability, cost, reliability and maintainability is the starting point for integrated product development.

A designer's primary objective is to design a functioning product within given economic and schedule constraints. However, research has shown that decisions made during the design period determine 70% of the product's costs while decisions made during production only account for 20% of the product's costs.

Further, decisions made in the first 5% of product design could determine the vast majority of the product's cost, quality and manufacturability characteristics. This indicates the great leverage that DFM can have on a company's success and profitability.

However, the application of DFM must consider the overall design economics.

It must balance the effort and cost associated with the development and refinement of the design to the cost and quality leverage that can be achieved.

In other words, greater effort to optimize a product’s design can be justified with a higher value or higher-volume product.

Design effectiveness is improved and integration facilitated when:

- ✓ Fewer active parts are utilized through standardization, simplification and group technology retrieval of information related to existing or preferred products and processes.
- ✓ Producibility is improved through the incorporation of DFM practices.
- ✓ Design alternatives are evaluated and design tools are used to develop a more mature and producible design before releasing for production.

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- ✓ Product and process design include a framework to balance product quality with design effort and product robustness.

The History of Manufacturing (see also Table 1), dates back to about 5000 B.C, and it is older than recorded history; also, primitive cave and rock markings made with tools that were manufactured for these purposes, and primitive manufacturing of products for various specific uses began with articles made of wood and stone.

3.2 Design for X

Generally, **Design for manufacture** is a component of Design for X, where DFX means:

1. Design for Manufacture
2. Design for Assembly
3. Design for Environment
4. Design for Safety
5. Design for Reliability
6. Design for Maintenance
7. Design for Aesthetic features
8. Design for Economy
9. Design for Ergonomics

Design for Manufacture

DFM refers to the general engineering art of designing products in such a way that they are easy to manufacture. The basic idea exists in almost all engineering disciplines, but of course, the details differ wildly depending on the manufacturing technology.

Traditionally, the DFM method evaluates the feasibility and cost of manufacturing the product at the operation level.

Design for Assembly

Design for Assembly (DFA) is a process by which products are designed with ease of assembly in mind. If a product contains fewer parts it will take less time to assemble, thereby reducing assembly costs. In addition, if the parts are provided with features that make it easier to grasp, move, orient and insert them, this will also reduce assembly time and assembly costs

In many cases, DFM and DFA are used together in terms of DFMA. The manufacture refers to the manufacturing of the individual parts of a product or assembly and to assemble refers to the addition or joining of parts to form the completed product. So, the term „Design for Manufacture" (DFM) means the design for ease of manufacture of the collection of parts that form the product after assembly and „Design for Assembly" (DFA) means the design of the product for ease of assembly. Design for manufacture and assembly (DFMA) is a combination of DFA and DFM.

DFMA is used for three main activities[Boyrodh]:

1. As the basis for concurrent engineering studies to guide the design team in simplifying the product structure to reduce manufacturing and assembly costs, and to quantify the improvements.

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2. As a benchmarking tool to study competitors' products and quantify manufacturing and assembly difficulties
3. As a should cost tool to help control costs and to help negotiate suppliers contracts.

Design for environment. (DFE) is a product design approach for reducing the impact of the products on the environment.

Design for safety. The goals of the design process are usually manifold. The resulting system must not only satisfy its functional requirements but also have to fulfil certain non-functional requirements. One of such requirements is safety. A safe product does not cause injury or property loss and does not pollute the environment. There are three aspects to design for safety.

a. Make a safe product.

b. If it is not possible to make the product inherently safe, then design proactive devices like guards, automatic cutoff switches, pressure relief valves, to mitigate the hazard.

c. If step *b* cannot remove all the hazards, then warn the user of the product with appropriate warnings like labels, flashing and loud sounds.

Design for reliability

Reliability engineering is the discipline of ensuring that a system will be reliable when operated in a specified manner.

Reliability engineering is performed throughout the entire life cycle of a system, including development, test, production and operation.

Design for maintenance (Serviceability)

Serviceability is concerned with the ease with which maintenance can be performed on a product. Products often have parts that are to be replaced at periodic intervals. It is important to anticipate the required service operations during the design of the product. Provision must be made for disassembly and assembly. For example, don't make an automobile design that requires the removal of the panel to access the oil filter. Also, remember that service usually will be carried out in "the field" where special tools and fixtures used in factory assembly are not available. The best way to improve serviceability is to reduce the need for service by improving the reliability of the components and systems.

Design for aesthetic features

Designers have many aesthetic qualities to improve the marketability of manufactured products: smoothness, shininess/reflectivity, texture, pattern, curviness, colour, simplicity, usability, velocity, symmetry, naturalness, and modernism.

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Design for economy

It is important to note that cost is also a dimension of quality. Economically successful products are profitable; that is, they generate more cumulative inflows than cumulative outflows. The main objective of all manufacturers is to make a profit. So the producer should give a cost-effective design. Based on the cost and other considerations, the designer should select material or manufacturing processes.

Design for ergonomics

Ergonomics (or human factors) is the application of scientific information concerning humans to the design of objects, systems and environments for human use. Ergonomics is the study of the interaction of a person with a machine.

Information derived from Ergonomists contributes to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people

3.3 Design for manufacture method

In order to apply the method, gathering DFM information is necessary. The main information can be collected from:

- Sketches, drawings, product specifications, and design alternatives.
- A detailed understanding of production and assembly processes
- Estimates of manufacturing costs, production volumes, and ramp-up timing.

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Synthetically, in fig. 4, are presented the main elements of a manufacturing system.

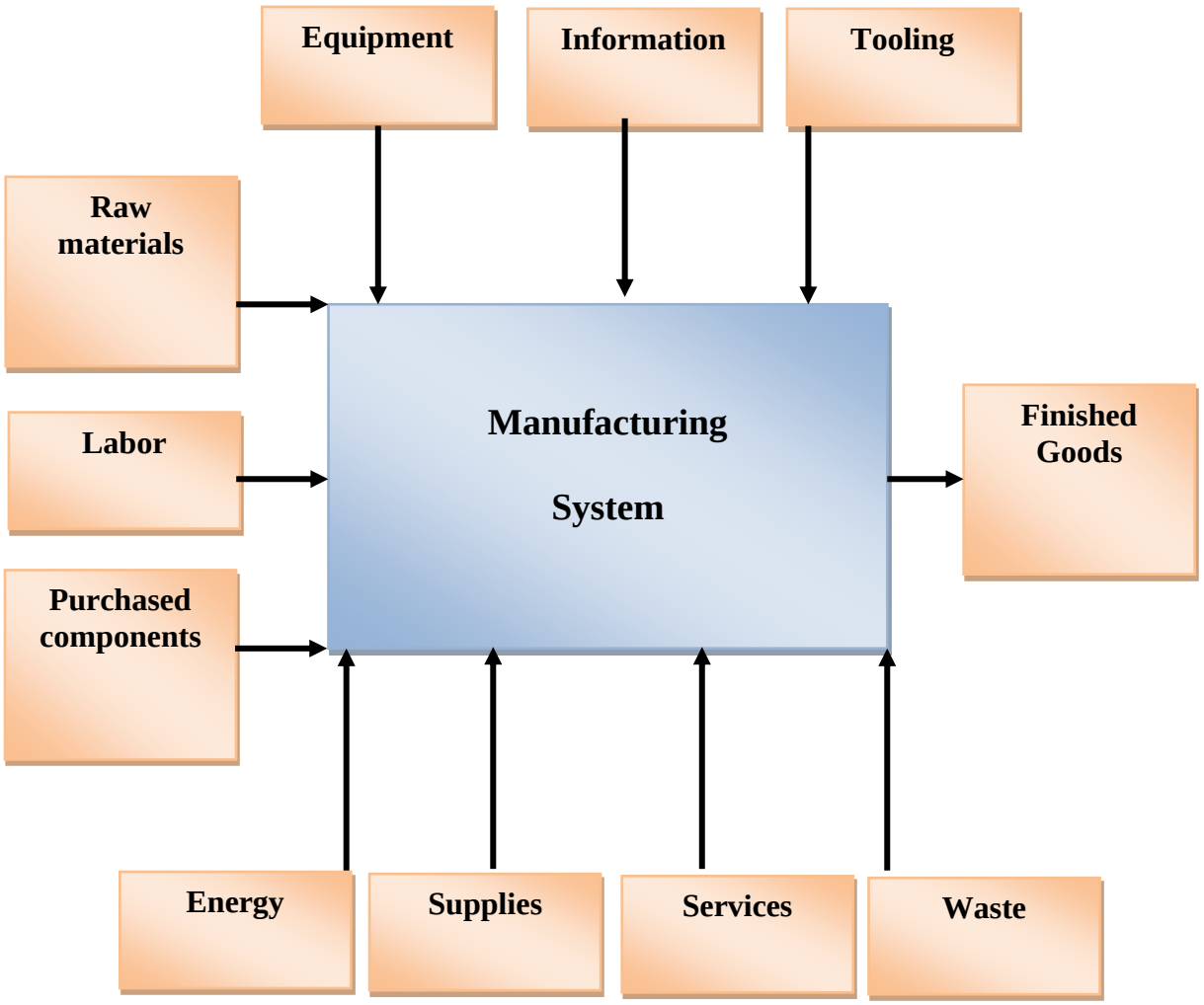


Figure 11. The main elements of a manufacturing system

The principle for the DFM method is presented below, fig. 5.

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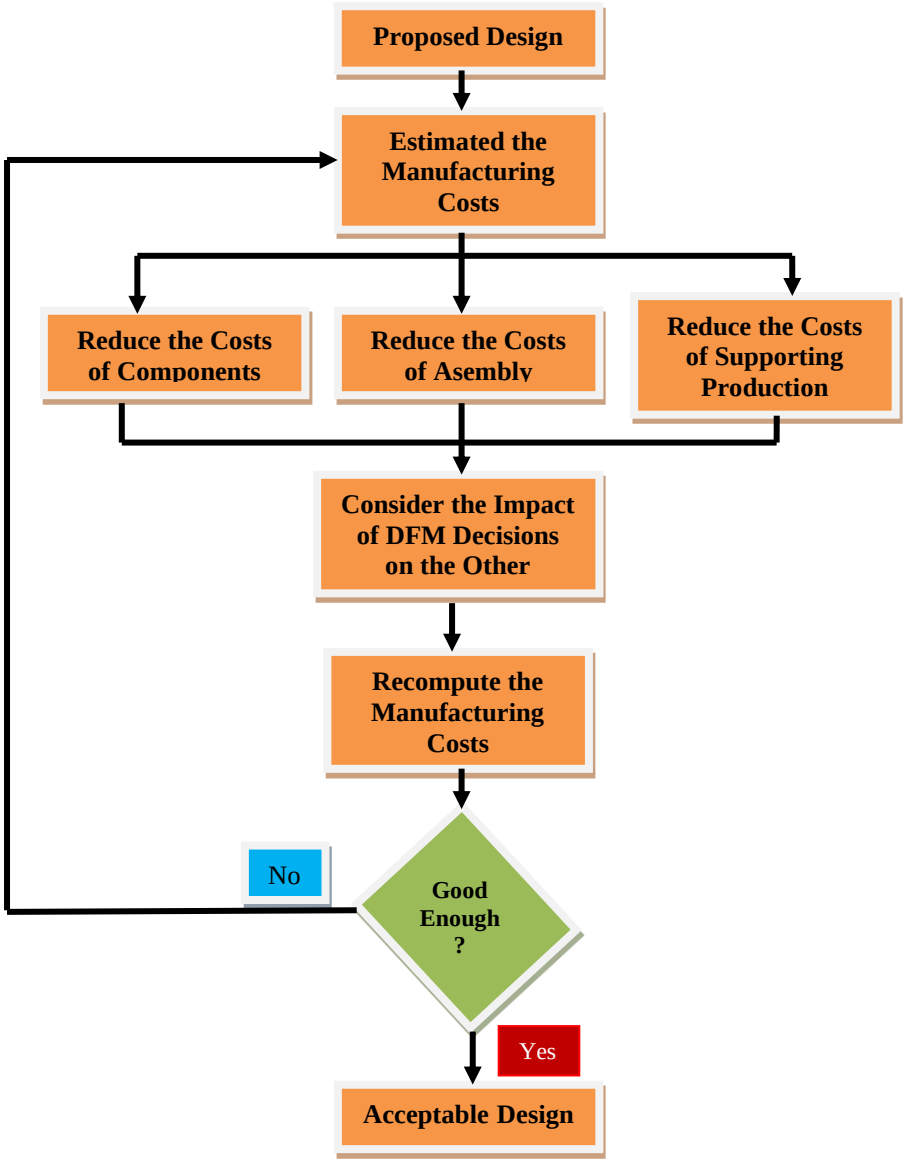


Figure 12. The principle of the DFM Method

Manufacturing Costs can be defined as the sum of all expenditures for the inputs of the system (i.e. purchased components, energy, raw materials etc.) and for disposal of the wastes produced by the system.

The elements of the manufacturing cost of a product are:

- ✓ Cost for components
- ✓ Cost for assembly
- ✓ Overhead costs

Component Costs (parts of the product) refer to:

- ✓ Parts purchased from supplier
- ✓ Custom parts made in the manufacturer's own plant or by suppliers according to the manufacturer's design specifications

- Assembly Costs refer to labour, equipment, & tooling, the cost for handling etc.

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- Overhead Costs (all other costs) refer to:
  - ✓ Support Costs (material handling, quality assurance, purchasing, shipping, receiving, facilities, etc.)
  - ✓ Indirect Allocations (not directly linked to a particular product but must be paid for to be in business).

3.4 Cost estimation process for the conceptual and detailed design

In the conceptual design stage, it helps decision making, whereas, in the detailed design stage, it facilitates the design assessment to eliminate mistakes in product design. Figure 13 describes the working capability of the system, which is divided into three options.

1 - The system offers decision support to compare alternative materials at the conceptual design stage.

2 - The system provides decision support to compare alternative manufacturing processes at the conceptual design stage.

3 - The system helps to assess the design mistakes and estimates the manufacturing and total cost of the product along with other values in the detailed design stage.

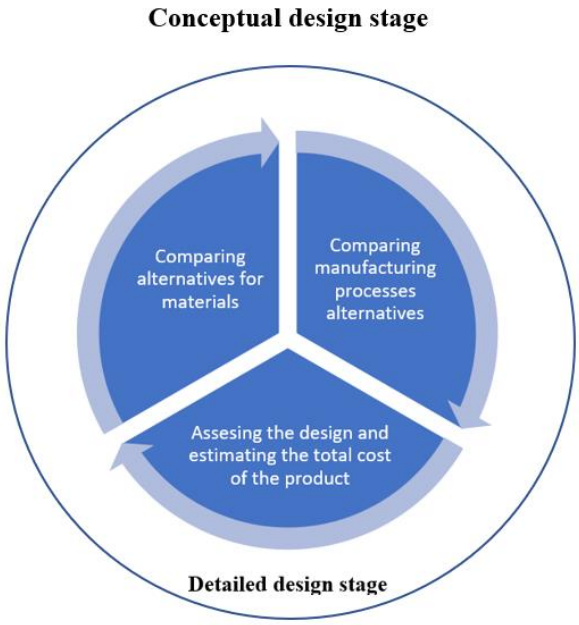


Figure 13. The working capability of the system

The cost estimation process for the conceptual and detailed design stages is illustrated in Figure 14. For the conceptual design, the estimation process follows the five steps:

In step 1 (See Figure 14), the system prompts the designer to choose the values from a comprehensive options list. The designer selects the values and specifies his/her preferences.

In the 2nd step, the designer is required to input the targets of each value.

In step 3, he/she constructs a conceptual part model and specifies alternative manufacturing processes, alternative materials and complete CAD model information. Once the information has been provided, the system examines each feature for its compatibility by applying the Poka-yoke (mistake proofing) rules stored in the knowledge database, in step 4.

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These Poka-yoke rules help to identify the machines' availability at the manufacturing facility and make a manufacturability assessment. If the feature does not accomplish the Poka-yoke criteria, then the system prompts the designer to modify the part model. Once each feature is found to be suitable for manufacturing, the system generates an estimate of manufacturing time, cost and all other values required by the designer.

Steps 3 and 4 (Figure 14) are repeated until manufacturability, manufacturing cost and other required values of the entire product are estimated. After that, the system displays the matrix for communicating alternatives to express the output of all values.

Finally, in step 5, a solution narrowing down method (quantification method) has been put in place to eliminate the weak solution.

Once the strong solution is selected in the conceptual design stage, it is further developed by the designer in the detailed design stage. Final details, CAD/CAM model, FEA (finite element analysis) tests, and assembly and product structure are finalised in the detailed design stage.

The estimation process is composed of four steps, out of which steps 1 and 2 are similar to the conceptual design stage.

In step 1 (Figure 14), required values and their preferences are provided by the designer, whereas in step 2, each value's target is supplied.

In step 3, the designer specifies the material, manufacturing process and CAD model information. After providing detailed information, the system applies Poka-yoke principles to detect any design mistakes in step 4 (Figure 14). Once the product is identified as mistake-proof, manufacturing time, cost and all required values are estimated.

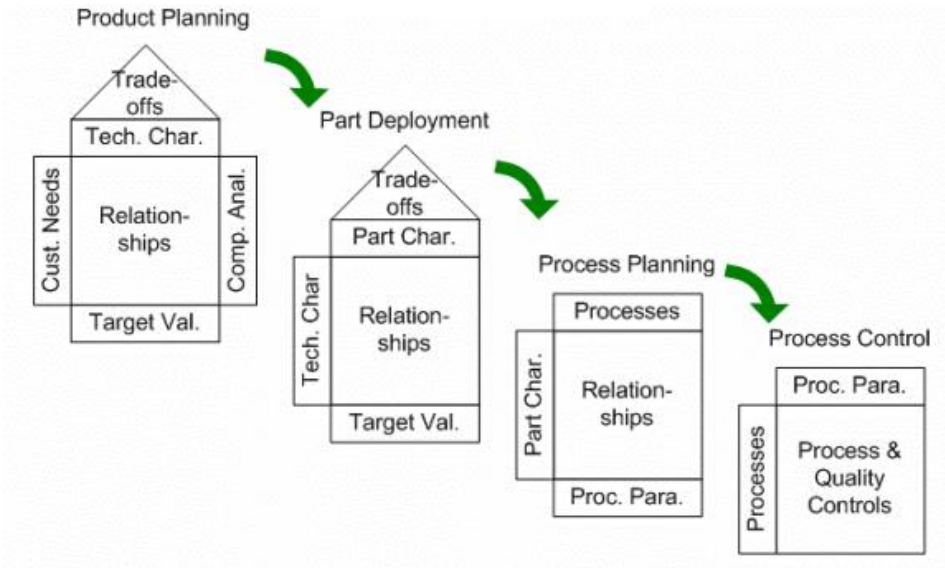


Figure 14. The Phases of Quality Function Deployment

3.4.1 DFM in Conceptual design

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Conceptual design is the process by which customer needs are translated into requirements on function (what the design must do) and performance (how well it does it). Design freedom is at its highest here; this freedom is ‘spent’ by making design commitments whose effects may not be known fully until production begins. Often only rough estimates of manufacturability are available in conceptual design. DFM must help direct the allocation of design freedom toward designs with high manufacturability.

The key concept here is ‘designs’: Toyota’s successful use of set-based design underscores the value of delaying design commitment when there is no clear-cut ‘best’ design.

For DFM in conceptual design, this means developing multiple functional approaches and propagating them through further design stages, eliminating or revising candidates as they are proven inferior.

The decision-based design provides a normative framework for culling design candidates underestimated performance metrics. Performance metrics are continually refined through the design process.

Perhaps the most commonly used DFM tool throughout all stages of product development is Quality Function Deployment (QFD). QFD was first put forth in 1966 in quality assurance work by Akao and Oshiumi.

Subsequent research used the matrix to address technical trade-offs in the quality characteristics by adding a “roof” to the top of the matrix, which became the “House of Quality.” QFD converts customer demands (WHATs) into quality characteristics (HOWs) and systematically develops a quality plan for the deployment of the finished product.

In practice today, QFD is used to translate the voice of the customers into a set of design elements that can be deployed vertically top-down through a four-phase process: Product Planning, Part Deployment, Process Planning, and Process Control.

Figure 12 shows the methodology flow of the four phases of QFD. During each phase, one or more matrices are prepared to help plan and communicate customer needs, technical characteristics, and design and process information.

From a technology development standpoint, DFM in conceptual design presents two main issues: how to develop functions in response to common DFM desires (e.g., low part count, low part complexity, ease of assembly, and loose tolerances) and how to close the QFD ‘loop’ to propagate standard downstream concerns back into conceptual design.

For the former, the current state of the art is the collocation of design and manufacturing team members. As enterprises become less vertically integrated, collocation becomes impractical; reverse engineering can substitute as a means of accessing ready manufacturing experience. By providing designers with access to a broad, consistent basis of experience, reverse engineering can potentially improve the degree to which manufacturability can shape conceptualization.

For the latter issue, integrating DFM into QFD can be achieved through an iterative process that brings the results of process planning and control matrices into the part deployment matrix.

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For example, once a process plan has been conceived, features that make components easier to fabricate or easier to assemble into the final product can be added to the list of technical and part characteristics. Such iterations ease the transition to embodiment design and allow manufacturing to be considered at the earliest stage of design.

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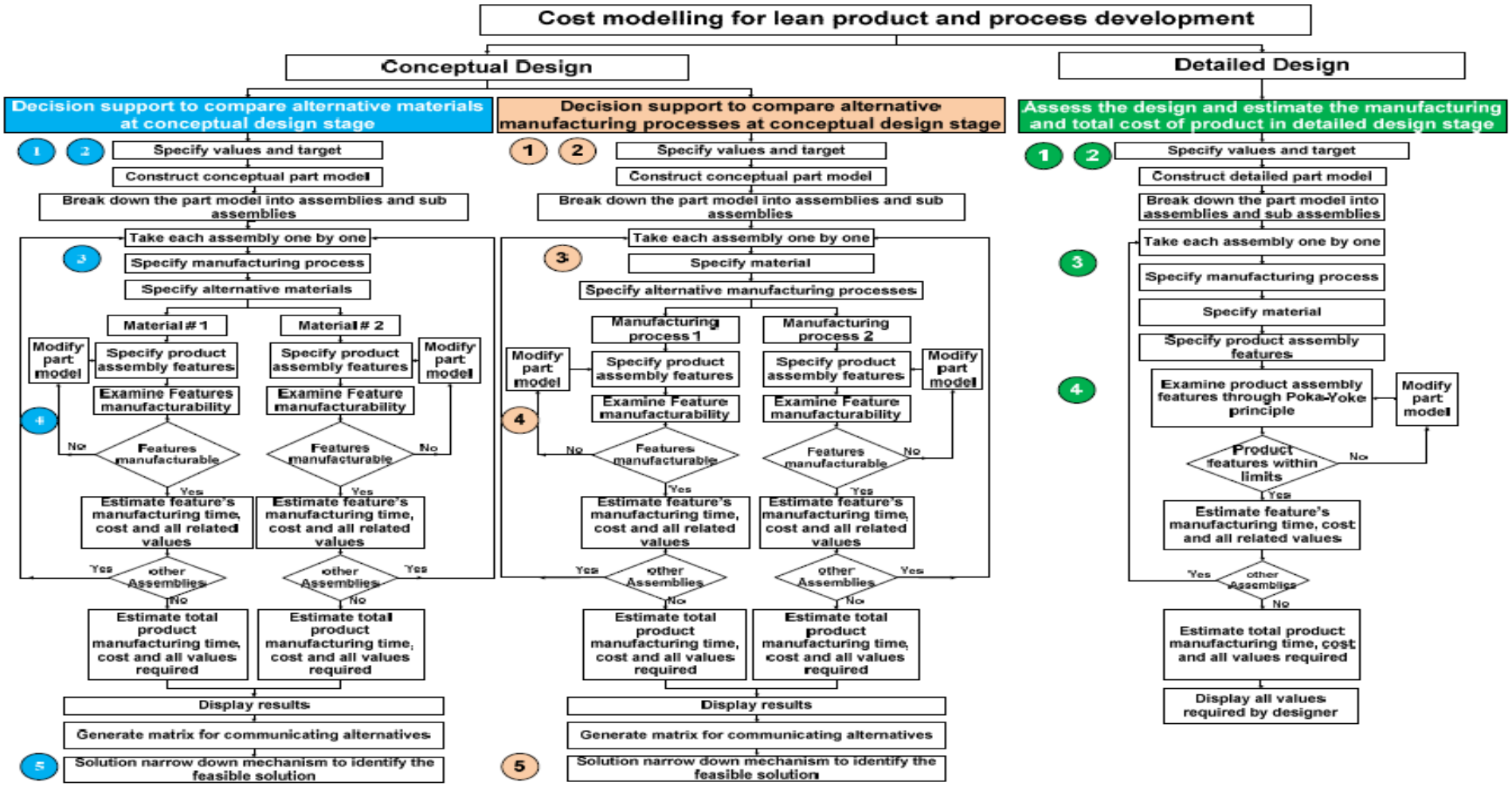


Figure 15. Cost estimation process for the conceptual and detailed design

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3.4.2 DFM and Concurrent Engineering

Concurrent product and process engineering is the practice of simultaneously designing a product to fulfil particular functions and the manufacturing process by which it will be made.

More generally, concurrent engineering is the practice of simultaneously developing solutions that address multiple life cycle issues. In practice, engineered systems are usually too complex to truly consider all issues simultaneously.

More commonly, concurrent engineering (and DFM) is accomplished through an iterative "spiral" design process (shown in fig. 8) in which marketing experts, designers, manufacturing engineers, and other personnel jump back and forth between identification of customer needs, design of the product, and assessment of manufacturing issues.

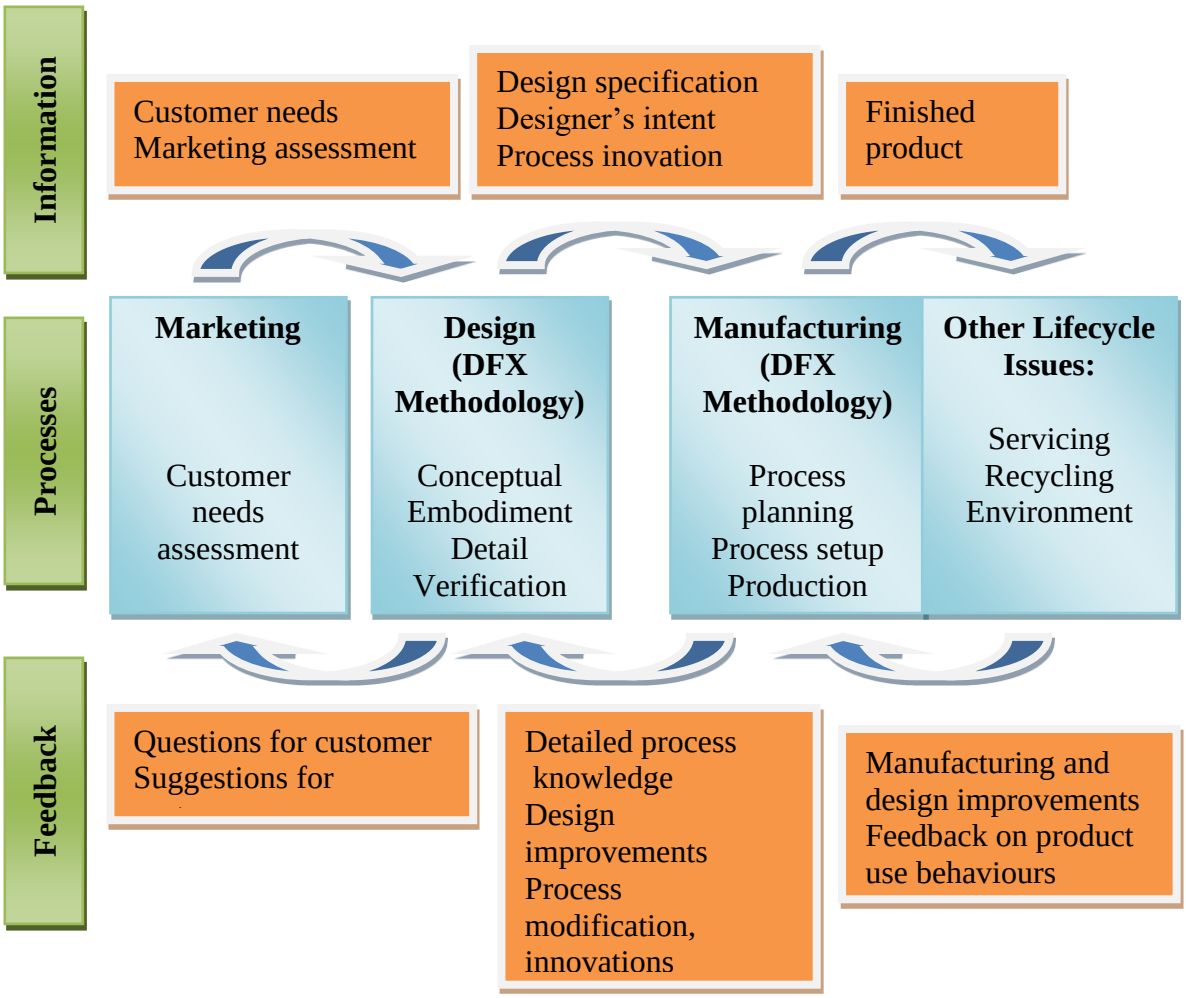


Figure 16: The Design for X Cycle

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Barriers to effective DFM and concurrent engineering occur when the people performing marketing, design, and manufacturing cannot communicate or share knowledge. For example, when designers lack detailed knowledge of the current manufacturing practices and the manufacturing engineers are not available to provide this assessment, the designers may not be able to perform sufficient manufacturing assessments of their designs.

The result may be a commitment to a design that is unnecessarily expensive to manufacture. In some sense, the basic objective of DFM is not new. Manufacturers and craftspeople have always tried to design products that are inexpensive to manufacture. Before the industrial revolution, the salesperson, designer, and craftsperson were often the same person. This person had a detailed understanding of the customer's needs, how the design would meet those needs, and how it would be made. Concurrent engineering naturally occurred within that person's head.

However, as industries have grown in size and complexity, marketing, design, and manufacturing departments have evolved into separate organizations, each with its own specialized knowledge. While this makes the streamlined creation of complex products possible, it has also increased the knowledge and communication barriers between these areas. The recent trend towards moving manufacturing facilities overseas has exacerbated these communication difficulties.

The result is that DFM and DFX are more difficult to accomplish, product quality and customer satisfaction may be compromised, and much time and money may be lost. The goal behind many DFX tools is to supply designers with manufacturing, quality, environmental impact, or other life cycle knowledge that is otherwise inaccessible.
This can be accomplished through many methods such as (1) the development of a set of manufacturability rules that designers apply to their designs, (2) software "auditors" and "critics" that automatically apply such rules to electronic CAD designs and provide advice for improvement, cost analysis, and (3) simulation models that predict the product's performance during various life cycle phases. Examples will be described in the following sections of various ways in which these methods may be applied in any or all the life cycle stages shown in Figure 17.

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4. DESIGN AUTOMATION REQUIREMENTS FOR SUPPORTING INTEGRATED PRODUCT DEVELOPMENT

4.1 Introduction

In many companies, product and process design are fragmented and difficult to manage and coordinate. CAD/CAE tools automate the design and development process but, in many cases, cause the rapid proliferation of designs without regard to the impact on the rest of the organization. While these tools are to varying degrees integrated, often these systems will be used to create an item's geometry on paper to communicate with other functional areas of a company.

One survey indicated that the typical company re-creates an item's geometry five or more times in such areas as customer proposals or marketing specifications; conceptual design; detail design; finite element analysis; other engineering analysis; detail drafting; fabrication or assembly sketches; work-cell device programming; tooling and fixture design; and training and service manuals. Each time part geometry or product design information is independently maintained in a separate system or independently created on paper, another source of redundant design information is created that needs to be managed.

Non-integrated systems also require additional effort to transfer data from one system to another. This allows errors to creep into the process, and data can be mishandled or lost. Delays are inherent in this process and extra effort is required to coordinate activities.

Technology and information integration represent one dimension of overcoming these traditional problems. Integrated design and manufacturing automation systems and databases are the basis for the Engineering blueprint of the future. This will allow manufacturers to cost-effectively improve product and process design while facilitating the integration of design activities with the production process.

Product and process design will be greatly enhanced using integrated databases and information systems to maintain and optimize the use of design information.

Product and process design information must be treated more as a corporate-wide resource. This information must be stored and maintained in a logical, consistent, non-redundant and usable manner. There must be a shift to definition-oriented design information that can directly drive downstream processes with little or no human interpretation and planning. Current standards such as IGES need to be improved upon so that this data can be readily accessed and used without regard to technical constraints.

Evolving standards such as the Standard for the Exchange of Product Model Data (STEP) will provide a more complete set of product data in a neutral format. This design

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information must be distributed to workstations, controllers, and other systems as required for use. Changes to product and process design data must be managed in accord with the company's data access and configuration management procedures.

By focusing on maintaining product and process design information electronically, paper-based representations of this data can be minimized. As paper drawings are avoided, there will be reduced manual handling and storage of documents, reduced time to access the most current design of a part, and prevention of errors from avoiding the use of outdated drawing information. Design and administrative activities can be streamlined.

When design information is maintained electronically, it can be readily analysed and designs improved so that more mature and producible designs are developed more quickly. Most importantly, this is the basis for definition-oriented designs.

However, maintaining definition-oriented product and process design information electronically requires several supporting technologies. Further, these islands of technology must be linked physically, organizationally, and electronically to achieve this integration of data. These technologies include the following:

- ✓ CAD/CAE with solids modelling and features representation as to the mechanism for defining and maintaining product design information electronically and extensive analysis and simulation of products early in the development cycle
- ✓ Product data management to manage product data in digital form, provide configuration management of this data, and facilitate the development process workflow
- ✓ Automation of process design, process specification and manufacturing planning through definition-oriented design information and tools such as computer-aided process planning (CAPP) and work-cell device programming (e.g., NC, robotic, and computer-aided inspection, and test equipment)
- ✓ Communications and data interchange of product design information internally and externally with suppliers and customers

When these technologies and integration concepts are effectively used, they will improve communication of product and process design within the engineering function, across the enterprise and externally with suppliers and customers.

To achieve the desires of efficiency and flexibility in the field of industrial production, a step-by-step evolution of the production systems was necessary, Figure 18.

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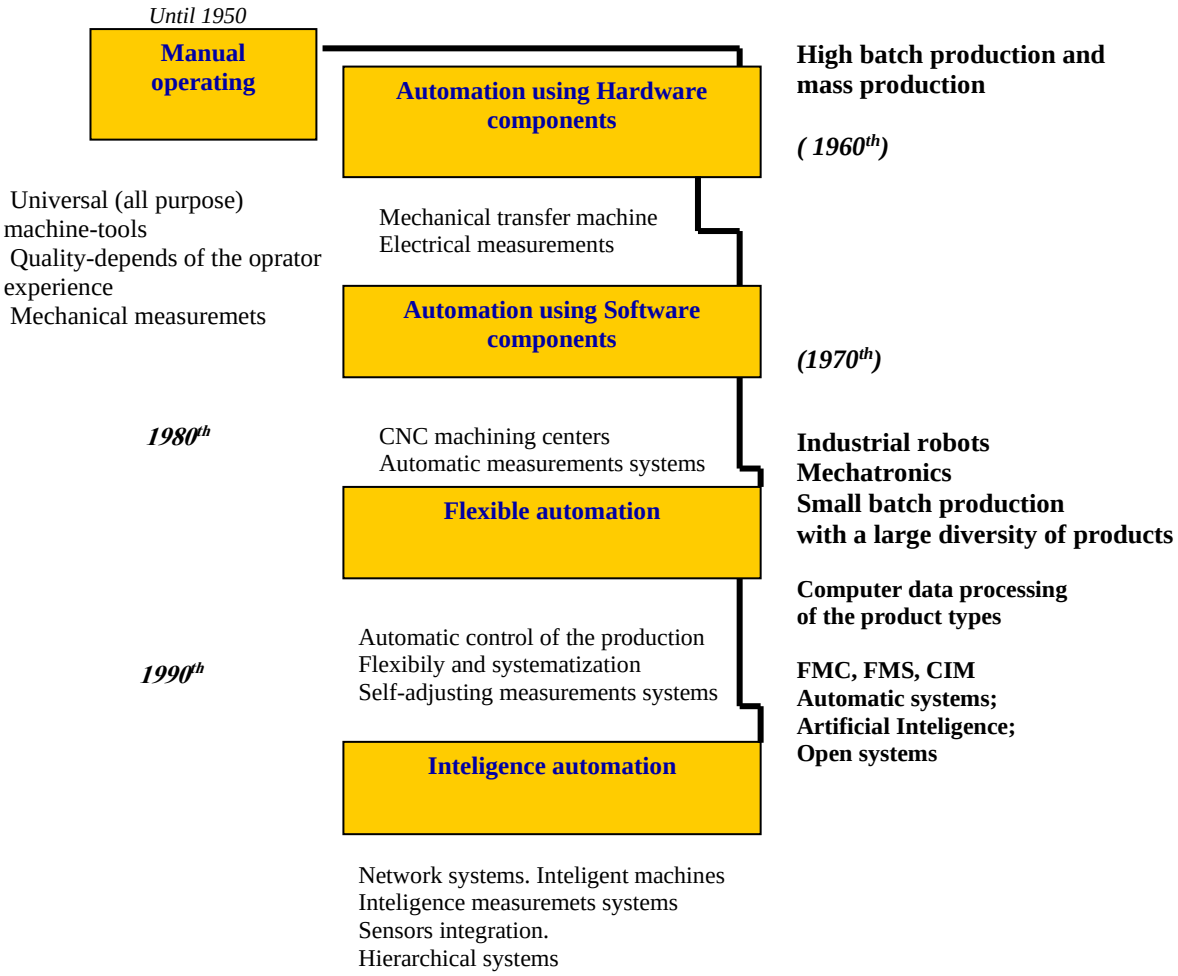


Figure. 18 The development of the production systems

4.2 Product design

Computer-Aided Design and Engineering (CAD/CAE) systems are the keys to developing and maintaining product design information electronically. Two-dimension (2-D) systems, oriented to drafting, maintain relationships of lines, arcs, and circles electronically.

The output of these systems requires human interpretation to obtain meaningful information. However, as CAD systems move toward solids, feature-based and parametric representation of items, this design information can be more meaningfully used without the same level of human interpretation.

Solids Modeling

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One basis for this design approach is to maintain a complete three dimensional solid model of each finished and in-process part in a product definition database. A rigorous representation of each part's boundaries avoids the ambiguities in a 2-D and 3-D representation of a part.

As parts and products become more and more complex, traditional 2-D and 3-D representations, even with hidden line removal, become difficult to understand and interpret. Solids modelling enhances visualization and communication of the design intent. Solids modelling with the evolution toward product or assembly modelling provides a more useful mechanism to represent how parts are put together to form assemblies. Newer solids modelling systems provide a complete definition of part geometry, topology and tolerances. This complete definition coupled with features representation provides information that can be more readily interpreted and used by downstream automated processes in manufacturing.

Features-based representation of design information and parametric design can enhance and augment solids-based representation of the design. Specification of features (e.g., holes, counter-bored holes, threads, pockets, slots, notches, cut-outs, bosses, fillets, chamfers, ribs, flanges, etc.) or design primitives can simplify the creation of the design.

Designing based on the geometric abstractions inherent in solid modelling's constructive solids geometry (CSG) or boundary representation (B-Rep) approaches is a more artificial and difficult to master process than specifying features.

With a features-based approach, a part's design then comprises a basic shape and a hierarchy of features and associated attributes. Feature attributes include dimensions and tolerances. Other information can be associated with individual features to provide design guidance such as design rules, restrictions, producibility indexes, costs, and process requirements.

Product design data such as features, dimensions, tolerances, finishes, etc., can be associated with specific manufacturing processes (e.g., a hole to a drilling operation) and even a specific piece of equipment. This capability will allow design tools to provide producibility guidance directly to the designer while the product or part is being developed. It also re-orients the designer from thinking in terms of just part geometry to also think in terms of manufacturing processes and, therefore, costs and quality implications associated with the part design. This type of definition-oriented design information will then facilitate generative process planning and computer-aided manufacturing.

A valuable aspect of modern CAD systems is their ability to not only render the design but to capture its *intent*. The concept of capturing design intent is based on incorporating engineering knowledge into a model by establishing and preserving certain

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geometrical relationships. The wall thickness of a pressure vessel, for example, should be proportional to its surface area and should remain so even its size changes. The parametric design allows a standard geometry to be specified once for an approved group of parts. By establishing one or more dimensions or characteristics as variable parameters with mathematical relationships to other dimensions, features or characteristics, multiple parts or assemblies can be readily specified by only varying these parameters while maintaining overall geometric and mathematical relationships. This approach provides variation with a minimum of design effort and process capability.

Analysis and Simulation

CAE also provides tools to help improve the maturity of the design by simulating the design and avoiding or minimizing the need to build and test prototypes. Finite element analysis as well as other engineering analysis tools can be used for testing loads and stresses, heat transfer, fluid flow, kinematics, circuit output and timing, and assembly interaction. By simulating important characteristics electronically, the design can be debugged and precious development time reduced. Newer analysis tools go a step further through design optimization capabilities. The designer specifies basic part geometry and geometry details that an optimization program is allowed to manipulate. By then stating design parameters such as weight requirements and required loads, the program will manipulate the part geometry to optimize meeting the requirements.

Reliability and maintainability are increasingly important considerations in product design as customers are increasingly considering the life cycle costs of a product. Tools are emerging to simulate product operating cycles, heat build-up, and wear, all significant factors in product failure. Solids modelling can be used to model accessibility to components and assemblies in products and systems for maintenance purposes and indicate more optimum approaches to designing the product for service and maintenance.

As these tools are refined and merged with design tools, the designer will be in a better position to consider the life cycle costs in the design of products.

Knowledge-Based Engineering

Artificial intelligence and, in particular, knowledge-based engineering systems provide a capability to define rules for effective product and process design in an integrated manner. Design rules can include producibility guidance to more effectively meshing the product design with the company's process capabilities. Expert and knowledge-based engineering systems have already been developed to help configure complex products such as computer systems as well as design products such as turbine

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engine blades. This configuration guidance can be extended to help design products to order from basic, pre-designed product modules quickly and inexpensively.

Assembly Modeling

Solids modelling, features and attribute relationships can be the basis for a more complete product definition. In addition to rigorously defining geometry and topology of individual parts, product assemblies can be defined through solids modelling by defining the:

- ✓ Instances or occurrences of each part in a hierarchical manner similar to a bill of material structure
- ✓ The relative location of each instance or occurrence of the part in terms of the part's x, y and z coordinates relative to the assembly's base or reference point x, y and z coordinates
- ✓ For each instance or occurrence of a part, the part's orientation in relation to the assembly's orientation
- ✓ Vectors or axes of rotation to describe the movement of parts within assemblies

This approach can yield a complete definition of the product's geometry and topology at any level in the product structure.

Product Structure

Since the relationship of a product's parts is a logical one maintained by the information system rather than a fixed physical relationship as represented on a drawing, it is possible to readily maintain more than one relationship. This will allow different views of part relationships in assemblies to correspond to the various departmental needs (e.g., engineering and manufacturing product structures) while maintaining rigour and consistency of the product's definition through this single database. Thus, this one logical database can support product and process design requirements as well as maintain part relationships to serve as a manufacturing bill of materials for MRP II. An integrated approach to developing, organizing and maintaining part and product definition data facilitates the design process, makes design data more readily usable and enhances integration with process requirements.

4.3 Product Data Management

This product definition database will not only provide geometric part information, but it can maintain information about the part's (or assembly's) various physical properties, functional characteristics, process requirements, cost, producibility, and

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design guidelines. The use of an integrated product definition database allows an organization to concentrate its product data management efforts on this database. Configuration management practices can be superimposed on top of product data management functions. Access control to each element in the product definition database can be specified. Read-only access can be given to personnel not directly involved with the design, development and planning process. Creation and maintenance access can be given to the individuals responsible for product and process design.

Engineering Changes

Engineering changes can be facilitated with this configuration management and administrative control embedded within the system. CAE/ CAD tools will enable engineering changes to be more thoroughly developed and analyzed to better define change impact. Once a design has been created, it can be checked out electronically to a workstation for engineering changes. When the changes have been made, they can be returned to the central database and placed in a queue for electronic approval by designated parties. In this manner, a Change Control Board (CCB) can even "convene" and provide individual members' input electronically. In addition to supporting engineering analysis, information related to procurement, inventory, manufacturing and cost is available for members of the CCB to evaluate, designate the effectivity of the change and determine the disposition of existing items.

4.4 Process design

Product design must logically extend beyond part geometric information, drawings and parts lists. It must include the design or specification of manufacturing processes including:

- ✓ The specification, design and layout of production equipment and processes
- ✓ Process plans to define how the product will be manufactured with the given production processes and capabilities
- ✓ Work-cell device programming (e.g., NC, robotic, insertion equipment, coordinate measuring machines, vision and computer-aided test equipment)
- ✓ Tool and fixture design

These process design, development and work-cell device programming tasks need to become linked to part or product design and development. CAD tools can work with part geometry and features to design or specify processes and work-cell envelopes.

Graphic production simulation tools can be used to test the resulting production system. Product definition, feature specification and group technology classification information drive CAPP - Computer-Aided Process Planning.

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Part geometry maintained in CAD is also used to develop tool paths, other NC programs, electronic component insertion programs, and photo-masks. This geometry also supports tool and fixture design. Functional characteristics, geometry, and specifications stored in the product definition database can be used to derive automated test equipment programs and coordinate measurement equipment programs.

When product definition information is developed and released, process engineering information must be similarly developed and released in this type of integrated environment. This will assure that when a new part is introduced or an engineering change is made, that the electronic release for production includes the correct process plans, tool requirements and work-cell device programs for the latest configuration and process capability.

As computer-aided manufacturing technology is utilized and integrated with the product definition database, part geometry and process information can be passed directly to production process equipment in DNC-fashion. The release procedures will include the electronic release of this information into appropriate libraries to download to work-cell controllers or make available to manufacturing personnel online as required. The physical drawings, process plans and NC tapes will not need to be manually assembled and coordinated to support the manufacture of an item

4.5 Data interchange

Engineering and product definition information must be communicated and used across the enterprise. In addition, the use of engineering information extends beyond the company's facility. Engineering needs to exchange product definition and configuration data including part geometry and other textual information with suppliers and customers. Electronic Data Interchange (EDI) is a first step in the commercial world to utilize standards for ordering parts and material, but it lacks interchange of geometric information.

The Initial Graphics Exchange Specification (IGES) is the current standard for exchanging geometry data, but it does not contain all required digital product data and IGES translations may not provide a complete translation of geometric data. More comprehensive standards will be required. The Standard for the Exchange of Product Model Data (STEP) is an effort to establish product data standards related to physical design information (geometry, topology, tolerances, and form features, functional design information, product administrative information, and product life cycle information). Establishing a single product data model with tools to provide ready access to this product data will enable direct use of this data and enable a move away from the traditional engineering drawing and other product documentation.

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Digital Manufacturing Master's degree to set specialists for the dawn of the industry 4.0



Project number:
2019-1-RO01-KA203-063486

Computer modelling and simulation

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2 OBJECTIVES

This module will enable students to understand the importance of computer modelling and simulation, focusing on the digital manufacturing aspects of these areas. The aim of the course is to present the process and technologies of construction design, the concept and areas of CAD, product and process modelling, computer drawing/editing, finally, methods and systems of computer geometric modelling

2.1 Learning outcomes

On successful completion of this module, a student should be able to:

- Gain knowledge of the basics of computer-aided parallel engineering.
- Gain knowledge of computer design resources, resource sharing, system design, and management.
- Gain knowledge of current areas of virtual reality (VR) development
- Create the product or process model using CAD systems.

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3 INTRODUCTION TO CAD SYSTEMS

3.1 History of CAD systems

The first generation of Computer-aided Design (CAD) systems was developed in the 1960s by Ivan Sutherland. His invention was called Sketchpad (Figure 1). In Sketchpad, the designer could draw with a special pen on the computer monitor. This idea has proved so useful that even today improved versions of it can be found, e.g. pressure sensitive TFT monitors etc. True, this system took hours to perform in a fraction of a second on today's computers.

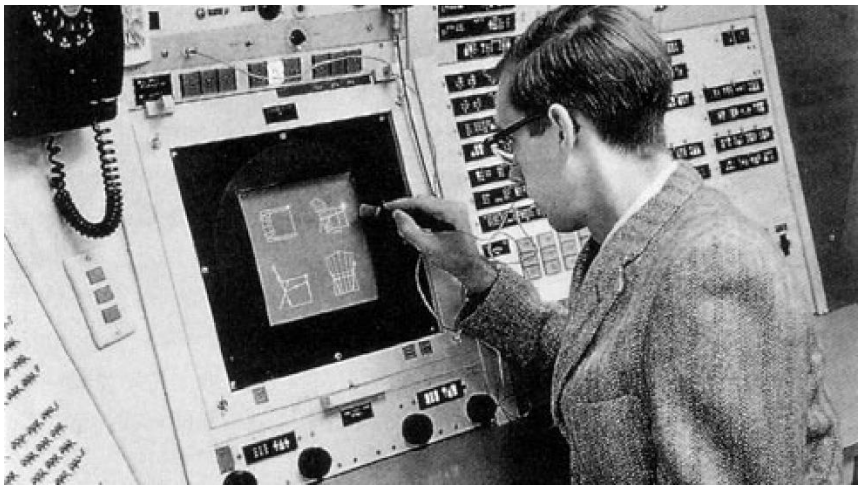


Figure 1. Ivan Sutherland and Sketchpad in the 1960s (*Web*, 2018).

Later in the 1960s, several other automotive and aerospace companies developed their own design systems. These systems were very expensive at that time and only could handle curves but not surfaces. This has several disadvantages, such as no NC programming is applicable, no impact test can be realized before the manufacturing.

In the 1970s the software development remained mostly in the automotive and aerospace industries. These companies often had their own CAD developing departments, and they were integrated into their own internal systems. Most CAD software was still 2D, but it made the job easier, reducing the possibility of an error and the possibility of re-using the drawings. The most significant software of this era was CADAM which was later used to develop the first 3D software, CATIA. Towards the middle and end of the 1970s, as the performance of computers increased, their size decreased, and they were able to display better and better graphics, CAD / CAM systems began to become more widespread.

However, the diversified path of development, many different systems have given rise to another major problem. Each system was not able to communicate with each other, the

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systems lacked any standardization. In 1979, Boeing, General Motors, and NIST (National Institute of Standards) agreed on the first standard to allow data transfer between systems. This was the IGES (Initial Graphic Exchange Standard) format, which was introduced in 1980 (*Web*, 2018).

In the 1980s the UNIX workstation has been developed. This marked the beginning of a new direction aimed at producing computers optimized to run low-cost, small-scale, high-quality, low-maintenance CAD systems. In 1980, IBM introduced the first PC to the market, and in 1981, Autodesk introduced AutoCAD Release 1 software running on the IBM PC. The first widely available 3D design software, the Pro/ENGINEER 3D was introduced in 1987 (Figure 2). Competitors did not attach much importance to it, but to everyone's surprise, they sold a record amount of Pro/ENGINEER licenses within 18 months of its release. There were very simple reasons for this. Pro/ENGINEER has finally offered a user-friendly user interface with icons, drop-down menus and the like. This is where the so-called history-tree (model tree) first appeared, on which we can follow the individual features, constraints, etc. succession, relationship.

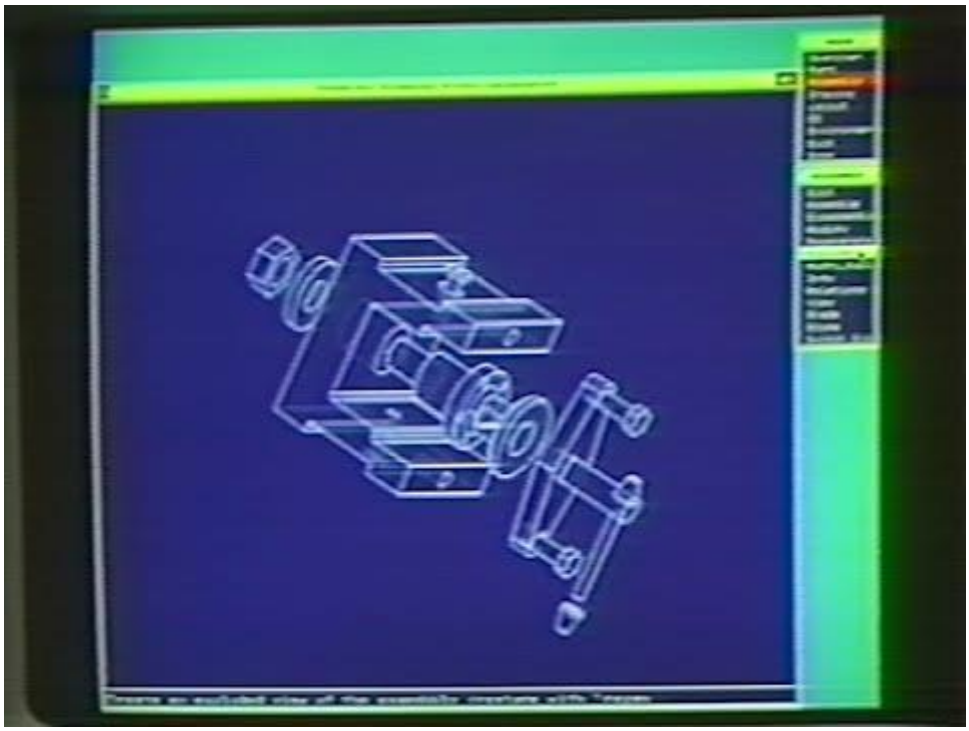


Figure 2. Pro/ENGINEER 3D introduced in 1987 (*Pro|ENGNEER Jig Demo*, 1987)

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In 1990, Boeing decided to move completely to digital design, abandoning paper-based work altogether. Encouraged by this, the big companies decided to commit to one of the CAD software. The surface and body models have already fit side by side in the systems. The handling of shape features was still a problem to be solved in some systems, although translators have already appeared. Graphical display tools already have plenty to meet your expectations. Input devices have not evolved much since the beginning, with a keyboard, a mouse, and a pressure-sensitive digital tablet. Networks were already in place, but the bandwidth was still a major hurdle. Simulation options are still limited but are already available in engineering practice. During this period, SolidWorks appeared on the market. Although it offered only about 80 % of the features of the Pro/ENGINEER, it was only 20 % of the price of the Pro/ENGINEER. In 1996, Intergraph released its software called SolidEdge. They sold this with their very high-performance graphics computers. In 1999, the long-awaited CATIA v5 was released. The first is truly a windows version, finally with a truly windows user interface, user-friendly icons, menus and many other convenience features. Other leading companies, including Autodesk, have followed this path with the release of their first non-AutoCAD-based software, Inventor.

In the 2000s, integrated manufacturing systems have been developed. Ford was the first to demonstrate how much time could be saved with the integrated manufacturing system when it introduced the new Ford Mondeo in 2000 in the C3P (Ford's own integrated design system). This reduced the total design and production time to 1/3 of the time previously required. The integrated manufacturing system not only saved time but also eliminated problems such as poor sizing or lack of components, which were common. Now, however, the parts can be assembled in the virtual space, so it immediately becomes clear if it doesn't fit in the space allotted to it. Collision testing and motion simulation can be performed (*Web*, 2018).

Nowadays, the ownership of development companies is changing almost constantly, more and more companies are being created, which are integrating more and more CAx systems on a common platform, with the same user interface, thus satisfying the needs of users. The goal is to be able to solve all the tasks that arise during the design with the product of the given company. Simulations and finite element analyses have become commonplace, and new tools have emerged in the field of input and output devices.

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3.2 General types and features of CAD systems

In Computer-aided Design (CAD), we use workstations (or only computers) to optimize design processes in the digital environment. With the help of CAD software and systems the productivity, quality, and communication can be improved in-between the designers and the manufacturing engineers. CAD software is usually using vector-based graphics, and the design environment can be realized in 2D or 3D. CAD software can be used in different fields of design and manufacturing, such as automotive, electronics, architecture, etc. Of course, different manufacturing and design areas set up different requirements. Thus, the CAD systems can be classified into different groups (Kátay et al., 2012):

- Application area. Usually, generally applicable systems are available nowadays, but specialized modules can be used for each area of industrial design and manufacturing.
- The modelling environment can be 2D and/or 3D.
- The applied modelling method can be curve, surface, solid or hybrid.
- The modelling method can be parametric or direct. In parametric modelling (Figure 3) the designer captures design intent using features and constraints, thus the user is allowed to automate repetitive changes. In direct modelling, the geometry can be captured much quicker, without features and constraints, thus this type of modelling method is often compared to modelling with clay (Brunelli, 2017).

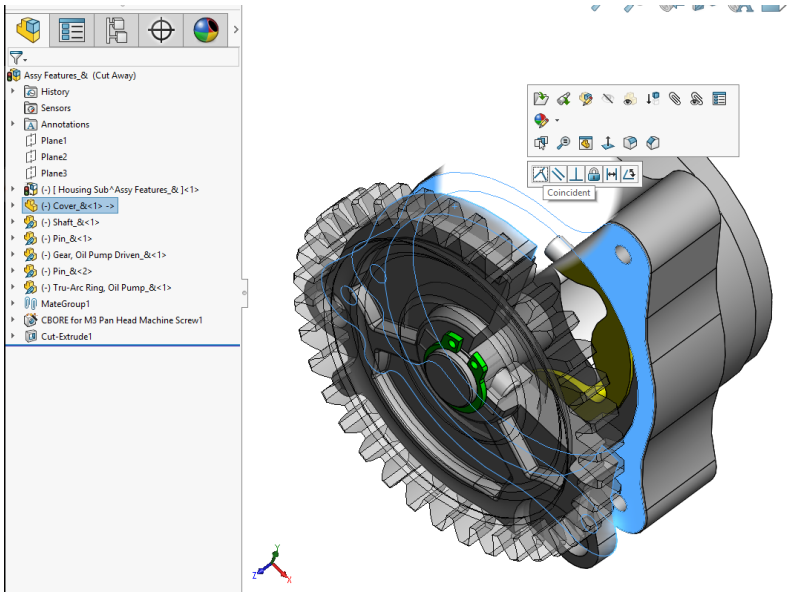


Figure 3. Parametric design in SolidWorks CAD software (Roemer, 2017)

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The modern CAD systems have several common properties and features (Kátay et al., 2012):

- The modelling is based on 3D parametric shape features or volume modelling.
- Free-form surface modelling.
- Bidirectional parametric associativity: the model can be modified from different aspects and the effect of these modifications is mutually exclusive (e.g. the modification of the shape properties of the 3D model appears in the drawing, the meter modified in the drawing changes the 3D model).
- Modeling a complete assembly, the components of which can be parts or other assemblies.
- Preparation of a technical drawing from the volume and surface model.
- Preparation of workshop drawings and parts lists.
- Provide rendering aids (hatching, rotating, removing obscured lines, etc.).
- Reuse of design details.
- Easy model variability.
- Generate standard parts based on catalogue.
- Adaptation of plans to design rules and specifications, simulation of designs without prototyping.
- Kinematics, collision analysis, tolerance analysis.
- Possibility to exchange data with other software (export, import).
- Direct connection to rapid prototyping and rapid production systems.
- Mass and moment of inertia calculation.
- Design of sheet metal parts.
- Design of flexible pipes and cables.
- Wiring of electrical components.
- Etc.

With the development of CAD systems, the needs started to grow for computer-aided manufacturing (CAM) and computer-aided engineering (CAE) software. After the digital revolution in industrial design and manufacturing computer-aided process planning (CAPP), computer-aided quality assurance (CAQA), computer-aided production planning and scheduling (CAPPS), computer-aided storage and transport (CAST) tools are also playing a significant role in todays digital manufacturing processes. In this module, we will focus on

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computer-aided design, modelling and simulations techniques in terms of digital manufacturing.

3.3 Process of industrial design

It is needed to be mentioned that computer-aided technologies, as listed in the previous section, are not only supporting industrial design but architectural (Figure 4), medical and textile industries, however, this module only focuses on the mechanical industrial design aspects.

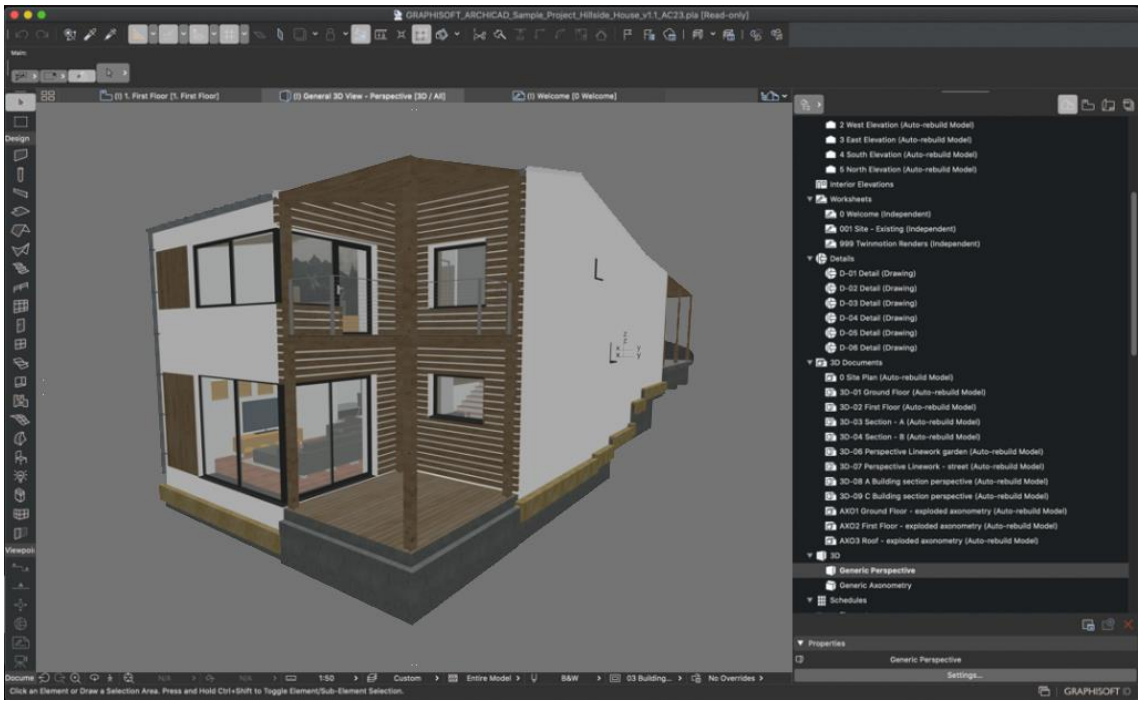


Figure 4. Architectural design software (Archicad 24) environment by Graphisoft (*Graphisoft,* 2021)

The subject of the design can thus be diverse, but the main steps of the design process can be standardized (Figure 5). The first step in design is the development of the product concept, during which the technical, economic, quality and environmental requirements of the design to be determined based on market expectations.

During the conceptual design, we determine the type of construction (new, redesigned, modified), the functions of the product, the scientific relationships that form the basis of the operation, the structure of the product, the value of the parameters that determine the operation, the shape and colour scheme.

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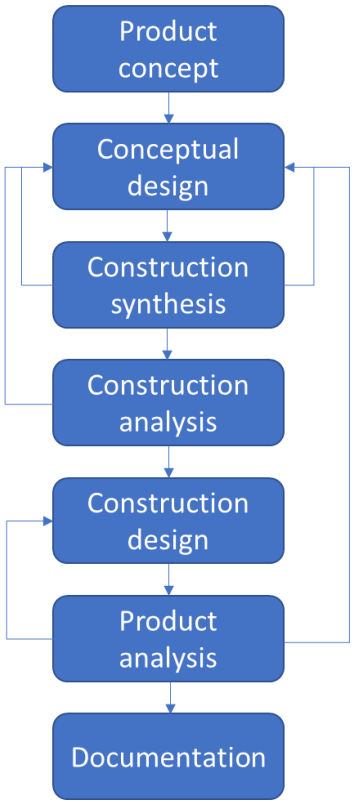


Figure 5. General steps and connections of industrial design (Kátay et al., 2012)

During the construction synthesis, the system-based modelling of the product is performed, it is divided into subunits and parts, the approximate size, shape and material characteristics of the parts are determined.

The structural analysis is organically linked to the design synthesis, during which the loads and stresses of the parts and components are determined, the operation of the product is simulated, and the technical parameters of the optimal design are determined.

Detail design aims to determine the shape, material, material characteristics, size, tolerances of dimensions that affect the operation, and to systematize additional information required for manufacturing.

During product evaluation, the conformity of the product is examined. Conformity can be assessed from several aspects: performance, installability, manufacturability, cost, relevant standards, safety regulations, and so on.

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During the elaboration of the product documentation, we prepare the assembly drawings and component drawings of the product, as well as the related parts list, material requirements plans, operation, maintenance, assembly and test descriptions (Kátay et al., 2012).

4 GRAPHIC GEOMETRY MODELLING TECHNIQUES

For geometric modelling, different levels exist. Graphical elements can be levelled from points, lines, curves, surfaces volumes and features to a whole, integrated design. To represent these graphical objects, different displaying and modelling techniques can be used. These modelling techniques basically can be wireframe modelling, surface modelling, and solid modelling. For a more advanced approach, the solid models can further be processed by space decomposition, feature-based or knowledge-based modelling techniques. The summary representation of these modelling techniques can be seen in Figure 6.

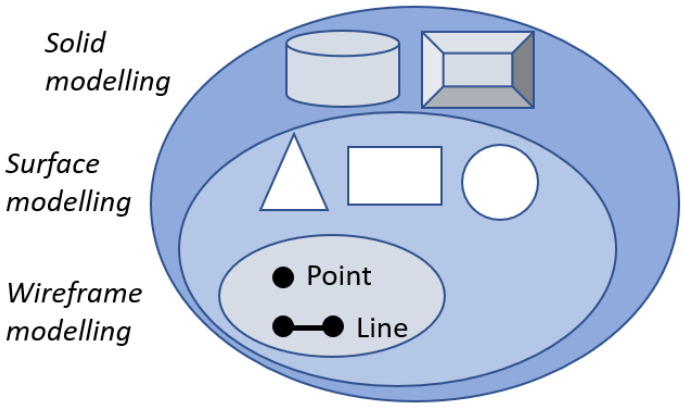


Figure 6. Different levels of geometry modelling.

4.1 Wireframe modelling

In wireframe modelling, the modelling elements are points, lines or curves. The object is represented by its boundary edges: circles, arcs, or straight/curvy lines. In this modelling level no masses, surface areas, volumes are available, as only frames represent the geometry. To display and to create a wireframe model, the coordinates of each element need to be added, thus this type of geometry modelling is very time consuming, and a more experienced user is needed for the processing. Nowadays, wireframe modelling is only used to support other types of modelling techniques. One of the fundamental drawbacks of wireframe modelling is that the displayed model does not clearly illustrate the modelled object. A further disadvantage of this modelling mode is that all edges are visible in the displayed image, and visibility cannot be displayed (Figure 7). Due to the lengthy and cumbersome

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data entry, it is not suitable for shape design and more complex forms. Due to the lengthy and cumbersome data entry, it is not suitable for shape design and more complex forms (Bi, 2021; *Web*, 2018).

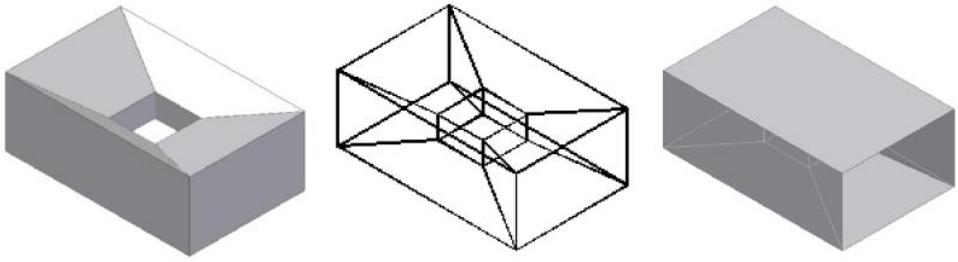


Figure 7. Example of the disadvantages and display errors of wireframe modelling (*Web*, 2018)

4.2 Surface modelling

In surface modelling, the geometry is displayed by a finite number of surface 'patches'. This model has enough information to display the visibility correctly. The only information is missing from a surface model is the thickness. Thus, no information can be given on the mass, density, etc. The surface model is suitable for more complex shapes, obscured line art, or shaded images but is still not suitable for calculating volume or mass characteristics, collision testing, and for making numerical models for engineering calculations.

One subgroup of surface modelling is the boundary-representation (Figure 8). The boundary-representation combines the geometric and topological structure treatment of wireframe modelling with a description of the surface patch of surface modelling. Since the mantle of every real physical object is closed and continuous, mantle modelling considers the mantle of the object to be finite, continuous, and closed, where the sheets forming the mantle are bounded by edges and the edges are defined by the nodes.

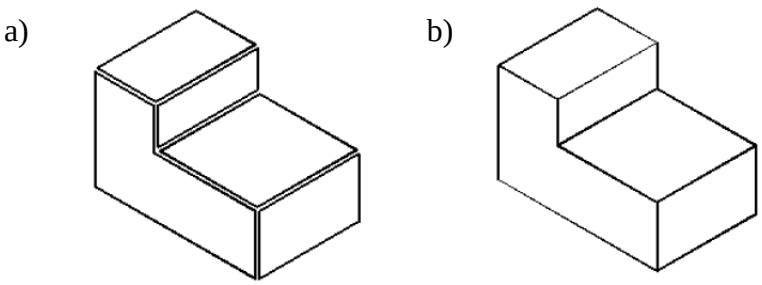


Figure 8. Comparison of surface modelling (a), and boundary representation modelling (b) (*Web*, 2018)

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4.3 Solid modelling

In solid modelling, the volumetric information is also defined. Solid modelling describes objects as a finite, closed, regular set of points. The solid model is a complete, characteristic, and concise description of the object. The data structure also describes the basic units that make up the body and their relationships. Solid modelling is significantly simpler than either the wireframe, the surface, or even the boundary-representation modelling. To specify 3D in solid modelling basically three ways are available. The first way is to give a solid by a 2D sketch and a 1D depth. The second way is to give a solid by a 1D path, 1D thickness and 1D width. And the third way to give a 3D solid is by 1D path a 2D profile (Bi, 2021)

A more advanced level of solid modelling is the so-called space decomposition method. In space decomposition, the solid is represented by a set of 3D cells. The cell size determines the precision of geometric representation. Space decomposition modelling is widely used to represent a continuous domain by a set of discretized elements and vertices in numerical simulations such as finite element analysis (FEA) (Bi, 2021).

4.4 Feature-based modelling

In feature-based modelling, the graphic elements are treated as features. The solid object is then composed of a set of constitutive features by the operations called constructive solid geometry (CSG). These operations can be a union (∪), intersection (∩), and difference (\) (Figure 9).

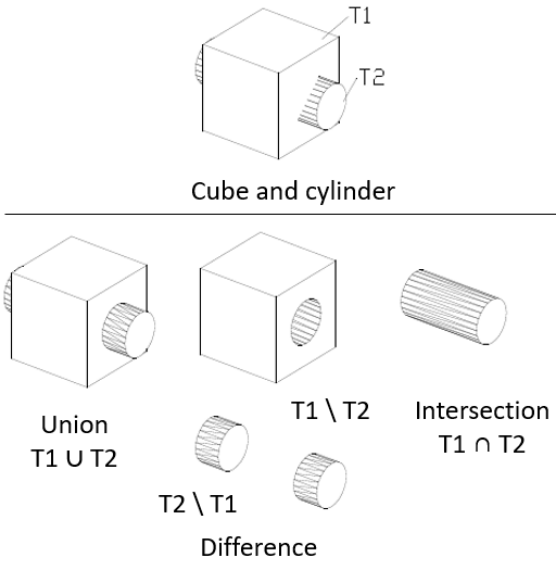


Figure 9. Boolean operations of CSG modelling method (*Web*, 2018)

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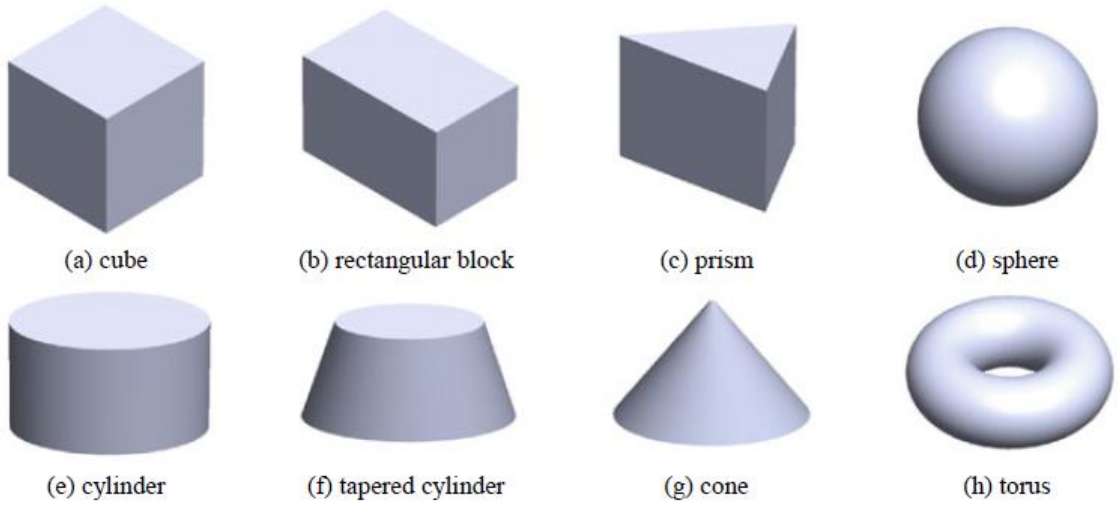


Figure 10. Primitive objects for feature-based geometric modelling (Bi, 2021; *Web*, 2018)

The operation can be done on the 8 primitive objects such as, cube, rectangular block, prism, sphere, cylinder, tapered cylinder, cone, and torus (Figure 10). Creating the 3D geometric model, the primitives can also be tailored by tools such as extruding, revolving, sweeping, and lofting.

4.5 Knowledge-based modelling

For the designers, it is very useful to take design knowledge into attention, using any type of geometric modelling method. Design knowledge helps the modellers to highlight main attributes, simplify the modelling process, reducing modelling times and improving productivity, facilitate product evolution, to share design concepts improving knowledge sharing and communication. For knowledge-based modelling the design intents should be used. Design intents are embedded in a graphic model, and the design intent updating the dimensions and relations automatically. If the design intent of a product cannot be represented, it can mislead the product model, thus design intents must be carefully selected and defined by an experienced designer.

5 CAD SYSTEMS IN DIGITAL MANUFACTURING

Digital manufacturing recently imposed new requirements against CAD systems. CAD models and other product data now need to be portable and shareable outside of the engineering department and within the larger product lifecycle management (PLM) process of a manufacturing organization. PLM is increasingly being used to manage products from conception and design, through manufacturing and distribution, all the way through

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maintenance, service, and ultimate disposal or recycling. Thus, most of the bit international manufacturing companies started using integrated systems. These integrated systems include a product data management (PDM) system that integrates and centralizes CAD data from all sources and automates engineering processes, such as changes, validations, and approvals. Digital mockups make design changes are also visible in real time (*Web - design*, 2021).

5.1 Integrated CAD software for digital manufacturing

On the software development side also integrated and comprehensive solutions are needed. 3D digital data that comes directly from CAD models are increasingly needed in this age of Industry 4.0. Industry 4.0 requires that digital models of both the product and manufacturing process are maintained, and also encompasses the Internet of Things for network connectivity for the product itself, and cloud computing to store and provide access to the large volumes of data involved. Digital 3D models are being used to create catalogues, manuals, installation and service guides, which substitutes the mandatory hard copies of these technical documents. The 3D CAD models are also used to create and to optimize machining instructions for example for CNC machining. First, the product design information in CAD will be transformed into information about a product's manufacturing and processing rules. The processing machines will be combined and ordered according to the scheduled procedure and work stages. Cutters, fixtures and measuring tools are then selected, cutting parameters are determined, and the manoeuvring time and auxiliary time in each procedure are calculated. In recent years, computer networks have provided a platform to enable CAD technology to coordinate and cooperate to be able to design online. Network technologies and information technologies are developing fast and multimedia visual environment technology, product data management system, distributed cooperative design and cross-platform, cross-regional, synchronous and asynchronous information exchange and sharing, as well as group collaboration and intelligence design between multi-businesses, multi-teams, many people, multi-applications, are all the subject of deep research and are entering into the practical stage, which forms a digital manufacture idea that centers on design (Zhou et al., 2012).

Several specially designed integrated software can be found in the market nowadays. For example, Autodesk® Fusion 360™ (Figure 11) is a specially developed cloud-based CAD/CAM integrated software. This software can handle more then 50 file types making it

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easier to transform CAD modelling into machining. Full CNC programs can be written using the digital model allowing the users to machine the parts more effortless. The Fusion 360 software is able to include 5-axis programming, toolpath optimization, process automation, on-machine verification, and more. This results in reducing CNC programming time, make better use of CNC machinery, and improve the quality and value of machined parts. The software also includes rapid prototyping tools reducing the design and manufacturing time, thus the design can almost be realized instantly (*Autodesk*, 2021).

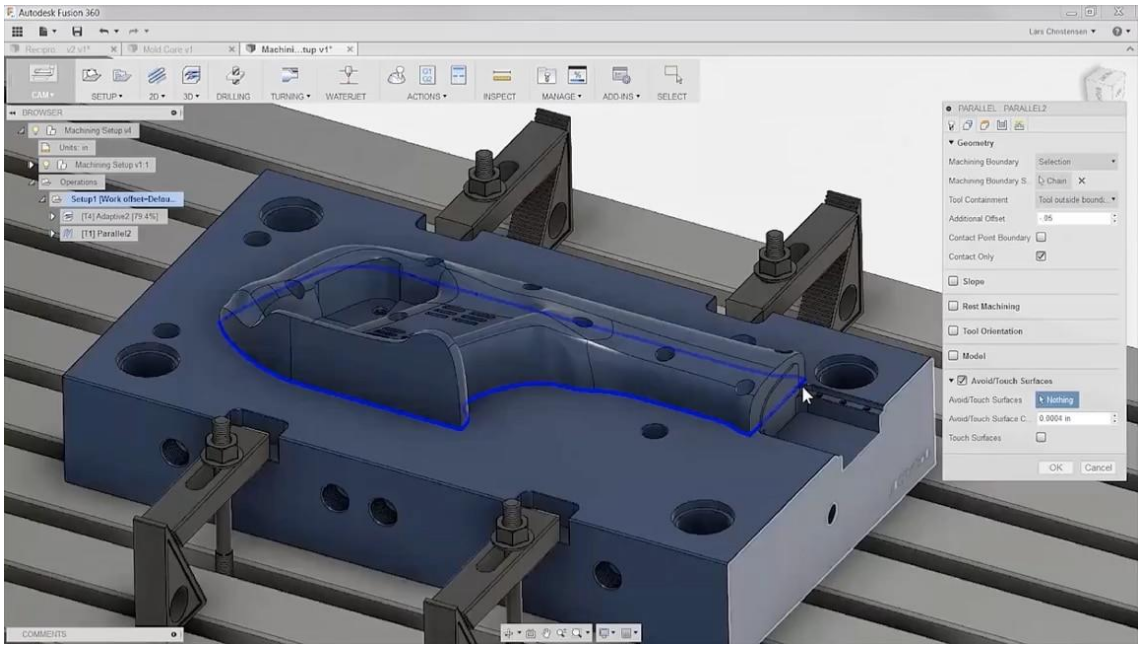


Figure 11. Design and manufacturing interface in Autodesk Fusion 360 (*Autodesk*, 2021).

5.2 Virtual reality in computer-aided design

The earliest CAD systems only allowed 2D modelling. However, nowadays CAD systems are much more integrated and solid models can be realized in 3D, helping manufacturing processes to optimize parameters and helping engineers to understand how their design could be integrated into a machining step. On the other hand, it must be mentioned that 3D CAD models are also displayed on the 2D screen, using shading, for example. So, the models are only representing real world geometries. To solve this problem virtual reality and augmented reality can be used to get a truly accurate depiction (Andy, 2017).

Virtual reality enables designers to see their model in real 3D. Thus, the model can be truly walked around and can also be compared to other real size objects for scaling. As such, designs become more “real” in virtual reality. Users can even break apart their virtual models

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into individual pieces—something which would be impossible in real life. The ability to create realistic virtual prototypes and models reduces the need for prototyping, helping to reduce the cost of production. In turn, clients no longer need to wait for a physical model to be produced before they can see—and thus approve—a design (Andy, 2017).

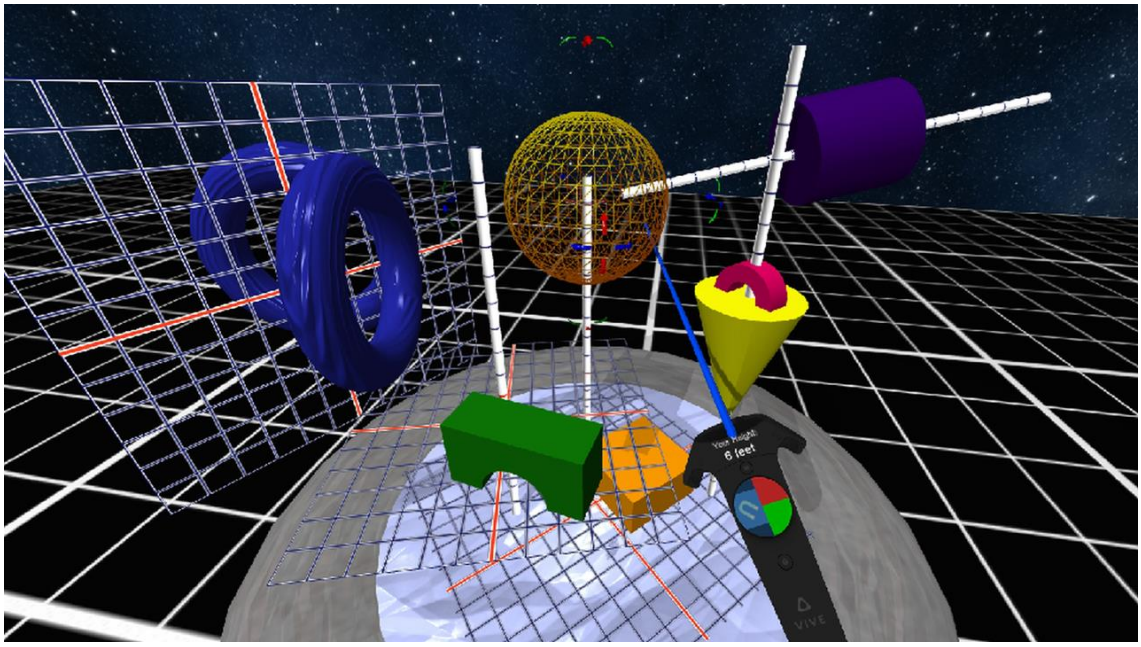


Figure 12. Computer-aided design with the help of virtual reality in MakeVR software (*VR*, 2021)

In a VR-based software the designer can create a model directly in virtual space, rather than on a screen. This allows the possible partners to see the design process in 'real life' in front their eyes, which reduces the number of consultations and help both partners to meet their needs. One example of these software environments is MakeVR, which is a 3D virtual reality-based designer software (Figure 12).

In augmented reality (AR) the designer or user is also wearing a headset. With the headset, the whole physical environment, for example, the office, shop, etc. can be seen in the virtual space. The real size CAD modell is displayed in 3D, which can be controlled, rotated zoomed, etc., also by hand.

It is meaningful that, the traditional big CAD software programmers are also developing AR and VR-based solutions. For example, SolidWorks (Figure 13) or Autodesk XR (extended reality) is an integrated solution with 3D CAD modelling and VR/AR. One of the fastest growing markets in the world of XR is virtual training. With XR techniques the educators

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and the students do not have to travel to on-site assembly, maintenance or installation practice courses, but XR can be used to connect students from different part of the world. This also improves knowledge sharing and standardization, which are significant aspects in digital manufacturing.



Figure 13. Extended reality (XR) based design in SolidWorks (*SolidWorks*, 2017)

5.3 Virtual prototyping with extended reality CAD systems

Virtual prototyping (VP) is an extensively researched area nowadays is digital manufacturing. Before the manufacturing processes, virtual prototyping can be a useful tool to check the panning and the manufacturing feasibility. Also, VP can help in the evaluation of the assembly, installation, etc. After the manufacturing, virtual prototyping provides a basic toll for development from the initial concept. Feedbacks, modification suggestions can affect the initial design. VP has several advantages compared to physical prototyping (Zhou et al., 2012):

- VP can replace physical prototypes. Before the manufacture, the designers can easily use VP and XR CAD systems to modify the initial concept.

- VP is able to provide meaningful evaluation of future products for testers throughout every stage of design.

- Through the use of VP, the design of technical requirements, manufacturing performance, maintainability and their realization become possible and easy.

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Virtual prototyping aims to use the powerful advantages of virtual reality technology in visual aspects as well as the interactive function of exploring virtual objects to carry out product design, interactive modelling and analysis functions in the aspects of geometry, function and manufacturing. The second step of virtual prototyping is virtual manufacturing (VM). VM is an integrated, synthetic manufacturing environment to enhance all levels of decision and control. This vision could be updated to ‘‘Manufacture in networked computers’’. The virtual manufacturing system (VMS) focuses on the cost of manufacturing products, manufacturing and the benefits and risks, with the goal of product design and manufacturing of the world-class standard (Figure 14)(Zhou et al., 2012).

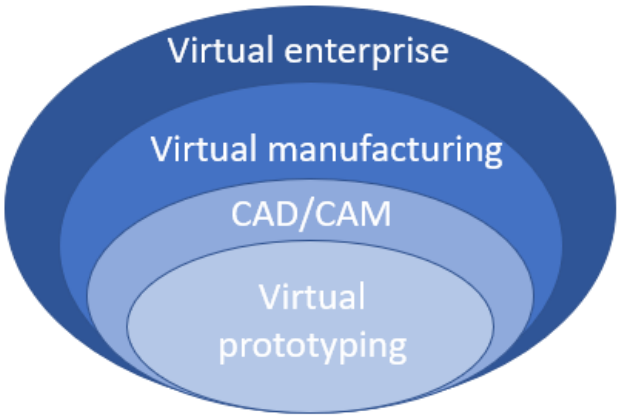


Figure 14. Virtual manufacturing dimensions (Zhou et al., 2012)

6 REVERSE ENGINEERING IN PRODUCT DESIGN AND MODELLING

In a product design process, forward design and reverse engineering concepts can be differentiated from each other. In forward design, the first step is designing the concept, then using CAD systems to produce 3D models. The 3D models then can be translated into manufacturing steps. In reverse engineering, we analyse a pre-existing product in order to recreate it. Reverse engineering is widely used in the case of complex, irregular products. For reverse engineering 3D digital measuring tools are essential. The geometry should be accurately measured and digitalized into a 3D CAD model, which can be transferred into a digital manufacturing process after revision. After that the tool path can be generated using integrated design and manufacturing systems. The comparison of forward design and reverse engineering can be seen in Figure 15.

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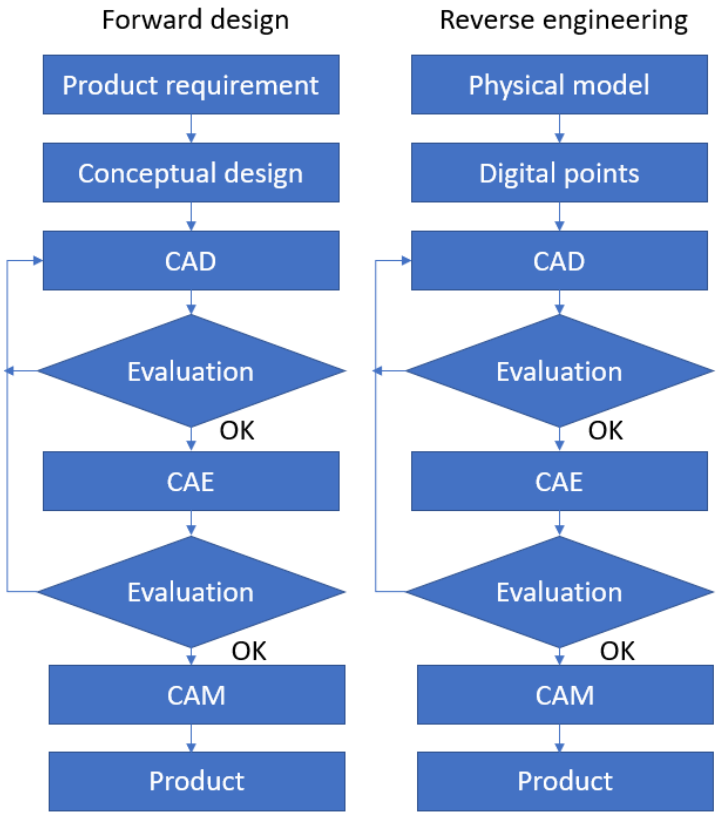


Figure 15. Forward design vs. reverse engineering in product manufacturing (Zhou et al., 2012)

Reverse engineering has 3 main steps (Zhou et al., 2012):

The first step is the data measurement. During this process we use 3D digital measuring tools to perfectly acquire the product geometry. With the advent of sensing technology, control technology, computer technology, manufacturing technology, and other related technology development, a variety of data measuring digital technology and digital methods appeared. The measuring method can be contact or non-contact. It is worth to mention that the same digital measuring tools can be used later in the product life-cycle, in the quality assurance.

The second step is the data processing. The collected measurement points need to be translated into processable formats for CAD systems. This translation includes smoothing the data points, sorting and simplification.

The third step is the model reconstruction. Based on the separated the treated data points the curves, surfaces of the models need to be generated. To ensure the quality and accuracy of the reconstructed surface, it is necessary to conduct surface error analysis and processing.

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6.1 Reverse engineering in digital manufacturing

As the rapid prototyping processes are widely available in automotive, railway, aerospace, etc. industries, reverse engineering is gaining more and more attention with the help of integrated CAD systems. Reverse engineering is used in new part design mainly as an imitation of the original product, or to reproduce the original design. Nowadays portable scanning tools are widely available even for smart phones. Applications like Trnio (Figure 16) or Qlone using the camera of a smart phone to acquire the required data for the later 3D geometric model building.



Figure 16. Model scanning using smartphone application Trnio (Carolo, 2020)

For more serious industrial purposes 3D scanners are widely available. These scanners are supported with a comprehensive software, giving real-time feedback during the scanning process. This allows less post processing time before the model building stage. The disadvantage of these 3D scanners is that experienced users are needed as the software has multiple functionalities. However, software developers provide 'autopilot' features, which automates the rough scanning process, and the user can later smooth or customize the 3D scanned model manually.

In the post processing step, integrated CAD programs are available. The scanned digital models usually acquired in a mesh-like file format. Mesh representation is common in rapid prototyping and additive manufacturing, however for further CAD system handling a more 'neutral' file format is needed. Thus, programs are currently being developed, which can transform the scanned mesh representation into more manageable CAD file formats. For

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example, Autodesk Fusion 360 software includes a so-called Meshmixer module, which enables ‘cleaning up’ the scanned geometry and transforming it into processable files for additive manufacturing techniques. Other CAD system developers also providing post-processing programs. XTract3D for SolidWorks (Figure 17) was specially designed for reverse engineering applications, aiming to facilitate the conversion from mesh to solid CAD models. A wide array of tools helping the proper tracing of the most complex geometries, and the user can import the mesh file from cloud directly to SolidWorks. Once that’s completed, the model is ready to be worked on in one of the most professionally-used CAD programs out there (Carolo, 2020).

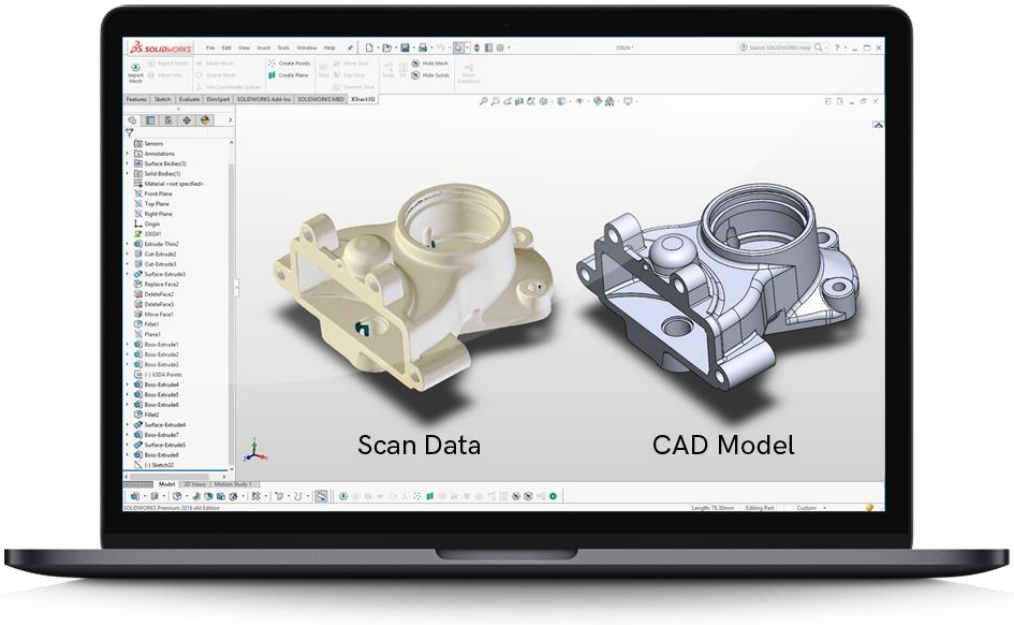


Figure 17. From the scanned geometry to a processable solid CAD model (*Solidworks*, 2022)

7 INTRODUCTION TO THE FINITE ELEMENT ANALYSIS

The finite element analysis (FEA) or so-called finite element method (FEM) is a numerical procedure that can be used to obtain solutions to a large class of engineering problems involving stress analysis, heat transfer, electromagnetism, and fluid flow. In general, engineering problems are mathematical models of physical situations. Mathematical models are differential equations with a set of corresponding boundaries and initial conditions (Moaveni, 1999). In a simulation, a computer is used to evaluate a model numerically, and data are gathered to estimate the desired true characteristics of the model. Schmidt and Tayler said the system is defined to be a collection of entities e.g. machines that act and

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interact together toward the output of some logical end (Schmidt & Taylor, 1970). The systems are categorized to be of two types. A discrete system is one for which the state variables change instantaneously at separated points in time. Continuous system is one for that the state variables change continuously with respect to time (Law & Kelton, 1991).

Today, it is a basic requirement that we can also handle information about the entire life cycle of a product in digital. These requirements are compiled by, among others, CAD systems (Computer Aided Engineering), CAM Systems (Computer Aided Manufacturing) and CAE Systems (Computer Aided Engineering). We can perform and manage the concept modelling, geometric modelling, numerical tests and simulations, workshop drawings and visualizations, documentation management, technology pre-processing, database management through standard communication (Mankovits & Huri, 2015).

To solve the problem, differential equations represent a balance of mass, force or energy. When possible, the exact solution of these equations renders the detailed behaviour of a system under a given set of conditions. There are parameters that provide information regarding the natural behaviour of a given system which includes a modulus of elasticity, thermal conductivity, and viscosity. On the other hand, there are parameters that produce disturbances in a system (e.g. external forces, moments, temperature difference across a medium). (Moaveni, 1999)

If the material and deformation have a non-linear behaviour, the task is already non-linear, which is difficult to solve. The exact solution of the mechanical-mathematical model is generally unknown. Then it must be solved in an approximate way.

7.1 How the FEM work

The finite element method is used in engineering studies to solve physical problems. Physical problems mean that a component or structure is under load. The physical model needs to be transformed into a mathematical model that leads to a differential equation. The finite element method solves this mathematical model. Since talking about a numerical procedure, the expected accuracy is an important requirement. The process of the FEM can be seen in Figure 18. (Mankovits & Huri, 2015)

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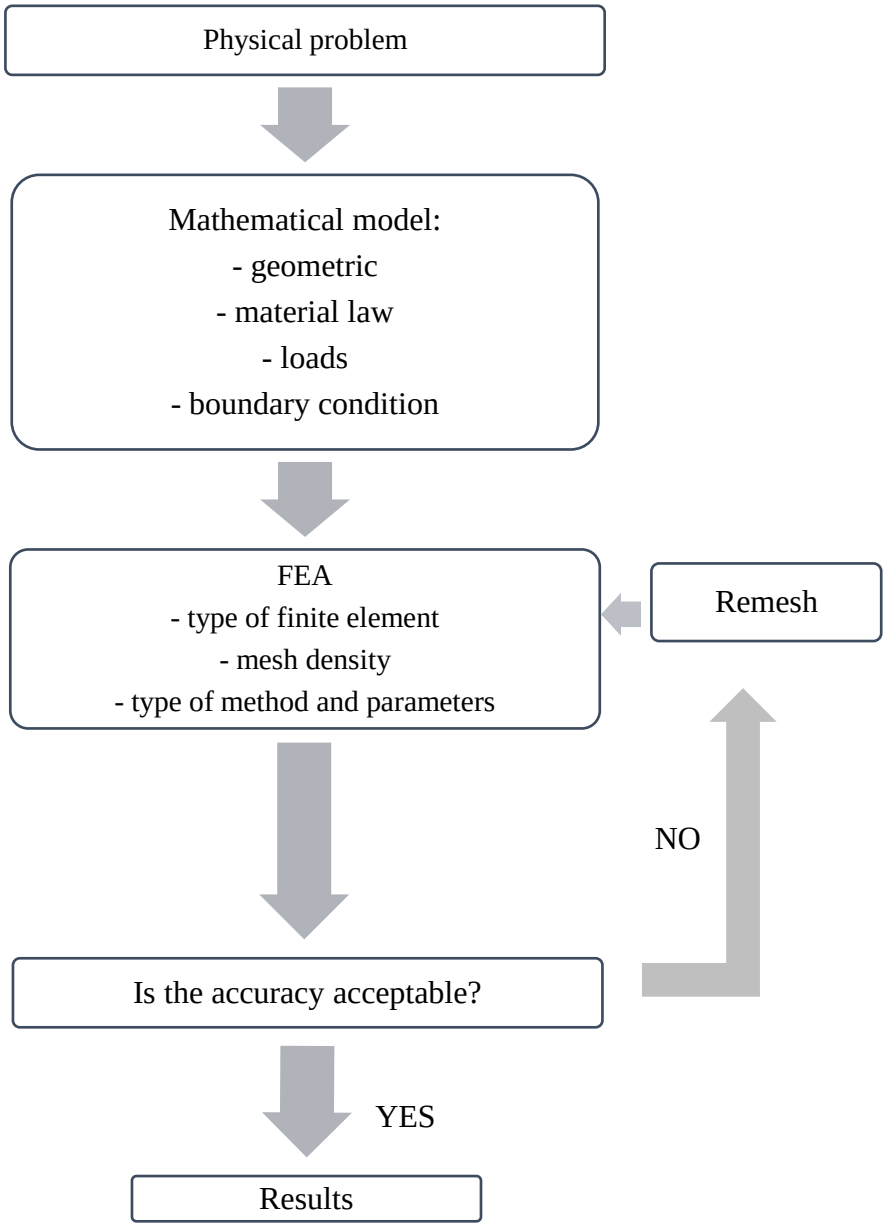


Figure 18. Process of finite element analysis

The main steps of the FEM are the following (Nikishkov, 2004):

1. Discretize the continuum. The first step is to divide a solution region into finite elements. The finite element mesh is typically generated by a pre-processor program. Pre-processing is concerned with the creation of the model and the definition of the way in which it is to be loaded. The pre-processor includes a graphics package that enables the user to build up the model of the component to be analysed and to display the model on the computer screen. (Akin, 2010)

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2. Select interpolation functions. Interpolation functions are used to interpolate the field variables over the element.
3. Find the element properties. The matrix equation for the finite element should be established, which relates the nodal values of the unknown function to other parameters.
4. Assemble the element equations. To find the global equation system for the whole solution region, we must assemble all the element equations.
5. Solve the global equation system
6. Compute additional results

The spread of the finite element method in practice has changed the classical production process, it is integrated into the production chain. A significant part of the manufacturing cost is the production of the test pieces and the execution of test run. These costs are only reimbursed in the event of many units and/or a high product price. This cost is significantly reduced by finite element simulation. The number of required prototypes is reduced by finite element simulation, if it is a well-modeled problem, the production of the prototype can even be omitted. By this time, series production can be set up immediately, and it is sufficient to carry out a test run on the zero series. (Moharos et al., 2011)

7.2 Basic concepts

7.2.1. Mathematical

Vector

A vector is an object that has both a magnitude and a direction. Geometrically, we can picture a vector as a directed line segment, whose length is the magnitude of the vector and with an arrow indicating the direction. The direction of the vector is from its tail to its head. We can define a number of operations on vectors geometrically without reference to any coordinate system. Here we define addition, subtraction, and multiplication by a scalar.

The deformation vector describes the displacement of a given unit vector.

Tensor

Tensor is an algebraic object that describes a multilinear relationship between sets of algebraic objects related to a vector space. Tensors provide a natural and concise mathematical framework for formulating and solving problems in areas of physics such as elasticity, fluid mechanics, and general relativity.

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Deformation tensor describes the deformation state of any point of an elastic body by assigning the deformation vector of a given direction to an arbitrary direction. The description is possible with three vectors in matrix or dyadic form in a given coordinate system. (Moharos et al., 2012)

7.2.2. Mechanical

Stress

Stress is the force applied to a material, divided by the material's cross-sectional area.

HMH-theory: Huber, von Mises, and Hencky theory is the most common used stress conception. The von Mises stress is a criterion for yielding, widely used for metals and other ductile materials. (Kovács, 2000)

The HMH equivalent stress:

$$\sigma^{HMH} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]}$$

The allowable stress is obtained from limit stress on the material of the structure by dividing it by the safety factor n.

7.2.3. Simulation

Elements

The geometry can be categorized as 1D, 2D, or 3D based on the dominant dimensions and then the type of element is selected accordingly. The body is divided with different shapes. The shape of the elements depends on the nature of the task, for example, in the case of a spatial task it can be the tetrahedron, in the case of planar tasks it can be the triangle, rectangle, in the case of bar structures the line element. The size of the elements is determined by the expected accuracy, more accurate numerical results are expected with a denser element division. The elements cover the entire range in one layer, without gaps or overlaps. (Vörös & Forberger, 2012)

Nodes at the corner points of the elements or even inside them can be selected. The movement of a node is described by *n* data, node degrees of freedom. The value of *n* is determined by the applied mechanical model, for example, for coordinates of two plane

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displacements $n = 2$ for plane tasks, or $n = 6$ coordinates per node for a spatial bar structure. If the number of nodes of an element is p, the degree of freedom characteristic number, $N = pn$. (Vörös & Forberger, 2012)

In different simulation programs, there are different elements used to cover a body.

SolidWorks Simulation currently includes solid continuum elements, curved surface shell elements (thin and thick) and truss and frame line elements. Solid elements have only displacement degrees of freedom. General shells have both displacement and rotational degrees of freedom at each node. However, membrane shells (like plane stress elements) have only displacement DOF. The shells are triangular with three vertex nodes or three vertex and three mid-edge nodes (Figure 19). (Akin, 2010)



Figure 19. SolidWorks Simulation shell (left) and solid element types (Akin, 2010)

Finite elements and rigid bodies are the fundamental components of an *Abaqus* model. Finite elements are deformable, whereas rigid bodies move through space without changing shape. While users of finite element analysis programs tend to have some understanding of what finite elements are, the general concept of rigid bodies within a finite element program may be somewhat new. The element families that the software is uses are a continuum, shell, beam, truss, and rigid elements (Figure 20). (*Getting started with Abaqus*, 2008)

Marc Mentat has another classification of the elements, so it is important to know which program we use. It can be found rod, plane, plate, hexahedral elements. Rod element deformations can only occur along the principal axis. The plane element has four-node, isoparametric quadrilateral uses bilinear interpolation functions, and the stiffness matrix is formed using four-point Gaussian integration. Plate element displacements can only occur perpendicular to the plane while the rotations act around the x- and y-axis. Eight-node, isoparametric hexahedral uses trilinear interpolation functions and the stiffness matrix is formed using eight-point Gaussian integration. (Öchsner & Öchsner, 2016)

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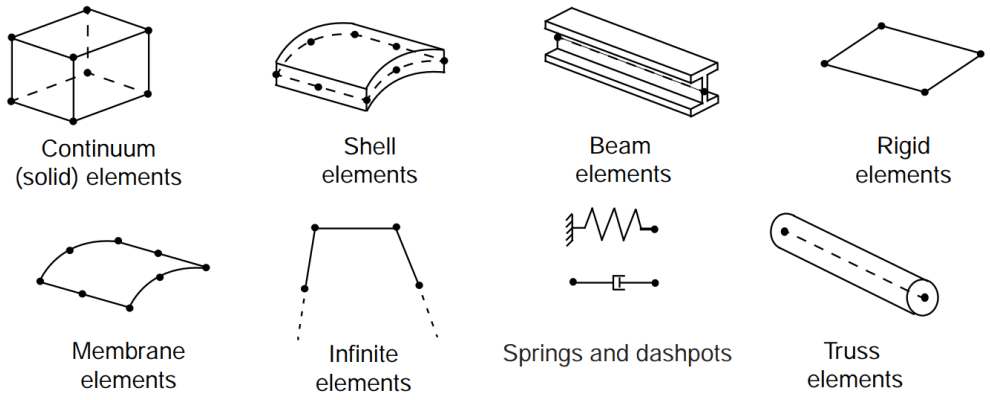


Figure 20. Commonly used element family in Abaqus (*Getting started with Abaqus*, 2008)

Initial condition

Initial conditions definitely influence the output distributions of terminating systems (Menner, 1995). Any initial conditions define the starting point (beginning state) for the first general step in the simulation. All general analysis procedures share the same concepts for applying loads and defining "time". The total time increases throughout all general steps and is the accumulation of the total step time from each general step. (*Getting started with Abaqus*, 2008).

Boundary condition

These conditions are essential to solve a problem. Boundary conditions make the task clear and obvious (Orbán, 2012). The algebraic system can be written in a general partitioned matrix form that more clearly defines what must be done to reduce the system by utilizing essential boundary conditions. In the followings, it can see some examples of the boundary conditions.

Figure 21 shows some of the boundary conditions that can be applied to the edges of a plate. A segment of a plate can be fixed or encased (left), simply supported (center), or mixed supported (right), or have a free edge. (Akin, 2010)

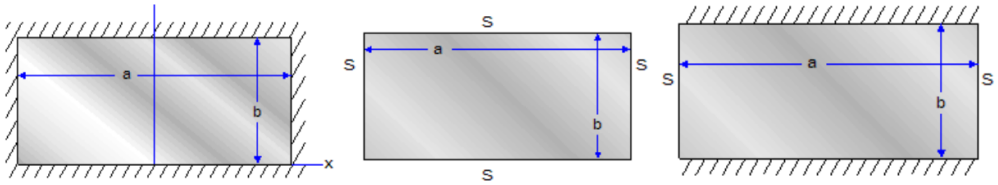


Figure 21. Some typical boundary condition options on rectangular plates (Akin, 2010)

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Most of the time, especially in non-linear analyses, it is required to specify a quantity such as the value of a boundary condition as a function of some other independent variable, for example, the time or location. Generally, such an association can be specified using several input file options but using the *table* feature of Marc usually reduces the number of required options and saves some time and effort. (Javanbakht & Öchsner, 2017)

In the case of an elasticity problem, two boundary conditions are needed to define based on Figure 22 (István et al., 2007; Moharos et al., 2011; Vörös & Forberger, 2012):

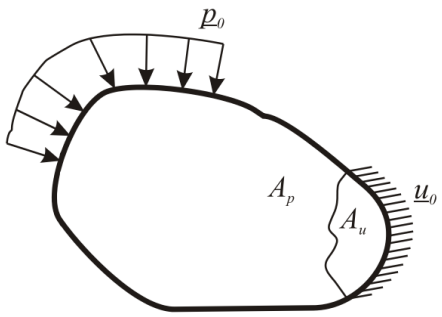


Figure 22. Sketch: boundary condition of an elasticity problem (Moharos et al., 2011)

Kinematic boundary conditions: the required $\boldsymbol{u}_0$ displacements (constraints) on surface A_u. The solution exists: $\boldsymbol{u} = \boldsymbol{u}_0$

Dynamic boundary conditions: the prescribed loads $\mathbf{p}_0$ on surface A_p (unloaded surfaces are also included because they have a known zero load). The solution exists: $\boldsymbol{p} = \boldsymbol{p}_0$

Other boundary conditions also occur, but the two types mentioned above occur most commonly.

Loads

Loads distort the physical structure and, thus, create stress in it. The most common forms of loading include point loads, pressure loads on surfaces, distributed tractions on surfaces, distributed edge loads and moments on shell edges, body forces, such as the force of gravity and thermal loads (*Getting started with Abaqus*, 2008).

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Mesh

The finite element mesh is the collection of elements and nodal points that make up the domain (Laforce, 2006). The name FEM is due to the principle that the continuous space is subdivided into a finite number of smaller and simpler geometries, namely the elements. This subdivision of the continuous space is called the mesh. (Lobos et al., 2009)

Geometry based – The mesh is associated with geometry. If the geometry is modified, the mesh will also get updated automatically. The boundary conditions could be applied on the geometry like a surface, edge etc. (*Web - meshing*, 2014)

Finite element based – The mesh is non-associative. The boundary conditions are applied on the elements and nodes only. (*Web - meshing*, 2014)

Modern software is able to mesh the geometry without setting any parameters. In this special case, the program uses a default setting which is appropriate for a rough estimation, although this only gives the user a line on the results. (Moharos et al., 2012)

Two aspects should be considered to determine if a mesh is good or not. The first has to deal with the representation level of the domain (RLD). This variable is measured as the difference between the areas or volumes of the actual domain and the final mesh. The second aspect is the quality. The perfect element can be described regarding some relations between the angles, edge's length, the distance between specific element's points, circumcircle, etc. Unfortunately, no “magic” quality measurement exists for an element, because it depends on the numerical method been used and on the problem being solved. (Lobos et al., 2009)

Some programs have been developed for the automatic mesh generation for the efficient idealization of complex domains with minimal interface with the analyst. Automatic mesh generation algorithms, capable of discretizing any geometry into an efficient finite element mesh without user intervention, have been developed. An automatic mesh generation program generates the locations of the node points and elements, labels the nodes and elements, and provides the element–node connectivity relationships. (Singiresu, 2005)

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8 HOW TO BUILD A SIMULATION

8.1 Defining the geometry

The planning and construction or part can be undertaken using a 3D model rather than separate plans and sections. Drawings are then generated from the 3D model, ensuring that the separate drawings always correspond and remain consistent with one another. There are two fundamentally different approaches to modelling the geometry of three-dimensional bodies: Explicit modelling, which describes a volume in terms of its surface. Implicit modelling by contrast employs a sequence of construction steps to describe a volumetric body (Borrmann et al., 2018)

In the most program, simple geometry can be defined with points and lines, but if a complex 3D designed model is necessary, an exported CAD file can be used. These file formats in general are .stl and .iges.

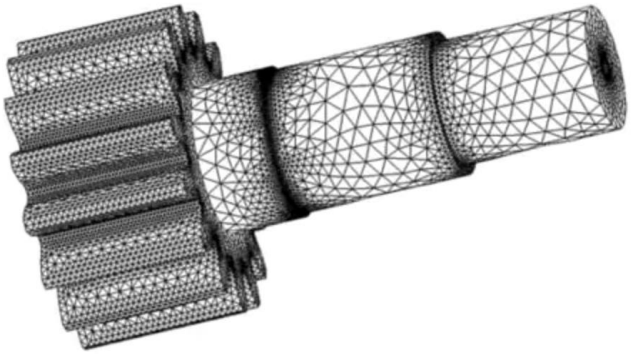


Figure 23. Imported .stl file in a simulation program (Web-stl, 2021)

STL file format describes only the surface geometry of a three-dimensional object without representing colour, texture, or other common model attributes. This file will encode the surface geometry of the object, the concept used at this step is called tessellation. Tessellation is the action of tiling a surface with geometric shapes, and especially triangles as it can be seen in Figure 23 (Web-stl, 2021). Each triangle is described by an outward normal and the coordinates of three ordered points. Such triangular meshes stored in STL format are used as definitions of the geometry of real solids for several industrial applications and also for rapid prototyping and manufacturing (Szilvási-Nagy & Mátyási, 2003).

STL file represents surfaces of CAD model, as a mesh of triangles. The quantity and size of the triangles determine how accurately the surface mesh represents the product. As the

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number of triangle increase and the relative triangle size decreases, the shape begins to be more accurate what is defined as facet resolution. (Petik, 2002)

IGES stands for Initial Graphics Exchange Specifications. Information exchanged using IGES includes circuit diagram, wireframe, freeform surface, or solid modelling representations. IGES finds its applications in traditional engineering drawings, models analysis, and manufacturing functions. The format can exchange both 2D or 3D design information between CAD programs. IGES provides a standard format by which the user can transfer product design data from one CAD system to another. IGES has information structures or entities to be used for digital representation and communication of product definition data. In other words, the IGES format treats the product definition as a file of entities. (Bhandarkar et al., 2000)

8.2 Choosing element type and mesh

For analysis, the software needs all three dimensions defined. It can not make calculations unless the geometry is defined completely (by meshing using nodes and elements).

The shape of 1D element is a line (it has translational and rotational displacement functions). When the element is created by connecting two nodes, the software knows about only one out of the 3 dimensions. The remaining dimensions is defined by the user. 2D element (surface element) is carried out on a mid surface of the part. These surface elements can have regular or irregular shapes. Since they account for plane stress and plain strain, they are often used to solve 2D elasticity problems. 3D elements are used when all of the 3 dimensions are comparable. 3D solid elements only account for translational displacements. (*Web - meshing*, 2014) A specific type of 1,2 and 3D elements can be seen in Figure 24.

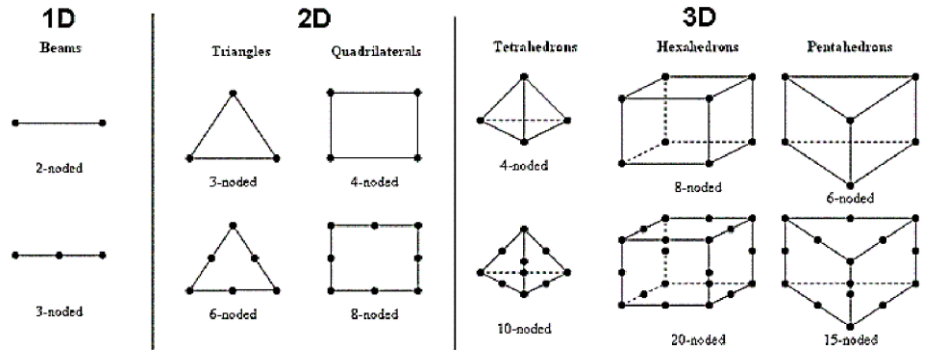


Figure 24. Different 1D, 2D and 3D basic elements (Rathinam, 2015)

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If the right elements can be chosen, the meshing starts. If the structure to model is complex in the sense that it contains many substructures with their own surfaces, which consist of triangles of very different size and quality, then the generated mesh must take into account these substructures and the joints between them, which constitutes additional problems during the mesh generation. (Gierdziewicz, 2021) Often the elements produced by an automatic mesh generator are not well-shaped, in which case it is useful to apply a mesh smoothing technique to improve the mesh. The most popular technique is Laplacian smoothing which seeks to reposition the nodes such that each internal node is at the centroid of the polygon formed by its connected neighbours (Ho-Le, 1988).

8.3 Explanation of the results

There are four basic decision-making approaches for deciding whether a simulation model is valid. Each of the approaches requires the model development team to conduct verification and validation as part of the model development process. Conceptual model validity is determining that (1) the theories and assumptions underlying the conceptual model are correct and (2) the model's representation of the problem entity and the model's structure, logic, and mathematical and causal relationships are "reasonable" for the intended purpose of the model. The theories and assumptions underlying the model should be tested using mathematical analysis and statistical methods on problem entity data. The behaviour data of the simulation model and the system are graphed for various sets of experimental conditions to determine if the model's output behaviour has sufficient accuracy for the model's intended purpose. Three types of graphs are used: histograms, box (and whisker) plots, and behaviour graphs using scatter plots, as the Figure 25 show. (Sargent, 2011)

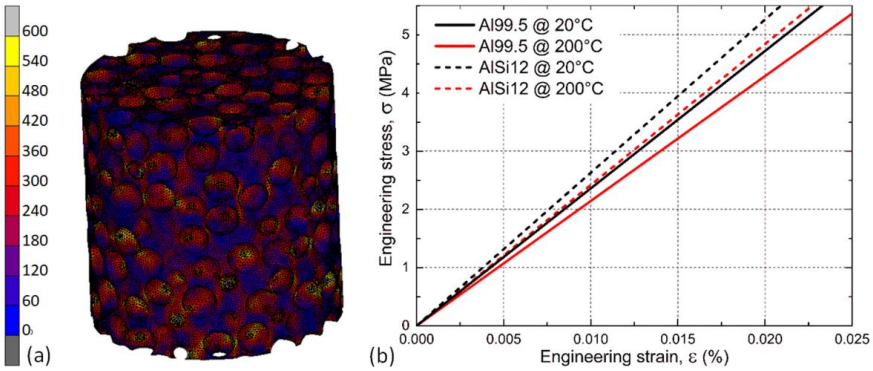


Figure 25. FEM model of AMSFs highlighting the von Mises stress distribution (a) and stress versus strain plots of the FEM results (b) (Katona et al., 2019)

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9 EXAMPLES FOR SIMULATION PROBLEMS

9.1 Forming – welding process

The summary is based on Bauer et al. research (Bauer et al., 2019).

Two main types of process were combined in a FEM simulation. Within the first step, the U-bending process formed the initial sheet in the shape of the die, and after the second and third steps was created the shape of a tube. After these, the welding was followed. The aim of the research is to compare the experiments, which can be seen in Figure 26, with the simulation.

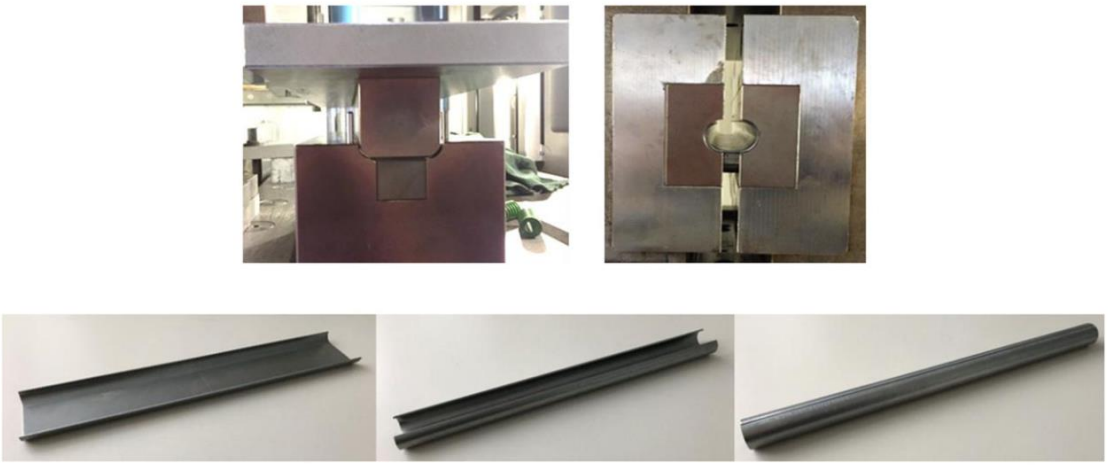


Figure 26. Forming tools for U and O bending (top) and three forming steps of U/O bending (below) (Bauer et al., 2019)

The initial pieces were DC04 steel sheets, with the dimensions of 300 × 63 × 1.5 mm. Simufact was using for the forming and also for the welding. The needed geometries were reconstructed from the experimental tools within CAD. The mesh was built up with advancing front quad meshes and an element edge length of 0.5 mm. A combined friction model with $\mu = 0.1$ and $m = 0.2$ was applied. The press stroke was set at 1 mm/s to the forming. After the forming motion, the press stroke included the return of the punch or die into the initial position, similar to the actual experimental processes. The weld seam was reconstructed after the geometry of the experimental weld seam with the element edge length of the tube remaining at approx. 0.5 mm.

The simulation was compared with a real manufacturing process. A good agreement between experimental and numerical results was found for tube manufacturing. The visible distortion

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is mainly caused by the thermal influences from the welding process. A faster cooling on both edges of the sample can lead to the effect that different stresses occur during the cooling process. Within the transition zone, a mixed area of weld metal and rough grain can be seen, while the numerical simulation shows a uniform field of weld metal (Figure 27).

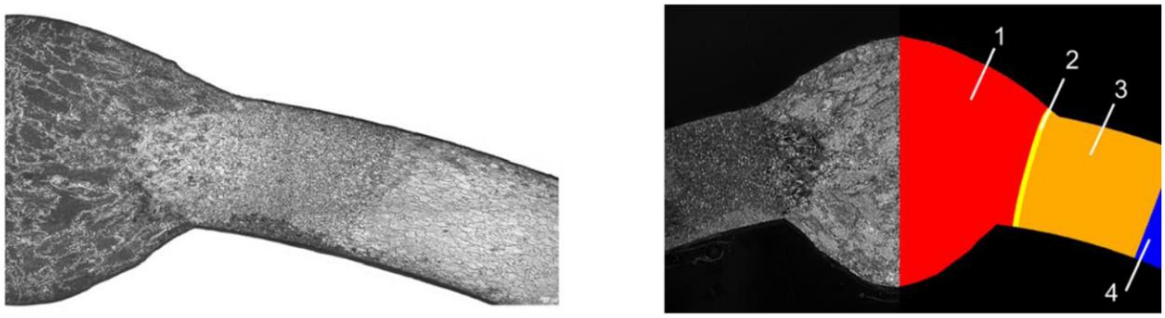


Figure 27. Macrograph of experimental weld bead (left) and comparison (right) (Bauer et al., 2019)

Some slight deviations were detected for the geometrical measurements over the length of the tube which might be caused by positioning of tube before and after welding process.

9.2 Additive manufacturing

9.2.1. Additive manufacturing using Monte Carlo model

Current models for microstructure prediction in additive manufacturing are often extensions of methods initially developed for directional solidification or welding. In this research, the general Potts Monte Carlo approach and modifications to the model for the study of solidification are presented. The method approximates a polycrystalline microstructure by assigning an integer ‘‘spin” to each lattice site. In the approach outlined below, the microstructure is evolved only within and immediately outside of the molten zone. This is reasonable as grain growth is not expected in regions far from the molten zone where grain boundary mobility is negligible. While the heat source is not directly simulated, its effect is imposed as a molten zone surrounded by a high-temperature, heat-affected zone (HAZ) having a steep thermal gradient. During additive simulations, the molten zone’s parameters are held constant. The molten zone’s geometry is defined by two coincident ellipsoids that share two axes but have independent lengths along the scan direction. The model incorporates layer remelting and epitaxial growth between layers through adjustment of the

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molten zone (Figure 28). Inactive regions are ‘‘masked” and evolution of these sites is not allowed prior to initial interaction with the molten zone. This masking does not affect time-evolution of the simulation, which is advanced by a fixed interval each time step. The model was shown to reproduce distinct and varied classes of AM microstructures reported in the open literature and does so with a reasonable qualitative and quantitative agreement. (Rodgers et al., 2017)

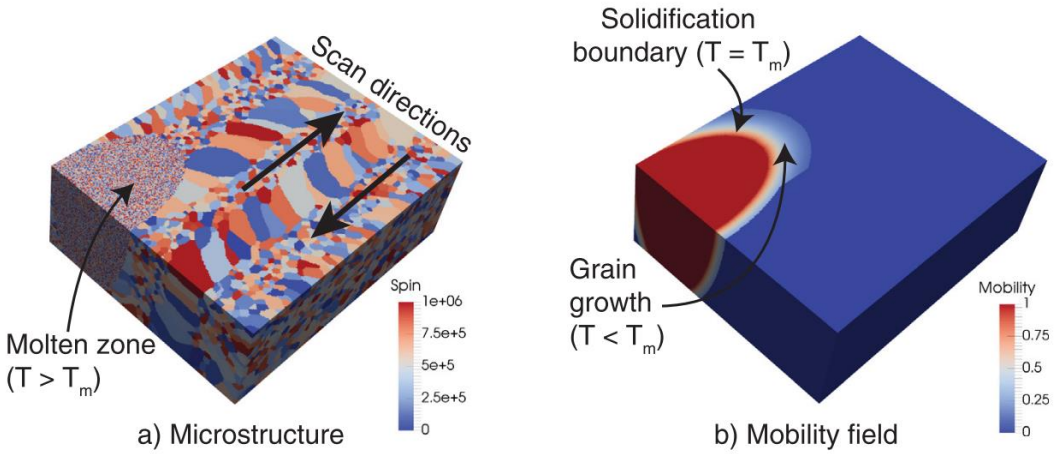


Figure 28. Schematic of a molten zone and HAZ scanning through a 1-layer thick 3D domain, two rasters in the layer have fully traversed the domain and the third is nearing completion (Rodgers et al., 2017)

9.2.2. Modelling of laser bad power fusion additive manufacturing

Modelling of the selective laser melting (SLM) process has some similarities with modelling of welding, but with two significant differences. First, in SLM, we must be able to model the new physics associated with the interaction of the laser with the metal powder, including radiation absorption and scattering, powder melting, and melt wetting. The second is a possible significant simplification of the description. It is clear that additively manufactured material quality degrades when the energy deposited exceeds the threshold for keyhole mode melting. (King et al., 2015)

The powder is an assembly of metal particles, taken here to be spheres, with sizes appreciably larger than the laser wavelength and with a complex refractive index appropriate to the material and the wavelength. A realistic powder has a distribution of sizes and a non-uniform geometrical arrangement, generally with porosity greater than that of an ideal array.

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To generate the powder geometry (Figure 29), Boley et al. used a particle-packing algorithm (Boley et al., 2015).

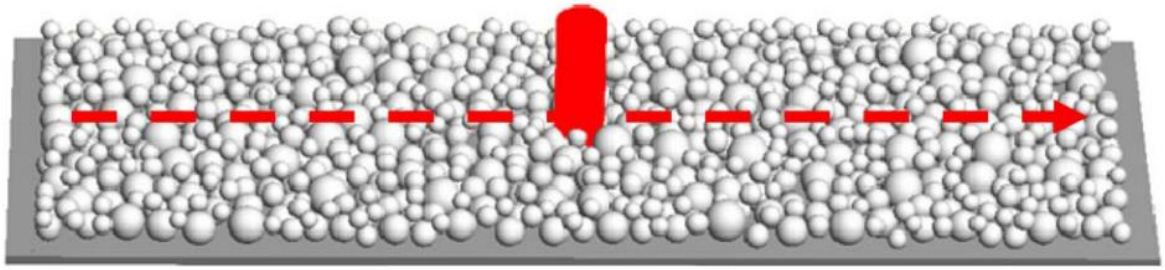


Figure 29. Powder with a Gaussian distribution of sizes. The length of the bed is about 1100 µm, and the beam path is indicated (Boley et al., 2015)

The discrete element methods (DEM) is a natural choice for modelling behaviour of particle beds to analyze the selective laser sintering process, in which particles are heated sufficiently to begin to sinter together but do not develop into a convecting melt pool. The DEM method is capable of thermo-mechanical analyses, with some calibrations required for certain parts of the model. The initial conditions in a random powder bed are set by allowing a number of particles to settle on a flat plate under the influence of gravity. (King et al., 2015)

The thermal conductivity of the particle powder bed is computed “on the fly” from first principles. All that is required is the thermal conductivities of the bulk material and of air at a given temperature. The powder has lower thermal conductivity than bulk stainless steel. This is because the particles are at point contact and the heat diffusion in gaps between the particles depends strongly on the gas’s thermal conductivity, which is lower than that of the metal. (King et al., 2015)

9.3 Forging

Computer simulation of forging is a technique that enables the behaviour of the workpiece material in a forging operation to be predicted. This primarily concerns the plasticity of the workpiece material and associated tools and can be described in terms of stresses, strains and microstructural changes that are brought about as a result of the process. (Bramley & Mynors, 2000)

High dimensional accuracy and surface quality of drop forgings at the suitable loading of forging die can be achieved by reduction of forging temperature in the area of warm forging. The temperature range concerning steel at warm forging processes is approximately from

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600 to 800 °C. Simufact.forming program is suitable for the simulation of hot, warm as well as cold bulk forming processes. Figure 30 shows that the material flow in the closed die cavity at the forging with ring billet placed in the bottom of a hub is incorrect because of lap formation. (Kapustová & Görögová, 2018)

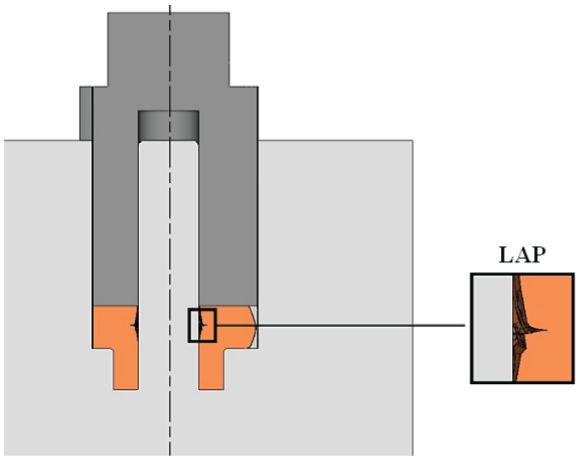


Figure 30. Incorrect material flow in die cavity (Kapustová & Görögová, 2018)

The numeric simulation proves that the highest values of the effective plastic strain and temperature have been observed in the area of the fillets from the ring to the hub.

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Digital Manufacturing Master's degree to set specialists for the dawn of the industry 4.0



Project number:
2019-1-RO01-KA203-063486

Energy Systems
-
an overview

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2 OBJECTIVES

This module aims to document energy systems. Various types of renewable energy systems are reviewed and discussed. During this course, the following objective:

1. Describe the different renewable energy system
2. Explain the operation and the application

2.1 Learning outcomes

On successful completion of this module a student should be able to:

1. Obtain advanced knowledge and critical understanding of the theory, principles and applicability of: Energy systems
2. Describe the different methods of producing energy
3. Discuss the different methods that can be used to reduce green house effect
4. Classify the different energy systems

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3 RENEWABLE ENERGY SYSTEMS

Even if the use of fossil fuels can be reduced significantly, and accepting that nuclear power is no long-term alternative, the question remains as to how the future supply of energy can be secured. The first step is to significantly increase the efficiency of energy usage, i.e. useful energy must be produced from a much smaller amount of primary energy, thus reducing carbon dioxide emissions. The increasing global population and the unsatisfied demand of the developing countries will more than cancel out possible reductions due to higher energy efficiency. Renewable energies will be the key to this development, because they are the only option that can cover the energy demand of Earth in a climatically sustainable way. (Quaschning, 2014)

4 HYDROPOWER

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and typically price-competitive technology. Hydropower has among the best conversion efficiencies of all known energy sources (about 90% efficiency, water to wire). It requires relatively high initial investment, but has a long lifespan with very low operation and maintenance costs. The levelized cost of electricity for hydropower projects spans a wide range but, under good conditions. Hydropower can provide important services to electric power systems. Storage hydropower plants can often be operated flexibly, and therefore are valuable to electric power systems. Specifically, with its rapid response load-following and balancing capabilities, peaking capacity and power quality attributes, hydropower can play an important role in ensuring reliable electricity service. In an integrated system, reservoir and pumped storage hydropower can be used to reduce the frequency of start-ups and shutdowns of thermal plants; to maintain a balance between supply and demand under changing demand or supply patterns and thereby reduce the load-following burden of thermal plants; and to increase the amount of time that thermal units are operated at their maximum thermal efficiency, thereby reducing carbon emissions. In addition, storage and pumped storage hydropower can help reduce the challenges of integrating variable renewable resources such as wind, solar photovoltaics, and wave power. (A. Kumar et al., 2011)

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The role that hydro will play in future energy networks is also changing. Most of the early hydropower projects were developed to provide continuous supply (base load) to the power system. This pattern will continue in countries where hydropower provides a significant share of power generation. As other electricity generation technologies have developed, however, the role of hydropower has evolved to encompass a supporting service. Given its unique abilities to store energy and move quickly to full capacity from a standstill, it has assumed importance in peak loading when demand requires it. (W. Turkenburg et al., 2012)

There is a general view that hydroelectricity is the renewable energy source par excellence, non-exhaustible, non-polluting, and more economically attractive than other options. And although the number of hydropower plants that can be built is finite, only a third of the sites quantified as economically feasible are tapped. Hydropower plants emit much less greenhouse gas than do thermal plants. Greenhouse gas emissions of hydropower are caused by the decay of vegetation in flooded areas and by the extensive use of cement in the dam construction. Unfortunately, there are local impacts of the use of rivers, social as well as ecological, and they are gaining importance as people become aware of how those impacts affect living standards. (C. W. Turkenburg, n.d.)

The classification according to size (installed capacity) is the most frequent form of classification used. Yet, there is no worldwide consensus on definitions regarding size categories, mainly because of different development policies in different countries. Small scale hydropower plants have the same components as large ones. Compared to large scale hydropower, it takes less time and efforts to construct and integrate small hydro schemes into local environments. It has therefore been increasingly used in many parts of the world as an alternative energy source, especially in remote areas where other power sources are not viable. These power systems can be installed in small rivers or streams with little or marginal environmental effect. Impacts on ecosystems will vary, however, not so much according to installed capacity or whether or not there is a reservoir, but by the design, where intakes, dams and waterways are situated and how much water flow is used for power generation compared to how much that is left as instream flow. The concept of small versus large hydro gives an impression of small or large negative impacts. This generalization will not hold as it is possible to construct rather large power plants with moderate impacts while the cumulative effects of several small power plants may be more adverse than one larger

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plant in the same area. It is more fruitful to evaluate hydropower based on its sustainability performance and based on the type of service provided as opposed to a classification based on technical units with little or no relevance for nature or society. (Arun Kumar, 2011)

Most hydroelectric power is generated by dams across large-flow rivers. A dam built across river creates a reservoir behind it. The height of the water behind the dam is greater than that below the dam, representing stored potential energy. When water flows down through the penstock of the dam driving the turbines, some of this potential energy is converted into electricity. Hydroelectric power, like other alternative sources, is clean and relatively cheap over the long term even with initial construction costs and upkeep. But because the river's normal flow rate is reduced by the dam, sediments normally carried downstream by the water are instead deposited in the reservoir. Eventually, the sediment can clog the penstocks and render the dam useless for power generation. (Al-Juboori, n.d.)

Large-scale dams can have a significant impact on the regional environment. When the river is initially dammed, farmlands are sometimes flooded and entire populations of people and wildlife are displaced by the rising waters behind the dam. In some cases, the reservoir can flood hundreds or thousands of square kilometres. The decreased flow downstream from the dam can also negatively impact human and wildlife populations living downstream. In addition, the dam can act as a barrier to fish that must travel upstream to spawn. Aquatic organisms are frequently caught and killed in the penstock and the out-take pipes. Because of the large surface area of the reservoir, the local climate can change due to the large amount of evapouration occurring. Most modern hydro-power systems are used to drive electric generators, although some special purpose mechanical systems are still useful such as the hydraulic ram pump. A complete hydroelectric system includes the pipe (penstock), flow control, the turbine, the electric generator, fine control of the generator and wiring for electricity distribution. The dam ensures a steady supply of water to the system without fluctuations and enables energy storage in the reservoir. It may also be used for purposes other than generating electricity, e.g., for roads or water supply. (Al-Juboori, n.d.)

To generate electricity, water must be in motion. This is kinetic (moving) energy. When flowing water turns blades of a turbine, the form of energy is changed to mechanical (machine) energy. The turbine turns the generator rotor which then converts this mechanical

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energy into another form of energy - electricity. Since water is the initial source of energy, we call this hydroelectric power or hydropower for short. At facilities called hydroelectric power plants, hydropower is generated. Some power plants are located on rivers, streams and canals, but for a reliable water supply, dams are needed. Dams store water for later releases for such purposes as irrigation, domestic and industrial use and power generation. The reservoir acts much like a battery, storing water to be released as needed to generate power. Figure 1 shows components of a hydroelectric power plant.

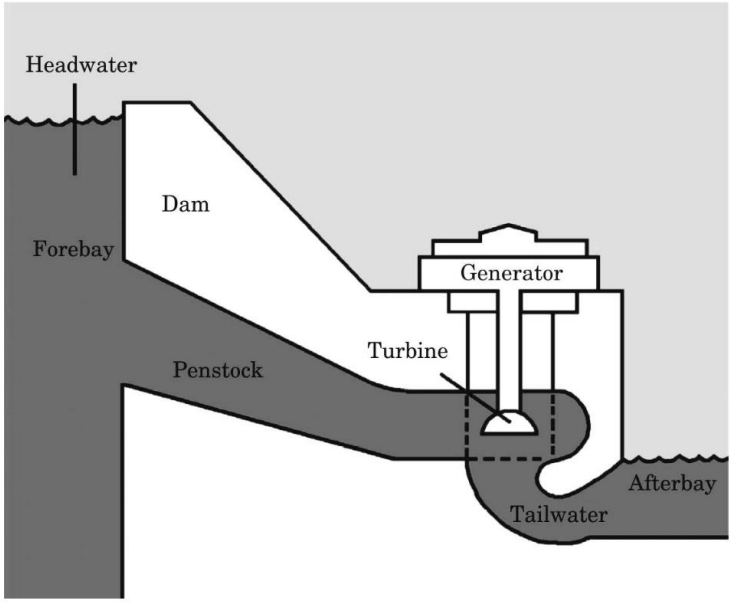


Figure 1. Hydro power plants components (Al-Juboori, n.d.)

5 SOLAR ENERGY

Solar utilization can be active or passive. Passive utilization is when a structure utilizes radiant heat with the help of building structural elements, based on the principle of the greenhouse effect, without mechanical intervention. Active use is the opposite of this: it uses some kind of building engineering equipment (Hestnes, 2000).

Passive solar design refers to the use of the sun's energy for the heating, cooling and day-lighting of living spaces. In this approach, the building itself or some element of it takes advantage of the natural energy characteristics in materials and air created by exposure to the sun. Passive systems are simple, have few moving parts, no mechanical systems, and require minimal maintenance. In contrast, active solar energy technologies require the transport of heat through a medium and thus need components to transform and transfer the

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solar energy. Active solar energy technologies reduce a building's fossil fuel energy requirements and associated fuel costs. Energy from active solar sources has two major applications or uses for homes and buildings. One is as a source of electricity, electricity and two is as source of heat for heat household hot water and space heating. Simple collectors, usually placed on the roof of a house or building, absorb the sun's energy and then transfer the heat to a media that moves it to points of usage. (Reyes & Rosen, 2007)

5.1 Solar radiation

The Sun is the central star of our solar system. It consists mainly of hydrogen and helium. The energy emitted by the sun is called solar energy or solar radiation. Despite the considerable distance between the sun and the earth, the amount of solar energy reaching the earth is substantial. The solar radiation at the top of the atmosphere, i.e. at an altitude of approximately 70 km, is called extraterrestrial radiation. As it makes its way towards the ground, it is depleted when passing through the atmosphere. On average, less than half of extraterrestrial radiation reaches ground level. Even when the sky is very clear with no clouds, approximately 20 % to 30 % of extraterrestrial radiation is lost during the downwelling path. (Oliveti et al., 2014; Wald, 2007)

When passing through the atmosphere, solar radiation with normal incidence is subject to two sources of attenuation: scattering and absorption. Scattering occurs when the radiation interacts with air molecules, water and dust in the atmosphere. The degree of scattering is determined by the wavelength of the radiation in relation to particle size, the concentration of particles in the atmosphere and the total mass of air that the radiation has to travel through. Absorption of solar radiation occurs in the UV range due to ozone and in the IR range due to water and carbon dioxide. In the process of absorption, the solar radiation is converted to heat, which is emitted by the particles as long-wave radiation. The effect of Rayleigh scattering is quite large and wavelength-dependent, as can be seen in Figure 2. (Widén & Munkhammar, 2019)

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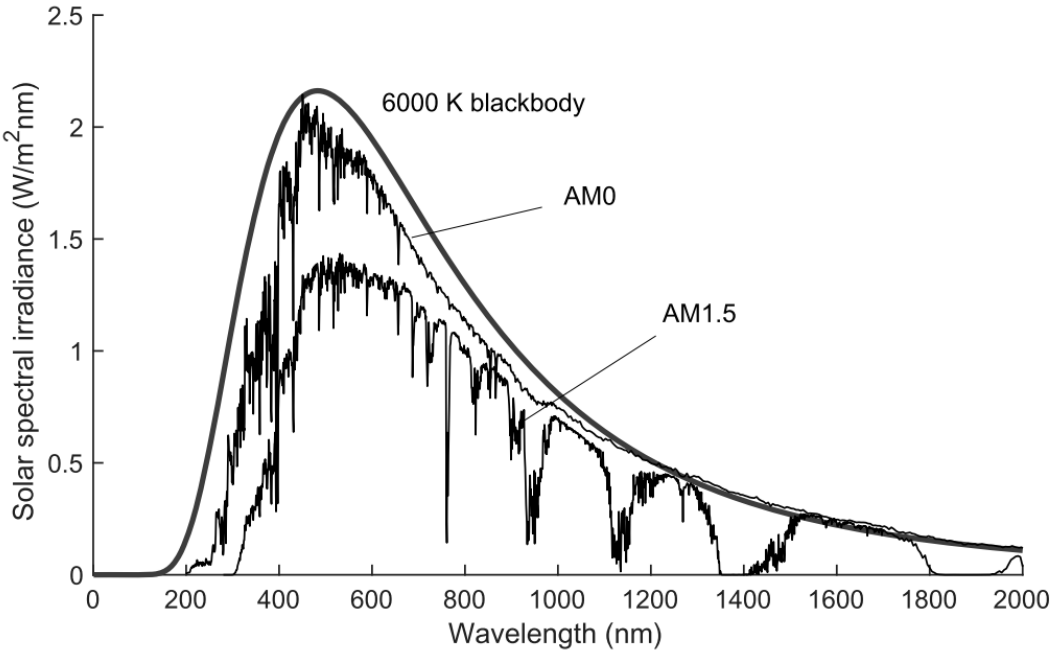


Figure 2. Typical spectral distribution of the solar irradiance at the top of the atmosphere at normal incidence for wavelengths from 200 nm to 2000 nm

5.1.1 Effects of different materials on solar radiation

Atmospheric

We see blue sky because atmospheric molecules scatter solar radiation much more in the blue than in the red part of the spectrum. In fact, the sky is made visible through the scattering process. On the other hand, sunsets and sunrises appear reddish because the blue light in the direct light is removed by scattering during the long path through the atmosphere, leaving the remaining reddish colours of the spectrum. Atmospheric gases also absorb solar radiation in selected wavelength bands. The UV radiation with wavelengths shorter than 0.3 mm is lethal to the biosphere. The UV radiation in the interval 0.2–0.3 mm is mainly absorbed by O_3 in the stratosphere. The small amount of radiation with wavelengths shorter than 0.2 mm is absorbed at higher levels by O_2, N_2, O, and N. (Fu, 2003)

Aerosol

Aerosols scatter and absorb solar radiation. Sulfate aerosols scatter primarily solar radiation and cause cooling of the Earth-atmosphere system. The increase in the reflected solar radiation at the top of the atmosphere due to such nonabsorbing aerosols is nearly identical

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to the reduction in solar radiation at the surface. Carbonaceous aerosols (black carbon and organics) absorb and scatter solar radiation. The presence of black carbon aerosols results in the absorption of solar radiation, which reduces the solar radiation reaching the surface. At the same time, these aerosols absorb the upward solar radiation reflected from below and reduce the solar radiation reflected in space. Therefore, the effect of black carbon aerosols opposes the cooling effect of other aerosols at the top of the atmosphere, whereas at the surface all aerosols reduce solar radiation. (Fu, 2003)

Clouds

Clouds are the most important regulator of solar radiation. By reflecting incoming solar radiation back to space, they cool the Earth–atmosphere system – the so-called cloud albedo effect. Clouds also absorb solar radiation in the near-infrared region. The cooling of the Earth–atmosphere system by the cloud albedo effect occurs primarily at the surface. The most straightforward and simple diagnostic measure of the impact of clouds on solar radiation is the short-wave cloud forcing, which is defined as the difference in the net solar irradiances at the top of the atmosphere between all-sky and cloudless conditions. Here the net irradiance is the incoming solar radiation minus the reflected radiation. Satellite measurements suggest that the global short-wave cloud forcing is about 45 W/m^2. Short-wave cloud forcings are maximized (about 120 W/m^2)in the summer hemisphere at about latitude 601 where solar input is large and low clouds are abundant, with a secondary maximum in the tropics. Note that the magnitude of short-wave cloud forcing is about ten times as large as those for a CO_2 doubling. Hence small changes in the cloud-radiative forcing fields can play a significant role as a climate feedback mechanism. (Fu, 2003)

5.1.2 Greenhouse effect

Much of the thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect (Figure 3.). The glass walls in a greenhouse reduce airflow and increase the temperature of the air inside. Analogously, but through a different physical process, the Earth's greenhouse effect warms the surface of the planet. Without the natural greenhouse effect, the average temperature at Earth's surface would be below the freezing point of water. Thus, Earth's natural greenhouse effect makes life as we know it possible. However, human activities,

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primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming. (IPCC, 2007; Zhai et al., 2007)

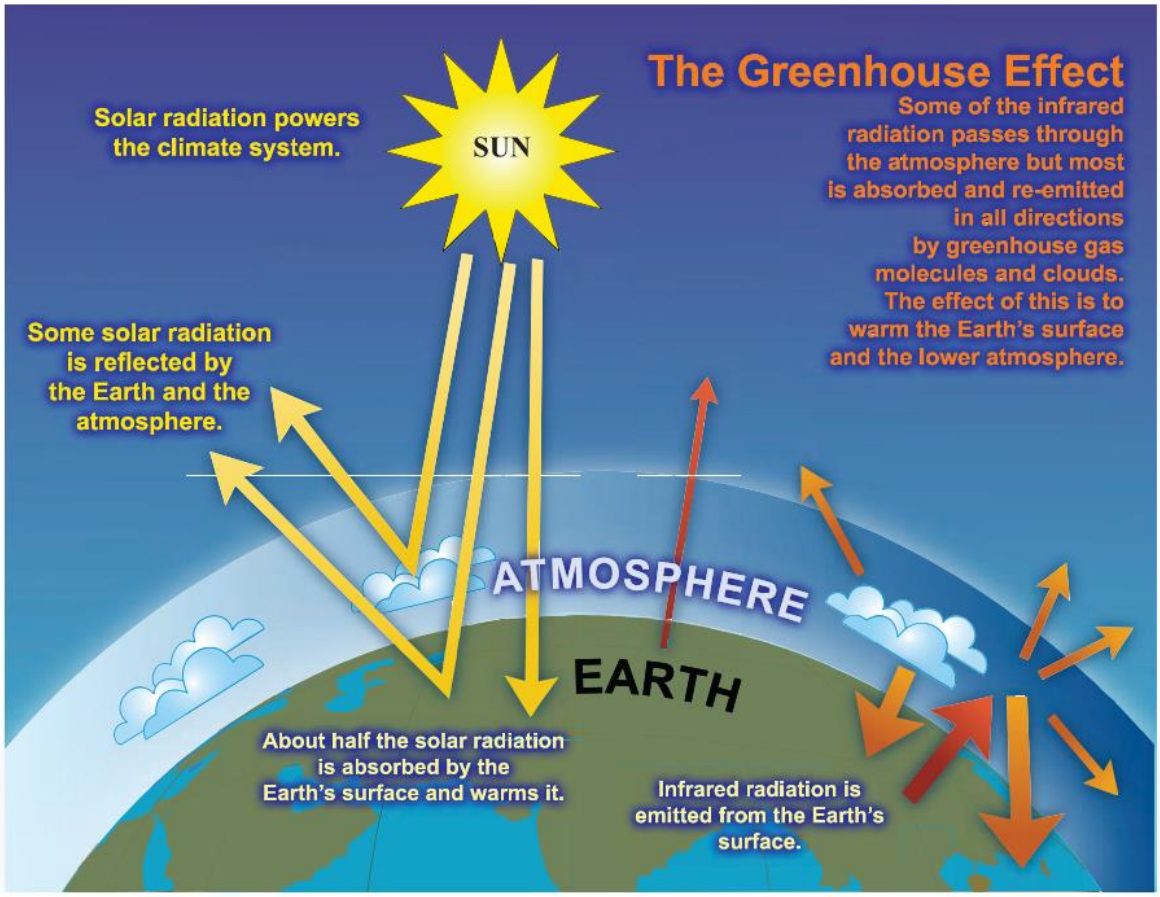


Figure 3. An idealised model of the natural greenhouse effect (IPCC, 2007)

5.1.3 Measurement of solar radiation

Pryanometer

Routine measurements of global solar irradiance are taken by pyranometers (Figure 4) that are placed horizontally flat. This gives the detector a full view of the sky dome and so accepts radiation from all directions within the dome. (Lysko, 2006)

Pyranometers measure global irradiance: the amount of solar energy per unit area per unit time incident on a surface of specific orientation emanating from a hemispherical field of view (2π sr), denoted $E_g\downarrow$. The global irradiance is then:

$$E_g\downarrow = E \cdot \cos(\theta) + E_d \quad (1)$$

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where Ed accounts for the diffuse sunlight. In many cases the surface of interest is horizontal such that the hemispherical field of view corresponds to the sky dome.

The global irradiance includes direct sunlight and diffuse sunlight. In the solar energy industry pyranometers are used to monitor the performance of photovoltaic (PV) power plants. By comparing the actual power output from the PV power plant to the expected output based on a pyranometer reading the efficiency of the PV power plant can be determined. Drops in efficiency may indicate that maintenance of the PV plant is required. Pyranometers can also be used to determine the suitability of potential sites for PV power plants. In this case pyranometers are used to determine the expected output of a PV installation. (Hukseflux, 2018)



Figure 4. Pryanometer (Hukseflux, 2018)

Pyrheliometer

Pyrheliometers (Figure 5) measure ‘direct solar radiation’ energy: the amount of solar energy per unit area per unit time incident on a plane normal to the position of the sun in the sky, coming directly from the sun itself. This is also called ‘direct normal irradiance’, often abbreviated to DNI. A pyrheliometer needs to be mounted on a solar tracker: a device that points the instrument at the sun throughout the day. all modern pyrheliometers use the same field of view, characterised by an opening half-angle of 2.5° (Figure 6). This means the measurement of direct solar radiation includes some ‘circumsolar’ radiation. Performing reliable pyrheliometer measurements in the field adds many practical aspects such as the pyrheliometer alignment, limitations on data availability due to precipitation and pyrheliometer maintenance and calibration. Pyrheliometers are mounted on solar trackers that point the instrument to the sun throughout the day. Many pyrheliometers have standardized tube diameters of 38×10^{-3} m. Contact the factory for tracker compatibility.

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When taking measurements, one should make sure the pyrheliometer has a clear window. Snow, frost, rain, dew or dust collecting on the window can absorb, scatter or focus radiation leading to erroneous measurements (see Figure 9). Modern pyrheliometers such as DR30, DR20 and DR15 are equipped with powerful window heaters to deal with snow, frost and dew and thereby increase the data availability. These heaters are especially designed to minimize any adverse effect on the radiation measurements. To avoid dust from collecting on the window frequent cleaning of the window is recommended. (Hukseflux, 2006)



Figure 5. Phyrheliometer

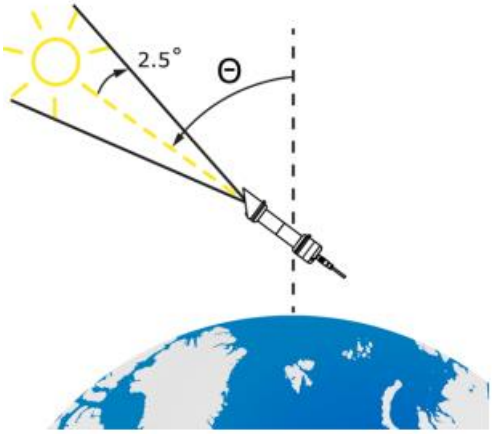


Figure 6. Pyrheliometers measure, characterised by a opening half-angle of 2.5°

5.2 Solar cells and collectors

5.2.1 Solar cells

Solar cells and solar panels have lots of uses. They are in everyday things like calculators, watches, and flashlights. There are solar-powered toys, radios, and MP3 players. There are solar-powered cell phones and pagers. Using solar power with devices like these means you never have to worry about batteries. Solar panels are sometimes used to make the electricity to light up road signs and bus stops. They may make the electricity that makes roadside emergency phones or parking meters work. Even some ATMs (machines that let you get money from or put money into your bank account) have solar panels. (Hantula, 2010)

A solar cell is any device that directly converts the energy in light into electrical energy through the process of photovoltaics. It can also be called a photovoltaic cell. Two types of crystalline silicon are used in the industry. The first is monocrystalline produced by slicing

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wafers (up to 150 mm diameter and 350 microns thick) from a high-purity single crystal boule. The second is multi-crystalline silicon, made by sawing a cast block of silicon first into bars and then wafers. (Isik, 2015; Mosiori, 2013)

A thin-film solar cell (TFSC), also called a thin-film photovoltaic cell (TFPV), is a second-generation solar cell that is made by depositing one or more thin layers, or thin-film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous and other thin-film silicon (a-Si, TF-Si). (Arun, 2019; Ranabhat et al., 2016)

Film thickness varies from a few nanometers (nm) to tens of micrometres (μm), much thinner than thin-films rival technology, the conventional, first-generation crystalline in most solar PV systems. Despite these enhancements, the market share of thin-film never reached more than 20% in the last two decades and has been declining in recent years to about 9% of worldwide photovoltaic production in 2013. Other thin-film technologies, that are still in an early stage of ongoing research or with limited commercial availability, are often classified as emerging or third-generation photovoltaic cells and include, organic, dye-sensitized, and polymer solar cells, as well as quantum dot, copper zinc tin sulfide, nanocrystal, micromorph and perovskite solar cells. (Arun, 2019)

There are basically three primary types of thin-film solar cells that have been commercially developed (Ranabhat et al., 2016):

- Amorphous silicon (a-Si and a-Si/μc-Si);
- Cadmium Telluride (Cd-Te); and
- Copper-Indium-Selenide (CIS) and Copper- Indium-Gallium-Diselenide (CIGS)

Third-generation solar cells are inherently different from the previous two generations because they do not rely on the p-n junction design of the others. This new generation of solar cells is being made from a variety of new materials besides silicon, including nanomaterials, silicon wires, solar inks using conventional printing press technologies, organic dyes, and conductive plastics. (Ranabhat et al., 2016)

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Organic or polymer cells are classified as such because the active layers of the cell are made of completely organic materials. These cells can either have a bilayer structure or a bulk-heterojunction structure, but the mechanism of both designs is the same. The active layer of organic solar cells is comprised of donor and acceptor materials for charge separation and transportation. (Ranabhat et al., 2016)

5.2.2 Solar collectors

Solar energy collectors are special kinds of heat exchangers that transform solar radiation energy into internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device that absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment, or to a thermal energy storage tank from which can be drawn for use at night and/or on cloudy days. (Kalogirou, 2004)

In this regard solar collectors are categorized into two main types: a) stationary collectors and b) sun-tracking collectors, in following the introduction of the collectors, these main types would be declared clearly. Stationary collectors are fixed in their position and do not track the sun. Sun-tracking collectors as the name of these types, trace the sun during the day to collect more energy compared to the stationary type. (Dabiri & Rahimi, 2016)

Stationary

Solar energy collectors are basically distinguished by their motion, i.e. stationary, single axis tracking and two- axes tracking, and the operating temperature.

The performance of a flat-plate collector (FPC in Figure 7) is not so complicated, it is just based on radiation passing a transparent layer and then set on an absorber layer that absorbs the solar energy as heat energy. The absorbed heat is then transferred to a kind of medium fluid that could be water, water plus antifreeze additive, or air in the tubes to increase its temperature for direct thermal use. The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector as the glass is

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transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect). (Dabiri & Rahimi, 2016; Kalogirou, 2004)

The collector plate absorbs as much of the irradiation as possible through the glazing while losing as little heat as possible upward to the atmosphere and downward through the back of the casing. The collector plates transfer the retained heat to the transport fluid. The absorptance of the collector surface for shortwave solar radiation depends on the nature and colour of the coating and on the incident angle. Usually, black colour is used. Today, commercial solar absorbers are made by electroplating, anodization, evapouration, sputtering and by applying solar selective paints. Much of the progress during recent years has been based on the implementation of vacuum techniques for the production of fin type absorbers used in low-temperature applications. The chemical and electrochemical processes used for their commercialization were readily taken over from the metal finishing industry. (Kalogirou, 2004; Maldonado et al., 2014)

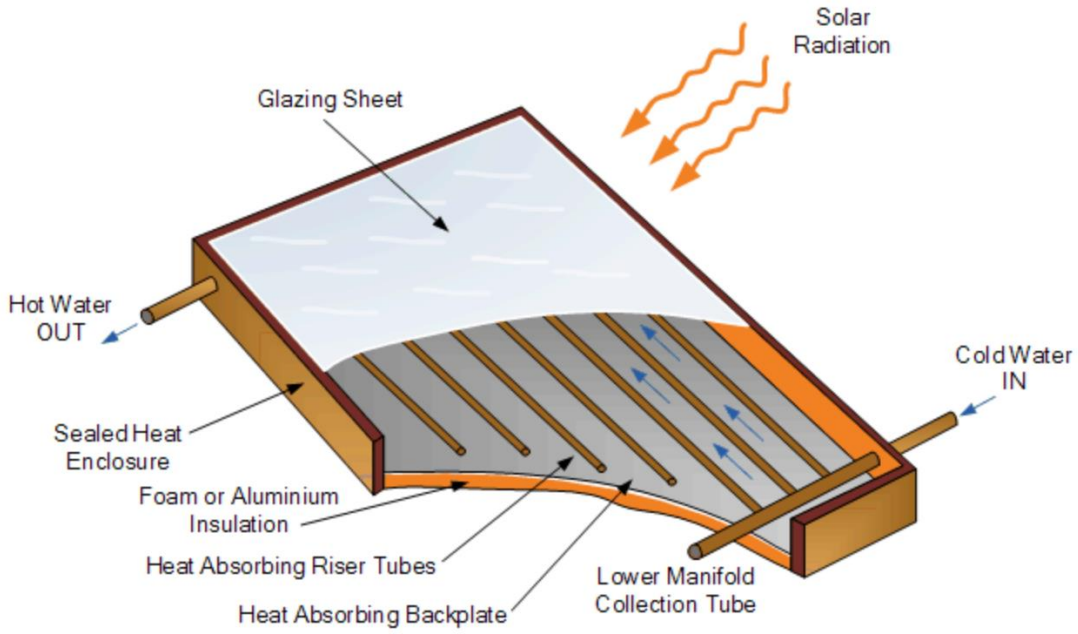


Figure 7. Flat plate collector (Web, 2020)

Compound parabolic collectors (CPC) are similar to flat-plate collectors should be fixed at a specific angle called acceptance angle based on its position, although some kinds of compound parabolic collectors can track the sunlight. For stationary CPC collectors mounted

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in this mode, the minimum acceptance angle is equal to 47°. This angle covers the declination of the sun from summer to winter solstices. (Dabiri & Rahimi, 2016)

Since the flat-plate collectors don't have a good performance in cloudy and cold weather due to the condensation of moisture on the surface of the plate, evacuated heat pipe collectors (ETC) were invented. These solar collectors consist of a heat pipe inside a vacuum-sealed tube. The vacuum envelope reduces convection and conduction losses, so the collectors can operate to higher temperatures than flat-plate collectors. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate) protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid such as methanol that undergoes an evapourating-condensing cycle. In this cycle, solar heat evapourates the liquid, and the vapour travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid return back to the solar collector and the process is repeated.

Sun tracking collector

In a type of sun-tracking collector, the working fluid can achieve higher temperatures in a concentrator system when compared to a flat-plate system of the same solar energy collecting surface. This means that higher thermodynamic efficiency can be achieved. The thermal efficiency is greater because of the small heat loss area relative to the receiver area. It is possible with a concentrator system, to achieve a thermodynamic match between temperature level and task. The task may be to operate thermionic, thermodynamic, or other higher temperature devices. Many designs have been considered for concentrating collectors. Concentrators can be reflectors or refractors, can be cylindrical or parabolic and can be continuous or segmented. Receivers can be convex, flat, cylindrical or concave and can be covered with glazing or uncovered. Concentration ratios, i.e. the ratio of aperture to absorber areas, can vary over several orders of magnitude, from as low as unity to high values of the order of 10 000. Increased ratios mean increased temperatures at which energy can be delivered but consequently these collectors have increased requirements for precision in optical quality and positioning of the optical system. (Kalogirou, 2004)

Solar parabolic trough collector (PTC in Figure 8) power plants have been at the core of modern utility-scale solar power generation for over three decades. In order to deliver high

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temperatures with good efficiency, a high-performance solar collector is required. Systems with light structures and low cost technology for process heat applications up to 400 °C could be obtained with parabolic through collectors. A metal black tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver When the parabola is pointed towards the sun, parallel rays incident on the reflector are reflected onto the receiver tube. It is sufficient to use a single axis tracking of the sun and thus long collector modules are produced. The collector can be orientated in an east–west direction, tracking the sun from north to south, or orientated in a north–south direction and tracking the sun from east to west. The advantages of the former tracking mode is that very little collector adjustment is required during the day and the full aperture always faces the sun at noon time but the collector performance during the early and late hours of the day is greatly reduced due to large incidence angles (cosine loss). North–south orientated troughs have their highest cosine loss at noon and the lowest in the mornings and evenings when the sun is due east or due west. (Kalogirou, 2004; Nation et al., 2017)

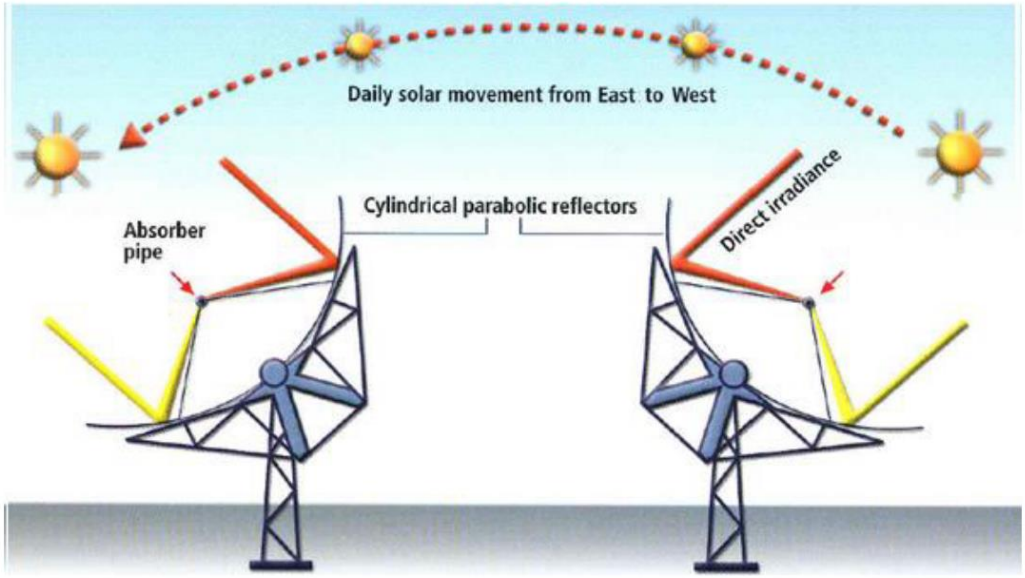


Figure 8. Solar parabolic trough collector (Nation et al., 2017)

Linear Fresnel reflector (LFR) technology relies on an array of linear mirror strips which concentrate light on to a fixed receiver mounted on a linear tower. The LFR field can be imagined as a broken-up parabolic trough reflector (Figure 9), but unlike parabolic troughs, it does not have to be of parabolic shape, large absorbers can be constructed and the absorber

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does not have to move. The greatest advantage of this type of system is that it uses flat or elastically curved reflectors which are cheaper compared to parabolic glass reflectors. Additionally, these are mounted close to the ground, thus minimizing structural requirements. (Günther, 2011; Kalogirou, 2004)



Figure 9. Linear Fresnel reflector in the industry (Günther, 2011)

A parabolic dish reflector (PDR), shown in Figure 10, is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver. For this purpose tracking mechanisms similar to the ones described in the previous section are employed in double so that the collector is tracked in two axes. The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be converted into electricity using an engine-generator coupled directly to the receiver, or it can be transported through pipes to a central power-conversion system. Parabolic-dish systems can achieve temperatures over 1500 °C. (Kalogirou, 2004)

Parabolic dish concentrators concentrate light in a point which is called the receiver. They benefit from their geometry to achieve one of the highest efficiencies among all solar energy technologies. These systems collect the beams coming from the sun, and parallel to the axis of the parabola, and reflect them to the focal point where the thermal receiver is located. The

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collector must be optimally oriented towards sun and that is why most of parabolic dish collectors use a two-axis tracking system to constantly track the position of the sun in the sky. The surface of the collector is covered with reflecting mirrors or other coating materials with high reflection coefficients. (Günther, 2011)



Figure 10. Parabolic Dish Stirling (Günther, 2011)

6 GEOTHERMAL ENERGY

Geothermal heat is constantly produced by the Earth from the decay of radioactive material in the core of the planet. The heat is moved to the surface through conduction and convection. In the crust, the temperature gradient is typically 30 °C/km but can be as high as 150 °C/km in hot geothermal areas. The best geothermal fields are generally found around volcanically active areas often located close to the boundaries of tectonic plates. Although some of the geothermal resources are located in populated, easily accessible areas, many others are found deep on the ocean floor, in mountainous regions, and under glaciers or ice caps. Even though the greatest concentration of geothermal energy is associated with the Earth's plate boundaries, some form of geothermal energy can be found in most countries; exploitation of geothermal systems in normal and low geothermal gradient areas for home heating has gained momentum during the last decade. Ground source heat pumps can be utilized almost anywhere in the world to produce heat from the ground near the surface, or from surface water reservoirs. (Loksha & Gehringer, 2002)

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Figure 11 shows the components of a typical hydrothermal (steam or water-based) volcanic-related geothermal system.

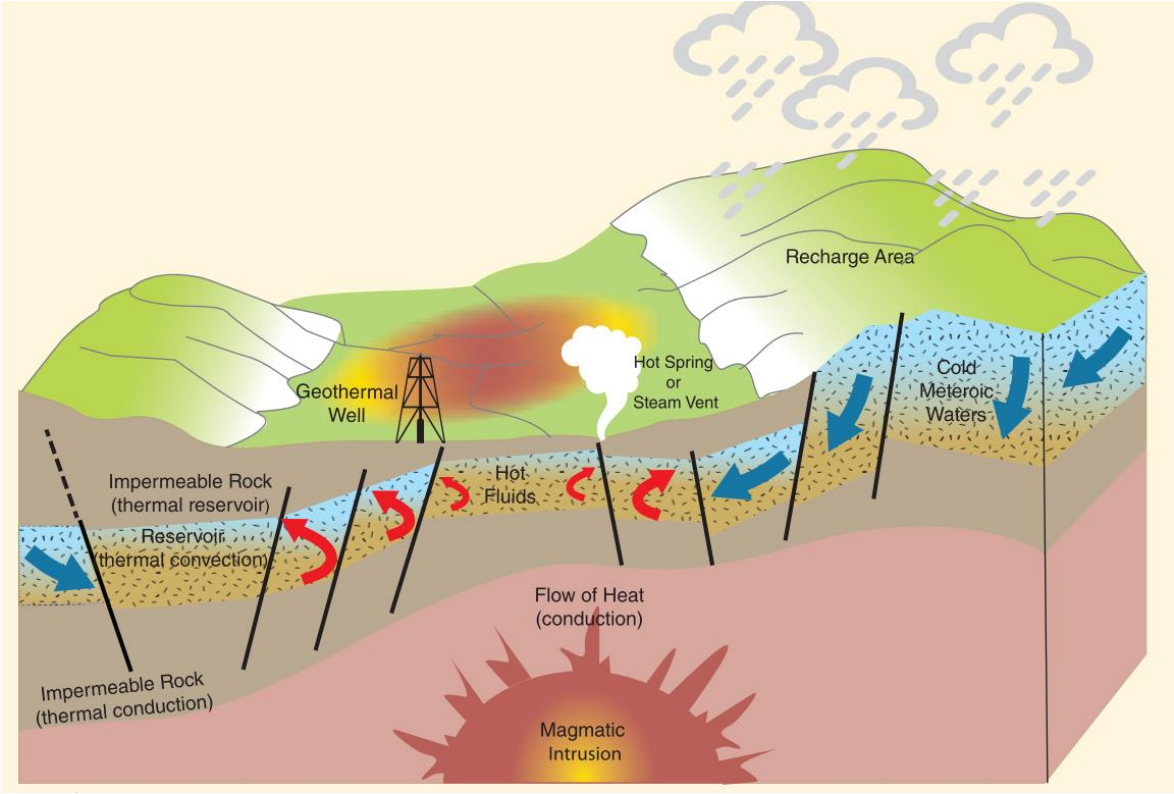


Figure 11. Schematic representation of an ideal geothermal system (Dickson & Fanelli, 2004)

Geothermal systems can also be classified as: convection-dominated systems, which include liquid-and vapour-dominated hydrothermal systems; conduction-dominated systems which include hot rocks; and hybrid systems that are sourced from convection, conduction, and high-heat-producing source rocks. Geologic aquifers that overlie radiating sources ofheat and gain heat via convection and/or conduction are sometimes called hot sedimentary aquifer systems. (Gutiérrez-negrín, 2013)

6.1 Utilization of direct used geothermal energy

The direct use of geothermal resources is the use of the heat energy or the fluid from geothermal resources without intervening medium as opposed to its conversion to other forms of energy such as electrical energy. (Jóhannesson & Chatenay, 2014)

Direct heat use is one of the oldest, most versatile and also the most common form of utilization of geothermal energy. Bathing, space and district heating, agricultural

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applications, aquaculture and some industrial uses are the best-known forms of utilization, but heat pumps are the most widespread. There are many other types of utilization, on a much smaller scale, some of which are unusual. (Dickson & Fanelli, 2004)

In Europe the main share of installed thermal potential is for geothermal heat pump system (68%) and district heating (15%), while balneology, aquaculture and deicing amount to 11% and industrial and agricultural processes to 6%. The agricultural applications of geothermal fluids consist of the plant growing temperature control in open fields and greenhouses. Thermal water can be used in open-field agriculture to heat the soil and, sometime, to irrigate it where ponds and rivers are not available. Soil heating is provided by burying thin pipelines where warm fluids are circulated. The greatest drawback in this heating is the cost, and this technique results economic only in few cases. Heating the soil in buried pipelines without the irrigation system could also decrease the heat conductivity of the soil, because of the drop in humidity around the pipes, and consequent thermal insulation. The best solution seems to be that of combining soil heating and irrigation. The chemical composition of the geothermal waters used in irrigation must be monitored carefully to avoid adverse effects on the plants. The temperature control in open-field agriculture prevents any damage ensuing from low environmental temperatures, extends the growing season, increases plant growth, and boosts production. It also sterilizes the soil, increasing productivity. (Manzella, 2017)

Geothermal heat pumps also play an important part for individual space heating or cooling with the use of either ground or water source heat pumps. Such applications are fairly common now in Europe. Space cooling from geothermal can be successfully achieved with heat pumps. (Jóhannesson & Chatenay, 2014)

Groundwater aquifers and soil temperatures in the range of 5 to 30 °C are being used in these systems. Geothermal heat pumps (GHP) utilize groundwater in wells or by direct ground coupling with vertical heat exchangers. Heating of individual rooms and buildings is achieved by passing geothermal water (or a heated secondary fluid) through heat convectors (or emitters) located in each room. The method is similar to that used in conventional space heating systems. Three major types of heat convectors are used for space heating: 1) forced air, 2) natural air flow using hot water or finned tube radiators, and 3) radiant panels. All

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these can be adapted directly to geothermal energy or converted by retrofitting existing systems. (Lund, 2010)

6.2 Electricity generation

Electricity generation mainly needs steam to rotate a turbine that activates a generator, which produces electricity. Most power plants still use fossil fuels to boil water for steam, whereas geothermal power plants use steam produced from or heated by underground hot fluids. Three main types of technology are available: dry steam, flash steam and binary cycle, depending on the characteristics of the geothermal fluid. Power plants that use dry and/or flashed steam to spin turbines are the most commonly deployed form of geothermal electricity generation. These plants use the heat energy contained in water and steam flowed from geothermal wells to spin turbines, converting thermal and kinetic energy to electrical energy. (Gutiérrez-negrín, 2013; Manzella, 2017)

Geothermal power plants mainly come in two groups, namely, steam and binary power cycles. These cycles operate at high geothermal fluid enthalpy. The single flash cycle contains only one throttling valve (expansion valve) through which the geothermal fluid is expanded, and one separator to separate the vapour from the liquid after the expansion process in the expansion valve. This separation occurs at constant pressure and temperature. The vapour generated is sent to a steam turbine to produce electricity while the liquid is reinjected back to the ground. The geothermal fluid in the well is above 182 °C for the flash steam power plants. Flash steam power plants use a condenser to condense the steam leaving the turbine and then reinject it into the ground. (El Haj Assad et al., 2017)

6.2.1 Dry steam power plants

In dry steam plants the steam (Figure 12) is piped directly from underground wells to the power plant, where it is directed into a turbine/generator unit. To use this plant, geothermal fluids must be in a vapour state when they reach the surface. In dry steam reservoirs, the dry steam is obtained by digging wells that are 7000–10.000 feet deep, after which the steam is transported through a pipe from the well to the turbine generator in order to generate electricity. Moreover, the condensed water from the turbine can be used to cool the power plants. Using dry steam reservoirs is an efficient and successful way of generating electricity, but it is rarely used. As for hot water reservoirs, the hot water from the wells is connected to

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one, two, or more separators to convert the water into steam. This steam then flows through pipes towards the turbine to produce electricity, after which the steam is condensed and used to cool the power plant system. This type is more common than the previously described dry steam reservoirs. (El Haj Assad et al., 2017; Manzella, 2017)

Conventional dry steam turbines require fluids of at least 150 °C and are available with either atmospheric (backpressure) or condensing exhausts. In the backpressure system steam is passed through the turbine and vented to atmosphere. This cycle consumes twice more steam per produced kilowatt-hour (kWh), at identical turbine inlet pressure, than a condensing cycle. However, backpressure turbines may prove rewarding as pilot or/and stand by plants in case of small supplies from remote isolated wells and for generating electricity in the early stages of field development. They become mandatory in case of high non condensable gas contents, in excess of 12% in weight, in the vapour phase. (*Geothermal Electricity and Combined Heat & Power*, 2007)

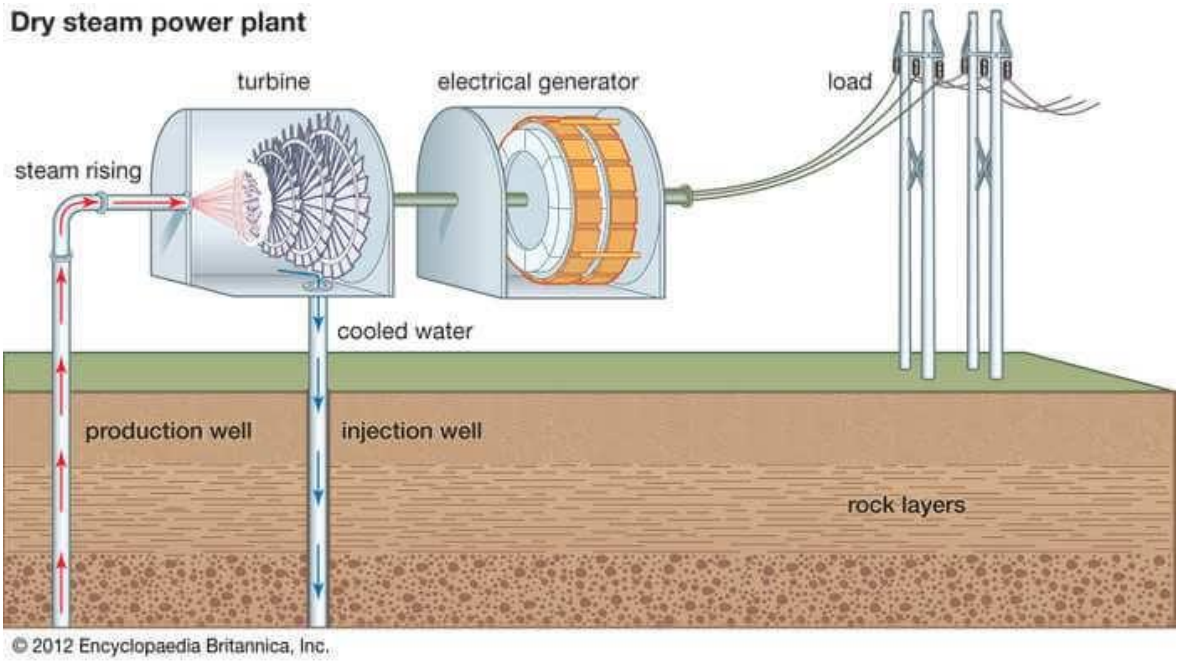


Figure 12. Schematic of dry stream power plant (Web, 2021a)

6.2.2 Flash steam power plant

Flash steam power plants (Figure 13) are the most common type of geothermal power plant. The steam, once it has been separated from the water, is piped to the powerhouse where it is used to drive the steam turbine. The steam is condensed after leaving the turbine, creating a

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partial vacuum and thereby maximizing the power generated by the turbine-generator. The steam is usually condensed either in a direct contact condenser, or a heat exchanger type condenser. In a direct contact condenser the cooling water from the cooling tower is sprayed onto and mixes with the steam. The condensed steam then forms part of the cooling water circuit, and a substantial portion is subsequently evapourated and is dispersed into the atmosphere through the cooling tower. Excess cooling water called blowdown is often disposed of in shallow injection wells. As an alternative to direct contact condensers shell and tube type condensers are sometimes used, as is shown in the schematic below. In this type of plant, the condensed steam does not come into contact with the cooling water, and is disposed of in injection wells. (Mburu, 2009)

When the reservoir is reached by wells, the mixture of water and steam of liquid-dominated systems flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. This change of state for pressure drop, called flash, gives the name to the technology. The original and flashed steam is then separated from the water and used to power a turbine/generator. The liquid phase is separated by the steam and piped to be reinjected back in the subsurface. From this point on the equipment is the same of a dry steam plant, and this plant is called single-flash plant. Depending on the thermodynamic condition of the fluids, it could be economic to obtain a second (sometime even a third) flash from the separated fluid, producing more steam from its boiling. This double-flash steam power type of plant differ from the previous ones for the equipment required for the secondary flash. Flash steam plants have an average size of 30MW_e.(Manzella, 2017)

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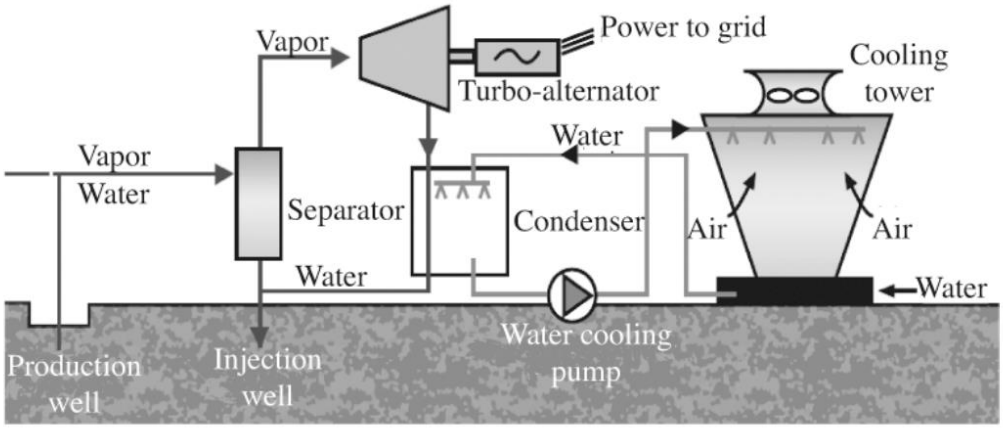


Figure 13. Simplified flow diagram for single flash geothermal power plant (Manzella, 2017)

The double (dual) flash steam power plant has the same working principles as the single flash power plant except that in the former, two separators are used which result in both high- and low-pressure steam flows that run the steam turbine. Double flash geothermal power plants produce a higher power output than single flash geothermal power plants but at a higher cost. The cost of the dual flash is higher than the single flash due to the use of more piping, a second separator, and low- and high-pressure steam turbines. To compensate for the high cost of a double flash power plant, an exergy analysis has been used as an effective tool to maximize the power output and hence improve the efficiency of the double flash power plant. Using two separators leads to the use of a two-stage steam turbine, whereby one stage operates at high pres- sure and the other at low pressure. Dual flash power plants are able to produce up to 15–25 % more power than a single flash power plant as their power production capacity is in the range of 4.7 MW–110 MW. (El Haj Assad et al., 2017)

6.2.3 Binary plants

Generating electricity from low or medium temperature geothermal fluids and the waste hot fluids coming from separators in liquid-dominated geothermal fields has made considerable progress since improvements were made in binary fluid technology. Binary plants (Figure 14) utilize a secondary working fluid, usually an organic fluid (typically n-pentane) with a low boiling point and high vapour pressure at low temperatures as compared to steam. The secondary fluid is operated through a conventional Rankine cycle: the geothermal fluid yields heat to the secondary fluid through heat exchangers, where the secondary fluid is heated and vaporizes. The vapour produced drives a turbine then is cooled and condensed,

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and the cycle begins again. Binary plant technology is a cost-effective and reliable means of converting the energy available from liquid-dominated geothermal fields with temperatures up to 200 °C into electricity. By selecting suitable secondary fluids, binary systems can be designed to utilize geothermal fluids with temperatures well below 100 °C. However, such low temperatures would severely impact the financial viability of projects, depending on their location, their direct use options, and the power tariff offered. (Loksha & Gehringer, 2002)

In reservoirs where temperatures are typically less than 220 °C. but greater than 100 °C binary cycle plants are often utilized. Figure 14 shows the principal elements of this type of plant. The reservoir fluid (either steam or water or both) is passed through a heat exchanger which heats a secondary working fluid (organic) that has a boiling point lower than 100 °C. This is typically an organic fluid such as Isopentane, which is vaporized and is used to drive the turbine. The organic fluid is then condensed similarly to the steam in the flash power plant described above, except that a shell and tube type condenser rather than direct contact is used. The fluid in a binary plant is recycled back to the heat exchanger and forms a closed loop. The cooled reservoir fluid is again reinjected back into the reservoir. (Mburu, 2009)

All five components associated with the basic binary cycle (preheater, evapourator, turbine, condenser and pump) are steady flow devices and can be analysed as steady flow processes. In this analysis, the kinetic and potential energy changes are usually small relative to the work and heat transfer terms and are usually neglected. The heat exchangers do not involve any work, and the pump and the turbine are assumed to be isentropic. The heat exchangers are assumed to be well insulated, and all the heat transfer is between the geothermal fluid and the working fluid. (Fernando et al., 2013)

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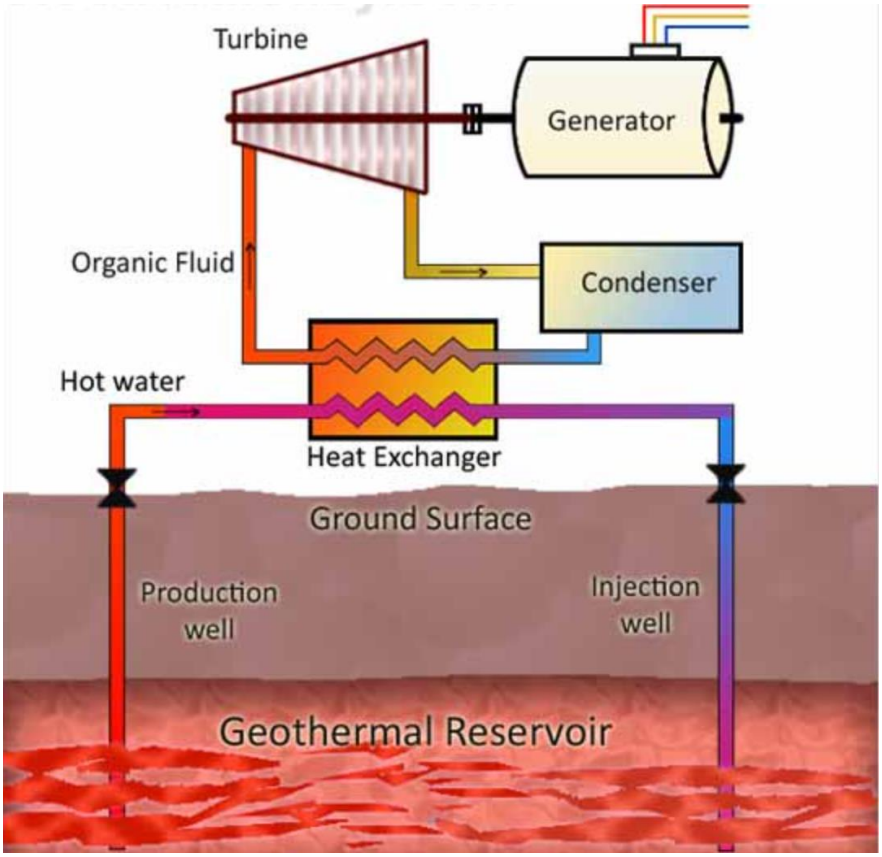


Figure 14. Schematic of the binary system

7 BIOMASS ENERGY

Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass. Typically photosynthesis converts less than 1 % of the available sunlight to stored, chemical energy. The solar energy driving photosynthesis is stored in the chemical bonds of the structural components of biomass. If biomass is processed efficiently, either chemically or biologically, by extracting the energy stored in the chemical bonds and the subsequent 'energy' product combined with oxygen, the carbon is oxidised to produce CO_2 and water. The process is cyclical, as the CO_2 is then available to produce new biomass. (McKendry, 2002)

Biomass refers to all organic matter existing in the biosphere, whether of plant or animal origin, as well as those materials obtained through their natural or artificial transformation. Biofuels derived from biomass include firewood, wood shavings, pellets, some fruit stones such as olives and avocados, as well as nutshells. Of these, cut and chopped firewood is the

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least processed, and is usually burned directly in domestic appliances such as stoves and boilers. The chips come from the crushing of biomass both agricultural and forest, with their size being variable depending on the manufacturing process from which they are derived, or the transformation process that they have undergone. Finally, pellets are the most elaborate biofuel, and consist of small cylinders 6 to 12 mm in diameter and 10 to 30 mm in length that are obtained by pressing biofuels with binders. Pellets are used especially in fuels with a low energy/volume ratio. Fruit stones and seeds, as well as fruit husks, though used to a lesser extent than other standardized fuels such as fuelwood, wood chips and pellets, also represent an increasingly used solid biofuel. Indeed, it has been shown that mango stone, peanut shell and sunflower seed husk have a high energy potential, with a Higher Heating Value (HHV) similar to other commercialized biofuels. This fact, together with the increasing worldwide production of these by-products, makes them especially attractive for thermal energy generation, as well as to reduce CO_2 emissions. Biomass is present in a variety of different materials: wood, sawdust, straw, seed waste, manure, paper waste, household waste, wastewater, etc. (Khan et al., 2015)

7.1 Biomass classification

Based primarily upon the biomass moisture content, the type of biomass selected subsequently dictates the most likely form of the energy conversion process. High moisture content biomass, such as the herbaceous plant sugarcane, lends itself to a ‘wet/aqueous’ conversion process, involving biologically mediated reactions, such as fermentation, while a ‘dry’ biomass such as wood chips, is more economically suited to gasification, pyrolysis or combustion. Aqueous processing is used when the moisture content of the material is such that the energy required for drying would be inordinately large compared to the energy content of the product formed. (McKendry, 2002)

Biomass contains varying amounts of cellulose, hemicellulose, lignin and a small amount of other extractives. Woody plant species are typically characterised by slow growth and are composed of tightly bound fibres, giving a hard external surface, while herbaceous plants are usually perennial, with more loosely bound fibres, indicating a lower proportion of lignin, which binds together the cellulosic fibres: both materials are examples of polysaccharides; long-chain natural polymers. The relative proportions of cellulose and

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lignin is one of the determining factors in identifying the suitability of plant species for subsequent processing as energy crops. (McKendry, 2002)

7.1.1 Wood

Forests and woody crops are a source of energy through the conversion of woody biomass into convenient solid, liquid or gaseous fuels to provide energy for industrial, commercial or domestic use. Already biomass provides about 11% of the world's primary energy supplies. About 55% of the 4 billion m^3 of wood used annually by the world's population is used directly as fuel wood or charcoal to meet daily energy needs for heating and cooking, mainly in developing countries. In addition, large quantities of industrial wood waste are used to generate heat, steam and electric power in developed countries. Bioenergy systems often use biomass that would otherwise be unmerchantable and the conversion of biomass may involve biochemical, thermochemical, or physical/chemical processes. (Bioenergy, 2002)

The woody biomass includes different components, mainly consisting of carbohydrates and lignin. Generally, this category consists of materials such as trees and roots residues, bark and leaves of woody shrubs both above and below ground, which can be converted into energy by direct combustion (or gasification) or through numerous conversion processes. (Tursi, 2019)

Removals consider the volume of all trees, living or dead, that are felled and removed from the forest, other wooded land or other felling sites. They include natural losses that are recovered (i.e. harvested), removals during the year of wood felled during an earlier period, removals of non-stem wood such as stumps and branches (where these are harvested) and removal of trees killed or damaged by natural causes (i.e. natural losses), e.g. fire, windblown, insects and diseases. Roundwood includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other forms (e.g. branches, roots, stumps and burls (where these are harvested)) and wood that is roughly shaped or pointed. Fuelwood is roundwood that will be used as fuel for energy purposes such as cooking, heating, or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel), round or split, and wood that will be used for the production of charcoal (e.g. in pit kilns and portable ovens), wood pellets and other agglomerates. It also includes wood chips to be used for fuel that are

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made directly (i.e. in the forest) from round wood. It excludes wood charcoal, pellets, and other agglomerates. (Camia et al., 2021)

Wood and wood waste are used to generate electricity. Much of the electricity is used by the industries making the waste; it is not distributed by utilities, it is a process called cogeneration. Paper mills and saw mills use much of their waste products to generate steam and electricity for their use. However, since they use so much energy, they need to buy additional electricity from utilities. (*Use of Biomass*, 2016)

7.1.2 Herbaceous (plants/grasses)

Herbaceous dedicated energy crops including switchgrass (Panicum virgatum), Miscanthus (Miscanthus spp.), energycane (Saccharum spp.), and sorghum (Sorghum bicolor) will play an important role in future sustainable bioenergy feedstock production. (Lee et al., 2018)

Generally, herbaceous biomass resources belong to one of the following two main groups, i.e., agricultural residues and energy crops. (Tursi, 2019)

I. Agricultural residues are by-products of food, fibres, or food industries. Some of these by-products are collected for different end- uses, such as animal feed. In any case, these residues are not fully monitored and their availability across different regions and their potential applications as bioenergy are not fully clear.

II. Energy crops, on the other hand are exploited only in the bioenergy sector.

Switchgrass (Panicum virgatum L.) is a native warm-season, perennial grass indigenous to the Central and North American tall grass prairie. Switchgrass is historically found in association with several other important native tall grass prairie plants such as big bluestem, indiangrass, little bluestem, sideoats grama, eastern gamagrass, and various forbs (sunflowers, gayfeather, prairieclover, prairie coneflower). Switchgrass grows well in fi ne to coarse textured soils, and in regions where annual precipitation falls between 15 and 30 inches or more per year. It is an immense biomass producer and can reach heights of 10 feet or more in wetter areas of the country. In general, ecotypic differences are related to local soil and climatic characteristics, with eastern and southern varieties adapted to higher moisture conditions, and western and northern varieties adapted to drier conditions. (Rienhart, 2006)

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Miscanthus is a genus comprising 14–20 species of perennial, C4 grasses native to eastern Asia, N. India and Africa. Miscanthus species are now found and commonly naturalized in North and South America as well as in Europe, Africa, Asia and Europe (Heaton et al., 2010). Similar to switchgrass, giant miscanthus translocates most of the nitrogen, phosphorous, potassium, and other minerals in the aboveground biomass to the rhizomes and root system by late fall but the movement of nitrogen to belowground structures continues even after frost. Even though substantial amounts of biomass are removed each year at harvest, this movement of nutrients into the rhizomes and root system accounts for the ability of the plant to sustain growth year after year with little supplemental fertilizer input. (Williams & Douglas, 2011)

The raw material that enabled man to discover the possibility of the production of sugar was a plant containing sweet juice found in the humid regions of New Guinea which was later called as 'sugarcane', the botanically classified species of Saccharum officinarum. Considering the struggle of food against energy, the energy cane, therefore, should be planted in areas of soil and climate worse than those reserved for the production of food or even conventional sugarcane and also will be more environmental-friendly as it requires less use of fertilizers, herbicides, and pesticides, products that are among the biggest offenders of the environment and human health. Because they produce more stalks, energy cane allows a higher multiplication ratio (1:30 or more, against the 1:10 common rate of sugarcane cultivars), which turns out to be another great economic advantage. (Carvalho-Netto et al., 2014)

7.1.3 Aquatic plant

The term aquatic biomass includes macroalgae, microalgae, and emerging plants. In nature, there are about 55,000 species and over 100,000 strains of brackish water, freshwater, and terrestrial algae. The great advantage of using these simple organisms is their ability to convert sunlight, water, and CO_2 into a wide variety of metabolites and chemicals that end up in algal biomass. (Tursi, 2019)

Aquatic biomass contains mainly macrophytes with long plant stems, meaning its biodegradability and the way it can be handled by biogas plants differ markedly from that of algae. The biomass from these aquatic macrophytes (plants large enough to be seen by the

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naked eye) has swollen in volume. Many of these plants, the so-called neophytes, are not originally domestic, so they are not well regulated by the local ecosystem. Their excessive growth not only upsets the local eco-balance but also impairs the use of rivers and lakes for sports and recreation. (Herbes et al., 2018)

7.1.4 Animal and human waste

Rapidly developing food and agriculture industry generates large amounts of waste (peelings, seeds, mill cakes of juice and beer production, distillery stillage, whey, mushroom substrates, fish waste, slaughter waste and others) which are useful for renewable energy production (Drozyner et al., 2013). Biowaste management has emerged as a standard proactive in developing countries now. International experience shows that energy and nutrients could be recovered from human waste through anaerobic digestion. Biogas digester could produce biogas from human waste (also known as septage) which could be used directly as cooking fuel and indirectly through conversion to electricity. Among the constituents, methane and hydrogen are the two combustible gaseous components of biogas, which are mixed with two inert gases (Carbon Dioxide and Nitrogen) and water vapour. Apart from livestock waste, human waste is also a valuable resource that could provide energy and fertilizer. (Mukherjee & Chakraborty, 2016)

7.2 Production of biomass

7.2.1 Combustion

Combustion (schematic diagram can be seen in Figure 15.) can be applied for biomass feedstocks with water contents up to a maximum of 60 %. Fuel constituents besides C, H, and O are undesired since they are related to pollutant and deposit formation, corrosion, and ash. The most relevant constituents in native biomass are nitrogen as a source of NO_X, and ash components (e.g., K and Cl as a source of KCl) that lead to particulate emissions. Native wood is usually the most favourable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass such as straw, miscanthus, switch grass, etc., have higher contents of N, S, K, Cl, etc., which lead to higher emissions of NO_X and particulates, increased ash, corrosion, and deposits. Biomass combustion is a complex process that consists of consecutive heterogeneous and homogeneous reactions. The main process steps are drying, devolatilization, gasification, char combustion, and gas-phase oxidation. The

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time used for each reaction depends on the fuel size and properties, temperature, and combustion conditions. (Nussbaumer, 2003)

The minimum size of a combustor is primarily determined by the rate at which heat is released from the fuel, i.e. how fast it can be burned, safely and efficiently. Provided that the fuel and oxygen (air) are well-mixed, the combustion rate is largely dependent on the rate of evaporation or devolatilisation of fuel particles which is, in turn, dependent on their surface-to-volume ratios. With liquid fuels, it is comparatively easy to produce small particles, with droplets of diameter typically 10 to 100 micron, by "atomising" the liquid by forcing it through small orifices or jets. With wood, it is possible to produce small particles by grinding larger particles but this process requires specialised and expensive machinery and is wasteful of energy. (James et al., 2003)

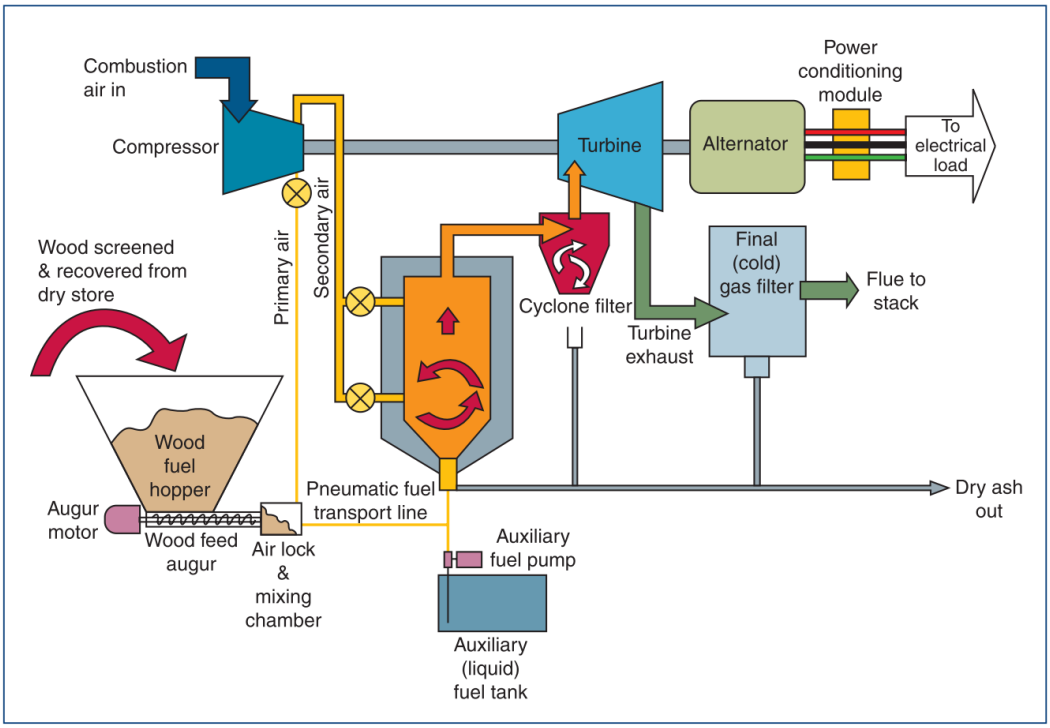


Figure 15. Schematic of the bioturbines system (James et al., 2003)

7.2.2 Gasification

Gasification is a thermochemical process that transforms carbonaceous materials such as biomass into usable fuels or chemicals. The main advantage of employing biomass for gasification is its carbon-neutral nature. It utilizes carbon dioxide during photosynthesis and therefore does not add to carbon inventory, when it is burned. During biomass gasification,

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a mixture of many gases, predominantly carbon monoxide and hydrogen, is released as the output product of the gasification process. The amount and heating value of the product gas are dependent upon many variables including raw material, gasifying agents, operating variables, design of gasifier, and catalysts. Generated syngas can be directly utilized for heating and/or power generation or as a raw material for chemical feedstock production. (Sikarwar & Zhao, 2017)

During the gasification process, biomass undergoes a combination of drying, pyrolysis, combustion, and gasification reactions. Biomass gasification has been developed as a waste valorisation method to obtain products such as syngas, H_2, CH_4, and chemical feedstocks. The conventional gasification technologies include fixed bed (updraft and downdraft), fluidized bed, and entrained flow reactors, as demonstrated in Figure 16. (Farzad et al., 2016)

The gasifier bed can be a fixed bed or a fluidized bed. Fixed bed gasifier can be classified further as updraft (countercurrent) or downdraft (concurrent). In the updraft gasifier, the feed (biomass) is introduced from the top and moves downwards while gasifying agents (air, steam, etc.) are introduced at the bottom of the grate so the product gas moves upwards. In this case, the combustion takes place at the bottom of the bed which is the hottest part of the gasifier and the product gas exits from the top at a lower temperature (around 500 °C). In the fluidized bed gasifier, the feed is introduced at the bottom, which is fluidized using air, nitrogen and/or steam and the product gas then moves upward. There are more particulates in the product gas from this gasifier. Fluidization of the bed enhances the heat transfer to the biomass particle leading to increases in reaction rates and conversion efficiencies. Fluidized beds also are able to tolerate a wide variation in fuel types and their characteristics. A fluidized bed can be either a bubbling fluidized bed or a circulating fluidized bed. (Ajay Kumar et al., 2009)

Gasification takes place at a high temperature in the presence of an oxidizing agent (also called a gasifying agent). Heat is supplied to the gasifier either directly or indirectly which raises the gasification temperature to 600–1000 °C. Oxidizing agents are typically air, steam, nitrogen, carbon dioxide, oxygen or a combination of these. In the presence of an oxidizing agent at high temperature, the large polymeric molecules of biomass decompose into lighter molecules and eventually to permanent gases (CO, H_2, CH_4 and lighter hydrocarbons), ash,

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char, tar and minor contaminants. Char and tar are the result of incomplete conversion of biomass. (Ajay Kumar et al., 2009)

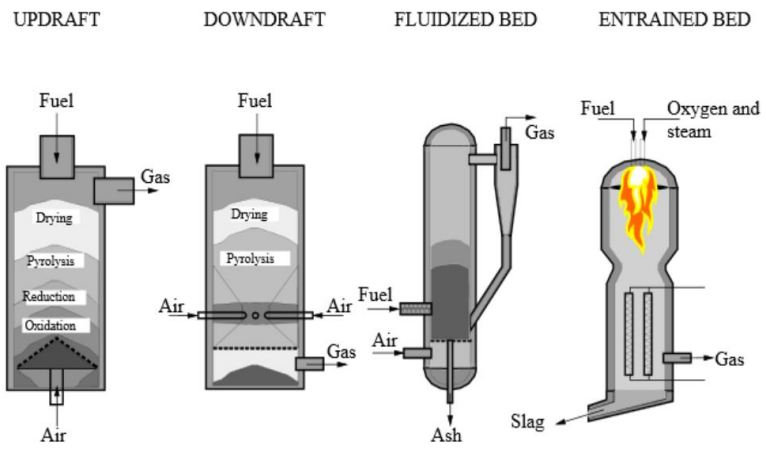


Figure 16. Conventional gastification technologies (Farzad et al., 2016)

7.2.3 Pyrolysis

Slow pyrolysis is conducted for a relatively long time may reach several days. It is usually performed at relatively low temperatures not exceeding 500 °C and slow heating rates, from 0.1 to 2 °C per second. Char and tar represent the major products in slow pyrol- ysis, because the long residence time of gases and other pyrolysis products, in the pyrolytic converter, allows repolymerization/recombination reactions to take place. However, the type of biomass is, also, an important factor for determining the ratios of char, tar, and gas produced. (Fahmy et al., 2020)

Fast pyrolysis is a high-temperature process in which biomass is rapidly heated in the absence of oxygen. As a result, it decomposes to generate mostly vapours and aerosols and some charcoal. Liquid production requires very low vapour residence time to minimise secondary reactions of typically 1 s, although acceptable yields can be obtained at residence times of up to 5 s if the vapour temperature is kept below 400^0C. After cooling and condensation, a dark brown mobile liquid is formed which has a heating value about half that of conven- tional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process that is carefully controlled to give high yields of liquid. Research has shown that maximum liquid yields are obtained with high heating rates, at reaction temperatures around 500 °C and with short vapour residence times to minimise secondary reactions. (Bridgwater et al., 1999)

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7.3 Biogas and biofuel

Biogas is an interesting renewable energy source. Biogas is a natural fuel, not a fossil fuel, and it has a high calorific power value. The lower calorific value (LHV) is in the range 13.720–27.440 kJ Nm^{-3} for methane (CH_4) concentrations of 40 and 80%, respectively. concentrations of 40 and 80%, respectively consortia of microorganisms. A biogas pre-treatment stage is required in order to remove some compounds and/or to adjust the CH_4 concentration. The end-use of the biogas dictates the depuration target. For all applications, it is usually necessary to reduce the hydrogen sulphide (H_2S) concentration. H_2S is a colourless, toxic and flammable gas that has a characteristic odour of rotten eggs. H_2S causes corrosion, damage to equipment and it harms the environment due to the sulphur oxide emissions produced. (Ramírez et al., 2015)

Biogas can be used for all applications designed for natural gas. Not all gas appliances require the same gas standards. There is a considerable difference between the requirements of stationary biogas applications and fuel gas or pipeline quality. Boilers do not have a high gas quality requirement. Gas pressure usually has to be around 8 to 25 Mbar. It is recommended to reduce the H_2S concentrations to values lower than 1.000 ppm which allows maintaining the dew point around 150 °C. Gas engines do have comparable requirements for gas quality as boilers except that the H_2S should be lower to guarantee a reasonable operation time of the engine. Otto engines designed to run on petrol are far more susceptible to hydro- gen sulphide than the more robust diesel engines. The utilisation of biogas as vehicle fuel uses the same engine and vehicle configuration as natural gas. In total there are more than 1 million natural gas vehicles all over the world, this demonstrates that the vehicle configuration is not a problem for use of biogas as vehicle fuel. However, the gas quality demands are strict. With respect to these demands the raw biogas from a digester or a landfill has to be upgraded. (Wellinger & Lindberg, 2000)

Biofuels can be defined as liquid fuels produced from biomass for either transport or burning purposes. They can be produced from agricultural and forest products, and the biodegradable portion of industrial and municipal waste.

Bioethanol is a distilled liquid produced by fermenting sugars from sugar plants and cereal crops (sugarcane, corn, beet, cassava, wheat, sorghum). A second generation of bioethanol

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– lignocellulosic - also includes a range of forestry products such as short rotation coppices and energy grasses. Bioethanol can be used in pure form in specially adapted vehicles or blended with gasoline. Bioethanol can be blended with gasoline in any proportion up to 10 % without the need for engine modification. (Dufey, 2006)

Biodiesel or vegetable oil methyl ester (VOME) is produced from the reaction of vegetable oil with ethanol or bioethanol in the presence of a catalyst to yield mono-alkyl esters and glycerine, which is then removed. Oil is produced from oily crops or trees such as rapeseed, sunflower, soya, palm, coconut or jatropha, but it can also be produced from animal fats, tallow and waste cooking oil. (Dufey, 2006)

8 WIND ENERGY

The kinetic energy in the wind is a promising source of renewable energy with significant potential in many parts of the world. The energy that can be captured by wind turbines is highly dependent on the local average wind speed. Regions that normally present the most attractive potential are located near coasts, inland areas with open terrain or on the edge of bodies of water. Some mountainous areas also have good potential. In spite of these geographical limitations for wind energy project siting, there is ample terrain in most areas of the world to provide a significant portion of the local electricity needs with wind energy projects. (Tong, 2010)

8.1 Properties of wind

Wind varies with the geographical locations (Figure 17), time of day, season, and height above the earth's surface, weather, and local landforms. The understanding of the wind characteristics will help optimize wind turbine design, develop wind measuring techniques, and select wind farm sites. (Tong, 2010)

Wind speed is one of the most critical characteristics of wind power generation. In fact, wind speed varies in both time and space, determined by many factors such as geographic and weather conditions. Because wind speed is a random parameter, measured wind speed data are usually dealt with using statistical methods. For this reason, an accurate determination of the probability distribution of wind speed values is very important in evaluating the wind speed energy potential of a region. Wind energy potential can be determined by wind

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measurements of a certain investigation region depending on years. In the literature, the Weibull distribution is commonly used in practical studies related to wind energy modelling. (ÇELİK & YILMAZ, 2008)

Wind shear is a meteorological phenomenon in which wind increases with the height above the ground. The shaft height of wind measurements and wind energy utilization equipment is often different, it is necessary to know the value of wind speed at different heights. The value of a wind speed measured at a known height is converted into a typical wind speed at the axle height of the recovery plant using a simple power factor:

$$u(z) = u(z)_{10}(\frac{z}{z_{10}})^{\alpha} \quad (2)$$

where u (z) is the desired wind speed at height z and u (z_{10}) is the known wind speed measured at 10 m. The 'α' in the exponent on the one hand it depends on the roughness of the surface, which is α=0. 14 in a completely open area covered with short grass, α≥0.4 in the case of very rough surfaces. On the other hand, from the stability of the atmosphere, where it is α=0. 17 for the unstable air stratification characteristic of the day, while α≥0. 4 is usually associated with the stable and inversion situations characteristic of the evening and night. (Csoknyai et al., 2013)

In addition to air temperature and humidity characteristics, wind speed near the surface is influenced by three factors: surface roughness (plants, trees), obstacles (buildings, walls) and topography. Behind the obstacles, the movement of the air becomes a vortex, turbulent. The vortices can rise vertically up to three times the height of the obstacle and can be detected horizontally at a distance of twenty times the height behind the obstacle.

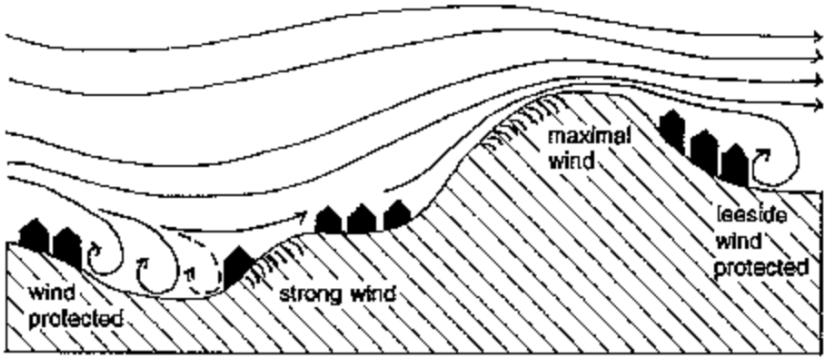


Figure 17. Way of the wind behind the obstacle (Gut, 1993)

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However, in order to obtain optimum wind turbine performance, the location of the wind turbine has to be placed as far as 10 times the height of the obstacle as a minimum allowable distance, or installation should be made in a taller tower which will surely have an increase on the total cost of the wind turbine. (Didane et al., 2016)

Wind speed persistence is another important factor to take into account when dealing with wind energy, since it offers useful information on the general characteristics of the wind at a given site. The wind speed persistence is defined as, a measure of the mean wind speed duration over a given period of time at any location. Properties of wind persistence towards the seasonal variations are required since the energy output of a wind turbine depends significantly on the velocity distribution of the site. Due to these different velocity distributions, a completely different energy output would be obtained, if a wind turbine is installed in two sites with the same average wind speed. Moreover, if two wind turbines with the same output rating are installed at the same site, but different in the cut-in, rated and cut-out speeds, they may generate varying energy output as well. (Didane et al., 2016)

The wind power energy can define as:

$$E = \frac{P}{t} = \frac{1}{2} A \rho_a v^3 \quad (3)$$

with E: kinetic energy, A:area, ρ_a: specific density of the air, v: wind velocity. In this context, the energy content of wind depends on the density of the air. This is often affected by the air thermometer and humidity. The warmer the air, or even the higher its humidity, the lower its density. (Wagner, 2017)

8.2 Wind turbines

A wind turbine, as described in this book, is a machine that converts the power in the wind into electricity. This is in contrast to a ‘windmill’, which is a machine that converts the wind’s power into mechanical power. As electricity generators, wind turbines are connected to some electrical network. These networks include battery-charging circuits, residential-scale power systems, isolated or island networks, and large utility grids. In terms of total numbers, the most frequently found wind turbines are actually quite small – on the order of 10 kW or less. In terms of total generating capacity, the turbines that make up the majority

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of the capacity are, in general, rather large – in the range of 1.5 to 5 MW. (Manwell et al., 2009).



Figure 18. Types of wind turbines (Al-Shemmeri, 2010)

There are mainly two types of wind turbine: horizontal axis and vertical axis. The horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT) are classified or differentiated by the axis of rotation of the rotor shafts. The different types of turbines can be seen in Figure 18.

The most common design of wind turbines and the type which is the primary focus is the horizontal axis wind turbine (HAWT) in Figure 19. The major components of modern wind energy systems typically consist of the following:

- Rotor, with 2 or 3 blades, which converts the energy in the wind into mechanical energy onto the rotor shaft;
- Gearbox to match the slowly turning rotor shaft to the electric generator;
- The tall tower supports the rotor high above the ground to capture the higher wind speeds;
- A solid foundation to prevent the wind turbine from blowing over in high winds and/or icing conditions;
- Control system to start and stop the wind turbine and to monitor the proper operation of the machinery.

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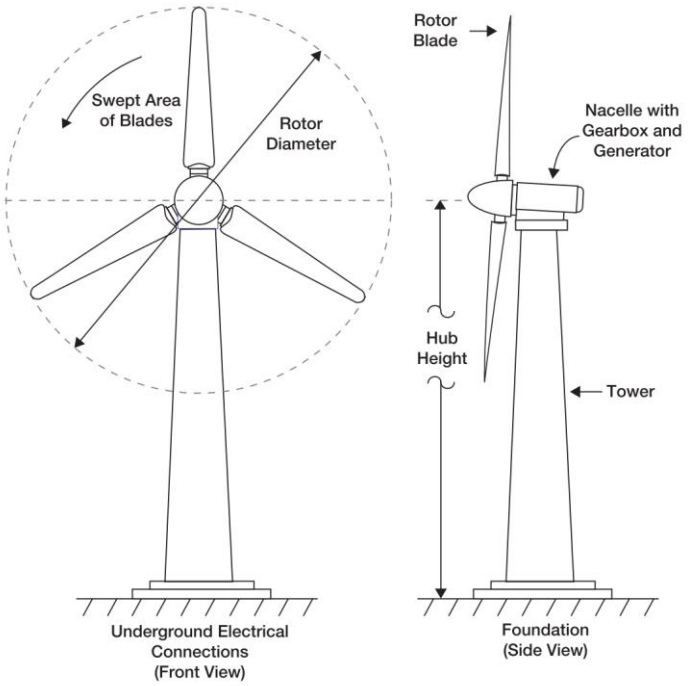


Figure 19. Schematic image of HAWT (Canada, 2004)

Based on the configuration of the wind rotor concerning the wind flowing direction, the horizontal-axis wind turbines can be further classified as upwind and downwind wind turbines (Figure 20). The majority of horizontal-axis wind turbines being used today are upwind turbines, in which the wind rotors face the wind. The main advantage of upwind designs is to avoid the distortion of the flow field as the wind passes through the wind tower and nacelle. However, because of the influence of the distorted unstable wakes behind the tower and nacelle, the wind power output generated from a downwind turbine fluctuates greatly. (Manwell et al., 2009; Tong, 2010)

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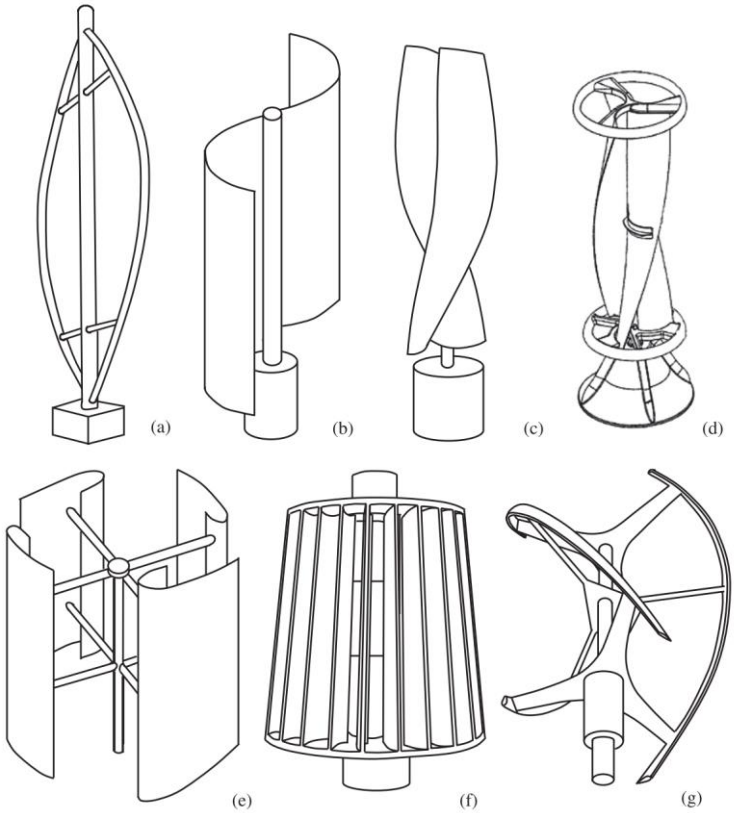


Figure 20. Types of VAWT a) Darrius, b) Savonius, c) Solarwind, d) Helical, e) Noguchi, f) Maglev, g) Cochrane (Tong, 2010)

8.3 Application of wind turbines

A variable speed wind turbine control method within a wide range has the following advantage and disadvantage compared to those for narrow range speed control. The advantage of a variable speed wind turbine control method in a wind range is that it allows for very low speed to obtain higher energy from the wind. On the other hand, the disadvantage is that the power converter must be rated to 100 % of the nominal generation power. The main objective of power converters to be used for wind energy applications is to handle the energy captured from the wind and the injection of this energy into the grid. The characteristics of the generator to be connected to the grid and where to inject the electric energy are decisive when designing the power converter. To attain this design, it is necessary to consider the type of semiconductor to be used, components and subsystems. (Carrasco et al., 2011)

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8.3.1 Onshore wind farms

Large wind turbines are generally placed in groups to form wind farms, also known as wind parks. These may contain anything from two or three individual machines to more than a hundred machines producing hundreds of megawatts. Gigawatt onshore wind farms are firmly in prospect for the coming decade, especially in countries with large, remote, windswept areas of limited landscape value. Repeated over a wind farm as a whole, such effects give rise to array of losses that reduce annual energy production. There are two spacings to be considered: downwind and crosswind. Generous downwind spacing minimises interference by a turbine's wake on its downstream neighbours and, although there are no hard and fast rules, a value between 8 and 10 rotor diameters is often recommended to limit total array losses to below 10 %. If we take a 2 MW HAWT with a rotor diameter of around 90 meters as typical of large, modern onshore wind farms, this implies a downwind spacing of around 800 meters. The need for crosswind spacing is less clear. On the face of it a spacing of just over one rotor diameter might seem enough to avoid expensive arguments between adjacent machines! But the situation is complicated because most sites do not have a single, dominant, prevailing wind direction; turbines use their yaw motors to face different wind directions at different times of day and in different seasons of the year. Clearly, a 90° change of wind direction converts crosswind into downwind, and downwind into crosswind. In practice a spacing of about 5 rotor diameters is often chosen for the nominal crosswind direction which, combined with a downwind spacing of 800 metres, implies a land area of about 0.4 km 2 per 2 MW turbine. However the actual value depends on turbine size and the wind regime at a particular site. (Lynn, 2012)

8.3.2 Offshore wind farms

Offshore wind power or offshore wind energy is the deployment of wind farms sited in bodies of water. Higher wind speeds are available offshore compared to on land, so offshore farms' electricity generation is higher per amount of capacity installed. Onshore wind energy is currently near the development limit in some countries due to visual and noise impact constraints that make it increasingly difficult to find appropriate sites for future growth. Offshore wind energy developments have greatly reduced visual impacts, less turbulence, and lower noise constraints allowing higher turbine rotor speeds and larger turbines.

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Moreover, offshore wind energy possesses several properties enabling significant cost reduction such as higher full-load hours per year, longer lifetimes and higher electricity production. Offshore wind power plants can produce up to 50 % more electricity than their onshore cousins, due to higher and steadier wind speeds. (Giebel & Hasager, 2016)

Offshore wind speeds are relatively uniform with lower variations and turbulence, which reduces the wear of the offshore wind turbine components and consequently increases their lifetime. Moreover, due to the lower surface resistance, wind speeds over offshore sea surfaces are typically 20 % higher than those over nearby lands, which is proportional to a 45 – 60 % increase in the power captured. Thanks to steadier ocean climates, the full-load hours per year of offshore wind turbines are higher than those of the onshore ones. Also, the wake effects in offshore wind farms are smaller at higher wind speed which offers another significant benefit in allowing a higher density of wind turbines. (Giebel & Hasager, 2016)

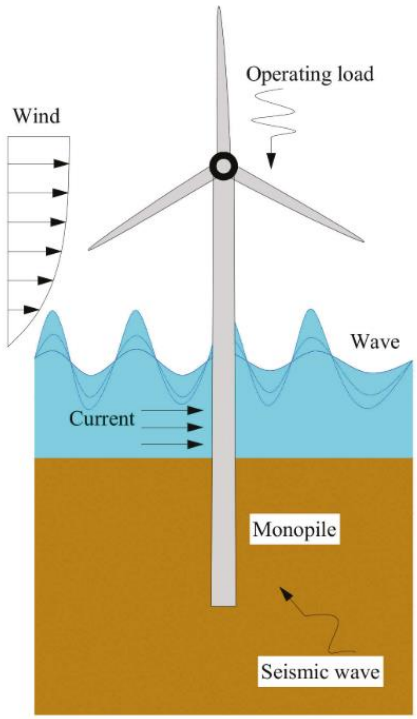


Figure 21. Front size of offshore wind turbine (Esteban et al., 2020)

Offshore wind turbines are typical high-rise and flexible structures with low natural frequencies, which can be very close to the frequencies of offshore dynamic loads such as winds, waves, currents and seismic waves (Figure 21). Accordingly, vibration characteristics

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or dynamic impedances of pile foundations are of great concern to designers. (Esteban et al., 2020)

9 HEAT PUMP SYSTEMS

A heat pump is a device that extracts thermal energy from a low-temperature source (such as the outside air or ground) and transfers it to a higher-temperature sink (such as the heated indoors of a building). For instance, a household refrigerator may be thought of as a heat pump. While cooling the food products, it takes thermal energy from them. The outside coil, on the other hand, transfers thermal energy to the ambient air. The food acts as the source, the air in the kitchen as the sink. (Goldschmidt, 1984)

A heat pump usually extracts energy from the environment. Air, groundwater, the earth or river water are common. If the energy is extracted from the ground, this is known as shallow geothermal energy. An energy source temperature that is as high and constant as possible is the key to high efficiency. The temperature must not drop off too much in winter, when the most heating power has to be provided. For groundwater and the ground, the heat exchangers have to be very large in order to avoid any local subcooling. When choosing the heat source, factors such as investment cost, efficiency, availability and obtaining permission have to be weighed against each other. Using low-order waste heat such as exhaust air or cooling water is particularly cost-effective. (Web, 2021b)

Heat pumps can operate at outdoor temperatures between about -20 to -25 °C and 25 °C. They typically cover a temperature range of about 50-70 K, depending on the refrigerant used and the system design. Larger temperature gaps can be overcome by a staged design combining two compressors, typically with different refrigerants, that lift the temperature in two stages from outdoor temperature to useful temperature level. In this case, the heat provided by the first heat pump unit is the energy source for the second refrigeration process.

Industrial heat pumps are most often bespoke systems designed to cater to specific needs. Depending on the system design and refrigerant used, a temperature difference of about 70 K is covered with a maximum useful heat of around 150 to 170 °C. The majority of applications is providing heating at 30 – 55 °C and hot water at 55 to 65 °C. The latter can be increased by deploying CO_2 heat pumps that efficiently provide hot water at 90 °C. One of the

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challenges in industrial heat pump design is the selection of components that can operate at higher temperatures on the side of the energy source. (Web, 2018)

There are two common types of heat pumps: air-source heat pumps (ASHP) and geothermal heat pumps (GHPs). Either one can keep your home warm in the winter and cool in the summer.

9.1 Air source heat pump

The ASHP units can get heat from the air even when the temperature is as low as -20 °C. The ASHP unit exploits the physical property of a volatile evaporating and condensing fluid, i.e. refrigerant or working fluid. The heat from the outside air is absorbed at low temperatures by the ASHP refrigerant and released when it is condensed. The compressor of the unit compresses the working fluid to make it hotter on the side to be heated. Electricity is required by the unit to drive the compressor. And the hot and highly pressurized vapour is cooled down in a heat exchanger, i.e. a condenser, until it condenses into high pressure and moderate-temperature liquid. The condensed refrigerant then passes through a pressure-lowering device, i.e. an expansion valve or a metering device. The low-pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat again. The circulation is repeated. A simple circulation diagram of the ASHP unit is shown in Figure 22. (“Air-Source Heat Pumps,” 2001; Zhou et al., 2018)

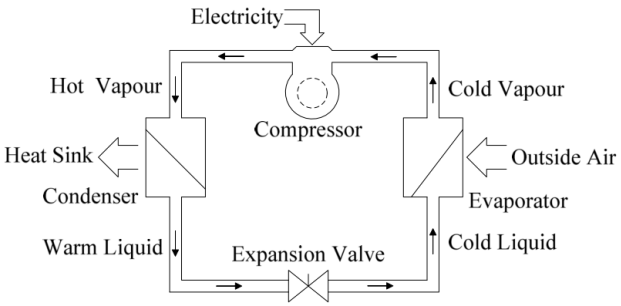


Figure 22. The circulation system of an ASHP unit (Zhou et al., 2018)

The compressor speed of the fixed-speed ASHP unit is constant. Normally the ASHP unit operates intermittently in the on or off mode to adjust the heating power to the temperature required in the house with a fixed speed. If the temperature reaches the set value, the compressor stops working. Otherwise, it starts working and adjusts the temperature by constantly starting and stopping the compressor. When a variable-speed compressor is used,

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the ASHP unit can advantage of partial loads from the oversized heat exchangers according to the load and thus increasing its efficiency.

9.2 Geothermal heat pump

Geothermal heat pumps are viable nationwide. They use the Earth as a heat sink in the summer and a heat source in the winter, and therefore rely on the relative warmth of the earth for their heating and cooling production. Through a system of underground (or underwater) pipes, they transfer heat from the warmer earth or water source to the building in the winter, and take the heat from the building in the summer and discharge it into the cooler ground. Therefore, GHPs don't create heat; they move it from one area to another. ("Geothermal Heat Pumps," 1998)

The GSHP system utilizes the shallow earth surface, 1-100 m, to harness its heat energy in order to meet human thermal comfort needs. The system operates basically by relying on the temperature difference between the ground and the air. For example in winter, the ground temperature is warmer than the air temperature, while in summer, the ground temperature is cooler. These temperature differences allow the transfer of heat energy in achieving building thermal demand throughout the year. (Singh et al., 2019)

The main parameter used in describing the system is based on the ratio of the amount of useful energy that can be obtained to the input power used to run the system. This parameter is commonly referred to as the coefficient of performance (COP) of the system. It is defined as:

$$COP = \frac{energy\ output\ after\ heat\ pump\ (kW)}{energy\ input\ for\ operation\ (kW)} \quad (4)$$

During heating operation, the system should aim for a COP value of 4 and 6 in cooling operation. (Singh et al., 2019)

10 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service. Environmental inputs and outputs refer to the demand for

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natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transport routes used at, or needed for, raw materials extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment. LCA approaches are generally guided by standards but a professional code of practice has also been developed. (Hoogervorst et al., 2004)

10.1 Methodology of LCA

A typical LCA study consists of the following stages (Figure 23): (Jacquemin et al., 2012; Jensen et al., 1997)

1. Goal and scope definition. This step consists of drawing the studied system boundaries to ensure that no relevant part is omitted.

2. A detailed life cycle inventory (LCI) analysis, with a compilation of data both about energy and resource use and on emissions to the environment, throughout the life cycle. Often based on a mass and energy balance, this step compiles and quantifies inputs (raw materials and energy) and outputs (wastes and other emissions) relative to the system throughout its life cycle.

3. An assessment of the potential impacts associated with the identified forms of resource use and environmental emissions. This step consists of aggregating and identifying the environmental burdens quantified in the inventory analysis, into environmental impact categories such as climate change, stratospheric ozone depletion, tropospheric ozone creation (smog), eutrophication, acidification, toxicological stress on human health and ecosystems, resource depletion, water use, land use, noise and others. Moving from inventory to impact assessment is one of the most difficult steps of LCA, largely discussed in the literature and implying many inconsistencies between LCA practitioners.

4. The interpretation of the results from the previous phases of the study concerning the objectives of the study. This last part allows conclusions to be drawn concerning environmental damages generated by the system, using results provided by the impact assessment step.

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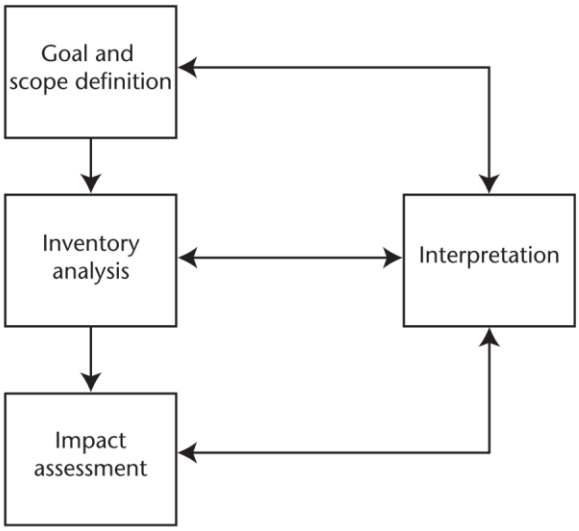


Figure 23. Outline of generic life cycle assessment (LCA) process (Gnansounou, 2017)

10.2 Application of LCA

Product development is an extensive and complex process consisting of several phases (e.g. planning, conceptual design, embodiment design and detailed design) and iterations between them. It is carried out by interdisciplinary project teams which, when it comes to the design of products for mass production in large-scale industry, may include hundreds or even thousands of members. The process is characterised by time pressures and the constant need for trade-offs between competing issues such as performance, shelf-life, aesthetics, the need for and ease of maintenance, production costs, production facilities, market constraints and legal requirements. Environmental issues need to be considered alongside all of these other issues. (Tillman, 2010)

In particular, the classification adopted by them has been followed to clarify the type of tools that the designer may already use, and to propose a new tool overcomes limits and gaps of the others. Bovea and Belis (2011) have been classified the tools considering the follow criteria: (Bovea & Pérez-Belis, 2012; Luglietti et al., 2016).

- methods applied for the environmental assessment;
- product requirements that need to be integrated in addition to the environmental one (multi-criteria approach);

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- whether the tool has a life cycle perspective (i.e. it considers all the stages of the life cycle of a product);
- the nature of the results (qualitative or quantitative);
- the stages of the conceptual design process where the tool can be applied;
- the methodology is taken as a basis for such integration

LCA methods can be used to analyze energy systems. In principle, the scope for such analyses can range from the analysis of individual energy production technologies to, ultimately, the analysis of complete national energy systems. A convenient functional unit for energy supply systems is the amount of energy produced. For electric power systems, the kilowatt-hour of electricity produced is an example. However, an account must be made of various factors such as operation times (load factor), time patterns in the supply of energy (especially for solar and wind energy), and capacities. These factors make that kilowatt-hour of electricity produced from one source (e.g., coal, natural gas, wind, solar, nuclear) not fully comparable to a kilowatt-hour produced from another source. So long as the total power generation mix satisfies certain demands regarding, for example, reliability, comparisons on a kilowatt-hour basis can be made. When high levels of intermittent supply sources (e.g., solar, wind) require the installation of storage options, these should be included in the LCA. For fossil fuel-based energy systems, important environmental impacts will result from the energy conversion processes (mostly combustion) and the waste and flue gas treatment directly related to these conversion processes. In cases such as nuclear power, solar power, and wind power, the environmental profile of the materials used will largely determine the total environmental profile. (Nieuwlaar, 2013)

Life cycle assessment has also been used to assess different energy systems from an environmental viewpoint. LCA aims to account for all material flows, direct or indirect, induced by an energy cycle. Since induced flows occur at many geographically different points under a variety of different conditions, it is not practicable to model the fate of all emissions. Usually, only the total emissions of greenhouse gases or other pollutants are evaluated. This method is also called life cycle emissions assessment. This approach can be justified for greenhouse gases and other pollutants with long residence times in the

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atmosphere. For sulphur dioxide, nitrogen oxides, ozone and particulates, however, this approach is unsatisfactory. (Hall et al., 2004)

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1. INTRODUCTION TO THE PROCESS DED-ARC

Additive processes are a way to manufacture objects obtained from Computer Aided Design (CAD) models. The first step of the whole process is the creation of a 3D model of the desired geometry. After the first task is completed, it is necessary to divide the wanted structure in a set of layers, which will then be produced one by one forming the final piece. [1] This strategy differs from subtractive manufacturing because, as the name indicates, there will be an addition instead of a subtraction of material, heavily influencing the amount of material that is used as there will be a very reduced amount of waste in comparison. Additive manufacturing (AM) includes many different technologies for the creation of a part, such as binder jetting, powder bed fusion, sheet lamination, VAT Photopolymerisation, material extrusion, material jetting, or directed energy deposition (DED), which will be the cornerstone of our work.

2. DED-ARC MANUFACTURING STRATEGY

2.1 DED-Arc variants

In respect to DED-Arc variants, it can be divided in three main types depending on the welding technology used, according to the equipment used to generate the arc, namely, TIG, MIG-MAG and Plasma Welding. TIG refers to Tungsten Inert Gas, also known as GTAW (Gas Tungsten Arc Welding), which uses a non-consumable tungsten electrode to establish an electric arc with the working piece, melting both base material and addition material. Through the torch flows an inert gas, which protects the melted material from the weld pool from atmospheric contamination. This process is, usually, associated with good quality and mechanical properties of the weld bead, however, it is more difficult to automate than MIG and allows lower deposition rates than the other two welding processes. MIG-MAG refers to Metal Inert/Active Gas, also known as GMAW (Gas Metal Arc Welding), in which the arc is established between the consumable electrode and the workpiece. It can use inert, active or mixtures of both gases, depending on material, application, or budget of the build, being inert gases the most expensive option. Depending on variants, such as CMT and Tandem MIG, and its transfer modes, different bead qualities and deposition rates can be achieved. CMT arises as a free spatter, low heat input and very precise variant, suitable for high quality builds. Tandem MIG reveals itself very useful for intermetallic construction, as it will be discussed later in this document, in the deposition rate subsection. This method is the easiest to automate since the wire is fed through the torch, as it is a consumable electrode.

Plasma Arc Welding, PAW, is similar to TIG since it also uses a tungsten electrode to establish the arc, still, in this process, the arc is constricted to pass through a nozzle,

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causing separation of the ionized gas (plasma) from the rest of the shielding gas, increasing its velocity and energy density and reducing the arc's cross-sectional area, thus increasing penetration keeping a low heat input. As in TIG, the wire must be fed separately which complicates automatization.

WAAM	Energy source	Features
GTAW-based	GTAW	Non-consumable electrode; Separate wire feed process; Typical deposition rate: 1-2 kg/hour; Wire and torch rotation are needed;
GMAW-based	GMAW	Consumable wire electrode; Typical deposition rate 3-4 kg/hour; Poor arc stability, spatter;
	Cold metal transfer (CMT)	Reciprocating consumable wire electrode; Typical deposition rate: 2-3 kg/hour; Low heat input process with zero spatter, high process tolerance;
	Tandem GMAW	Two consumable wires electrodes; Typical deposition: 6-8 kg/hour; Easy mixing to control composition for intermetallic materials manufacturing ;
PAW-based	Plasma	Non-consumable electrode; Separate wire feed process; Typical deposition rate 2-4 kg/hour; Wire and torch rotation are needed;

Figure 1: Comparison of the three DED-Arc main types [2]

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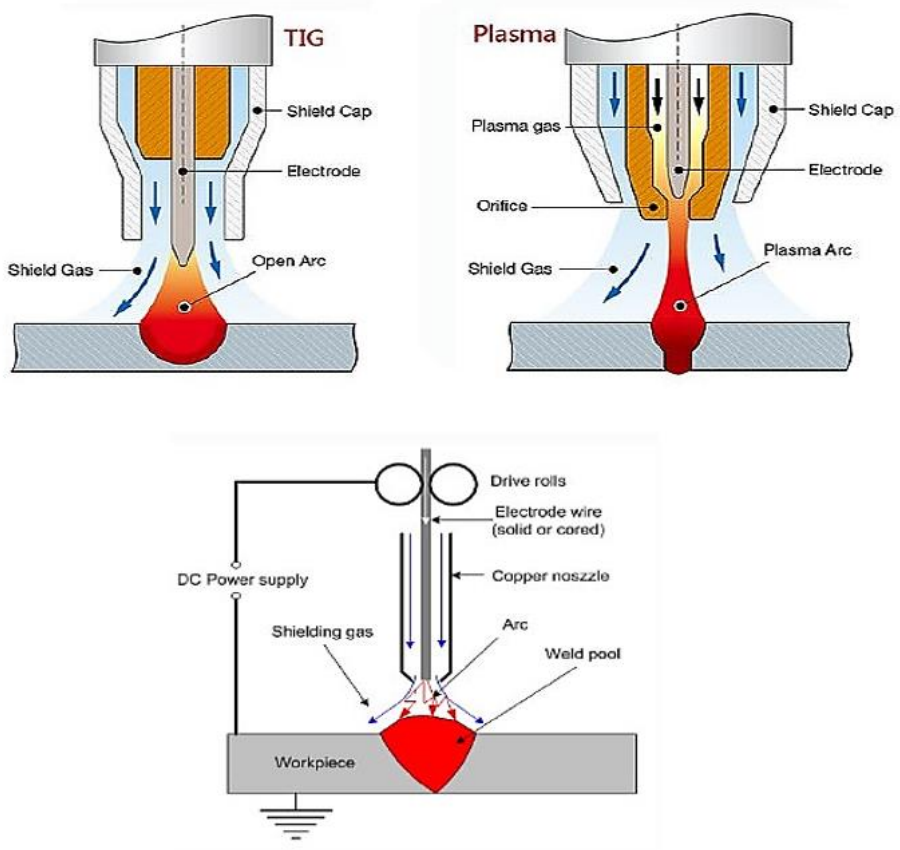


Figure 2: TIG, MIG-MAG and Plasma illustrations [3]

2.2 Fixturing

Fixturing refers to the procedure of securing an object so a manufacturing process can be carried out. This is usually achieved with fixtures. These devices are required to be robust in order to sustain the vibrations and to hold the weight of the workpiece. It is important to have a fixture that suits both the workbase and the worktable. A good fixture will ensure that the established tolerances are met, while providing a stable and rapid procedure, in a way that allows for mass manufacturing, with high quality products.

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2.2 Positioning and Nesting

Nesting is defined as the process of building a layout for the manufacturing of a set of parts in an efficient way. In subtractive manufacturing this is often achieved by laying out the cutting patterns on the workspace, which can be, in most cases, sheet metal, in order to minimize the raw material waste.

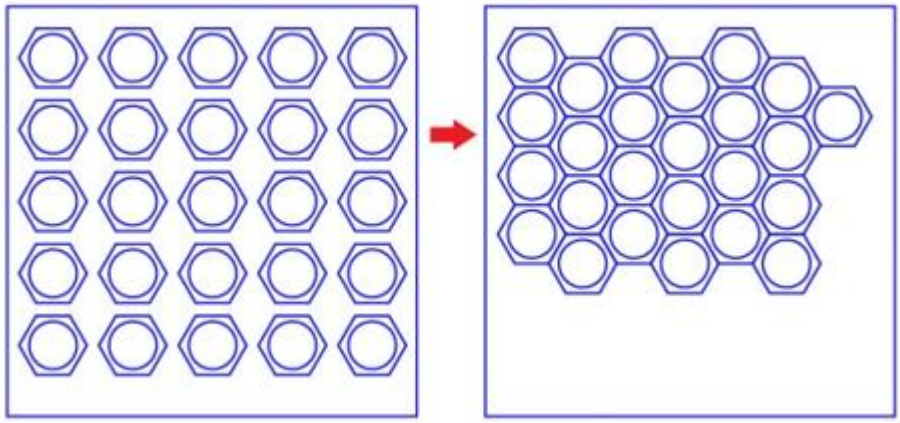


Figure 3: Nesting in subtractive manufacturing [4]

The same principle can be applied for additive manufacturing. This entails in arranging as many parts as possible into the workspace, obtaining a high part density while still ensuring a high-quality production. Nesting in AM allows an optimization of the process by minimizing the tool movements, when it is not producing any parts, and maximizing the productivity of each building session. To achieve effective nesting, it is important to consider that 3D parts usually consist of irregular shapes, whose cross sections may change with height. This can lead to interference between adjacent parts if not done properly [5]. Nesting can be done manually or automatically. Manual nesting is ideal for simple designs with shared lines, additionally, it is also free. Nevertheless, it can be time consuming, and it is not the indicated process for complex designs, as it may lead to human error resulting in having to repeat some procedures. n order to facilitate the nesting process, there are several software that offer the capacity of automated nesting, through computer algorithms, leading, in general, to the saving of time, money and material. As an example, we can look at the Materialise Magics Sinter Module, which provides a fast 3D nesting system. The following image illustrates how this software rearranges the parts

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for additive manufacturing. In DED-Arc, the process will not look like this, since there is no powder bed to support the pieces.

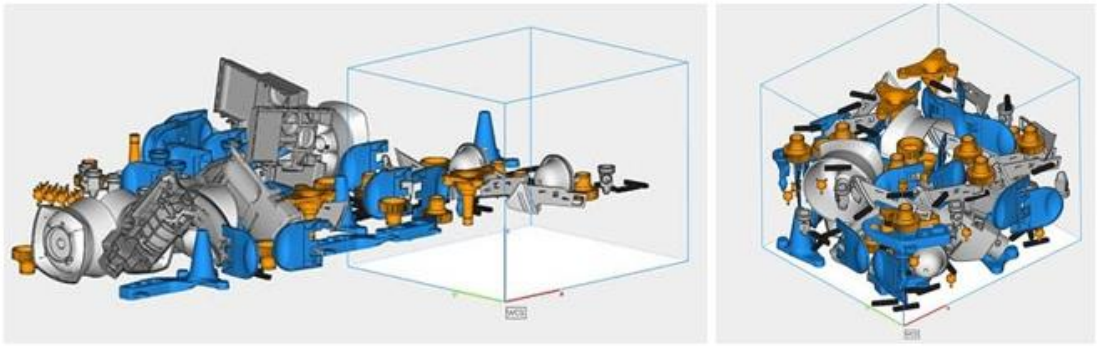


Figure 4: 3D Nesting in Materialise Magics Sinter Module [5]

Considering that DED-Arc is usually used for the manufacturing of large-scale metal parts, as opposed to Powder Bed Fusion, for example, nesting will not play such an important role in the production process, as it would in other cases.

2.3 Layer Thickness

Additive manufacturing processes are achieved with a layer-by-layer method. Each successive layer can be characterized by its height, which can also be referred to as the layer thickness. Although several different values can be chosen for this parameter, it is important to keep in mind that it will affect the quality of the product. For example, the larger the layer thickness, the lower the vertical resolution of the build, leading to the staircase effect, as shown in Figure 5. As observed, the smoothness of the surface is a direct consequence of the layer thickness. The more noticeable the staircase effect, the lower the smoothness.

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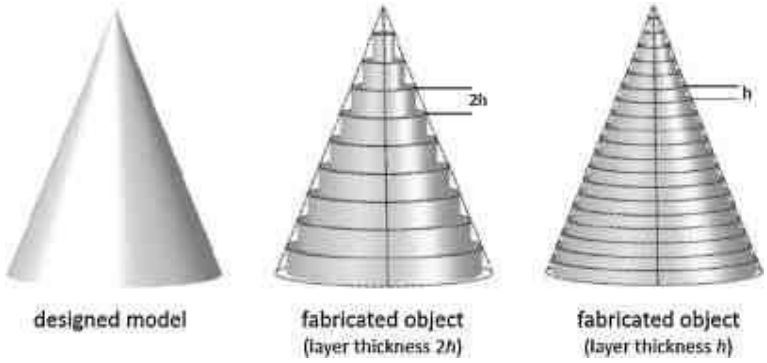


Figure 5: Staircase effect [6]

Another result of this variable is the printing time. Since a lower layer thickness will require more passes to finish the product, this will lead to a longer printing time. Therefore, layer thickness is one of the most important parameters to consider when it comes to planning DED-Arc strategy. Its choice will vary depending on the future application of the built component as well as the clients' demands. Sometimes this will result in a compromise between the quality and the production time. Usually, in DED-Arc processes, layers have a thickness of 1-2 mm.

2.5 Interaction of Layers

The interaction between layers has a big influence in the overall quality of the finished product. Through different printing directions and several heat exchanges among layers, we obtain distinct characteristics and mechanical properties.
Regarded the use of the following parameters: printing direction, "travel speed, wire feed rate, current, and argon flow rate"; in DED-Arc and its effects on "bead shape and size, bead roughness, oxidation levels, melt through depth, and the microstructure" [7].
Concerning the printing directions, the experiments made showed that there were no significant differences between depositions made in the same direction and in alternating directions. Another important observation was that, although the different parameters, the layers were able to achieve complete fusion between themselves without oxidation, which was concluded by the lack of interface between the layers. Therefore, we can conclude through these experiments that, even though there were changes among parameters, the welds obtained still had good mechanical properties indicating that the parameters listed above may not have the most influence when it comes to interaction of layers.

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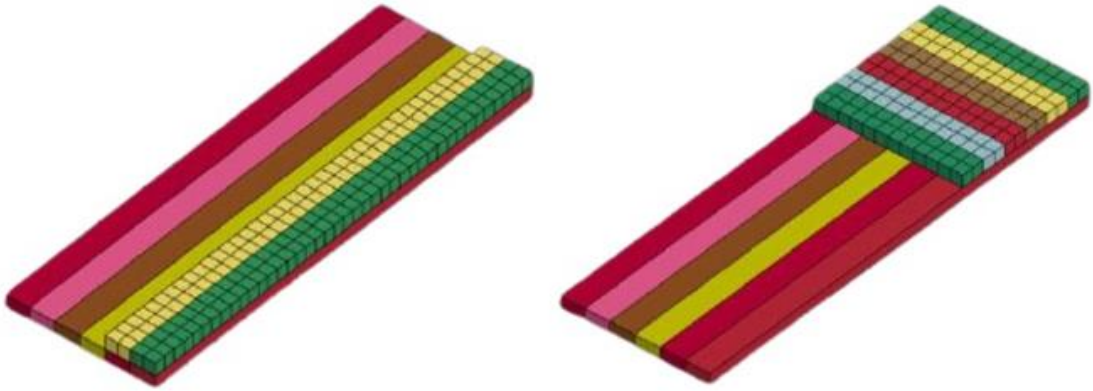


Figure 6: Printing directions [8]

Evaluating the effects of the thermal profile during the deposition of material along with the processes used to overcome the issues, one of the biggest challenges in the DED-Arc process is the variation of temperature between layers. Differences of temperature in thermal profiles can lead to distinct microstructures and, consequently, to a non-homogeneous structure. Throughout the material deposition process, the geometry of the build will suffer many changes which lead to variations of heat dissipation, and consequently, variations in the thermal profile.

This phenomenon is exemplified in three different situations. In (a), after the deposition of small amounts of material, as usually happens in the first pass, most of the heat is transferred to the substrate through conduction with a small portion of heat being transferred to the surroundings through convection and radiation. After adding a few more layers, obtaining a thin wall, as shown in (b), the heat dissipation will be opposite to the previous case, with most of the heat being dissipated to the surroundings by convection and radiation. In the last example, (c), we have a situation of multiple layers deposited adjacent to each other, resulting in additional heat transfer through conduction to the adjacent weld beads [9].

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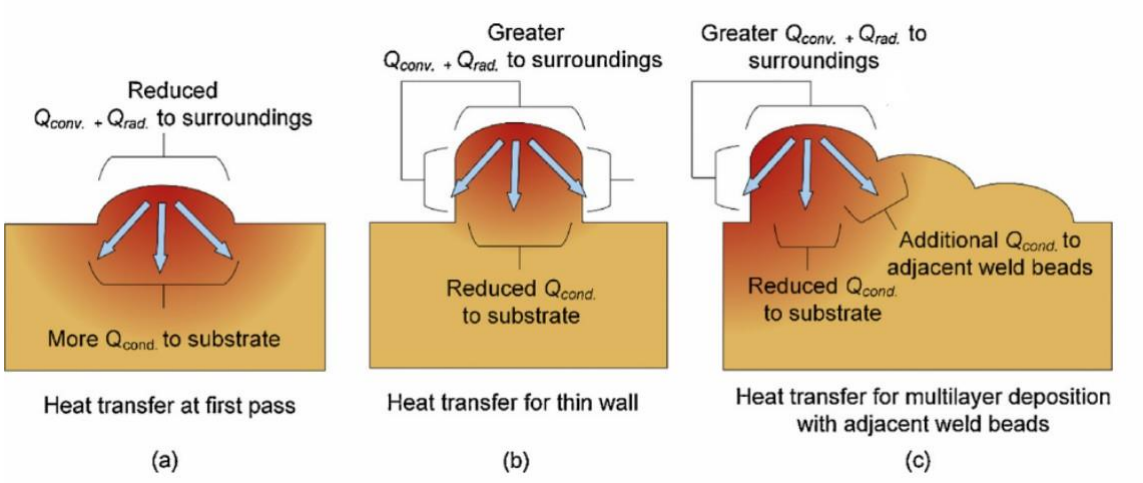


Figure 7: Heat Dissipation [9]

With the addition of subsequent layers, there is an accumulation of heat due to both the preheat of the preceding layer and the loss of effectiveness in heat dissipation. This will result in changes in dimension and in microstructure. In case (c), it becomes more difficult to obtain steady state deposition due to high amounts of variation of heat transfer in the welding direction. Both these situations will affect the properties of the structure in distinct locations, creating a heterogeneous material.

2.6 Gas System

Protection gases are important to remove atmospheric gasses from contact to the weld pool and the weld bead during its formation, thus reducing oxidation and porosity and preventing the inclusion of Nitrogen and Hydrogen, which are detrimental to the mechanical properties of the weld bead. Additionally, in arc welding, shielding gases also influence arc stability, heat transfer, penetration, and the metal transfer mode. Higher stability is related with lower ionization energy and thermal conductivity, usually associated with inert gases, opposite to heat transfer which is associated with greater thermal conductivity. Therefore, a balance is required depending on the application needs. A technique called gas modulation uses two different gases, supplied intermittently, to benefit from the good qualities of both. An excessive air flow can also be prejudicial in terms of penetration and porosity due to the creation of turbulent flow that drags gases from the atmosphere into the welding zone [9].

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Some materials, and some applications, are highly sensitive to the contaminations referred above, such as maraging steel or some Titanium alloys as Ti-6Al-4V, used in aerospace and chemistry industries. In the case of reactive metals, it is important that the components are manufactured in a vacuum or in an inert chamber. Thereby, more complex protection systems are used, for example inert chambers and flexible tents.



Figure 8: DED-Arc maraging steel layers built without iner chamber (torch shielding only) with side degradation due to oxidation [9]

The three types of environment that are most used in DED-Arc processes are the following:

- **Local Shielding** - This type of environment is used mainly in the production of large components where the quality of the part can be lower. This method is not as effective as the others since it is an environment where there could be more impurities, by occasional contact with atmospheric air. However, it has the advantage of being much more economical and practical than the others since it does not need a chamber.
- **Inert Chamber** - The use of inert gas chambers is important in some cases, to create a high-quality environment in a closed system, for some materials that require it. However it has the disadvantage of the high costs that is required to acquire the chamber and the associated components, in addition the preparation of time it takes.
- **Vacuum** - In this type of environment is where the components formed have the highest quality, however it has some disadvantages such as the high cost of the vacuum chamber, the energy wasted to generate the vacuum and support its forces.

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2.7 Wire Feeding System

The wire feeding system is a group of components that control the supply of addition material to the weld pool. This system regulates the wire speed, depending on the situation. More complex control strategies, such as wire oscillation feeding method, can be implemented, depending on the desired quality and materials involved. This oscillating method was found, in certain conditions, with ferritic stainless steel MIG welding, to help improve mechanical properties of the workpiece. A dual wire feeding system can be beneficial while producing parts with a composite material made of other two which are difficult to join in the same wire. Increase in tendency to develop porosity, due to variations in diameter or wire surface finish, such as cracks or scratches [9].

2.8 Deposition rate/Production Rate

Deposition rate is a variable that measures the amount of wire material deposited in the working piece per unit time and it is associated with productivity. Its value can be raised to increase the production rate, however increasing the quantity of material to melt in each time instant will demand higher heat input, for the same welding procedure, and aggravate the heat related problems previously discussed.
DED Additive Manufacturing, in general, can achieve higher deposition rates than other alternatives such as Powder Bed Fusion. DED-Arc is known to be a high deposition rate DED process with values between 1 and 10 kg/h, depending on the welding process and material. DED Arc deposition rate typical values for TIG range from 1-2 kg/h, for MIG range from 3-8 kg/h and Plasma range from 2-4 kg/h. With MIG-MAG high productivity rates are easily achievable than with TIG, however Plasma Welding is the process with the more energy dense arc of the three, at a cost of a significantly increase in equipment investment [2].
Since increasing productivity is usually a big concern, some methods and strategies were developed to increase even more the deposition rate of this building process. Wire pre-heating is a strategy in which the wire is pre-heated close to its melting temperature. This allows the wire feeding speed to be increased and, for the same arc heat input, melt more volume of material in each pass, thus increasing production rate. The wire is more commonly heat by resistance to the flow of an electric current. Localized pre-heating of the zone where the weld pool will be formed can also help increase the deposition rate without increasing the spatter or disturbing the metal transfer consistency. In the aerospace industry, a DED-Arc equipment manufacturer, Norks Titanium, uses plasma

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welding with another plasma torch in front of the main one to create the desired pre-heating. Other researchers have been investigating the use of a laser beam for this pre-heating purpose.
Using the oscillation wire feeding method, mentioned above, it can be achieved a quicker and a more stable droplet transfer, resulting in a better Weld bed Surface quality, allowing the increase of the metal transfer rate [10].

2.9 Hybrid Build Strategies

Hybrid build strategies can be defined as the combination of additive manufacturing with other conventional manufacturing processes. These technologies were developed with the intention of integrating the different characteristics of the chosen processes, based on the requirements of the final part. Thus, hybrid build strategies can be used as way to improve not only the quality and functionality of the product, but also the process itself.
One application of this strategy is the combination of DED-Arc manufacturing and forging [11]. An advantage of DED-Arc is that it can be used for the manufacturing of products of large scale, which is something that can be difficult to achieve in forging, as well as in other processes. However, the parts manufactured through DED-Arc will not have the same mechanical properties as the forged ones. Therefore, the combination of these two methods can be favourable in these situations while also achieving a more efficient process.

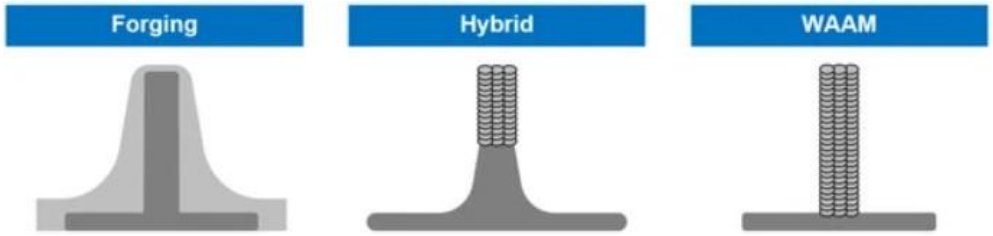


Figure 9: Hybrid build: DED-Arc and Forging [11]

The most common hybrid strategy combines additive with subtractive manufacturing. In this case we will look at the example of DED-Arc with milling, which consists in the deposition and subsequent removal of excess material [12]. This hybrid strategy can be used to fabricate stiffened panels used in a variety of industries like aerospace, aviation and automotive. It was concluded that when compared to joining and machining methods, the hybrid strategy was much more effective considering that it allowed a low weight

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construction without the waste of raw material [12]. As seen in figure 10 b), this method deposits the needed material to build stiffeners on a thin plate followed by a milling of the irregular surfaces, contributing to significant savings in material resources, as opposed to the situation in figure 10 a).

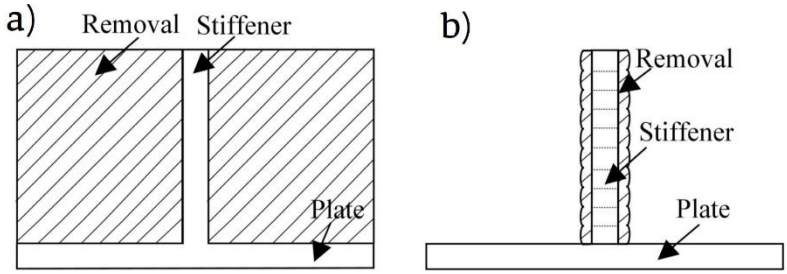


Figure 10: Hybrid build: Additive Manufacturing and CNC [12]

Additionally, using the milling process after DED-Arc manufacturing can provide a better surface finish and more precise geometrical parameters. Figure 11 shows a before (left) and after (right) of the application of the subtractive process. However, this can turn out to be a more complex method, as its planning requires the operator to consider not only the milling parameters such as spindle speed and tool-feed rate, but also DED-Arc parameters like travel speed and wire-feed rate. This is important because the dimensions of the obtained bead will have a direct influence on cutting procedure [13].



Figure 11: Hybrid build: Additive Manufacturing and CNC [13]

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2.10 Parameters adjustments along the layer

Heat input is a key factor in all types of welding. It is a measurement of the quantity of energy that is transferred to the material during the welding process, and can be obtained by combining different parameters, as in the following equation.

$$Heat\ input = \frac{Voltage \times Current}{Travel\ Speed}$$

Equation 1: Quantity of energy transfer during welding process

Therefore, heat input, increases with the increase in voltage or in current, or with a decrease in travel speed. Since the increase in current causes an increase in heat input, there will also be an increase in the melt through depth. Apart from the heat input, current also influences the roughness of the bead, which decreases with the increase of current. It is also important to note that an increase in current will increase the bead width, but the bead height will remain approximately constant.
Travel speed is the speed at which the torch moves along the path, and it affects many aspects of the DED-Arc process. As illustrated down below, it can be observed that with the increase of travel speed there is a decrease in bead width and bead height which implies a decrease in cross sectional area. Additionally, there is also a decrease in heat input which leads to a lower melt-trough depth and an increase in roughness [14].

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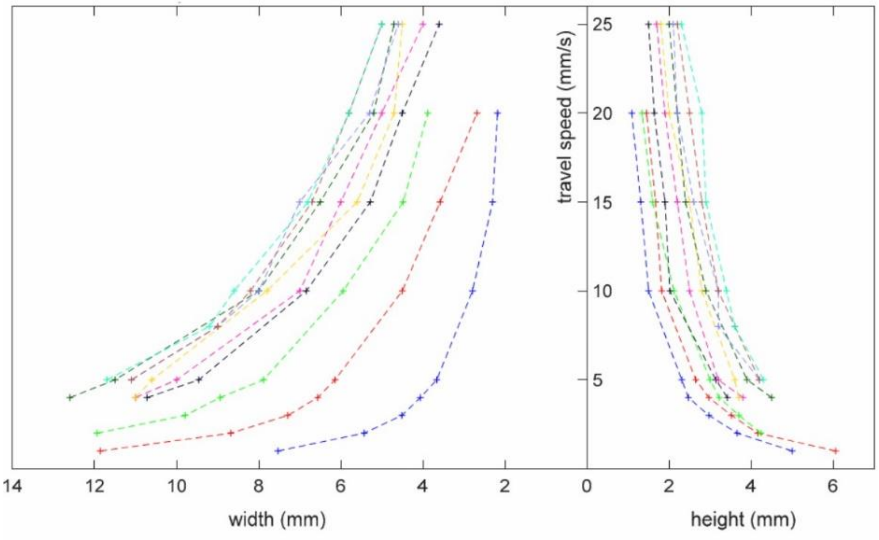


Figure 12: Variations of width and height with travel speed and wire feed rate [14]

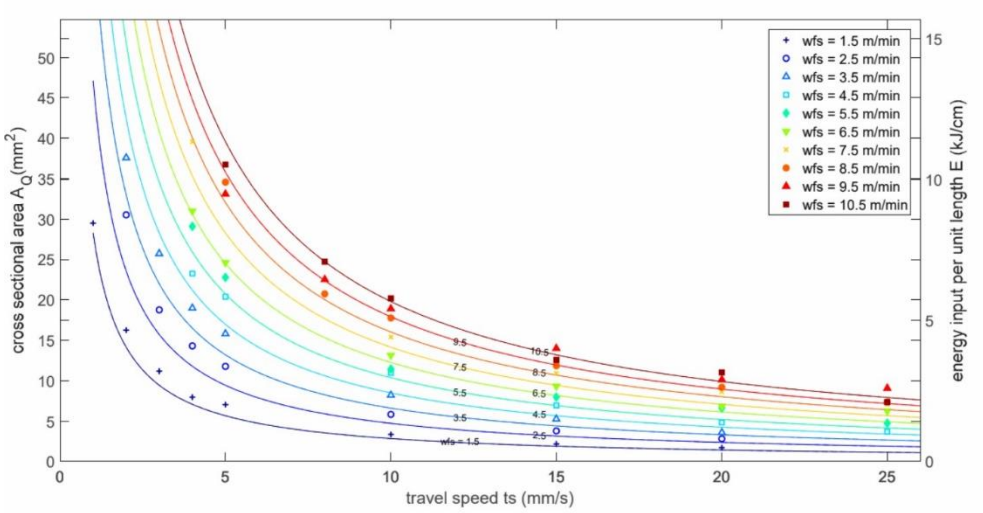


Figure 13: Parameters variations with travel speed and wire feed rate [14]

Referring to the graphs shown above, the evolution of cross-sectional area and heat input can be analysed with the changes in wire feed rate. Increasing the wire feed rate, there is a consequent increase in the geometric parameters, with the bead width suffering a more significant change than the bead height, resulting in an increase in aspect ratio, which is the relation between the dimensions of the cross sections: bead width / bead height. As the aspect ratio increases, the wetting angle decreases.

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Wetting is defined as “the ability of liquids to form interfaces with solid surfaces” [15]. In welding it refers to how the deposited material behaves on the working surface. Wetting is a parameter that has great influence in surface finish, affecting the quality of the build. To measure this phenomenon the contact angle, also referred to as the wetting angle, is used. This is the angle between the contact surface and the surface of the liquid. When this angle is bigger than 90 degrees adhesive forces are lower than cohesive forces, which means that the attractive forces among the molecules of the liquid overcome the attractive forces between solid and liquid, creating a droplet. When below 90 degrees the opposite happens and the liquid is able to spread itself on the solid surface, which is considered good wetting [15]. A complete wetting would be considered with a contact angle equal to 0 degrees, although in practical situations one can assume complete wetting for angles below 5 degrees.

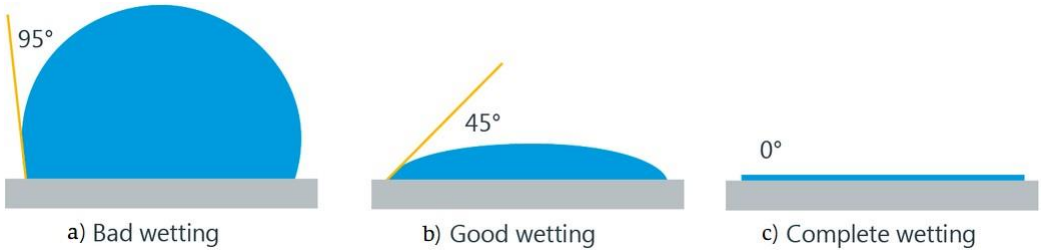


Figure 14: Variations in wetting angle [15]

For structures that require multi-bead deposition, it is important to consider overlapping in order to make the build more consistent. For this purpose, some multi-bead overlapping models were developed, such as the Flat-top Overlapping Model (FOM) and the Tangent Overlapping Model (TOM). Firstly, the geometry of a single bead must be considered: bead height (h), bead width (w) and a centre distance (d) between adjacent beads. Regarding overlapping there will be an overlapping area, which is the area under the intersection of the two beads, and an area of valley, whose geometry will depend on the used model. Centre distance is responsible for the outcome in overlapping influencing the surface quality. If d is lower than w, then there will be overlapping, increasing the overlapping area, and decreasing the area of valley. The opposite will happen if d increases [16].

The first model, FOM, considers an ideal overlapped surface, with an area of valley defined by a straight line that connects the top of both weld beads and the boundaries of the beads. This model can be used to find the centre distance at which the area of valley

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and the overlapping area are equal. This is referred to as the optimal centre distance, whose value is considered to be:

$$d_{opt} = 0.667w$$

Equation 2: Optimal centre distance

Since the assumptions made by this model are not completely verified by experimentation, it will lead to errors when compared to experimental bead profiles. This is especially important for pieces that require multiple layers, as there will be a build-up of errors.

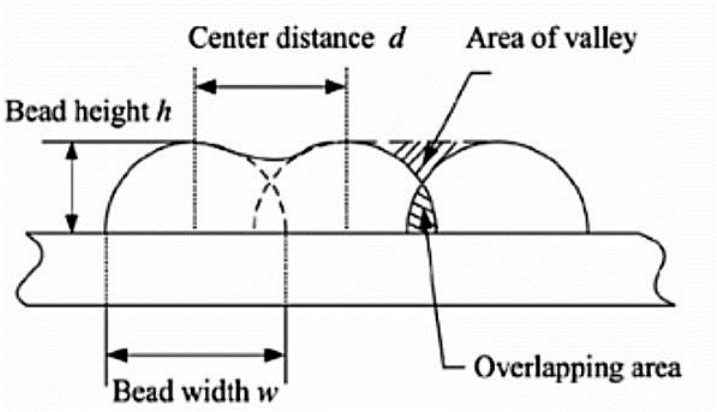


Figure 15: Flat-top overlapping model (FOM) [16]

Therefore another method, TOM, was developed. This method is similar to the previous one, with the major difference being that the area of valley is now delimited by BEC: with point B having the same horizontal coordinate as point A, and BC being tangential to the profile of bead 2 in point C. By varying the centre distance, the optimal centre distance, d_{opt}, at which the area of valley and the overlapping area have the same value, can be obtained. For Tangent Overlapping Method, the optimal centre distance is considered to be $d_{opt} = 0.738w$. This variable can also be called critical centre distance, d^*, as it defines the value of the center distance from which the height of the second bead will change. If $d < d^*$, then the height of the second bead will increase, if $d > d^*$, the height remains approximately constant [16].

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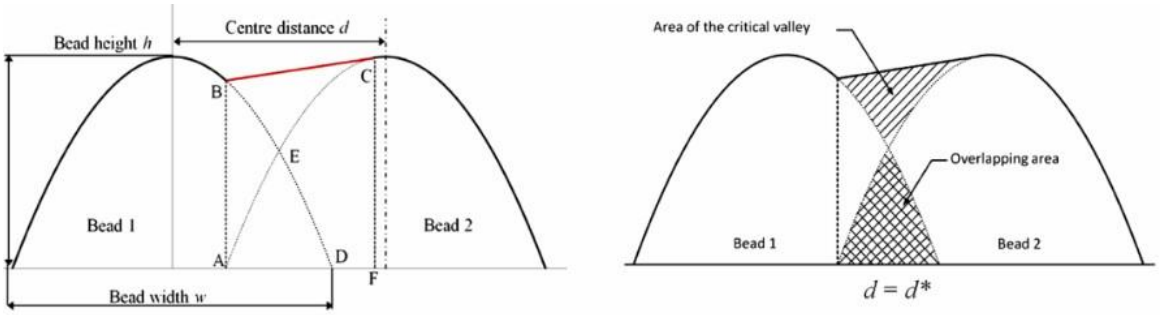


Figure 16: Tangent overlapping model (TOM) [16]

As can be observed down below , the height of bead 2 evolves towards the value of the height of bead 1 with the increase of centre distance. For values of $d < d^*$ the overlapping is considered unstable due to the height difference of the beads. On the contrary, for values of $d \geq d^*$ the overlapping is stable. It is important to note that according to TOM, the value of d_{opt} for FOM would be seen as an unstable overlapping [16].

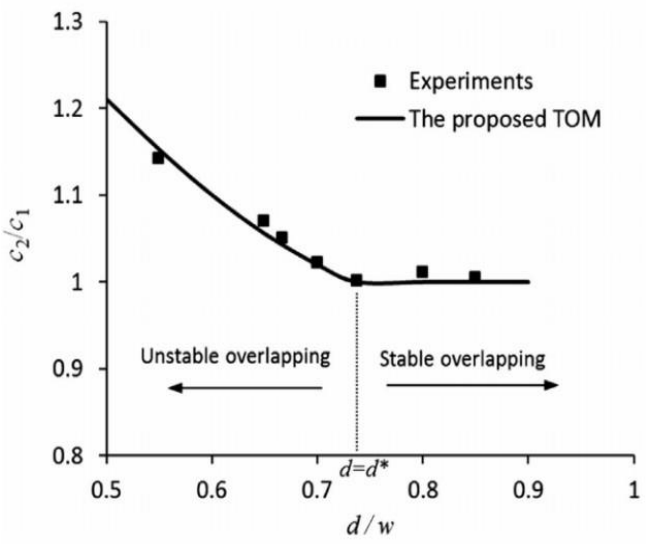


Figure 17: Variation of the height ratio (c2/c1) with the center distance (d/w) [16]

As previously mentioned, TOM is a different version of FOM to better represent what happens in experimental overlapping procedures. Therefore, it is expected that the relative errors obtained through TOM is lower than the ones obtained through FOM, what can be confirmed by observing the Figure 18.

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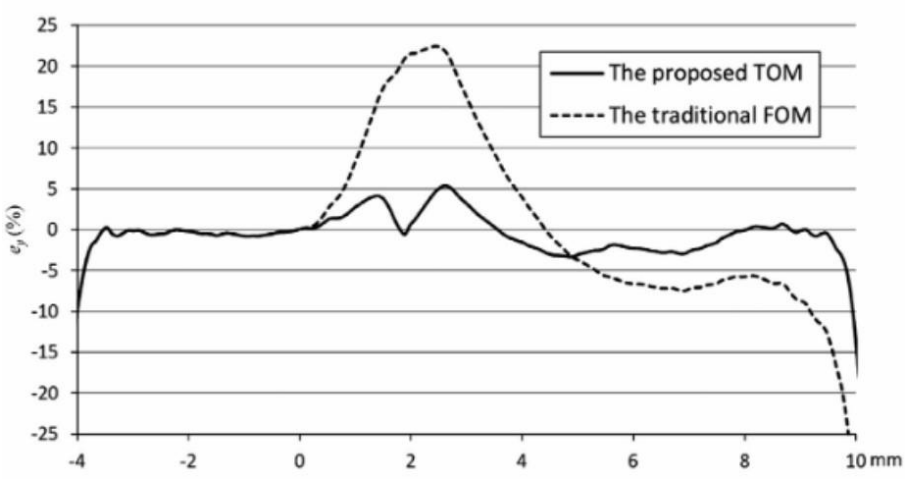


Figure 18: Relative errors between overlapping models [16]

Regarding the feeding mode, the wire can be fed co-axially or externally to the torch [17]. In the case of external feeding, the wire can be placed in different sides of the torch, resulting in front feeding, back feeding or side feeding. External feeding allows the operator to control the wire feed and heat input in a more customized way. However as there are more variables to consider, it can turn out to be a more complex procedure. The best wire feeding direction option can depend on the used material, as every direction can lead to good surface quality when combined with the proper material [17]. The feeding angle can also be adjusted resulting in different surface finishing.

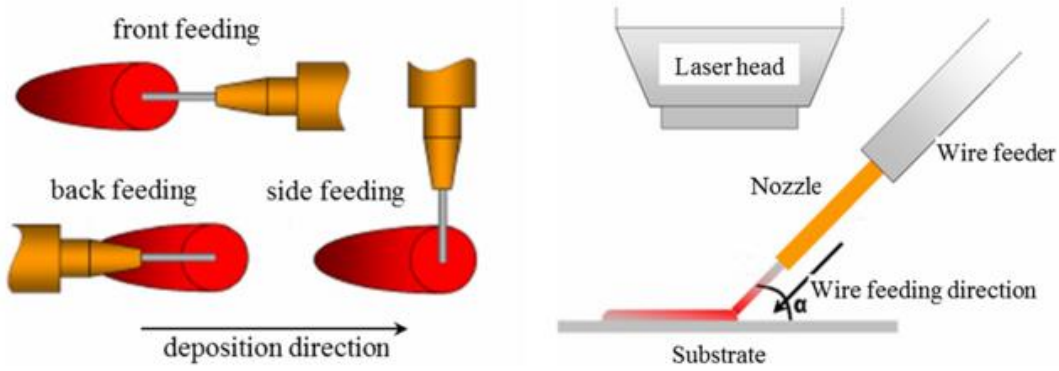


Figure 19: Wire feeding directions and feeding angle [16]

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3. DED-ARC ASSOCIATED PROBLEMS

3.1 Distortion and Residual Stress – Heat related problems

Excessive heat input due to the need for high deposition rates and large temperature gradients frequently cause problems in DED-Arc such as distortion, residual stresses, and even undesirable microstructures, which makes the part in construction obsolete, since it won't be able to perform as intended. Therefore, it is important to keep in mind its causes and the problems that can come up with it, such as a reduction in fatigue life and stress corrosion resistance, and even mechanical failure of the part. DED-Arc is prone to distortion as it is a process that involves the local heating of metal. During the localized heating, the working section becomes much hotter than the surroundings, which leads to local stresses and consequently to distortion. If the thermal changes were to happen uniformly throughout the build, distortion would not be a problem. Distortion types can vary from longitudinal and transverse shrinkage to bending, angular or rotational distortion. Thin-walled components are particularly sensitive to this type of deformations because of the greater temperature and temperature gradients achieved.

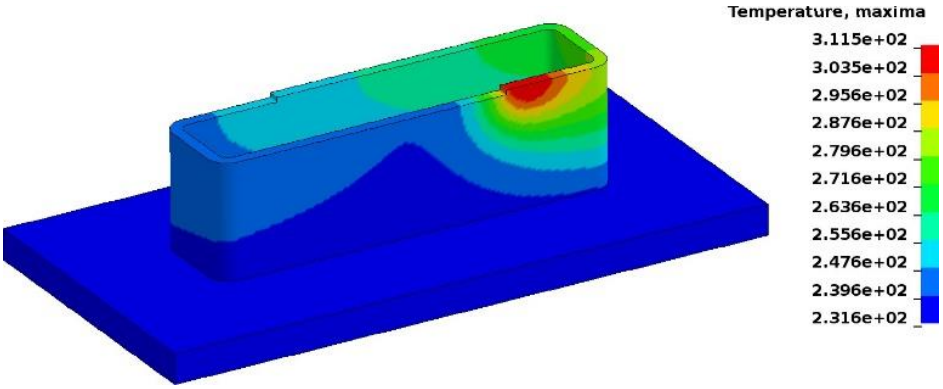


Figure 20: Localized heating

Residual stresses are stresses that remain in the piece after the fabrication, without any load applied. These are related to different levels of deformation along with the piece, either due to temperature gradients or to the type of loads applied during the building process. Usually, tension residual stresses are the ones that weaken the piece. Some post-process methods can reduce or eliminate tension stresses and even induce compression ones, which can be beneficial. Fortunately, there have been some research and

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development in terms of methods and systems to minimize distortion and residual stresses.
The first strategy, which is simpler and easier to implement, is allowing the part to cool for a period of time, between each layer. This period can have a fixed duration, determined by trial and error, or a variable duration, until the workpiece is below a certain temperature.

A schematic representation of this solution can be seen in figure 21. However, the trial-and-error method demands a great amount of experimentation and the temperature can be difficult to measure with accuracy in every point of the part. The lack of uniformity in heat dissipation due to variations in geometry and the interaction with adjacent layers introduces even more complexity to the temperature control problem. In addition, this method drastically reduces productivity due to the successive brakes. The cooling rate can be increased with forced convection. Some studies show that using Nitrogen gas (N_2) with 5% Hydrogen (H_2) can be a very cost-effective mixture to use in forced convection but the possible inclusion of (N_2) might be a problem for some materials. Although an inert gas such Argon (Ar) can also be used, it would much increase the overall cost of the build.

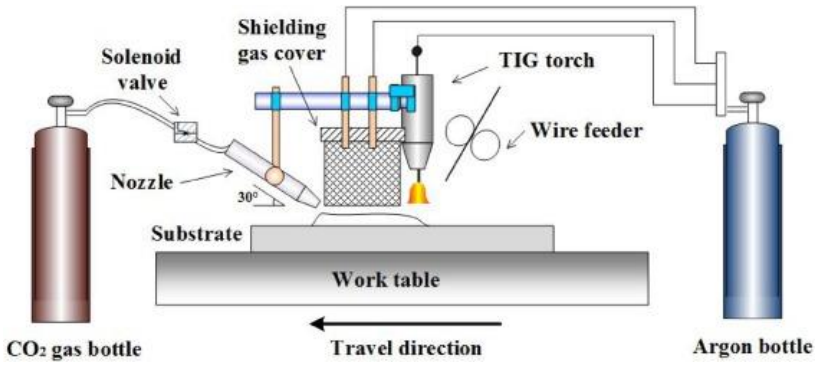


Figure 21: Schematic diagram of a DED-Arc system with interpass cooling [9]

Mechanical tensioning and restriction are two methods to avoid distortion, yet they may induce residual tension stresses which is not beneficial. They also rely on the thickness and stiffness of the substrate plate and introduce mechanical components to apply the tension needed, that need to be strong and are not cheap. Moreover, this technique can be incompatible with certain geometries. Despite all these disadvantages, the build can be performed without brakes for cooling.

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Another method that does not imply interrupting the building process and can perform better than the last one is volume cooling with substrate platform cooling. These specific platforms have built-in channels that allow a cooling fluid to circulate and dissipate heat from the whole piece, accelerating the solidification rate of the weld beads, thus improving the structural integrity of the build [9]. It enables continuous deposition yet relying on conduction in the workpiece, which can be a problem for larger components or materials with lower thermal conductivity. Depending on the cooling fluid, the quality of the build can vary. In case of water, a great rate of dissipation ca be achieved because of its high specific heat at the cost of greater spatter and possibly arc wander, which results in reduced precision and resolution and increases the need for surface finishing in post process. Other fluids with less electromagnetic interference might reduce this problem [9].

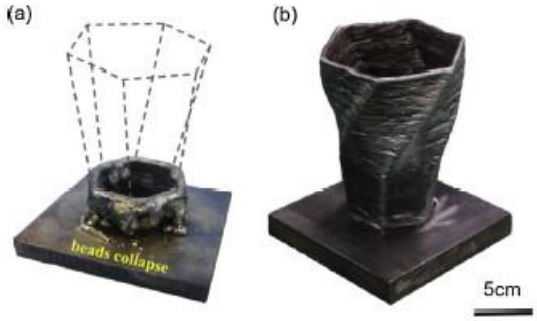


Figure 22: Workpiece volume cooling influence on structural integrity during the build [9]

Localized cooling of the weld pool (in-situ cooling) is another solution to this heat related problems. In this method a cooling device is positioned behind the welding torch and progressively cools the weld pool which more quickly reduces the temperature gradient, thus reducing the overall heat of the piece while maintaining the heat input and the wire feed speed. The cooling system can use several elements to perform its task, such as solid Carbon Dioxide (CO2), liquid Nitrogen (N2), other gases with forced convection or in some cases a thermo-electric device. The figure below shows the effect of this localized cooling in buckling deformation of 1.5 mm stainless steel welded sheets. Regarding in-situ cooling with forced convection in MIG-MAG DED-arc with Titanium (Ti), a system was developed by Wells and Lukens using water cooled Helium (He) that passes through a holed plate (impingement plate) that distributes the gas. This method was found to improve the Titanium microstructure [9].

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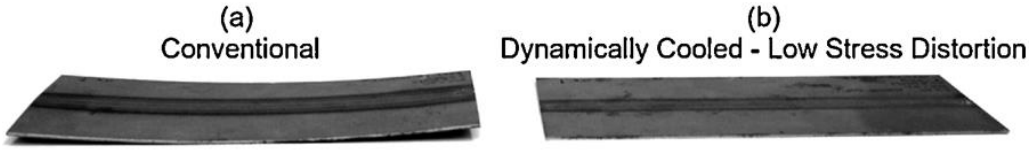


Figure 23: Dynamic cooling of 1.5 mm SS316 L stainless steel [9]

Another method that does not imply interrupting the building process and can perform better than the last one is substrate platform cooling. These specific platforms have built-in channels that allow a cooling fluid to circulate and dissipate heat from the whole piece. It enables continuous deposition yet relying on conduction in the workpiece, which can be a problem for larger components or materials with lower thermal conductivity. Depending on the cooling fluid, the quality of the build can vary. In case of water, a great rate of dissipation can be achieved because of its high specific heat at a cost of greater spatter and possibly arc wander, which results in reduced precision and resolution and increases the need for surface finishing in post process. Other fluids with less electromagnetic interference might reduce this problem.

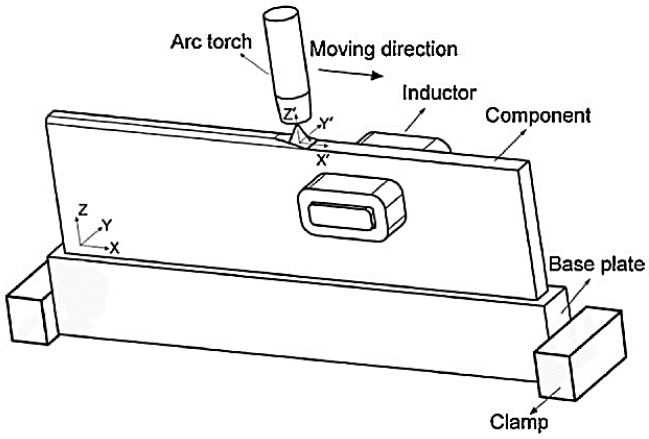


Figure 24: Induction pre-heating of the material ahead of the weld pool [18]

On the other hand, pre-heating the material ahead of the weld pool can also bring benefits to the weld in terms of residual stresses as it helps reduce temperature gradients in the workpiece, both along its spatial dimensions and during the time of the build. Other studies were developed using a laser beam as a complementary heat source for this pre-heating purpose on plasma welding DED-Arc variant, which proved to be beneficial as the protection gases were ionized by the beam, increasing arc´s energy density and arc´s

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diameter [37]. Another way to reduce heat input related problems is to reduce its magnitude. A MIG-MAG variant, CMT - Cold Metal Transfer, offers a solution for this situation, as in this technique the wire is lowered so that shot-circuiting metal transfer can occur, and the current is turned off. Then the wire is lifted, the current is raised, the arc is restarted, and the cycle repeats. Since the heat source is periodically turned off, the total heat input is reduced but still providing enough heat for the material to melt and be transferred to the working piece.

3.2 Weld Bead Defects – Porosity, cracks and Delamination

Porosity is a welding defect that results from contaminations in the molten metal in the weld pool. Inclusions of these contaminants and voids seriously reduce the mechanical strength and the fatigue life of the final piece and are points from where micro-cracks can propagate. These contaminants can come, either from the base material or from the addition material, since the metal surface, usually, contains some lubricants from manufacturing processes, moisture, or other solid particles. The level of porosity developed depend on the type of contaminants, the sensitivity of the building metal. One particularly sensitive material is aluminium, in respect to hydrogen, since its solubility is relatively low, and so, small amounts of hydrogen can easily form precipitates. Porosity can also appear due to complications related to the combination of path chosen – welding process used. Complex paths to build complicated geometries, associated with welding processes that lack lateral melting and can produce great amounts of spatter, creating inclusions and voids [2].
This problem can be minimized by increasing the overlap between each layer, i.e., by increasing the penetration on the previous layer, using specially developed variants of the traditional methods AC MIG (MIG with alternating current) or CMT-PADV (Cold Metal Transfer Pulsed Advanced), using an adequate good quality shielding gas, with impurity free piping and other hardware, by cleaning substrate and addition material and using good quality wire [2].

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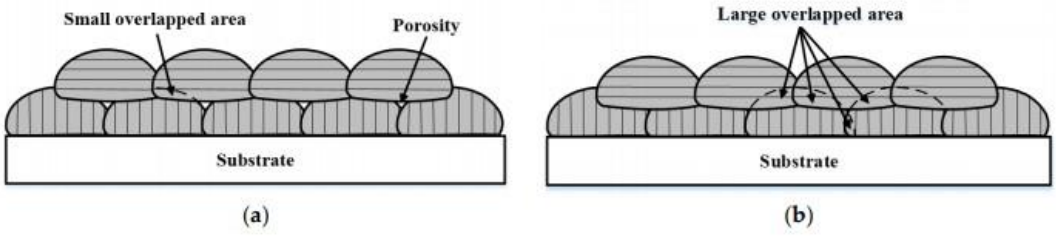


Figure 25: Porosity due to lack of overlapping (a); Elimination of porosity by increased overlapping (b) [19]

Another important problem is cracks. These can form during the solidification process or in grain boundaries, due to the stresses that arise with temperature gradients. Depending on material solidification characteristics and on the environment conditions, the tendency to cracking can change. Delamination or "separation of adjacent layers", occurs "due to incomplete melting or insufficient re-melting of the underlying solid between layers" [2]. This lack of fusion might be fatal to the workpiece functionality and post-process, generally, will not solve it.
Construction of components using two or more different materials can suffer from both these problems, when melting and chemical properties of both materials are not highly compatible.

4. POST-PROCESSING

In order to improve its quality, a finished DED-Arc weld part is then post-processed both thermally, to reduce residual stress and improve mechanical properties, and geometrically, to achieve the desired final geometry – with a good surface finish and the necessary geometrical tolerance. So, there are many post-processes that can be implemented, to transform a fabricated part into the final product. In this section some of them will be discussed.

4.1 Thermal Post-Processing

Post-process heat treatment is commonly used in DED-Arc welding to relieve residual stress, close pores and improve the mechanical performance of the material, such as increasing the material strength and making hardness control. The goal of this post-process is to change the microstructure of the material in order to obtain the required properties for a specific purpose, by changing grain size and orientation, precipitate phases, porosity and several mechanical properties. So, the thermal post-processing of

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metal affects grains through recovery, recrystallization, and growth. Different material requires different post-process heat. This is especially important for materials with a high carbon content, as these must be heat treated. On the other hand, this technique can also be damaging for other materials. In this section some of the post-process heat treatments will be presented.

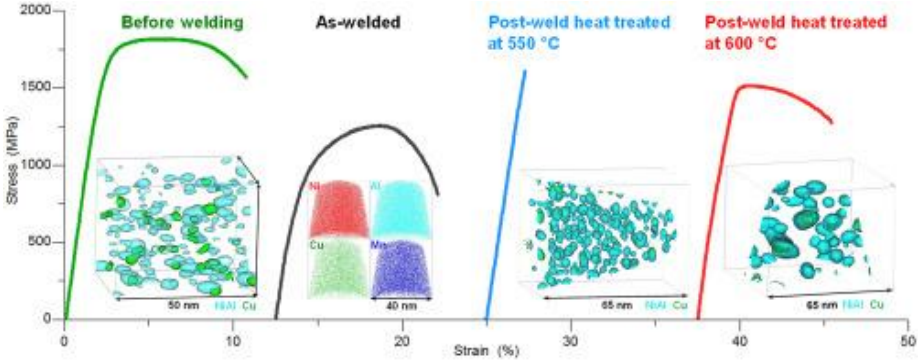


Figure 26: Material before and after heat-treatment [20]

4.1.1 Post-Heating

Usually, manufacturing processes create residual stress in metal that will affect the metal fatigue and corrosion and its ultimate tensile strength. So, it is possible to reduce or even remove metal stress. Metal stress relief can be applied to ferrous metal such as steel as well as non-ferrous alloys [21].

By increasing temperature, atomic diffusion increases and atoms in regions of high stress can move to regions of lower stress, which results in the relief of internal stress energy. DED parts are normally annealed for stress relief, usually prior to substrate removal, that will be discussed in the next topic. This treatment should be performed at a temperature high enough to allow atomic mobility but remain short enough in time to suppress grain recrystallization and growth (which is usually associated with a loss of strength). The metal should then be cooled uniformly [22].
The process does not make significant changes in the structural or mechanical properties of the material, it simply prepares metals for processing and reduces the risk of a material such as steel, becoming distorted, corroded or cracked.

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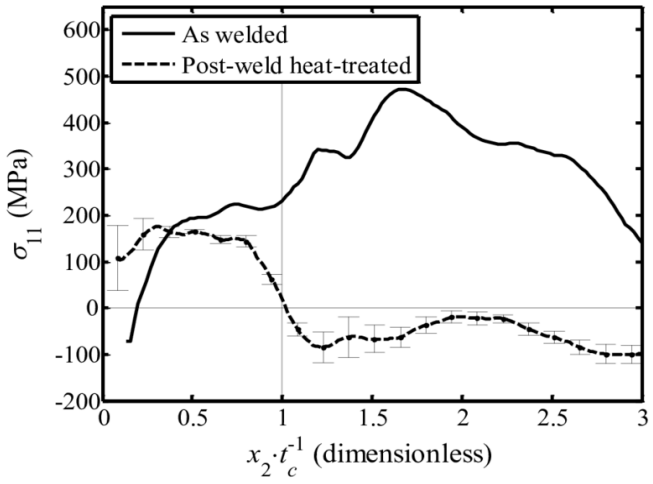


Figure 27: Evolution of Residual Stress with/without heat-treament [22]

4.1.2 Annealing

In the cold-worked metals, that are deformed at room temperature, the dislocation density increases so, in result, the microstructure is distorted. Because of that, annealing is used as a thermal post-process, that heats the material, to a considerably high temperature, maintaining that temperature for a suitable period and then cooling it. This “heating is necessary to provide the thermal activation energy needed to transform the material to a lower-energy state” [19]. That decreases the strength and hardness, while increasing the ductility, softening the metal.

Annealing involves three different stages: recovery, recrystallization, and grain growth.

In the first stage, the internal defects within the microstructure will be reorganized in order to achieve a “lower-energy configuration” [23]. However, some of the properties of the material are not affected, like the grain shape, orientation, strength and ductility. As a result, recovery allows to prevent stress-corrosion cracking or distortion, as it leads to minimization of the residual stresses.
Referring to recrystallization, there is the formation of new grains, without strain and with new orientations, grain sizes and grain morphologies. They will take the place of the badly deformed ones. The goal is to increase the ductility and decrease the strength to the same levels of the initial mechanical conditions. In recrystallization, there are significant

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changes in the mechanical properties, such as hardness, yield strength, tensile strength, elongation and reduction in area coefficient, for a relatively small temperature gradient.

As DED-Arc processes create columnar microstructures, recrystallization plays a very important role in the post processing, since there is the formation of equiaxed microstructures from the columnar ones. Equiaxed microstructures are composed by crystals of approximately equal dimensions in every direction. Therefore, recrystallization in DED-Arc combines the high strengths obtained by the equiaxed grains and the good plasticity from the original columnar grain material. Some materials, like metals with low melting temperatures, such as tin and zinc, can't be hardened using cold working because their temperatures of recrystallization are lower than the room temperature.
During the third and last stage, there is the growth of the grains that have been recrystallized previously, "at the expense of other recrystallized grains" [24]. This excessive grain growth can happen for one of two reasons: if the material is hold for too long at the annealing temperature, or if the heating temperature is too high.

In the Figure 28 is demonstrated the grain growth at three different stages. At the top, close to the surface, small grains with random crystalline orientation are formed, because near to the wall there is a higher rate of heat extraction and so, high supercooling, which provide the formation of these type of grains. In the middle zone, which is the columnar zone, is the region where the grains align with the grains of the previous zone, the ones that were oriented with the direction of heat extraction, and cause a growth acceleration, producing elongated grains. Near the bottom, small grains are formed, as a result of crystal nucleation or the migration of columnar grain fragments. So, the grains in this last region are again small and equiaxial [9].

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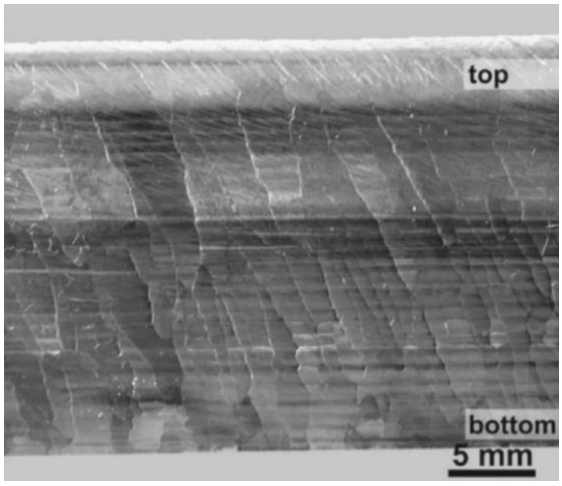


Figure 28: Large Columnar WAAM grain growth shown in Ti-64Al-4 V [9]

4.1.3 Hardening

Hardening is also a heat treatment post-process employed to harden alloys. The intention of hardening is to increase the hardness and tensile strength of the component. There are several hardening treatments that will be discussed.

The first of them is quench hardening, where the material is quickly heated and then cooled, that enables the amount of austenite to transform into martensite, in ferrous alloys. With that it is obtained a microstructure that provides high hardness properties and mechanical strength. After the formation of martensite, the generated stresses need to be relieved, so it is used the process of tempering to do that, and to reducing its hardness, to the desired values. So, tempering is always applied after quench hardening, to ensure dimensional stability and to achieve specific values of mechanical properties.
This process happens to heat the metal again, but here the temperature reached is much lower than the temperature used in quenching, as it can be seen in Figure 29, and then cooled at an appropriate rate that makes it possible to increase the ductility and elasticity of steel, the desired toughness, and the grain size of the matrix [25].

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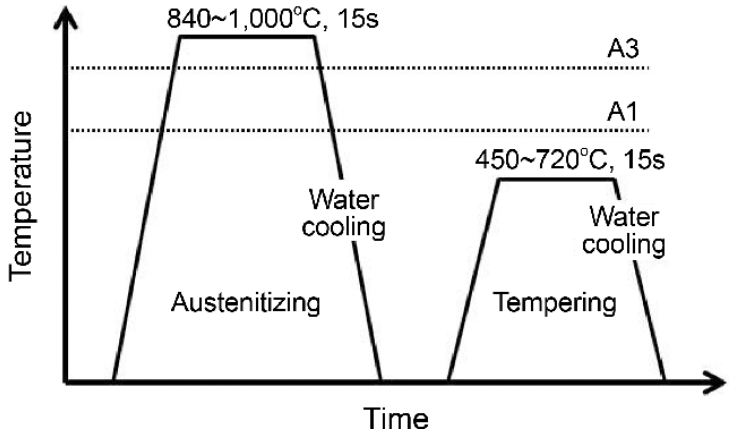


Figure 29: Effects of Quench Hardening and Tempering [25]

Another hardening process, which succeeds the other two, is precipitation hardening, also known as ageing. This process is described by heating metal alloys to a high temperature, so it can be dissolved and be transformed into a supersaturated solid solution, and after that be quickly cooled, until room temperature, "freezing the alloying elements in solution" [24]. In the next step, when the metal alloy is re-heated to an intermediate temperature, the base metal can reject the metal alloy in the form of a fine.
So, this heat-process can harden the metal alloy by creating solid impurities (precipitates) that will prevent dislocations in the structure, and the fact that are no dislocations, providing resistance to slips, will affect the plasticity of the material, conferring an increase of strength and hardness, also increasing its efficiency.
Some typical used alloys are aluminium, magnesium, nickel, and titanium alloys, and some of the alloys, like copper-beryllium alloys, age harden at room temperature.

4.1.4 Hot Isostatic Pressure (HIP)

As explained before, one of the most common problems/defects in DED-Arc welding is porosity, that cause a reduce of the density of the parts, and because of that, the components have low mechanical strength, by damage from micro-cracks.
So, associated with the post-process annealing, hot isostatic pressing (HIP) is a process where the components are subjected to an application of heat at the same time of high pressure in an inert gas, uniform in all directions, that means, isostatic. That will close internal pores and cracks, bonding the void surfaces with minimum distortion, these pores

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are filled with material. HIP also improves the mechanical properties such as higher strength and enhanced toughness. It affects the grain structure of the parts so it will increase fatigue resistance, and decrease the gas porosity, cracks and hot tearing susceptibility [22][26][27].

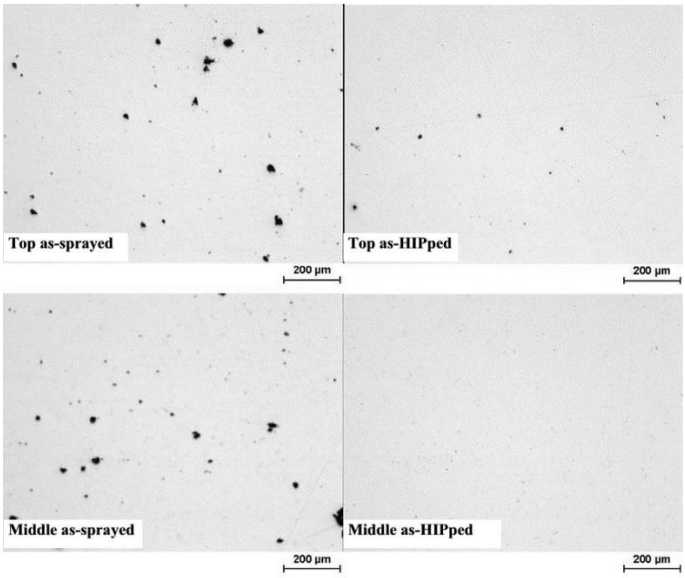


Figure 30: Porosity after HIP-cycles, for IN718 [28]

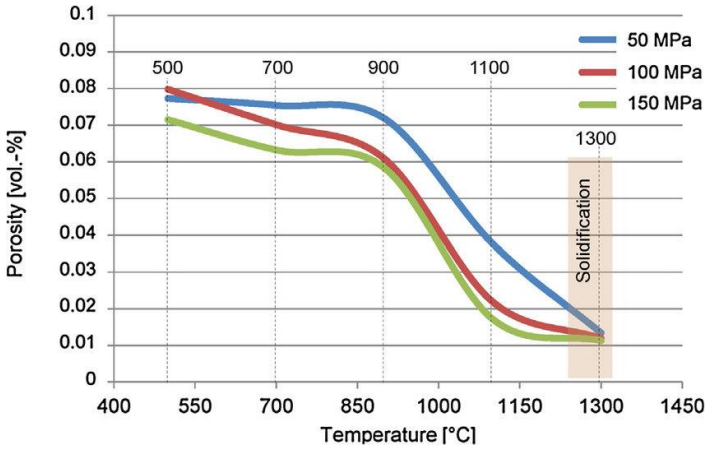


Figure 31: Porosity measured after HIP processing of IN718 (with different temperatures and preassures) [28]

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4.2 Surface Finishing

"In AM processes, since a surface is usually fabricated through deposition of a large number of weld beads side by side with (or without) overlapping and each weld bead is a parabola-similar curve and not a regular rectangle, the surface finish can be referred as surface roughness" [17], and so, the parts are typically machined to achieve a smooth surface finish, like in the example in the Figure 32, when they have a critical accuracy and surface roughness requirements, for example, to fit perfectly into a larger assembled product and performs as it is supposed to.
The best way to machine this part is to use CNC machines, associated with subtractive manufacturing. It is also beneficial for part geometries with surfaces that are difficult to access after build. In simple cases, polishing or grinding can be done with a rotary-tool or a belt sander. In other cases, it can be used chemical polishing, like on mesh structures. Although, in high-quality parts this process can be more complex. Despite all this, surface machining can´t remove some defects, like surface oxidation caused by thermal post-processing.

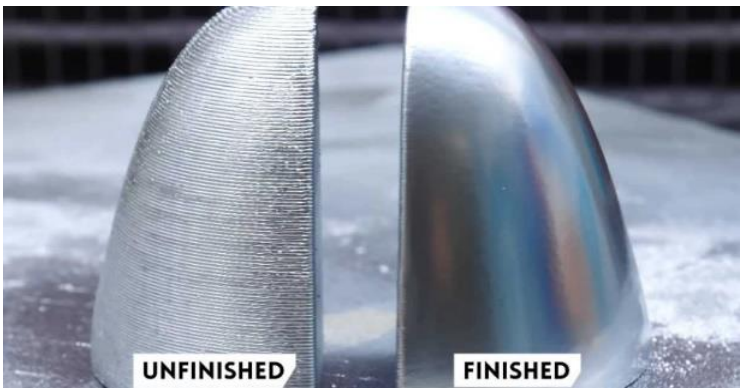


Figure 32: Part before and after surface finishing [29]

4.3 Interpass cold rolling

Interpass cold rolling is used as a post-process to get lower residual stress, and especially to bring more homogeneous material properties. This process has a particularity of being executed between each deposited layer.
In DED-Arc welding processes, the thermal gradient with deposition layers and alternate re-heating and re-cooling process results in a part that has anisotropic microstructural evolution. With the cold rolling technique, microstructural anisotropy can be reduced through plastically deforming the deposition layers [2].

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Interpass cold rolling uses a slotted roller to refine the microstructure and improve tensile strength, supporting external force. That is why it allows more homogeneous material properties. Generally, during this process, high dislocation density is produced, and these dislocations can act as preferential spots to absorb atomic hydrogen, allowing its diffusion to the surface. So, that way, porosity can be reduced or even eliminated with this post-process too [2]. A disadvantage of this technique is that it only works with simple deposited parts, due to the geometrical limitation, and so it limits the range of industrial application.

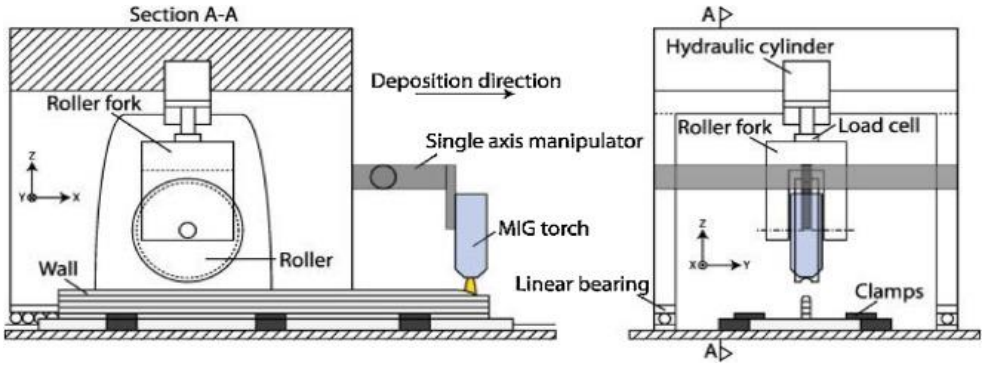


Figure 33: Schematic diagram of an interpass cold rolling system developed at Cranfield University [2]

4.4 Peening and ultrasonic impact treatment (UIT)

Peening and UIT, are both cold treatments that improve mechanical properties, by imposing compressive stress at the treatment surface to release tensile stress.
Usually, the mechanical peening process helps to relieve tensile stresses, developed on other cooling processes executed before, although there is no significant variation. It can produce compressive stresses and strain hardening of the surface metal. Peening is also known for promoting a higher hardness, which is not highly advantageous and that is why this is not a common post-process [23].
Ultrasonic impact treatment is part of the high frequency mechanical impact processes, using ultrasonic energy, that, applied to the work part, acoustically couples, creating harmonic resonance. This process produces grain refinement and grain size reduction, increasing microhardness so the mechanical strength is improved and surface residual stress decreases, turned into compressive stresses [23].
Although both techniques are good post-process treatments, they have no significant effect on the internal residual stresses in large metal parts fabricated using DED-Arc.

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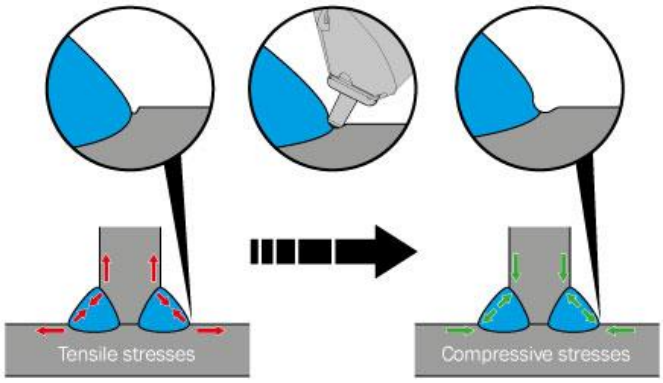


Figure 34: Material before and after UIT [23]

4.5 Support and substrate removal

A finished DED part is typically attached to the build substrate. After a part is fabricated support structures and substrate material must be removed. DED processes may require machine clean-up, but the finished parts are not encased in feedstock.

6. DED-ARC BUILD SUBSTRATE, FEEDSTOCK AND OTHER CONSUMABLES

6.1 Substrate

The feedstock is set in the substrate in the DED-Arc processes. For most cases, the substrate has the same composition of the set material, in order to ease how it adheres to the component and how stable that bond is.
The substrate chosen for a DED process is very important due to the residual stresses that are generated in this process. If the chosen substrate is not the correct one for a given process, which means that the filler wire is not compatible with the substrate material, this gives rise to a distortion phenomenon called warping. This phenomenon affects the component's accuracy, cause delamination and can cause damage such as the lack of fusion between layers [30].

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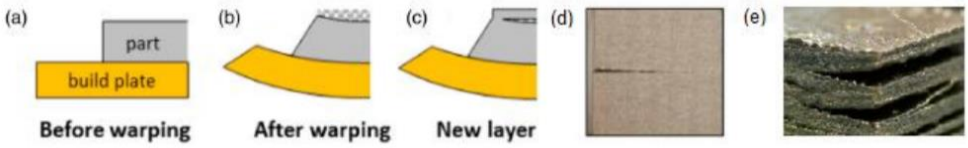


Figure 35: Schematic of build plate wraping Effect during processing (a – c) and resultant lack of fusion (d) or delamination (e) [30]

DED processes are processes that produce high amounts of energy which generate high temperature fields and high temperature gradients. Therefore, the metallurgy of the final piece as well as the structural performance of the pieces end up undergoing changes due to plastic deformations and residual stresses existing during the process. One of the ways to reduce residual stresses would be to reduce the accumulation of heat during the deposition of the metal, that is, if the substrate is heated before the DED process implies reducing the thermal gradients during the deposition of the first layers of the metal [31]. The following image shows the transition from the unstable stage to the practically stable stage during the DED process. During the unstable stage, the thickness and width of the deposited layers are affected when the heat is absorbed by the substrate that is initially cold [31].

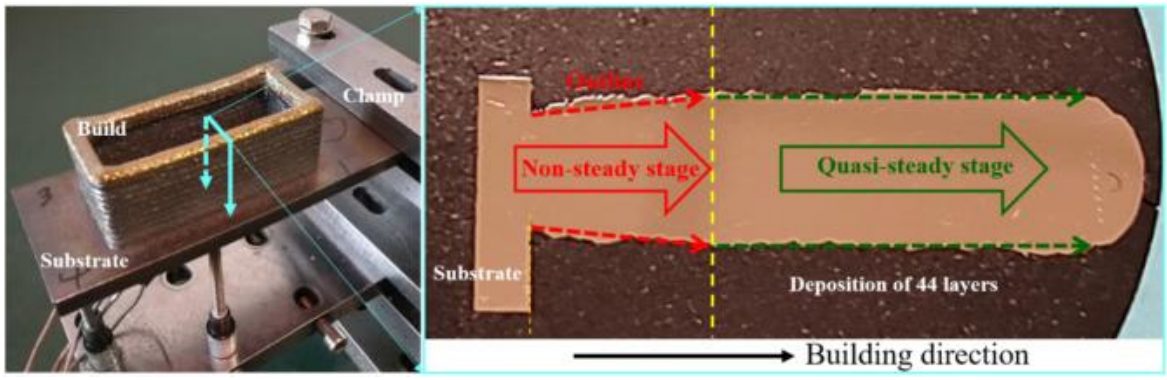


Figure 36:The transition from the non-steady stage to quasi-steady stage of a part deposited by DED [31]

The width of the first layers deposited in the DED-Arc process is less thick compared to the last ones due to the rapid cooling, which is caused by the large area of the substrate and due to its initial temperature. In the following figure, it is possible to observe that with the increase in the temperature in the substrate, the heat conduction decreases, and the heat losses also decrease, which results in smaller temperature gradients.

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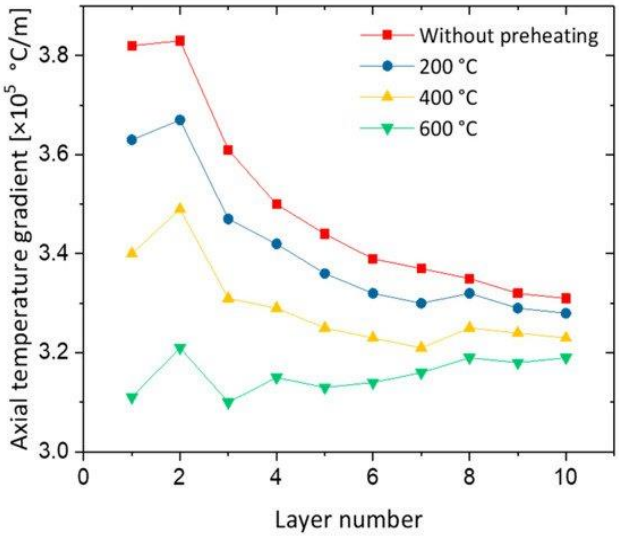


Figure 37: Temperatue gradients variation from the first to the tenth layer [32]

As it turns out, the benefits of preheating the substrate in the deposition of the first layers reduce residual stresses and, therefore, temperature gradients [32].
The following figure shows the von Mises stress indicator, that corresponds to the residual stress field at the end of the DED processes. All areas other than the ones in blue, especially the areas in red, are the location of the highest residual tensions. This is due to a cold substrate whilst the deposition of feedstock, which generates high temperature gradients in the unstable stage, occurring in the first layers' deposition. Thus, these high values are only observed in the contact zone between the substrate and the deposited material. By modifying the initial geometry of the substrate, heat dissipation can be increased, and its stiffness reduced. In addition, if the heat flow decreases through the initial heating of the substrate, it is also possible to reduce the thermal gradients in the unstable initial stage. However, the substrate's stiffness is reduced, thus implying a much weaker mechanical constraint between the deposited material and the substrate, which reduces the formation of plastic deformations, which also implies the introduction of distortions in the material [31].

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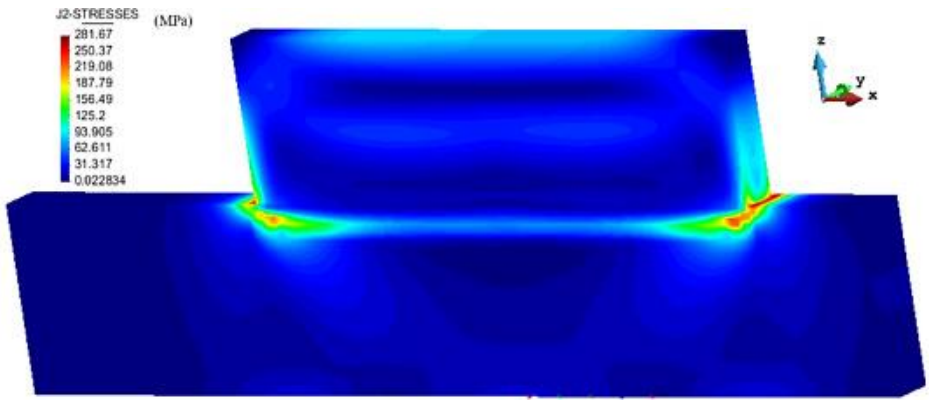


Figure 38: Residual von Mises stress field of the single Wall [31]

Below are some considerations that must be taken into account to reduce the residual stresses seen in the substrate [31]:

- Because the substrate is initially cold, before starting the DED process, it is necessary to supply some heat to it, so the temperature gradients can be reduced. They are very high in the deposition of the first layers and because of this pre-heating, the residual stresses are also reduced.
- Another way to reduce residual stresses is to round the acute angles of the substrate, to avoid the existence of these so that the flexibility of the substrate is increased.
- By reducing the size of the substrate, it is possible to reduce the residual stresses and plastic deformations, thus reducing the duration of the unstable stable and the mechanical restriction since the regiment and heat flow are reduced.
- When the substrate is hollow it heats up much faster than when the substrate is solid inside, so this is one of the ways to reduce residual stresses as it reduces the heat flow in the countertops which implies reducing the temperature gradients.

6.2 Feedstock

The feedstock is the material that is deposited on the substrate through an arc. In the case of the DED-Arc process, the type of feedstock is a solid wire, which can have different thicknesses according to their final purpose. The material used in this process comes in wire spools, for a high range of alloys, which can have different thicknesses according to their final purpose and are used ready to use. This is quite advantageous in the selection of materials, in their availability, cost and quality.

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In general, any type of material that is present in the form of wire can be used in the DED-Arc process. However, the most used materials in this process are magnesium, aluminium, titanium, and nickel-based alloys. The importance of each of these metallic alloys that were mentioned previously, and their applications are listed below:

Titanium-Based Alloys

Titanium alloys are widely used in the DED-Arc process for applications in the aerospace, biomedical industry and the manufacture of tools dedicated to working at high temperatures. These alloys have high strength, fracture toughness and good resistance to corrosion. The additive manufacturing with wire allows a good control of the microstructure of these titanium alloys since these materials are quite thermally sensitive. However, the most widely used titanium alloy in this process is Ti-6Al-4V.
Titanium was studied due to its formability and plasticity, which means that for the manufacture of titanium components through conventional processes, a massive block of raw material would be necessary and most of the material would be wasted. Because it is an expensive material, and the other manufacturing processes are also quite expensive, therefore, one method to reduce the time and cost of using titanium is to use the DED-Arc process [33]. With this process it is possible to manufacture large titanium components with complexity.



Figure 39:0,7-meter-long titanium wing flap support [34]

Nickel-Based Alloys

Nickel alloys are widely used in the nuclear and aerospace industries. These alloys are characterized by high resistance to high temperatures, low thermal expansion, and excellent resistance to corrosion. These alloys are difficult to machine due to abrasive

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carbide particles, so the DED-Arc process becomes a good technique to reduce material waste and the costs associated with processing this alloy [32].

Aluminium Alloys

Aluminium has high thermal conductivity, high thermal expansion coefficient and high hydrogen solubility. Aluminium alloys are difficult to weld due to the formation of an aluminium oxide layer and solidification behaviour. The use of the DED-Arc process in aluminium alloys is limited due to the porosity and turbulent puddle caused by the inversion of polarity, that results in low resolution of the components. However, using CMT technology it is possible to reduce the level of porosity in the components, due to the reduced heat input and results in finer equiaxed grains and makes the cleaning of the aluminium oxide and the substrate more effective. The aluminium is used to foundry repair parts, shipbuilding, on railways, on roads and in the aerospace and aeronautical industry [32].

Magnesium Alloys

Due to the fact that magnesium alloys are very light, they are important for aerospace, mechanical and biomedical industries in replacing aluminium and steel components in order to reduce the component's weight. As in the case of aluminium, magnesium also creates an oxide, but in the case of magnesium it is easier to remove it. This alloy can be recycled, has high specific strength and electromagnetic bending properties. The objective of using magnesium alloys in DED-Arc processes is to manufacture complex structures on a large scale, which would be impossible through conventional methods.

7. DED-ARC ADVANTAGES AND DISADVANTAGES

DED-Arc processes are used in the manufacture of additive metal structures, but they are also used to repair or add material to existing components. The DED-Arc process has been an alternative to traditional methods in the manufacturing of medium and large metal components, with high deposition rates and high level of automation.

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7.1 Advantages of DED-Arc

The DED-Arc method is a very promising technology to replace other classic methods used in the industry. Considering the characteristics of this DED-Arc process, it can be seen that, through this process, it is possible to solve existing problems in subtractive manufacturing processes, since this is a process in which the level of material waste is very close to zero, particularly in processes where the components do not require post-processing. Another characteristic of this DED process is that it does not require tools, moulds, or complex dies to produce the preforms.
Structures that require many components, in the case of conventional methods, they would be manufactured piece by piece. Through this method it is possible to manufacture a single component and obtain the same structure. The rate of deposition of material is quite high compared to other AM processes, so it is not wasted much time in the manufacturing of a component. The working area in this type of wire process is large, which requires less restrictions on the formats of the printed components, which gives greater versatility in the production of parts. DED-Arc is also very advantageous due to flexibility, as the desired product can be changed in a short time, which reduces costs.

7.2 Disadvantages of DED-Arc

Like any other process, DED-Arc also has its weaknesses, so it is also necessary to consider its limitations. Since the process has very little dimensional control, it has a weak surface finish, which means that it is often necessary to use post-processing on the components manufactured by this process. This factor increases the cost of production and limits its application in the manufacture of small components. On the other hand, the fact that it is an automated process makes it necessary to carefully define a route, which the machine that has the heat source must follow. However, with the appearance of stresses and deformations, it is necessary to realize that at certain points in the material defects may occur. Therefore, it is often necessary to redesign the projects initially developed, resulting in an undesired waste of time and resources, in the production of the components.
Another disadvantage observed in the DED-Arc processes is distortion and increased residual stresses, caused by high temperature gradients associated with the production of parts with complex geometries. Component tolerances and accuracy are affected by residual stresses and distortions, during the unstable phase that occurs at the beginning of the process.

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The DED-Arc process compared with other AM processes is the one with the lowest resolution in the developed materials [3].

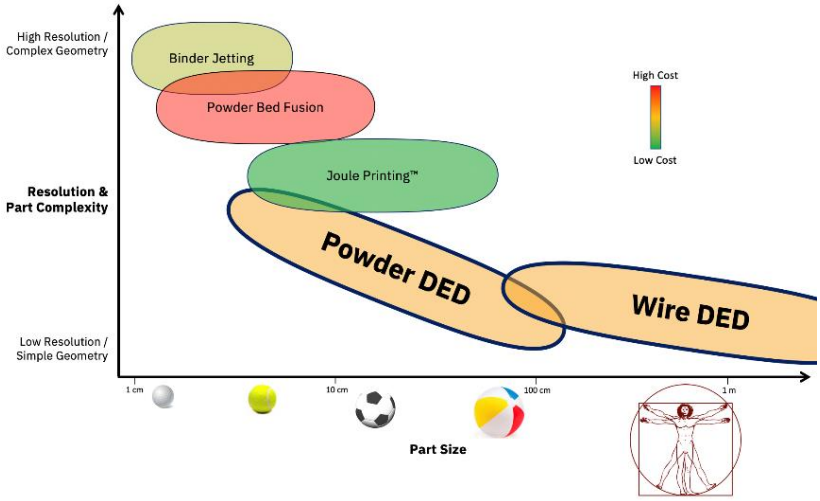


Figure 40: Comparison of Metal AM Technologies [3]

7.3 Speed of the DED-Arc process

The speed of the DED-Arc process affects its economy and its effectiveness. In DED-Arc processes, the printing speed of components is related to the resolution. The lower the resolution of the component, the faster the process. In the following figure, it appears that as the resolution increases, the process speed decreases, this is due to the complexity of the components, however the more complex the component, the more likely it is to require post processing [3].

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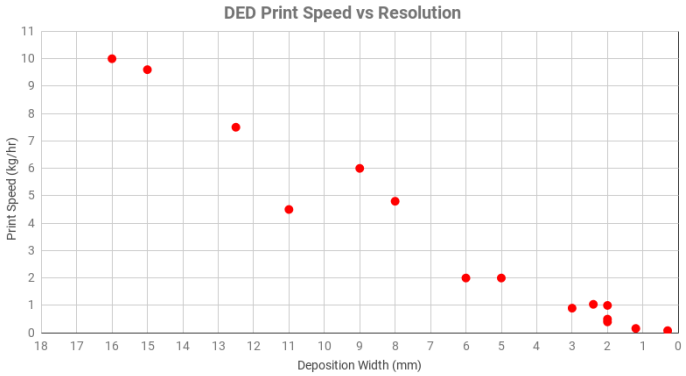


Figure 41: DED print speed VS resolution [3]

7.4 Economics of DED-Arc

As already mentioned, it is known that the high printing speeds in DED-Arc processes and the low cost of raw materials used in comparison with other processes used in additive manufacturing, make this wire DED-Arc process a low-cost process. However, it is also known that these processes are of very limited geometry due to the low resolution of the components, which implies more material deposited than that, which is necessary to produce the final piece. DED-Arc processes are most economically used for parts that are several meters long [3]. On the other hand, the production of small sized parts is not economical, since it implies long preparation times and other costs associated with construction [35].

The costs for several AM processes can be compared below. DED-Arc, labelled as “Wire DED” is one of the cheapest processes along with “Binder Jetting” and “Joule Printing” there is a big gap between these techniques and “Laser Powder Bed” and “E-beam Powder Bed”. It can also be observed that when compared with the other methods, DED-Arc has a very large post-processing cost.

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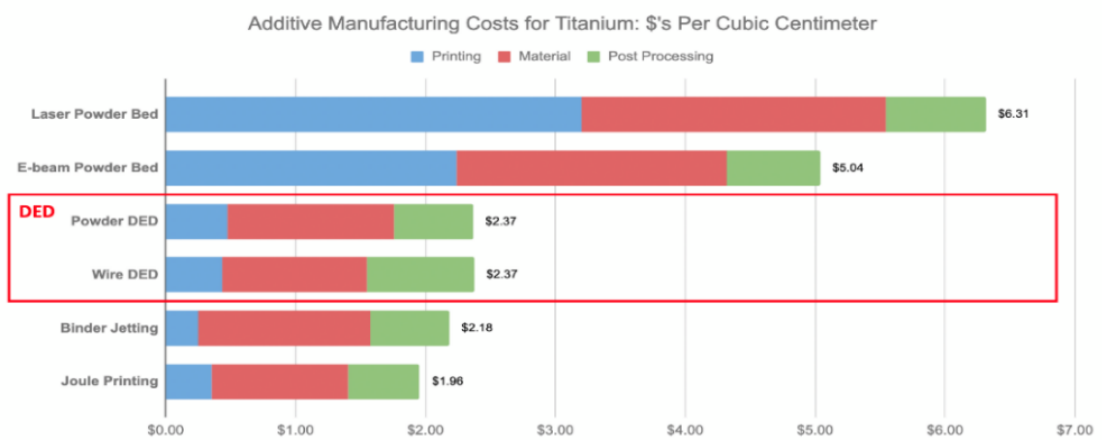


Figure 42: Additive Manufacturing Costs [3]

7.5 Wire vs. Powder

In the DED processes there are differences between those using raw material in powder and those using raw material in solid wire. The costs of the latter, in relation to powder systems, are usually much lower. Hardware systems based on a wire feedstock can print any type of weldable material, from high strength steel to stainless steel, copper, and aluminium alloys, but also to refractory materials. This system also offers more safety and quality than powder-based systems. One of the factors that limit powder as a feedstock, affecting its printing capacity and the mechanical properties of the components obtained, is the fact that powder absorbs a lot of oxygen and other elements present in the atmospheric air, making it very sensitive to the environment in relation to a wire process. [3] On the other hand, the use of powder will achieve components with a higher resolution, which implies having lower printing speeds compared to DED-Arc.

7.6 DED-Arc vs. other AM processes

DED-Arc is one of the additive manufacturing processes with many positive points in its application, both for industrial purposes and in rapid prototyping. On the other hand, it has a high rate of deposition of raw material when compared to other methods, thus requiring less time to produce a component. However, it has a negative aspect, which is the decrease in the dimensional and surface precision of the part, which does not occur in the other AM processes.

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7.7 DED-Arc vs. traditional processes

With improvements in this process, DED-Arc may become a substitute for conventional methods in the manufacturing of components. The systems used in this process allow the manufacture of large materials. One of the advantages of using this process over traditional methods is that the manufacturing cost does not increase with the complexity of the part. During traditional manufacturing it is quite common to remove excess material, and there are many materials with a high cost, such as titanium, which is widely used, and this can have a very high impact on the cost of production. However, components manufactured using DED-Arc do not remove material and therefore the material cost is much lower.

7.8 Typical DED applications

Through DED-Arc processes, companies achieve greater production flexibility and greater profitability. Through this method, globalization of production is possible, since 3D models can be shared anywhere in the world, allowing the production of the piece.
Finding use in the aerospace industry, this process can reduce time to market, as well as wasted material and time. This is due to its ability to produce large 3D printed metal parts and the use of lightweight materials, such as titanium [36].



Figure 43: Type of componentes obtained through DED-Arc [36]

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Directed Energy Deposition – Laser Beam (DED-LB) Manual

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1. INTRODUCTION TO THE PROCESS DED-LB

Additive manufacturing (AM) was born as a rapid prototyping manufacturing process with the process of joining materials in successive layer by layer to make objects. It allows designers to produce accurate physical prototypes directly from 3-Dimensional Computer-Aided Design (3D-CAD) model in few hours. These prototypes are used as test models before it is finalized as well as sometimes as a final product. Additive Manufacturing has many advantages over the traditional process used to develop a product such as allowing early customer involvement in product development, complex shape generation and it also saves time as well as money. Additive manufacturing possesses some special challenges that are usually worth overcoming such as poor surface quality, physical properties and use of specific raw material for manufacturing. To improve the surface quality several attempts had been made by controlling various process parameters of Additive manufacturing and applying different post processing techniques on components manufactured by Additive manufacturing. The main objective of this manual is to explore Directed Energy Deposition which is used in Additive manufacturing. DED-LB is a technology that works by melting material that is fed to a local site on the build layer, usually occurring within an inert gas atmosphere. While this can be used for nonmetal materials, it is predominately used with metals and metal alloys. Feedstock usually comes in the form of powder or wire and is melted with a focused energy source which in the case of DED-LB is a laser beam. DED-LB useful not only to create parts from scratch but also repair damaged parts with high precision. The mechanical properties of an AM part produced by wire-fed laser and powder laser deposition processes rely heavily on process parameters, load direction, and post build-up heat treatment. This process is very utilized in the aerospace industry since its one of the few processes that allows to easily create titanium and titanium alloys parts.

2. DED-LB MANUFACTURING STRATEGY

2.1 Fixturing

The Laser Metal Deposition (LMD), is a common name for Directed Energy Deposition (DED) processes that uses a focused thermal energy source (LASER) to melt powdered or wire metal at the focal point of the laser beam. Laser[1] equals a device having an

[1]The term “laser” is an acronym for “light amplification by stimulated emission of radiation”, which is a physical phenomenon for amplifying or generating coherent radiation (laser radiation). ISO 11145:2018(en), 3.19.1

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energized amplifying medium within an optical resonator that generates coherent electromagnetic radiation with wavelengths up to 1 mm by means of amplified stimulated emission. The machines[2] provide flexibility, precision and high efficiency for a wide variety of components. The high precision (with no backlash or wear) is achieved thanks to the linear motor-driven focusing head and optical scales on main axes. The higher overall equipment efficiency is accomplished by the reduced downtime and maintenance. There are no special skills needed for simplified maintenance.The demanding applications of reworking, repairing and coating deposition can be more easily handled thanks to an innovative laser head which exhibits a stable process behaviour. The controllers support up to seven axes of simultaneous movement and integrated automation for loading and unloading components and subassemblies, that is, robotics, automated stock entries, turntable or external feeding platform. The versatile machines provide different applications: not only Laser Metal Deposition but 2D/3D cutting and also welding in a single multipurpose solution with multiple machine configurations.



Figure 1: Example of Prima Additive's machine designs [1] Prima Additive, OPTOMEC®, RPM INNOVATIONS INC., TRUMPF, and DMG MORI are examples of companies that sell machines for this manufacturing process. There are several types of machines depending on the type of work desired.

The systems consist of a set of subsystems that are interconnected. All of these subsystems currently used consist of [2]:

[2]See Figure 1 and Annex A.

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- Control workstation;
- Laser source;
- Powder feeding system;
- Multi-axis CNC system.

In some cases, there are also a feedback control system and a controlled atmosphere chamber (inert chamber) in order to print reactive materials such as Aluminium and Titanium [3].

Regarding the configurations, the ones that can appear in the machines are:

Fixed Tables: Fixed tables exploit the very large working envelope to process large parts and provide great acessability from all sides. The accuracy of the part could be improved by better securing the substrate in the same position [3].

Split Cabin: The Split Cabin configuration allows the working volume to be separated in a removable wall and a sliding roof into two halves, where the parts are alternatively processed or loaded/unloaded in total safety. In this way, machine productivity is increased and, when needed for larger parts, the wall can be removed to restore the entire working envelope [3].

Turn Table: The installation of the turn table has the function of keeping the pool of fusion created in a horizontal plane. “This is the ideal solution for large-series production of medium to large-size parts” [3].

Automatic Shuttles: “The Shuttle Tables allow quick and automatic movement of parts and accessories outside the work area from the sides or from the front of the machine”. This perfect solution allows large, heavy parts to be handled outside the work area. It is also vital in the case of complex configurations [3].

2.2 Positioning and Nesting

There are many different configurations of DED systems, and the chosen configuration depends on the desired application. In DED, a multi-axis deposition head motion is possible and indeed quite useful, since the kinetic energy of powder particles being fed from a powder nozzle into the melt pool is greater than the effect of gravity on powders during flight. As a result, nonvertical deposition is just as effective as vertical deposition. If the substrate is very large and/or heavy, it is easier to accurately control the motion of the deposition head than the substrate. Conversely, if the substrate is a simple flat plate,

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it is easier to move the substrate than the deposition head. Thus, depending on the geometries desired and whether new parts will be fabricated onto flat plates or new geometry will be added to existing parts, the optimum design of the apparatus will change.

2.3 Layer thickness

Every part manufactured using a process of AM is built layer by layer. Therefore, layer thickness is one of the most important aspects to take into account as it varies depending on the parameters that the operator inputs into the machine. The implications of using powder or wire feedstock highly impact the DED process capability and the properties of the part being built. Layer thickness is highly determined by the wire diameter or the particle size distribution of the blown powder. Wire based processes can achieve higher deposition rates than powder-based ones, however it compromises the surface quality of the as-built part.

DED is a layer-by-layer manufacturing process. The laser beam generates a small molten pool - typically 0.25–1 mm in diameter and 0.1–0.5 mm in depth - on the substrate, into which feedstock material (wire or powder or a combination of both) is injected, leading to a growth in volume and mass of the melt pool. Layer thickness increased with the increase in the magnitude of energy provided (laser power), powder feed rate and powder gas flow. This is a result of having more material to deposit and more energy to also melt it. On the contrary, an increase in travel speed decreases layer thickness, due to the faster laser movement [40].

The wire/powder is melted as it enters the pool and solidifies as the laser beam moves away. Under some conditions, the powder can be melted during flight and arrive at the substrate in a molten state, however, this is atypical, and the normal procedure is to use process parameters that melt the substrate and powder as they enter the molten pool. A layer is generated by several consecutive overlapping tracks. The amount of track overlap is typically 25 % of the track width, which results in re-melting of previously deposited material, and typical layer thicknesses employed are 0.25–0.5 mm. After each layer is formed, the deposition head moves away from the substrate by one-layer thickness.

The first few layers may be thicker or thinner than the layer thickness set by the operator, depending upon the focal plane location with respect to the substrate surface and the process parameters chosen. As a result, the layer thickness converges to the steady-state layer thickness setting after several layers or, if improper parameters are utilized, the laser “walks away” from the substrate and deposition stops after a few layers [7].

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2.4 Dosing Factor

Primarily, when considering this topic, it is of vital importance to understand that it only makes sense to talk about powder doses and not wire doses. Considering that the powder is transported in doses to the material to be welded, it is necessary to explain how this whole process works. Powder is typically fed by first fluidizing a container of powder material (by blowing a gas through the powder and/or applying ultrasonic vibrations) and then using a pressure drop to transport the fluidized powder from the container to the laser head through the tubes [4].

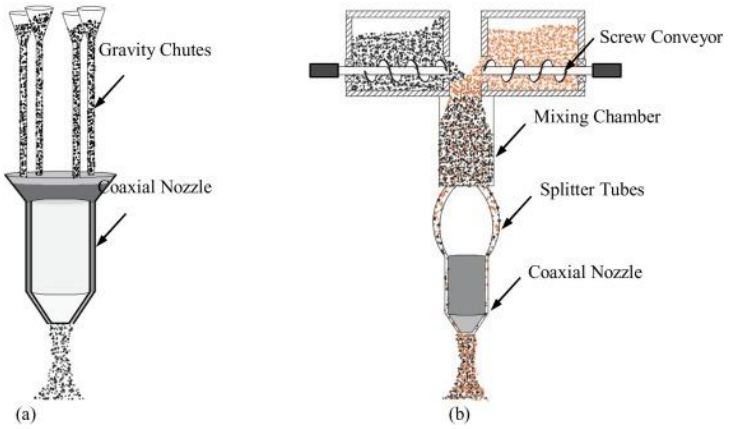


Figure 2: Gravity powder conveyance system (a) and Screw for powder metering (b) [4]

The dosing factor is the amount of powder needed to properly cover the exposure area of each layer without over or under dispensing powder. It is the quantity of powder added to each new layer by the initial container, which can increase or decrease [5]. For instance, if the container releases the same amount of powder that is deposited over the melt bath, it has a dose factor of 100%. Usually, greater values than 100% are required since the volume occupied by the material in a solid layer is smaller than in the powder form. In other words, there are different spreading behaviour over melted and unmelted powders. Thus, as a result of the layers solidification, there will be little or no space between powder particles, and so the area of powder bed is higher than the surface of melted areas [5].

It is important to note that, due to the changes needed throughout a process, this factor is commonly adjustable at any given time. Generally, at the beginning of a process, the values have to be adjusted to 150-200%, ensuring the full coverage of the new layer with powder material. Although, as the powder bed surface increases, it is also necessary to increase the dosing factor in the same ratio [5]. If the dosing percentage is insufficient,

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the term “short feeding” is used to describe it. This means that too low dosing factor of the powder, at the start of each layer, will not cover the entire melt bath. Consequently, it can lead to some negative impacts, such as porous parts or even complete build failure [5].

On the contrary, if the dosing percentage is too high, the amount of waste increases as unused powders are pushed into overflow containers. Therefore, these powders must go through the sieving process, a time and resource consuming process to filter out unusable powders, to be reused for future prints [6].

2.4.1 Powder Capture Efficiency

One of the advantages of using powder is that it is readily available when the material in question is metal or ceramic. When used, it is necessary to use excess powder because it is, unfortunately, impossible to have a 100% powder capture efficiency. At a first glance, it might seem that having to use excess powder might be a drawback, because more material is needed, driving the cost higher than it should. However, this also means that this process is more forgiving and 11 geometrically flexible because this excess powder flow enables the melted pool size to change, preventing swelling or overfeeding problems - which are the main drawbacks in material extrusion processes [7].

The use of powders helps to accomplish these changes in orientation more easily because the excess of powder flow allows for the dynamic levelling of the deposit thickness and melt pool in every region. To put it simply, it enables the melt pool to change size allowing it to fill the bottoms of the corrugated texture without making it too thick at the top where this happens. Contrarily, this is something that is hard to accomplish with wire feeding [7].

2.4.2 Powder Optimization

An addictive machine manufacturer created a software module - QM Coating - that controls the dose factor of the metal powder during the build process automatically. The operating principle of this software is based on the analysis of the application of each layer using a camera and photo diodes as seen down below. In this way, depending on whether an adequate quantity of powder has been applied, the powder dose factor is increased, reduced or a new coating is applied [8].

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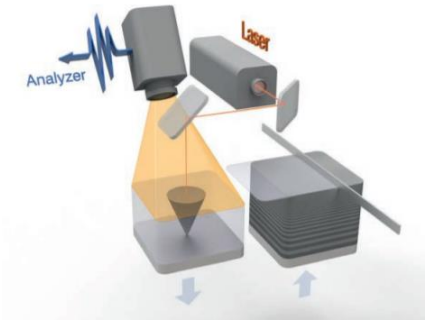


Figure 3: QM coating [8]

Some advantages of using QM Coating are:

- The real-time monitoring of the dosing factor;
- The reduction of setup times;
- The powder savings;
- The guarantee of an optimal coating throughout the entire build process.

The figure 4 below shows the differences in short feeding with and without the use of the software. In the first picture, the red parts illustrate the short feeding areas, and in the second image the graph highlights the continuous adjustments being made for the dosing factor in order to minimize waste [9].

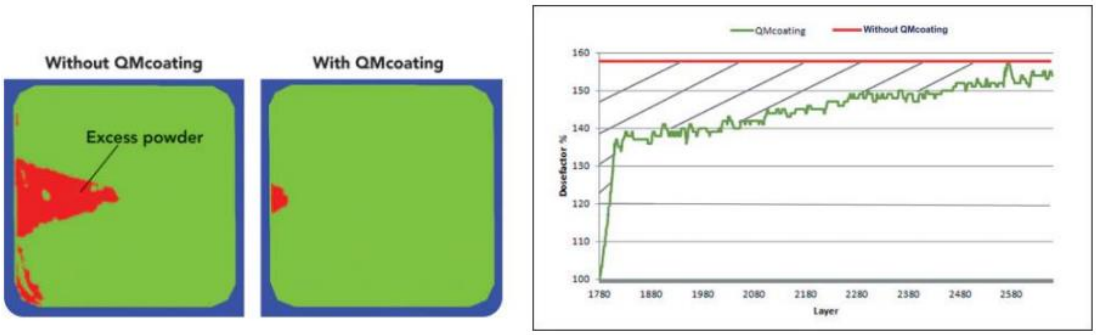


Figure 4: QM coating results [9]

2.5 INTERACTION OF LAYERS

In DED, as in other AM processes, one layer is fused to the material below, thus, in the as-built state, it is likely that the mechanical properties of the part are anisotropic in

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nature. When a laser is focused to a small spot size, there is a region above and below the focal plane where the laser energy density is high enough to form a melt pool. If the substrate surface is either too far above or too far below the focal plane, no melt pool will form. This localized heat input and heat removed through conduction, convection, and radiation create complex thermal gradients. When combined with the contraction of the melt pool during rapid solidification, plastic deformation and residual stress are induced and negatively impact the finished part, causing it to crack or distort.

As can be seen from the following figures, the microstructure of a DED part can be different between layers and even within layers. In the Ti/TiC deposit shown in Figure 5, the larger particles present in the microstructure are unmelted carbides. The presence of fewer unmelted carbides in a region is due to a higher overall heat input for that region of the melt pool. In Figure 6(a) it is possible to compare the thickness of the last-deposited layer with the first - or second - deposited layer and estimate the proportion of a layer that is remelted during subsequent deposition.

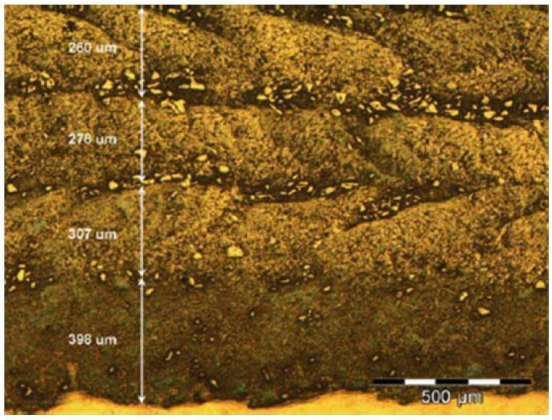


Figure 5: LENS-deposited Ti/TiC metal matrix composite structure

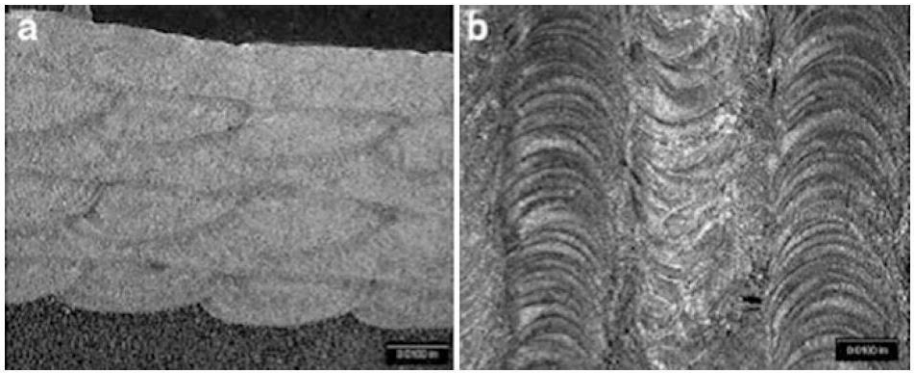


Figure 6: Co-Cr-Mo alloy deposit on Co-Cr-Mo alloy: side view (a) and top view of deposit (b)

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2.6 DISTORTION AVOIDANCE

Distortion can be defined as a deviation that occurs in a material in direct comparison to its original shape. This well-known phenomenon, besides being unexpected, is affected by several parameters such as the material proprieties and geometry as well as the residual stress state and surface preparation. Therefore, predicting distortion may prevent delamination, premature fatigue failure and buckling of components [10].

In AM, three distortion modes can be observed (angular distortion, buckling, and longitudinal bending). Less common, angular distortion and buckling, are both a result of transverse shrinkage. Besides this, longitudinal bending, which is mainly attributed to the contraction of the molten material after deposition [11]. DED-AM components have steep stress gradients and an anisotropic microstructure caused by the rapid thermo-cycles and the layer-upon-layer manufacturing [12]. Consequently, heat treatments are useful to diminish distortion. Moreover, distortion must be reduced in the process to guarantee the geometric accuracy of the final part.

During the past years, many studies have been developed to obtain more information along with solutions to solve this problem. Undesirably, this type of research is very difficult, due to the time spent and because this kind of studies use to work with complex simulations that can be done using Finite Element Modelling. Specially, it is important to refer that, for example, when working with thermal analysis the process involves difficult calculations, so it is important to make a set of assumptions and sometimes some simplifications. Moreover, this type of research demands a higher computational power which demands higher costs.

Nowadays, laser displacement sensors are used to measure substrate distortion. Taking advantage of this technology, a group of investigators studied the impact of directed energy deposition parameters on mechanical distortion of Ti-6AI-4V [13] .This research has shown that the effect of initial substrate temperature on distortion depended on the size of the substrate. Explaining briefly, two types of substrate were tested - one with 2.54mm thick and other with 12.7mm thick. The substrate was preheated before deposition and it was concluded that the preheating reduced the total amount of distortion while on thick substrates, preheating increased the amount of distortion. it is shown that the preheating of a substrate may result in changes on distortion [13].

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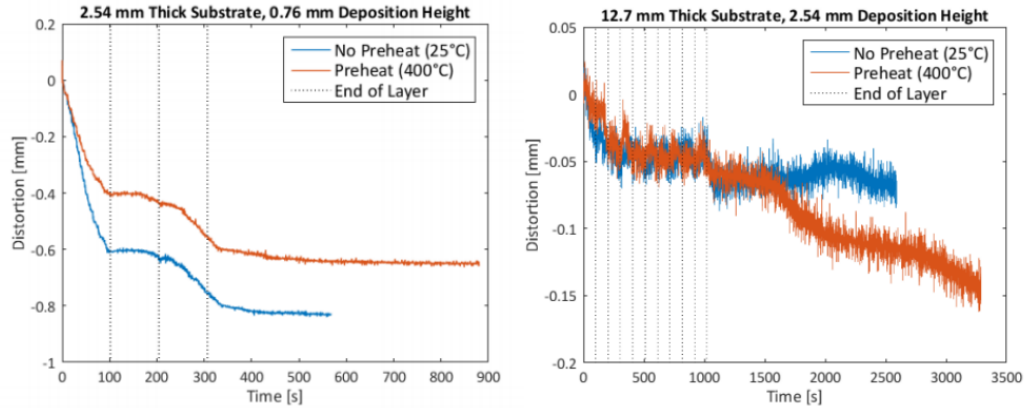


Figure 7: Effect of substrate preheating on distortion on a 2.54 mm thick substrate (left) and on a 12.7 mm thick substrate (right) [13]

By creating thermo-mechanical models, simulating residual distortions, usually along with residual stresses, several models can be produced [14]. These models can help the industry in the hard task of reducing distortion in DED, due to the possibility to control several parameters until the ideal ones are found for the desired objective. Furthermore, it is important to refer that the conclusions drawn based on the study of a given component or material cannot always be extrapolated. In addition, the control of distortion takes into account the studies developed during the past years for several materials, under many conditions.

Moreover, many other solutions can be found depending on several parameters. The combination of conventional processes and DED can create interesting solutions but, in some cases, it might originate undesired distortion. Some papers offer methodologies with the purpose of understanding and mitigating distortion using Finite Element Simulations (FEM).

2.7 DEPOSITION RATE/PRODUCTION RATE

2.7.1 Deposition Rate

Deposition rate is the ratio of added material mass deposited into the part to the total mass of added material used during the manufacturing process. The material can be in powder or wire form. For this reason, it is intuitive that both deposition rate and production rate are going to differ depending on the type of feeding material.

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The deposition can occur on a substrate or in an already existing part when a new geometry is desired. The deposition is controlled by relative differential motion between the substrate and the deposition head [7]. Deposition can be done vertically, but also non vertically because the kinetic energy of the powder particles, as they exit the powder nozzle, is sufficient to overcome gravity. As a result, this allows multi-axis deposition, making this process even more attractive due to its versatility which can become useful in various applications [7].

The powder melts as it enters the molten pool and solidifies as soon as the laser beam moves away. It is also possible to melt the powder before it reaches the part, but this is not commonly done. Not only does the molten pool that is generated has enormous cooling rates, ranging between 10^3 up to 10^5 ºC/s, but it also has large thermal gradients. These process characteristics are capable of producing nonequilibrium grain structures and unique solidification grain which are impossible to recreate through traditional processing structures - depending on the material being used. DED deposits the material, generating a layer after it solidifies. Then overlapping occurs (usually around 25% of the track width) and this is how the part is then created. Each lap has a thickness of around 0.25-0.5 mm. Knowing that each layer is very thin, it is important to stress that when a new layer is deposited above another existing one, it causes the layer bellow to re-melt [7]. To clarify, both types of feeding systems have their benefits and drawbacks. The selection of the proper feeding system should always be done after the determination of the deposit geometries, whether geometrical accuracy is crucial and whether there is a subtractive milling integrated with the additive deposition head.
When using a powder feeding system, it is important that the powder stream is aligned with the laser to minimize material loss. [15].

DED-LB processes are capable of achieving large volume deposition rates [16]. Despite this, a high deposition rate will lead to poor resolution and surface finishing [7], which

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are already a drawback in this type of AM. To attain better accuracy and surface finishing, it is required to adopt lower deposition rates and small beam sizes.

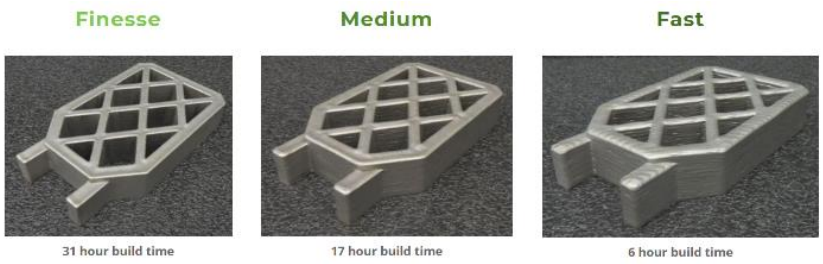


Figure 8: Build time influence on part's resolution and suface finishing [17]

2.7.2 Production Rate

Production rate is referring to the number of parts that can be produced during a given period of time. It is dependent on the parameters chosen by the engineer but also by the response time of the control system. For example, if the system's response time is long when measuring the height of a layer, the deposited part might have spots higher than it should in the same layer between two measurements. Therefore, it must be taken into account the computing power of the machine being used and also the sensor's settling time in order to mitigate unwanted imperfections. If such thing happens, the production rate will decrease due to the necessity to later remove those imperfections through machining [15].

It is important to set a maximum speed at which the operation can occur. During production, the velocity will be adapted according to layer thickness to achieve volume build rate balancing and prevent imperfections. In figure 9, *v* represents the current speed, *h* the desired layer thickness and *D* the laser beam diameter [15].

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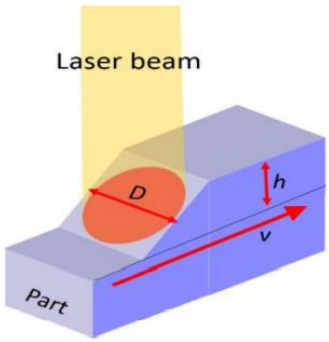


Figure 9: Visualization of DED-LB process [15]

The volume build rate can be calculated using equation 1, or equation 2 if one shall consider heat input and material properties:

$$V_{max} = v \times h \times D \quad (1)$$

$$V_{heat} = \frac{\varepsilon \times P_{laser} - P_{loss}}{c_p \times (T_{melt} - T_{powder}) \times \rho} \quad (2)$$

"P_{laser} represents the laser output, P_{loss} the heat loss rate from the melt pool, c_p the specific heat of the material, T_{melt} and T_{powder} the melting temperature and powder temperature, respectively, ρ the material's density, ε the laser efficiency and V_{heat} the theoretical volume build rate based on heat input and material choice. It is also important to refer that the laser efficiency is going to vary according to the material reflection rate" [15].

If the deposition rate is known, calculating build time is quite simple as there is only the need to use equation 3 [16]. Although, it must be stressed that this equation cannot take into account slight parameters variations, such as deposition rate, so it is only valid if the deposition rate is constant throughout the manufacturing process.

$$t_{per\ part} = \frac{part's\ mass}{deposition\ rate} \quad (3)$$

It is also relevant to consider the working volume of each machine. A bigger working volume allows repairs or modifications of large industrial components to be made. Therefore, it is important to decide what type of machine is best suited depending on the type of part that will be manufactured or a repair that is required. On the one hand, if a company only wants to manufacture parts whose volumetric dimensions are small, there

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is no need to invest in a machine with a large working volume as it will occupy more factory floor space than it is needed. On the other hand, if a company has a need to do repairs of large industrial components, then a machine with large volumetric rate is required so that the part to be repaired can fit inside it [16].
Overall, this process is capable of producing parts faster, when compared to other more conventional and cheaper production methods, due to the lack of need to do extensive surface finishing processes.

2.8 HYBRID BUILD STRATEGIES

Over the past few years, in order to achieve a good combination of deposition rate and accuracy, hybrid DED-AM manufacturing processes became a tendency among the industry. Additionally, depending on the hybrid processes, it can be classified into simultaneous, assisted, mixed and sequential processes of two or more physical processes and phenomena [18].
Hybrid strategy consists in integrating different DED-AM techniques with traditional manufacturing processes. Consequently, it results in a more interconnected, efficient and flexible manufacturing environment. Besides the cultural and technical challenges, when combined with Computerized Numerical Control (CNC) machining, using, for example, a single hybrid equipment, DED results in a powerful technology to obtain complex parts with a precise finish [19] (good surface roughness and low tolerances), employing minimal material and sometimes reducing the process time.

The strategy of integrating processes to create a hybrid cell, on Ramp-up of hybrid manufacturing technologies, is commonly divided into three main parts: process and parameter development; integration into a commercial manufacturing environment, evaluation and testing; knowledge and process management [20].

K. A. Lorenz et al. [21] on Review of Hybrid Manufacturing, briefly explain all these activities. The paper begins by explaining the importance of process and parameter development, referring that parameters, depending on the material and technique, can be easily accessed using several platforms or instead, for more difficult processes, various research, delineating the strategy to optimize parameters, can be consulted. However, for Hybrid Manufacturing Systems (HMS), it is ambiguous how the definition of the parameters will be handled [21]. The review states that integrating, for example, blown powder laser DED into a machine tool requires that some important technical challenges

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need to be solved. Some of the challenges are maintaining the working envelope of the machine tool as well as the use of coolant. The authors add that in an HMS the existing equipment usually consists of a laser and optics to generate and focus light on the substrate. So, it is crucial that the cleanliness of the optical chain is kept intact, in order to preserve the laser system and the beam quality [21].
In addition, it is reinforced by the researchers that many approaches during the past years used the processing heads attached off-spindle centre line. Moreover, when machining, the coolant strategy needs appropriate attention to make sure that the optics do not get contaminated. However, this paper mentions that given the recent HMS it appears that many of the issues have been solved. The authors conclude this topic saying that currently a special technology is used in some of these advanced systems, providing the storage in a machine tool magazine of processing tools. Additionally, during the machining process this ensures the protection of the tools from contamination [21].

To illustrate this subject, R. Liu et al. [22] on Aerospace Applications of Laser Additive Manufacturing, analyse a common layout of a hybrid manufacturing process for component repair. The authors present a particular system, figure 10, which includes two major systems – a Laser metal deposition system and a CNC milling machine system. Moreover, it is mentioned that the laser process provides the ability to spread metal powder locally in the defect area while the multi-axis CNC not only machines, but also does multi-axis deposition, in this particular study, for complex aerospace components.

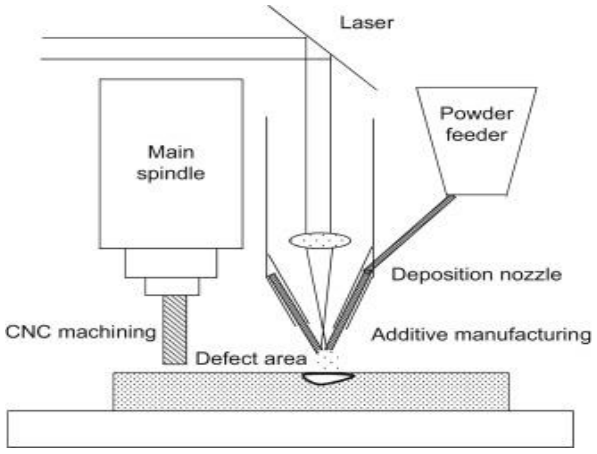


Figure 10: Common layout of a hybrid manufacturing process [22]

Many hybrid manufacturing researches and commercially available systems have been developed during the past decades, as mentioned above. Some examples are: Combined

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Metal Build Up (CMB), developed by Fraunhofer Institute of Production Technology & Fraunhofer Institute of Laser Technology; Hybrid Manufacturing, developed by ELB & Hybrid Manufacturing Technologies; Hybrid Multitasking, developed by Mazak & Hybrid Manufacturing Technology; Laser Aided Manufacturing Process (LAMP), developed by University of Missouri; along with many others [21].
On the last decade, for example, the company Hybrid Manufacturing Technologies (HMT) was formed to conceptualize a revolutionary approach to hybrid manufacturing, combining additive manufacturing and CNC machining [23]. In addition, HMT, specialized in hybrid subtractiveadditive systems, proposed many interesting solutions specifically to design, build, and integrate laser heads into existing CNC.
AM allows to create complex geometries, but with a poor surface quality. With Directed Energy Deposition type AM systems, either Laser Engineered Net Shaping (LENS) or Wire Arc Additive Manufacturing (WAAM), the material can be deposited with greater degrees-of-freedom using multi-axis coordinated motion, is not limited to depositing on planar surfaces and the surface geometry can not only be non-planar but can also be extremely complex.

2.9 PARAMETERS ADJUSTMENTS ALONG THE LAYER

It is in the norm, for AM machines to be pre-programed with optimized process parameters. The problem with relying on this is that their optimizations are directly related with their proprietary materials, and more often than not, different materials from different sources are used for different applications, this is why it is so important to rectify these optimizations for every change that is made to the system. The optimization of these parameters depend on various factors: material, geometry, application, etc. When talking about the quality of the final part, the consistency of the melt pool size and shape are crucial, and they are directly impacted by the deposition rate. Other important parameters to track are: laser power, motion speed, feeding rate, etc.As a pointer, lowering the laser power and increasing the feeding rate have similar effects of the part being processed. Likewise, increasing the laser power or the feeding rate and decreasing traverse speed all have similar effects as well – an increase deposit thickness. Track width hatch spacing must be set so that adjacent beads overlap, and layer thickness settings must be less than the melt pool depth to produce a fully dense product.
Sensors can be used to track many parameters in order to correct the in the moment, diminishing fluctuations and increasing the overall final quality of the part. These sensors

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can control, in real time, parameters such as: deposit height, melt pool size, shape and temperature, travel speed, powder flux, etc.

Sl. No.	Laser Power (W)	Nozzle type	Geometric Specification a. ϕ_T (mm) b. α c. F (mm)	Powder Mass flow rate (g/min)	Carrier gas flow rate (l/min)	Scanning speed (mm/s)	Track Dimension (mm)	Ref
1.	500	4-Jet Discrete coaxial	a. 1.19 b. 18.25° c. 9.27	6.5 (Inconel 718)	4	10.58	Height: 0.1-0.4 Width: 1-1.4	[134]
2.	2100	4-Jet Discrete coaxial	a. 2 b. ≈25-30° c. ≈10	21-31 (EuTroLoy)	-	8-15	Height: 0.87 Width: 3.32	[100]
3.	2100	Continuous Coaxial	a. 1-0.50 b. ≈26-30° c. ≈13 ± 2	8-15 (EuTroLoy)	-	8-15	Height: 1.06 Width: 3.48	[100]
4.	1000	Continuous Coaxial	a. 4 b. ≈30° c. 20	3 (Stainless Steel)	2-8 m/s (flow velocity)	10	--	[135]
5.	325	4-Jet Discrete coaxial	a. 1.12 b. 25° c. 8.76	30 (SS316L)	3.78	16.9	Dimension of the order of 0.50	[131]
6.	2.4	Continuous coaxial nozzle	a. 1 b. 27° c. 30	3.6 (SS304)	15	15	Height: ≈1 Width: ≈ 3	[103]
7.	2100	4-Jet Discrete coaxial	a. 1.5 b. 25° c. 13	6.17 (SS316L)	9	3-8	Height: ≈0.2-0.6 Width: ≈ 2-4	[109]
8.	4500	Single jet off-axis	a. 3 b. 45° c. 15	20-40 (SS316L)	20-40	-	Track area: 0.48-7.82 mm²	[118]

ϕ_T: Outlet Diameter; α: Powder injection angle from vertical; F: Powder stream focal point from the nozzle outlet

Figure 11: Geometric dimensions and process parameters for a typical DED system

A very important parameter to control, when using a powder feedstock, is its flow rate. There can be the misconception that a high flow of powder can directly increase the deposition rate and consequently the overall production rate. But this is not the case. When it is used an out of proportion flow of powder, much of it won't even come near the melt pool since they will collide with other particles and diverge from its course. Also, when a certain amount of powder is reached it will stay on top of the melt pool, creating a phenomena called "self-shielding effect". Only a certain amount of powder can be captured by the melt pool, so if the laser power remains unchanged, a surplus of powder deposition wont significantly change the deposition rate. This act, ultimately, only contributes to waste of material.

Velocity has an important role in DED processes. A high particle velocity, is directly correlated with a decrease in the capacity of the melt pool to catch powder, resulting in a decrease of the surface finished quality. Also, it decreases the time between the exit of the powder from the nozzle and the collision with the melt pool, this can lead to a decrease in radiative heating by the laser beam. Consequently, the higher the particle velocity higher the laser power required to melt the particles. The opposite is also true, a very low velocity also decreases the catching efficiency and the surface quality, because the particles can't break the tension layer of the melt pool.

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The angle of powder deposition, in the melt pool, has a significant influence on melt pool stability. When too many powder particles are directly in the path of the laser beam, the volatility of the melt pool increases, and significant spatter occurs.

3. EQUIPMENT AND ACCESSORIES

3.1 Optical System

The optical system used in this process consists of several components. To guarantee its correct functionality, all essential components must be installed and considered throughout the machine project. In addition, all optical components must be adapted to the wavelength of the produced laser beam that is emitted, which means that a system may not be compatible for different types of lasers. With that in mind, the main components are described below [24].

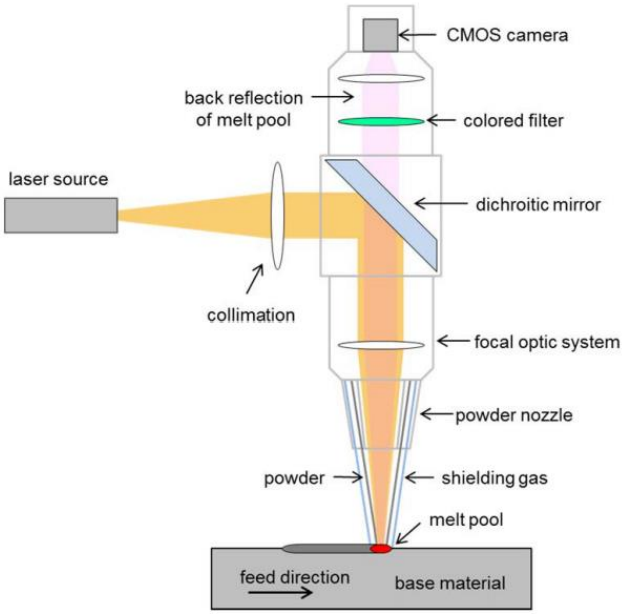


Figure 12: Schematic of a fibre-coupled diode laser system [25]

3.1.1 Laser Source

The laser source is responsible for providing the laser beam for the process. There are different types of laser sources currently available (typically between 500 W and 6000 W), each with diverse functional characteristics. The laser power is directly related to the size of the fusion pool and, consequently, to other process parameters. The relation

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between the increase of the melt pool size pool and the used laser power is almost linear [25].The types of laser mentioned in the sections below are the most commonly used.

3.1.2 Solid-state lasers

According to the authors [26], “the term solid-state laser refers to a laser whose gain medium consists of active ion species introduced as impurities in an optically transparent host material (typically crystals or glasses)”. The most common means of gain achievement are Nd:YAG, Nd:YVO4, Nd: Glass, among others [27].The possibility of being transport by flexible glass fibres comes from the fact that the light emitted has a wavelength around 1 μm. Since there is radiation emission, the operator must be provided with adequate protection for the eyes in order to do not damage his vision [24].

3.1.3 Gas lasers

With a similar working principle, “a gas (usually CO2) is electrically excited (pumped) via two electrodes, creating the laser beam, which is directed out of the laser source” [28].

The gas mixed with nitrogen provides a superior pumping efficiency and with helium provides cooling. The gas mixture can be carried out in two behaviours: stationary or flowing. Unlike solid-state lasers, these CO2 lasers emit radiation at a wavelength of 10.6 μm, not allowing the transport of radiation through the glass fibre. Alternatively, the optical path must be made through the reflection of a mirror [24].

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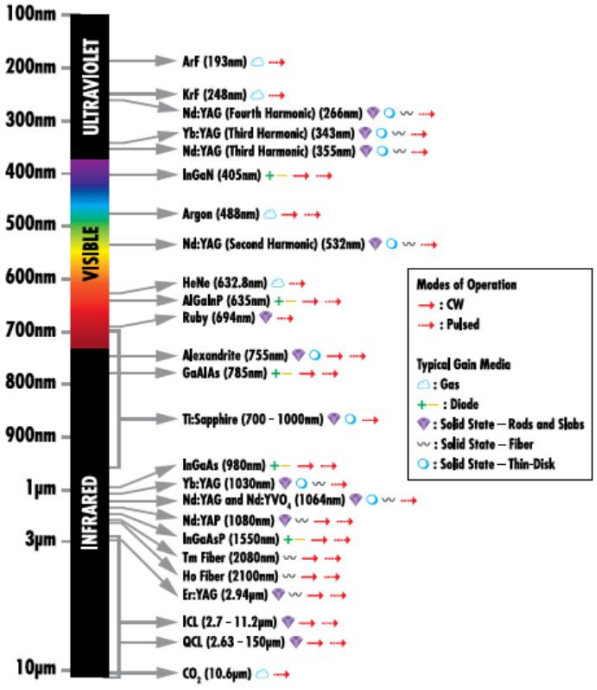


Figure 13: Common comercial lasers with typical modes of operation and gain media, where CW stands for continuous wave [28]

3.1.4 Diode lasers

“Diode lasers contain a semiconductor p-n junction as the gain medium”. They have the highest power-to-cost ratio and high-power conversion efficiency, high quantum efficiency and a wide range of wavelengths available [28]. Diode laser’s wavelengths vary between 790 and 1080 nm.

3.1.5 Chiller

The laser system has a chiller unit attached, responsible not only for cooling it, but also for cooling other machine components. Deionized (DI) water is commonly used as a coolant, and it must be adjusted to circulation system materials (since it can be highly aggressive with some materials). In this case, for example, DI water is destructive with copper [24].

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3.1.6 Laser head

"The laser head is the machine module responsible for adjusting the laser beam for its specific operations. It contains the laser focusing unit, which is a set of dedicated lenses for adjusting the focal position of the laser beam and the focus diameter. This focusing operation is achieved within the attached collimator". As mentioned before, at the end of the laser head, a process nozzle is attached. This component is chosen according to the laser beam properties required for a given function, influencing the achievable focal diameters and the position of the focus [24].

3.1.7 Collimator

The collimator, attached to the laser head, reveals to be an important module responsible for receiving the diverging light from the optical path (such as the fibre cable) and producing a parallel beam, increasing its output quality. Furthermore, it is responsible for the motor-driven focus positioning and diameter adjusting [24].

According to the physical requirements, the material of the collimator component should be made by high melting point and high-density alloys. Physical requirements aim that collimator components material should be made by high melting point and high-density alloys in order to effectively absorb the hard X-ray radiation [29].

3.2 Powder/wire Feeding System

3.2.1 Powder feed system

Powder-fed systems blow powder through a nozzle, which is melted by a laser beam on the surface of the part or the substrate, depending on its application [30]. Powder is considered the most versatile feedstock since most metallic and ceramic materials are already available in powder form. This process is highly precise and is based on an automated deposition of a thin layer. The need for the use of excess powder is explained by the fact that the capture efficiency is less than 100%, by not capturing all the powder in the melting pool. The recycling of the powder should only take place if it is recaptured in a clean and adequately sized state [7]. Excessive powder feeding is not considered a negative aspect, as it allows DED processes to be geometrically flexible and tolerant. The dynamic change in the size of the melt pool is only possible thanks to the excess powder flow [7].

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By focusing a laser on a small spot size, there is a region above and below the focal plane where the energy density of the laser is high enough to form a melt pool. The location of the melt pool in relation to the focal plane, the scan rate, the laser power, the powder flow rate and the surface morphology influence its height and volume. In practice, to form the first layer on a substrate, the focal plane of the laser is buried approximately 1 mm below the substrate surface. Thus, the lower part of the substrate material melts and becomes part of the melt pool flow [7].
The first layer consists of a mixture of melted substrate with material from the powder feeders. "The amount of material added to the surface to form the first layer is dependent on both the process parameters and the location of the focal plane in relation to the substrate surface flow" [7]. The use of powders has a clear advantage over the wire feed: the change in orientation between layers is easily achieved by the presence of excessive powder flow. It provides a dynamic levelling of the deposit thickness and the melting pool in each region of the deposited layer flow [7]. "Spherical particles in the range of 50-200 μm have the best feeding properties in this process". [31]. DED is distinguished by having the ability to produce fully dense objects, as well as gradients, in the manufacture of large and/or functionally graded components [31].

3.2.1.1 Types of feeding

Powder injection can be done using 3 methods [32]:

- Off-axis powder injection (there is only a single powder stream fed laterally into the laser beam);
- Coaxial continuous powder injection (the powder stream cone is produced and encloses the laser beam);
- Discontinuous coaxial powder injection (the laser beam is fed coaxially by three or more streams of powder).

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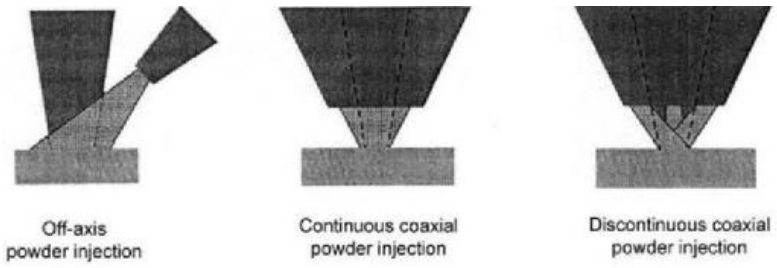


Figure 14: Types of powder injection methods [32]

Nozzle calibration is a critical step as the efficiency of the powder can be greatly improved with the correct set of parameters. The focus point of the powder flow must coincide with the focus of the laser beam, in order to guarantee a good deposition operation [24].

Off-axis powder feeding: Off-axis powder feeding consists in a single nozzle positioned laterally to the laser beam, and a single powder stream is created. The angle between the nozzle and the work piece (α) and the distance between nozzle tip and the workpiece (l) determines the position [33].
The positioning of the nozzle close to the melt pool implies that it is exposed to laser beam reflections. Water-cooled nozzle is a good solution to ensure long-term operation without any damage. "Deposition will vary based on other factors, such as the nozzle inclination, distance to the part or opening type and size" [24].

Continuous coaxial feeding: "Coaxial powder feeding is a method developed mainly in the last decade"[34]. It consists in powder introduction as a toroid around the laser beam, focused on a small spot size using the shielding gas flow. This feeding system allows a better powder capture efficiency and a better focus of the shielding gas, ensuring protection of the melt pool from oxidation [31]. Typical efficiency values of 40 to 50% are now replaced by values up to 90%, depending on ratio between the core diameter of the powder stream and the diameter of the laser beam in the workpiece. Therefore, the coaxial powder feeding has been popularly applied to fabricate complex 3D components. "Important process parameters include the apex angle of the cone, diameter of the powder stream focus, distance between focal point and nozzle tip and powder feeding properties"[24].

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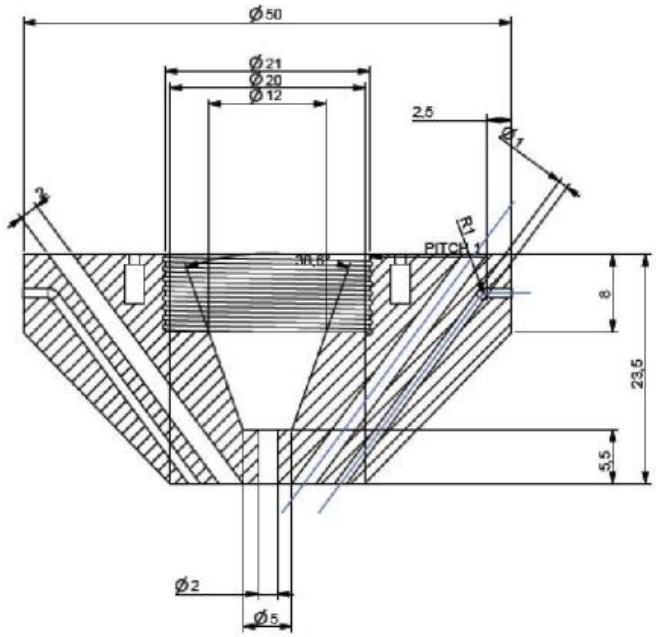


Figure 15: Coaxial nozzle design [32]

Discontinuous coaxial feeding: The discontinuous coaxial powder feeding consists of a coaxial powder head feeding with multiple nozzles (above 3) to produce a discontinuous coaxial powder stream (DCPS). DCPS is influenced by many characteristics such as spatial shape, mass concentration distribution, velocity and trajectory of particle that can directly affect the deposition outcomes including powder utilization efficiency, deposition rate, geometrical accuracy and clad quality. All of these characteristics are mainly determined by many operational parameters, such as conveying gas flow rate, powder-feeding rate, the number of nozzles, nozzle arrangement and size [35].

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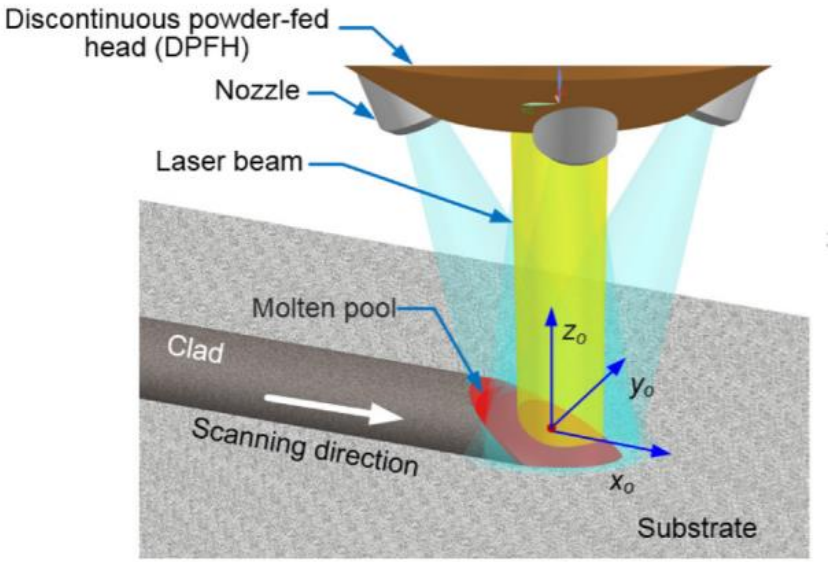


Figure 16: Schematic of the DCPS structure DCPS with four nozzles [35]

3.2.2 Wire feed system

In contrast to the powder feed, wire feeding usually provides better capture efficiency (as the volume of the deposit is always the volume of the wire that was fed) and lower part porosity, although it is more indicated for simple geometries or surface coating. During the DED-LB process, the laser melts the additive wire material. “The resulting layer has high hardness, wear and corrosion resistance as well as a higher density and stronger bonding to the base material compared to competing processes. Due to the low energy input into the substrate, distortion is minimized” [36]

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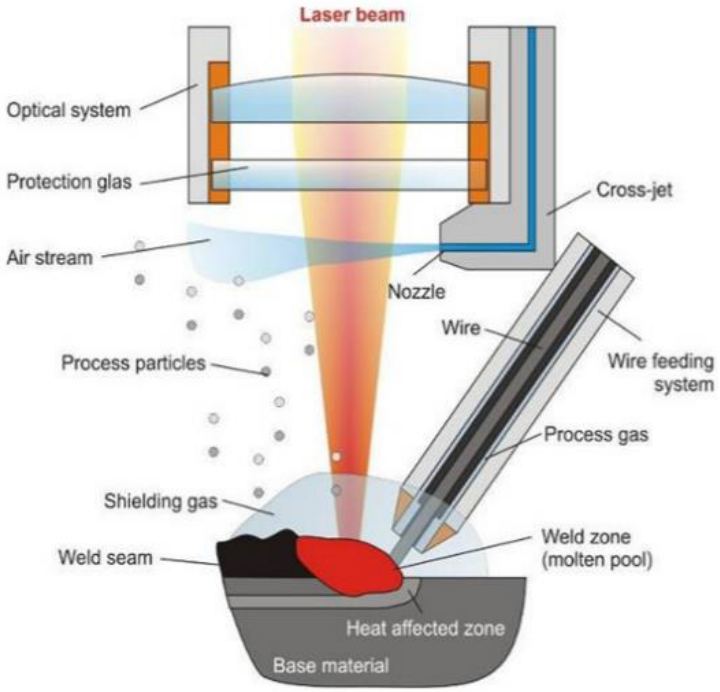


Figure 17: Schematic illustration of Wire-feeding DED-LB [36]

The main advantage of wire deposition is essentially the ability to achieve full material's efficiency. However, the greatest difficulty is in the delivery of the wire in complex geometries. The fact that it has a higher surface roughness, limits its applications in different fields of manufacture. From an economic point of view, the manufacture of wire material in contrast to the powder is comparable cheaper [31].

3.3 Gas System

In DED-LB process, the use of a gas system is required. In comparison with most arc welding processes, the gas system provides two main purposes. The most common one is to provide shielding properties to the melted powder/wire being used, however the gas used can also help in the transportation of the powder to the nozzle. Both these properties will be better explained below [37].

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3.3.1 Shielding Properties of Gas

Just like in Laser Beam Welding (LBW) the use of shielding gas in this process is often required. Since the process of DED-LB does not require a vacuum environment, unlike DED-EB (which uses an electron beam as a heat source), the melted material is exposed to contamination which can result in possible defects. One of the main dangers is the oxidation that can result from the oxygen present in the air near the machine that can cause porosity, lack of material, and therefore lead to cracking [38]. The most used gases are the inert ones, like argon for instance [39]. These are the best choice since a reaction between the melted powder/wire and the atmosphere is less likely to occur. The shielding gas is directed through a specific nozzle.

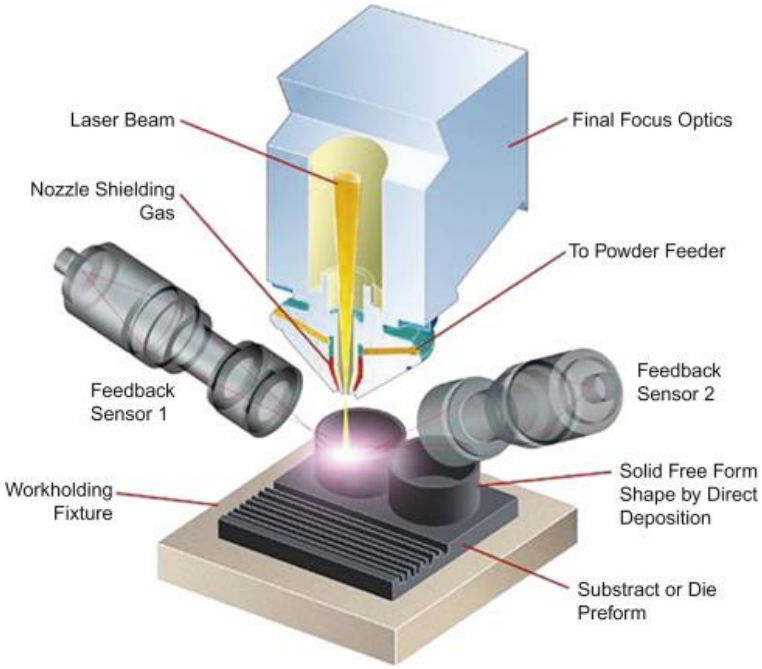


Figure 18: DED machine schematic [7]

3.3.2 Drawbacks of the use of carrier gas

The use of gas is quite common among DED setups, however, it brings some limitations to the process itself. It was stated [37] that there are several studies that show that high velocity particles lead to a significant decrease in powder capture efficiency and creates a poor surface finish to the melted and then solidified powder. These particles also tend

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to stick to the heated nozzle surface and to the trailing part of the clad track, resulting in a decrease on the service life of the nozzle. Some researchers have concluded that the use of shielding gas results in the increase of the convective cooling in the melting pool, leading to a higher energy dispersion [42].
If the shielding and conveyance gases are eliminated from the process, it is possible to obtain a higher heat intensity for the same laser beam power, resulting ultimately in a more energy efficient process.

3.4 Powder Feeding System

In DED-LB it is possible to feed the material in two distinct formats: powder and wire. The gas system plays a significant role when the first option is in use since the usage of gas brings advantages in the transportation of the powder. To better understand this, we must first identify the three main categories regarding powder handling for DED. These are powder metering, powder conveyance and powder delivery [37].

The first phase, powder metering, involves the measure of the correct amount of powder from the reservoir to be delivered in the melt-pool. Next, we have powder conveyance, which is the powder transportation from the metering setup to the nozzle itself, that is commonly done by an inert gas like argon, for instance. There are also other mechanisms such as vibration and gravity-driven system, however the use of a gas system does not play a significant role in these cases. Lastly, the third phase named powder delivery is performed via powder delivery nozzle and consists in the converging of the powder stream into a single focal point. All these three phases are often interconnected and have combined functionalities [37].

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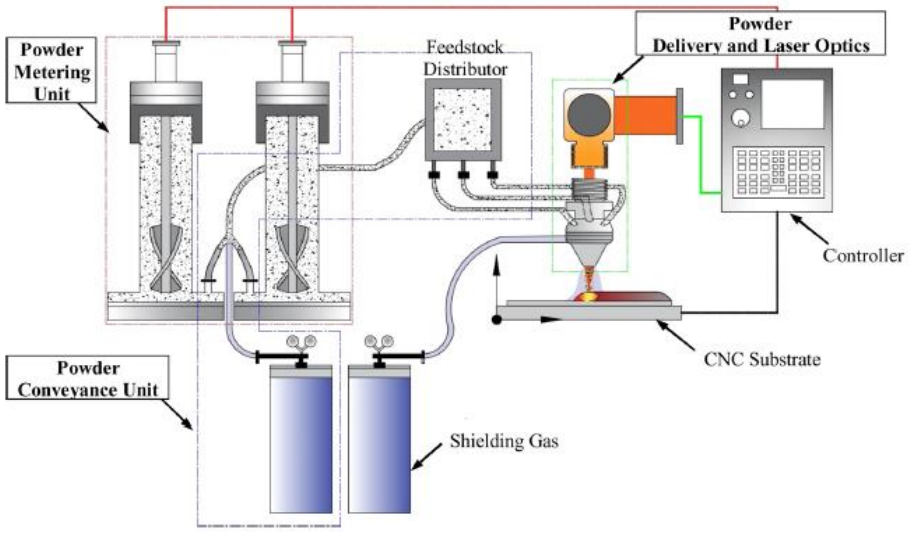


Figure 19: Powder feed DED setup [37]

3.4.1 Powder feeding and Conveyance Systems

In this topic we will address the main mechanisms that make use of gas in powder feeding and conveyance systems in DED-LB: Screw/Auger method and the pneumatic method.

The first one, screw or Auger method, is one of the oldest methods of transportation for granular matter. Although this system itself does not require the use of gas, there some variants that use a screw design and a confined gas chamber combined. This is achieved through a motor-driven screw that pushes the powder into the gas chamber, then, a stream of inert gas picks the powder from the gas chamber and leads it into the delivery nozzle [37]. This method of powder transportation and metering in DED was suggested back in 1988 by Steen and Weerasinghe. The conventional screw system and the one combined with the gas chamber can be visible in the figure 20.

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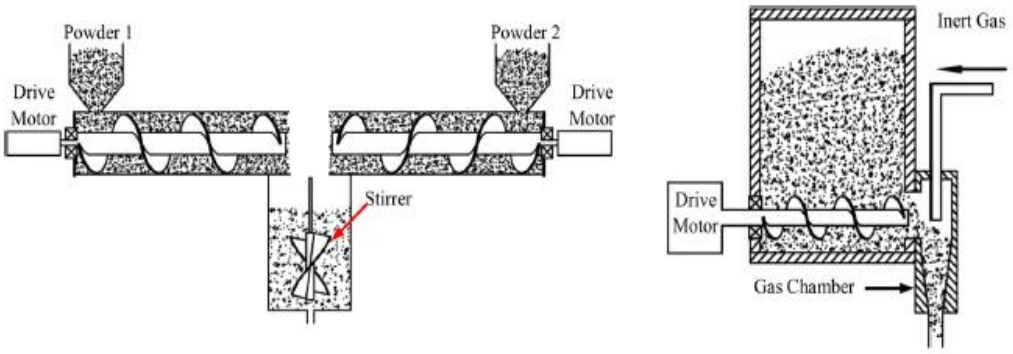


Figure 20: Conventional Screw System and Screw with confined gas chamber system [37]

The pneumatic method is one of the most popular systems used in feedstock handling in DED [37]. This method works by creating a pressure gradient within an elaborate system of interconnected tubes and conducts that facilitate metering and conveyance.

One of the systems that is worth mentioning was created by Francisco P. Jeantette, David M. Keicher, Joseph A. Romero, Lee P. Schanwald and was patented in 1996 [41]. This system features an index plate that rotates against a stationary base plate with holes at constant intervals. A passage for the powder is created when the hole of the base plate, one of the holes of the index plate, and an inlet port for the compressed gas all align with the outlet port of the system. When that happens, high velocity inert gas escapes the inside of the system, and by Venturi effect the powder is drawn into the stream [37].

There is also another mechanism worth mentioning, that features a metering wheel, through the geometry of which forms a cavity for the powder to drop into, which is then ejected using pressurized inert gas. The powder ejected from the cavity is then conveyed down the line using an inert gas. The variation in the rotational speed of the metering wheels is responsible for the change in the amount of powder accumulated in the cavity, resulting in the metering of the powder flow [37].

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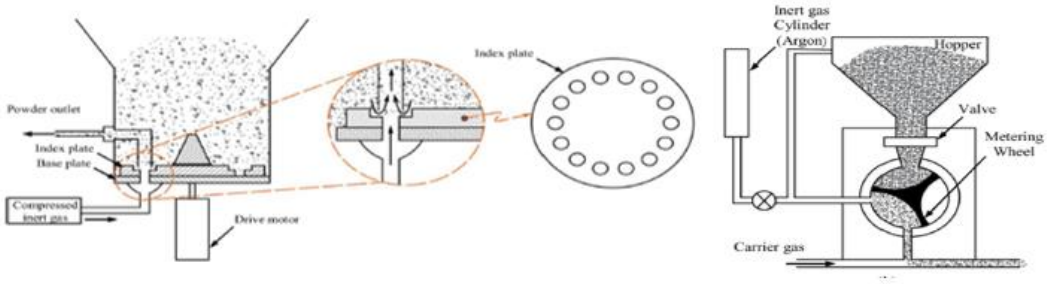


Figure 21: Pneumatic based mechanisms

3.5 Deposition Direction

When a laser beam focuses on the surface of a solid, powder, or liquid material, the light can be reflected, absorbed and transmitted, depending on the optical properties of the material. The portion of the laser radiation that the material surface absorbs, in the case of metals, causes an increase in the surface temperature required for AM melting, through the interaction between photons and the material [43].

One of the parameters to choose the most suitable laser for a process is the wavelength. The absorption rate in function of the wavelength, for some of the most common metals, is shown in figure 22. Consequently, it is possible to observe that, for lasers with shorter wavelengths there is higher absorptions of laser radiation by metals [43].

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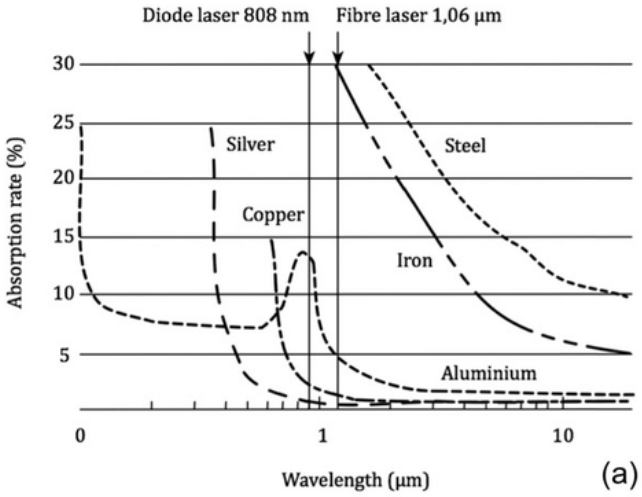


Figure 22: Graphic of absorption as a function of wavelength for most common metals [43]

It is also known that the quantity of incident energy that is reflected has to do with the angle of incidence of the laser beam and its polarization. The spatial distribution of the beam on the material surface also affects the maximum irradiance obtained and the resulting temperature distribution. Commonly, there are four types of lasers with different spatial distributions that are used in material processing: Multimode, Gaussian, Square (or rectangular) and Top Hat. The spatial distributions of Multimode, Square, and Top Hat are essentially used in surface applications since they do not vaporize or merge the layer deeply. In opposition, the Gaussian laser has those effects due to the maximum intensity and temperature located in the centre. For this reason, it is used for cutting and welding applications [43]. Regarding the deposition time, lasers can be classified as continuous, pulsed, or quasi-continuous. The first ones have their output nominally constant over an interval of seconds or longer. Pulsed lasers have periodic patterns of heat source, temperature variations and melt bath movements. However, if a laser has these two characteristics, it is called quasi-continuous, meaning that its pump source is switched on only for certain time intervals, which are short enough to reduce thermal effects significantly, but still long enough that the laser process is close to its steady state. This feature increases their field of applications because they have the benefits of continuous and pulsed lasers [43].

In the case of pulsed lasers, their optical power appears in pulses of some duration at some repetition rate, and consequently, they can improve the surface quality, causing less bead dilution and multidirectional solidification towards the centre of the melt bath.

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Another difference between continuous and pulsed lasers is that in the last, there is a periodic temperature fluctuation with the same frequency and the cooling rates are almost the double from continuous lasers [43].

3.5.1 Types of Nozzles

Nozzles are an essential part, which is subjected to wear, on DED-LB processes, located at the bottom of the laser head, close to the workpiece. Its configuration influences the deposition direction of the particles and consequently the way they are solidified [37].

Through the research that has been carried out and the advances of nozzle technology, it is possible to distribute regularly and effectively the particles over the melt bath. Nowadays, nozzles can be off-axis, coaxial (continuous or discontinuous) and central feed with an annular heat source. These are the different types of distribution where the powder is discharged into the interaction area with the help of carrier gas [37].

Firstly, an off-axis nozzle is laterally assembled and it is necessary to align and match the laser beam and the powder flow in the processing zone. Secondly, a coaxial nozzle follows a generic design layout for powder dispensing, and it means it is coaxially assembled with the laser beam, just behind the optical system. Finally, a central feed nozzle feeds powder perpendicular to the melt pool while the energy source is introduced at an inclination to the powder stream [37].

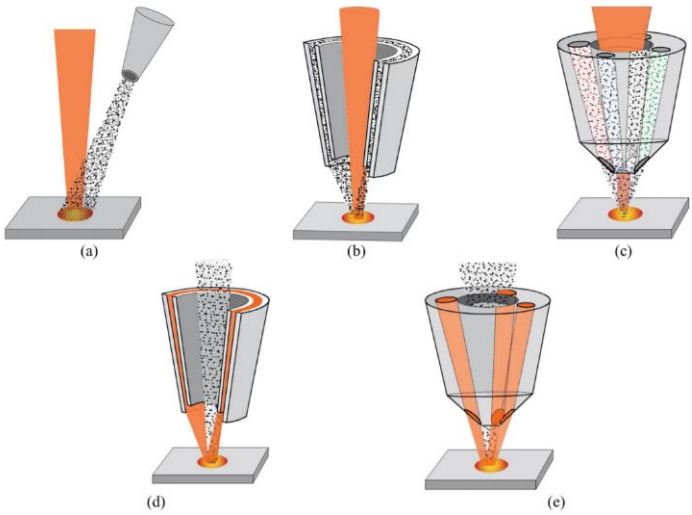


Figure 23: (a) off-axis, (b) discrete coaxial, (c) continuous coaxial and (d) annular laser beam nozzles [37]

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Figure 24 compares the differences between each nozzle configuration, its advantages and disadvantages, and also the characteristics associated with the deposition direction. Note: Central feed nozzles are not shown in the table because despite their advantages, they are very rare in DED setups due to the difficulty in its fabrication [44].

Analysing the table, the lateral nozzle has a skewed powder-laser energy distribution, just one direction of deposition and it is not axially symmetrical. This means it does not have a rotation axis, so it is suitable for specific requirements in terms of part accessibility. Regarding the coaxial nozzle, it is omnidirectional since it deposits in all directions due to a rotation axis. For this reason, it is suitable for AM deposition because it is able to produce more complex geometries. Also, it is important to note that the continuous coaxial nozzle has a very high efficiency but a limitation of approximately 20° in relation to the vertical, in opposition to the discontinuous one that does not have restrictions regarding the angle of deposition and consequently is found to have better accessibility for building features in AM applications [44].

Furthermore experiments state that with discontinuous nozzles, there is no influence of deposition direction and geometry of deposited clad on powder mass concentration at the welding point. In other words, a decrease in the deposition angle from 90° to 45° to the deposited track did not reveal relevant changes in those two parameters [45]. However, it is important to note that the deposition direction and its sequence combined with an overlay of layers are important factors in AM builds, for example, for the reason that it controls the width of deposited track, powder efficiency, cooling rate, residual stresses and laser power [53].

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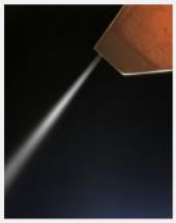
Powder feeding arrangement	Advantages	Disadvantages	Suitable for
Lateral or off-axis 	• Part accessibility • Width of deposited track: 0.5–25 mm • Laser power up to 20 kW maximum	• Directional deposition • Less powder efficiency • Alignment between powder and laser beam • No integrated protective gas feeding	• Directional deposition • Specific requirements in terms of part accessibility
Continuous coaxial 	• Unidirectional deposition • Width of deposited track: 0.3–5 mm • Applied laser power: up to 3 kW maximum • Powder efficiency: maximum 90% (diameter of powder-gas jet in the focus: minimum 400 µm) • Integrated protective gas feeding	• Restricted part accessibility • Gravity influence, no deposition for tilting angles >20 degrees because of inhomogeneous powder density distribution	• 3D deposition up to tilting angles of approximately 20 degrees • Largest effect from integrated protective gas feeding
Discontinuous coaxial 	• Unidirectional deposition • Width of deposited track: 2–7 mm • Applied laser power up to 5 kW maximum • Unrestricted 3D functionality • Integrated protective gas feeding	• Restricted part accessibility • Low powder efficiency (diameter of powder-gas jet in the focus: minimum 2.5 mm)	• 3D deposition up to tilting angles of 180 degrees (overhead processing is feasible)

Figure 24: Advantages and disadvantages of powder nozzles in additive manufacturing [44]

Another interesting experimente made, studied the possibilities of feed orientation for forward and backward directions using a powder feeder with an off-axis nozzle [46]. They defined three points and one distance to better illustrate their concepts and conclusions:

- Point O is the centre of the laser spot on the substrate surface;
- Point A is the intersection point of the axis of powder stream and substrate surface;
- Point B is the intersection point of the axis of powder stream and laser beam;
- Δx is the distance between point O and A. It is positive when point B is beneath point O and negative when is above

Note: When the nozzle and clad are in opposite sides of the laser beam, the direction of scanning velocity is positive, but when they are in same side, it is negative.

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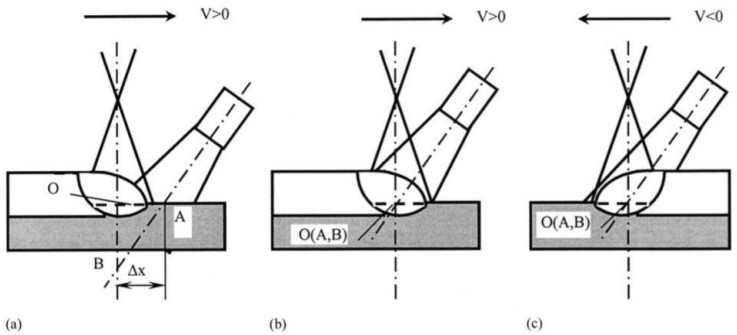


Figure 25: Powder injection point and direction of scanning velocity: a) V > 0 and Δx > 0 b) V > 0 and Δx = 0 c) V < 0 and Δx = 0 [46]

They stated that changing Δx, the height of single cladding layer H varied substantially because the amount of the powder injected into the melt pool changed too. Also, the amount of the powder injected into the melt pool with $\Delta x > 0$ was less than that with $\Delta x < 0$, since most of the powder was injected into the head part of the melt pool [46]. The study concludes that to obtain a higher capture efficiency, it is better to choose negative scanning velocity with negative Δx. Despite having a worse surface finish, as a result of the adhesion of the particle to the clad layer, this configuration is preferable. Hence, to obtain a good capture efficiency and a good surface finish, they recommend a positive scanning direction with the nozzle as close to the melt pool head as possible [46].

To sum up, the direction of deposition influences the solidification and growth of the grain between layers, and also its texture due to unidirectional and bidirectional deposition strategies [47].

3.6 Sieves and Filters

3.6.1 Sieves

Particle size distribution is generally classified as one of the most important powder properties for additive manufacturing. There are several techniques which determine the size of additive manufacturing feedstock and that can be applied in order to obtain a better result during the particles deposition [48].
When screening the particles for the initial container, a sieve can be used to control the size of the particles. Sieve analysis is considered to be one of the first techniques used to measure the particle size and is still used for metal powders. Firstly, the smallest particles

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are able to pass through the first sieve openings, and by gradually reducing the size of the mesh, it is possible to control and classify the different grain sizes. This classification depends on the type of sieve used and the number of openings per unit of measure. the sieve designation in relation to the size of the opening is found down below [48].

Sieve designation	Opening size, μm
No. 50	300
No. 60	250
No. 70	212
No. 80	180
No. 100	150
No. 120	125
No. 140	106
No. 170	90
No. 200	75
No. 230	63
No. 270	53
No. 325	45
No. 400	38
No. 450	32
No. 500	25
No. 635	20

Figure 26: Sieves sizes used in directed energy deposition [48]

It is important to note that the openings can widen due to the wear that agglomerates of small particles or irregular particles cause when passing through them [48].

3.6.2 Filters

When dealing with reactive, corrosive powders or powders with other special considerations, it is necessary to filter them. In this way, a company called Inert created a system for powder filtration, “including a filter cluster to collect reactive powders, water passivation of particulates, isolation valves and an electrically grounded design that prevents static electricity build-up or the potential ignition of particles” [49].

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Figure 27: Inert FP-1 Machine [49]

4. DED-LB BUILD SUBSTRATE

In DED process one of the main components is the substrate since it is the area where the melted material will be deposited. The substrate may be a flat plate or an already existing part where a new geometry may be added, given that this process is very commonly used for repair purposes [7].

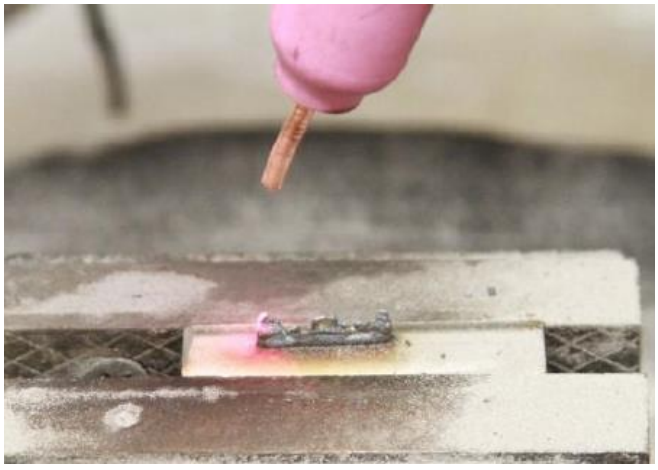


Figure 28: Flat Substrate [15]

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As it has been mentioned in previous sections, the deposition is controlled by relative motion between the deposition nozzle and the substrate. This can be accomplished through the movement of the nozzle, by the movement of the substrate, or by a combination of both [7]. When the substrate is large or heavy, it is easier to have an accurate control of the nozzle than the substrate. However, if the substrate is a small and flat plate, the movement of the substrate itself is easier than the deposition head. Thus, depending on the geometry that is required, where the new component will be fabricated - onto a flat substrate or onto an existing part - the desired relative motion will change.

4.1 Common defects

Since DED is characterized for having high temperature gradients and high temperatures fields, due to the use of a high energy density laser beam, both residual stresses and plastic deformations generally affect the final metallurgy and the mechanical properties of the built part [50]. In order to mitigate the residual stresses, the local heat accumulation during the metal deposition must be reduced, this can be achieved by the reduction of the scanning 37 length and also by increasing the scanning speed. The substrate distortion itself can be minimized by the optimization of the process parameters, such as source power, scanning feed and feeding rate [50]. The thermal distortion of AM parts depends on the material properties, the deposition strategy, the geometry of the part and finally, the preheating and colling conditions. The mitigation of residual stresses can also be achieved by the preheating of the substrate prior to the AM process, since the large thermal gradients, during the metal deposition of the first few layers, will be minimized [50].
It is also important to have in mind that during the non-steady stage, both the thickness and width of the deposited layers are affected by the heat absorption through the cold substrate. Once again, it is necessary to reduce the Maximum Thermal Gradients (MTG) in this stage as well. The MTG appear generally when the first layers are deposited. To enhance the DED process by reducing the MTG, it is mandatory, once again, to pre-heat the substrate in this initial phase or to reduce the heat flux from the HAZ to the workbench, through the substrate [50]. The non-steady stage can be observed below.

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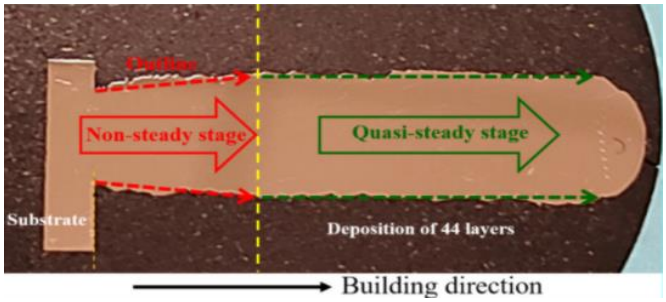


Figure 29: The transition from the non-steady stage to quasi-steady stage of a Ti-6Al-4V [50]

4.2 Influence of Inclined Substrate in DED

Usually, the substrate and deposited layer are placed horizontally, focusing especially on the influence of the laser and power feeding parameters. However, there is a noticeable difference between the formation of deposited layer on the horizontally placed substrate and on the inclined substrate. Study results showed that the angle of the inclined substrate influences the geometrical morphology of the deposited layer, that is caused by the diferences of the distribution of laser energy and powder flow. By increasing inclined angle, the maximum values of the laser energy density and powder flow decrease [51].
Gravity has a substancial role on the melt pool morphology during the deposition on the inclined substrate. In the upward scanning strategy, with increasing inclined angle the melt pool flows backwards and the front of the melt pool is concave. In the downward scanning strategy, the melt pool flows forward with increasing inclined angle and the melt pool is flatter. In both strategies, by increasing the angle, the deposited height decreases [51]. Fig. 30 shows the difference between the inclined substrate and the horizontally placed substrate regarding gravity.

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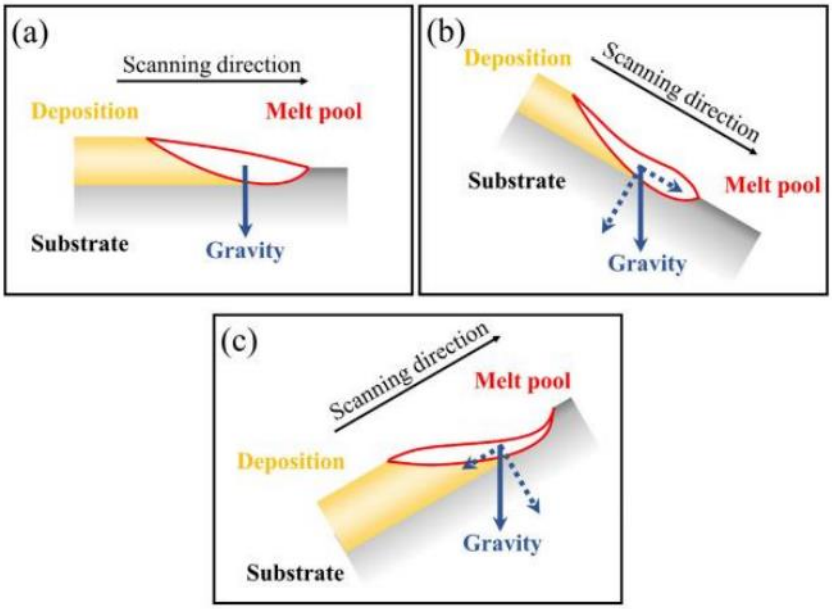


Figure 30: Schematic of the melt pool morphology under different scanning strategies: (a) horizontally scanning, (b) downward scanning, (c) upward scanning [51]

In the upward scanning strategy, in comparison with the the downward scanning strategy, the surface of the deposited layer has more adhering particles and the back edge of the melt pool has a lower energy, resulting in the partly melted particles remaining solid during the solidification process, forming adhering powder [51].

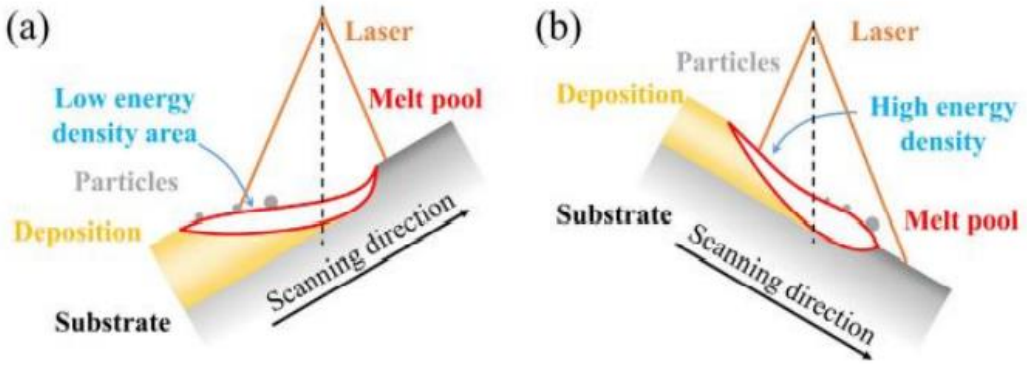


Figure 31: Formation of adhering powder under different scanning strategies: (a) upward scanning, (b) downward scanning [51]

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5. POST PROCESSING

When it comes to DED, this process can achieve complex geometries when printing a part, however, the surface finish and accuracy of the final part are often compromised. The most common defects in the components can come in the form of heat-induced distortions, solidified melt droplets, partially fused powders, and surface modifications induced by the laser tool motion and processing strategy [52]. Thus, post-processing, such as machining, is required to improve surface quality and accuracy.

Machining involves processes such as milling and turning. These two represent the most commonly used in surface finishing. Precise milling is referred as one of the types employed in post-processing when high precision is required, such as improved surface finish [53]. Milling and turning are also very required when there are features that are not produced during the deposition process that need to be created during post-processing [54]. The use of CNC turning and milling machines is also quite often in DED post-processing [53]. It is very common to combine laser beam deposition (LBD) machines with milling machines so that the whole part can be produced in a single environment.
For wire-based feedstock DED, the surface quality is often low, which can be seen through wavy surfaces and non-uniform wall thicknesses. In these cases, the use of machining is also required. Moreover, when the geometry of the part is so complex that there are difficult to access features, another subtractive method besides machining must be used, such as: abrasive flow machining, chemical polishing, and electro-chemical polishing [54]. There are also other types of post-processing that we can use rather than machining, which is heat treatment.

6. CONSUMABLES

6.1 Feedstock

The type of feedstock used in a metal AM process can greatly influence material cost, print speed, resolution, quality, and safety (figure 32). Predominantly, DED processes use metal in the form of either wire or powder. DED technology is also capable of using polymers and ceramics [7].

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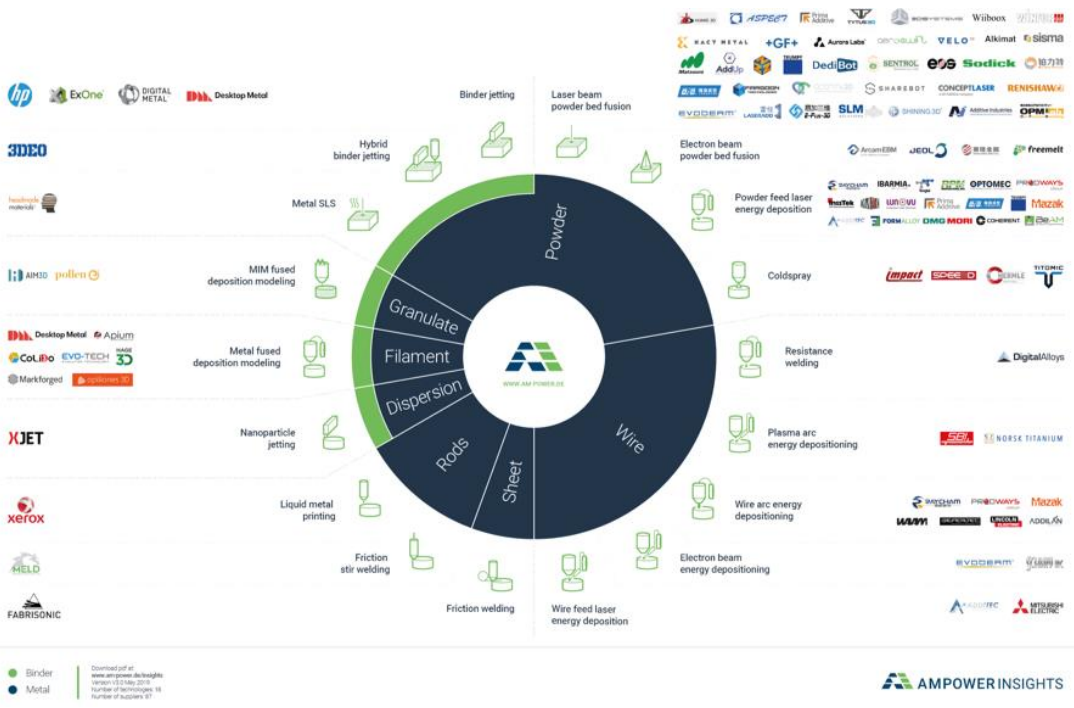


Figure 32: Metal Additive Manufacturing Technology landscape [55]

7. ADVANTAGES AND LIMITATIONS

Every manufacturing process has advantages and limitations and the DED-LB process is no exception. It is the balance between compromise and convenience that leads one to either choose this manufacturing process or not. For this reason, it is imperative to extensively comprehend both sides. With what has been described so far about this process, one can conclude the following bullet points.

The main advantages are:

- Good grip between the substrate and the deposited material;
- Wide range of alloys that can be used;
- Low level of dilution;
- Relatively high deposition rates;
- High productivity;
- Low impact on substrate's properties;
- Capability of manufacturing parts with complex geometries;
- Capability of creating a surface layer to improve the surface's properties;

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• Ability to precisely control the thermal input;
• Lower heat input;
• Less distortion and warpage;
• Exceptional metallurgical bonding;
• Excellent mechanical performance;
• High precision;
• The use hybrid processes, along with DED-LB, result in a more interconnected, efficient and flexible manufacturing environment;
• Hybrid processes result in a useful technology to get complex geometries with good surface roughness and low tolerances;
• In some cases, hybrid strategies employ minimal material and reduce the time associated with the process;

The main disadvantages are:

• High cost of the necessary equipment;
• Powder material is expensive;
• Design freedom more limited than Powder Bed Fusion;
• The need to have post-processing steps to obtain good surface rectilinity;
• The best results are limited to the most advanced and complex control systems;

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Power Bed Fusion – Laser Beam (PBF-LB) Manual

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Figure 30: In-situ images of the exposure of stripes with (left) and without (right) shielding gas flow support. The process without shielding gas flow is forming a glowing pillar out of condensate and vapor [24] 48

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1. Introduction to the Process PBF-LB

1.1 General Introduction to PBF, and PBF-LB Specifically

Powder Bed Fusion is a manufacturing process steadily improving to directly produce net-shape or net-shape metal tools or functional products. PBF presents an unlimited drawing freedom: complex shapes with a rapid, flexible and economical way, where the traditional techniques show their limits. Stability and small weight turn this technology suitable for the medical sector, but also automotive and aerospace fields. However, this technology also presents challenges: high material costs, slow setup, laborious post-processing and restrictions on material compatibility. In agreement with ISO/ASTM standard definition, this process is defined as an: “additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”.

Due to the modern techniques PBF workpieces near full density can be fabricated with mechanical properties at the same level of conventional parts, sometimes higher. This technology is strongly suitable for metals because it offers a nearly unlimited flexibility of geometry and complexity, together with the possibility to have fully dense parts generated without any further infiltrations.

Powder Bed Fusion – Laser Beam (PBF-LB) is one of the possible PBF processes that utilises a laser beam to melt and fuse metal powders together to form a part. It is the most mature and widely used metal additive manufacturing process, which produces parts where the conventional manufacturing shows limits.

PBF-LB begins with the creation of a 3D CAD model, which is numerically sliced into a number of finite layers. For each sliced layer, a laser scan path is calculated which defines both the boundary contour and the fill sequence, known as a scan pattern. Each layer is then sequentially recreated by melting sections of the CAD model on a layer of powder using a laser beam. After each layer is created, the powder is spread uniformly by a wiper and the process is repeated. The melted particles fuse and solidify to eventually form a component, layer by layer.

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1.2 Classification

Additive manufacturing processes are numerous. In the following image we can see a summary of the different additive manufacturing processes that are available in the market nowadays.

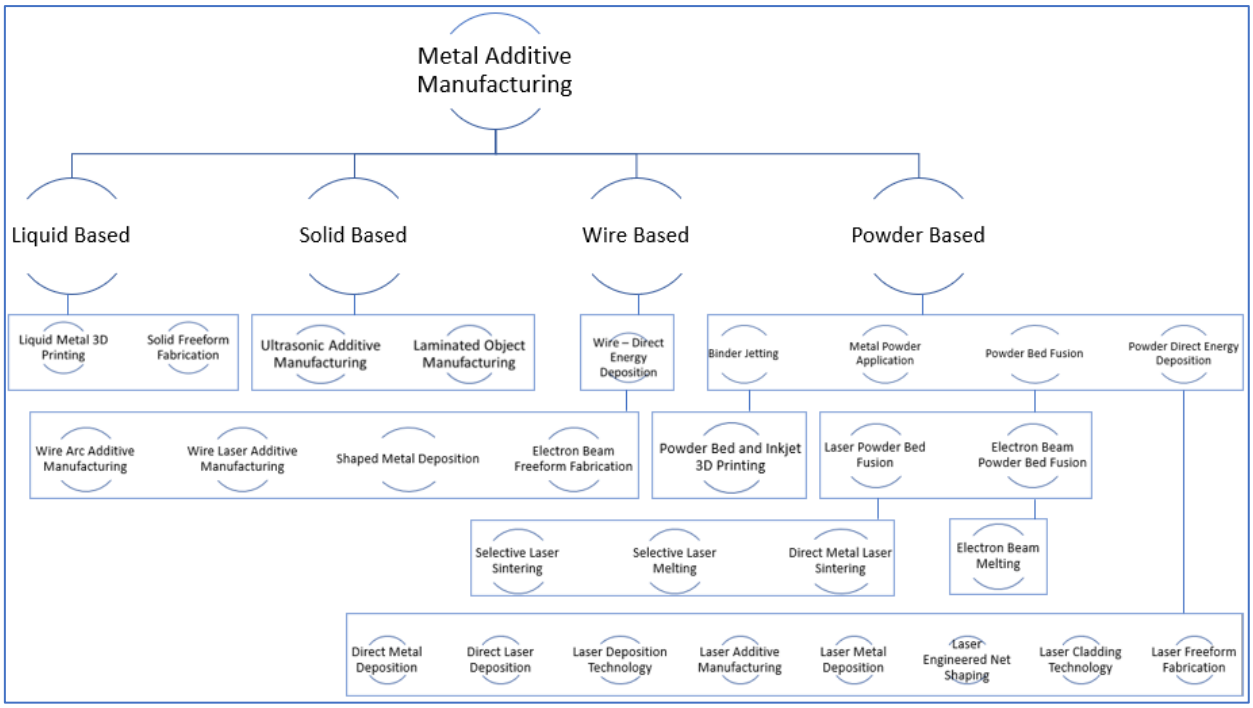


Figure 1: Overview of additive manufacturing processes [25]

But we will be focusing in PBF, in particular Laser beam. PBF-LB is sub-divided into these following techniques.

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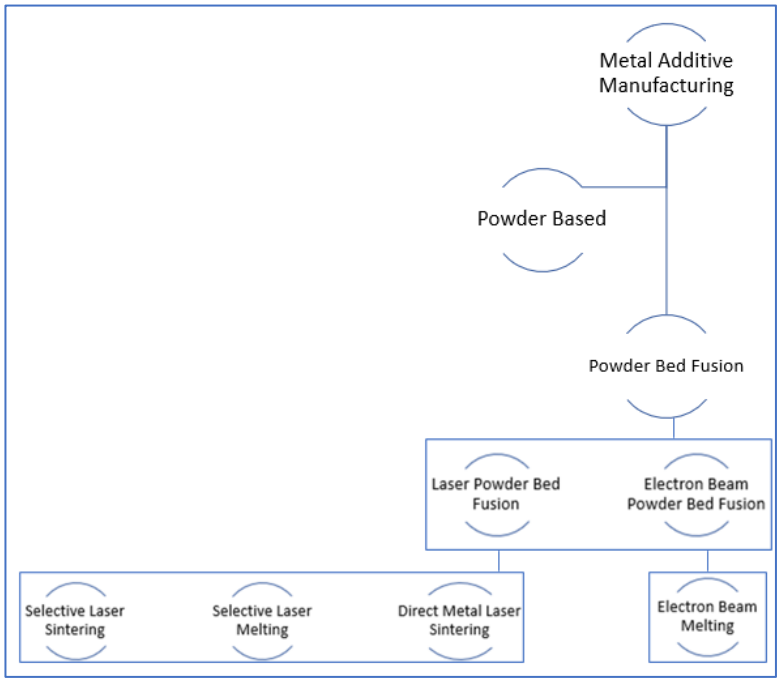


Figure 2: Overview of Powder Bed Fusion processes

Selective Laser Sintering (SLS) → SLS is a process that applies the same scheme of the general PBF process but without complete melting of the powder It only applies a densification of the powders by sintering, so by the application of heat and pressure on the piece in order to be able to decrease the number of voids that are present in the initial powder structure and doing so increases the density and consequently the mechanical properties of the final object. The following figure shows a diagram to represent the SLS technique of PBF. This technology was first developed at the University of Texas in Austin and introduced in the market in 1992 with polymers, only further this process has been applied also to metals (it was also named differently and the division is still maintained). This process of PBF is fast and accurate, superior quality surface is obtained with minimum material waste, no need of mould, other tools, or to design jigs and fixtures. By not having fusion of the powders, we don't need gas protection for the metal.

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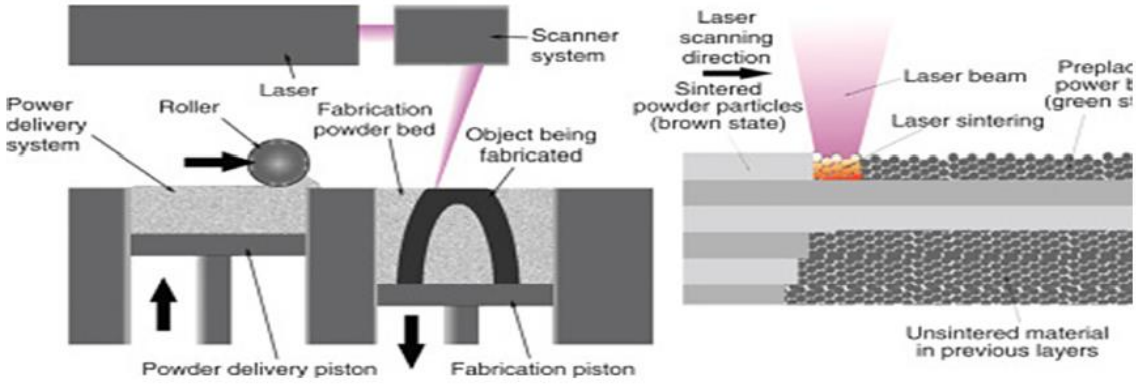


Figure 3: Illustration of the SLS process [1]

Selective Laser Melting (SLM) → This process was first introduced in Germany in 1999. Compared to SLS, this technique SLM is faster but requires inert gases protection to avoid oxidation. In fact, in this method, powder is melted rather than sintered. It is currently a very popular method for fabrication of metal parts. Recently, high power lasers with the development of fibre optics are also added in SLM to process different types of metallic materials such as tungsten, copper & aluminium. Therefore, various types of metallic materials can be used on SLM. This enabled many research opportunities to be developed in SLM for composite and ceramic materials. This method has the advantages to produce high-precision and high-quality products.

Direct Laser Metal Sintering (DLMS) → Direct metal laser sintering was first developed by EOS firm, Germany in 1995. DMLS is a laser-based AM technique, in which an object is developed with the use of metal (not plastic) powders. Similar to SLS, it is a layer by layer process with computer controlled laser technique. With the support of DMLS, it is possible to control the porosity of each layer, but not eliminate it completely. DMLS titanium implants are probably the most widely spread type of production of this kind.

1.3 Advantages and Disadvantages

Advantages:

- Design freedom
- High resolution and geometrical accuracy

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- Reduced material wastage and costs (superior buy-to-fly ratio)
- Improved production development cycle
- Capable of producing functionally graded parts
- Allows for fully customised parts to suit individual requirements
- Unused powder can be recycled and reused in some applications
- Increased part performance where functional elements can be optimised
- Component integration reducing part assembly and associated costs
- Weight savings through using material only where needed
- Capability to create intricate shapes
- Low production time for developing prototypes

Disadvantages:

- Need for post-processing
- Limited space which limits the part dimensions
- Relatively slow process – not ideal for production in series

1.4 Process Mechanics

As soon as the CAD profile is evaluated by the CNC program, the precise coordinates are defined, and the process can start. A limited lowering of the central build platform allows the placement of a correct powder amount from the levelling roller: the workpiece platform gets off, the powder platforms on both sides rise in order to preserve the requested powder amount. Meanwhile, the laser goes through the lens system and the 2D scanning mirror in order to strike a specific point on the powder bed, in agreement with the CNC coordinates. The laser melts the selected points and again another powder layer is applied. This cycle is repeated several times as long as the workpiece is built up completely, layer by layer. Post-processing is usually required after the process.

2. PBF-LB MANUFACTURING STRATEGY

2.1 Fixturing

A fixture is a work-holding or support device used in the manufacturing industry. Fixtures are used to securely locate (position in a specific location or orientation) and support the work, ensuring that all parts produced using the fixture will maintain conformity and interchangeability. It improves the production's economy by allowing smooth operation

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and quick transition from part to part, reducing the requirement for skilled laborers by simplifying how workpieces are mounted, and increasing conformity across a production run. The building chamber is temperature-controlled, being that the temperature is normally some degrees below the melting temperature of the metal. This facilitates the fusing of the various powder layers. The chamber is also filled with inert gas, typically nitrogen or argon, to avoid oxidation of the metal powder, while also introducing a convective cooling effect which difficult the heating of the system. A fixture differs from a jig in that, when a fixture is used, the tool must move relative to the workpiece, when a jig is used, it moves the piece while the tool remains stationary. In the case of PBF-LB we completely avoid the location problem since we have a previously programmed model that will operate with the laser always on the same area, so once provided a perfectly planar support that will permit the attachment of the first layer, and that it will remain perfectly still on its place without vibrations or movements the location problem is solved.

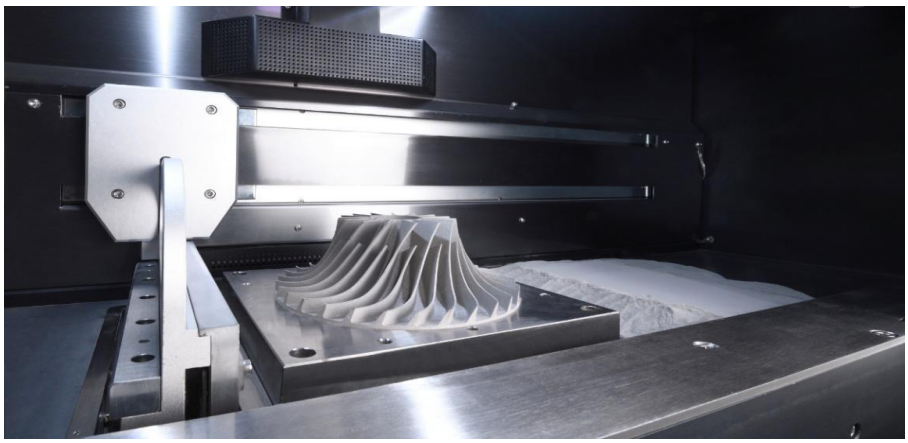


Figure 4: Support for PBF [2]

The only thing that we need to consider is that the plane needs to be able to move up and down to permit the deposition layer by layer of the powders and so the growth of the piece. This movement is not linked to the fixture itself, there will be a moving plane in which the fixture is linked. The fixture piece needs to be fixe to the moving support in order to avoid movements of the plane that will create misalignments between layers.

Regarding the support, we can consider that the initial support is given by the metallic plate in which the first layer is deposited, and the any additional support needed can be built up together with the piece.

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Figure 5: Complex piece with the complex support system built in [3]

With additive manufacturing the problem of complex supports is easily resolved by simply building up the support with the piece itself. By observing the image above, it is possible to observe how the support can be built in in order to save material and be easily removed once the procedure is finished.

2.2 Positioning and Nesting

To have an efficient Powder Bed Fusion process, it is important to plan correctly how many parts can be built in each batch. The machine can build several parts at the same time, which allows for more efficient production and less powder waste and energy spending. Therefore, there needs to be a correct positioning on the parts on the build platform. This process is called nesting and it involves fitting in as many parts as possible in the powder bed, achieving higher packing density, which allows for efficient use of powder and energy while maintaining part quality.
Nesting is done before the printing, during the batch design phase. It can be done for multiple platforms at the same time with certain software. There can be both bounding box nesting and Geometry-based nesting. Bounding box nesting is mostly used for smaller parts with simple shapes, as it consists of using the maximum x, y, and z values (length, width, and height) to build a box around the part. The nesting is based on the placing of the various bounding boxes. In the case of geometry-base nesting, the surface

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area of the part is taken into account. It is better for nesting parts with complex shapes. This technique allows for higher part density than bounding box nesting.

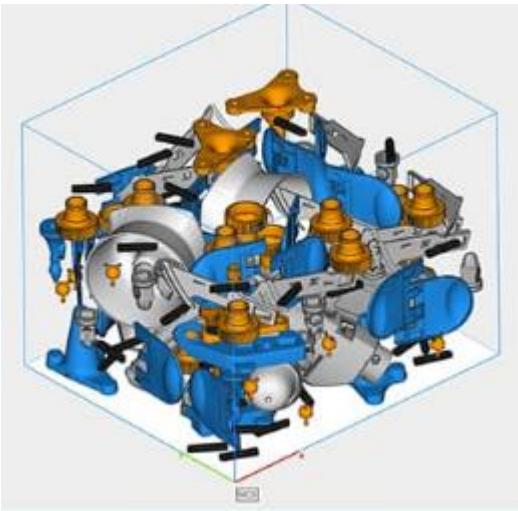


Figure 6: Example of nesting [8]

An important parameter to take into account when positioning the parts is how the heat will be distributed. If the parts are unevenly nested there will be varying temperatures which will cause unwanted shrinkage of the parts. To avoid this situation, the several layers should have a similar surface area, which can be evaluated through slice distribution maps. It is also important to leave at least a 1.5 mm gap between the parts to prevent them from fusing.

The benefit of this process is the maximization of the machine investment, by reducing the waste of resources such as time, labour, and raw materials. Consequently, there is a reduction in expenses. It allows for an increase in productivity and shorter lead times. If nesting is used wrongly, it can lead to material waste, printing errors, and bad quality parts.

2.3 Layer Thickness

The layer thickness is defined as the distance that the build platform is lowered for the spreading of a new layer of powder. Usual layer thickness fits in the range of 20 to 100 µm.

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As the number of slices increases, the print time increases. In other words, increasing the layer thickness can result in decreasing the total number of slices or layers. This can be a parameter for reducing the total build time and thereby driving down cost.
Increasing the powder layer thickness between each solidification phase with the laser could help speed up the overall time to manufacture a part. However, if the powder layer is too thick, then a melt pool with adequate depth to melt and fuse two successive layers may not be created. A thick layer of powder requires a slower scan speed or a higher laser power to achieve the same effective melt pool.

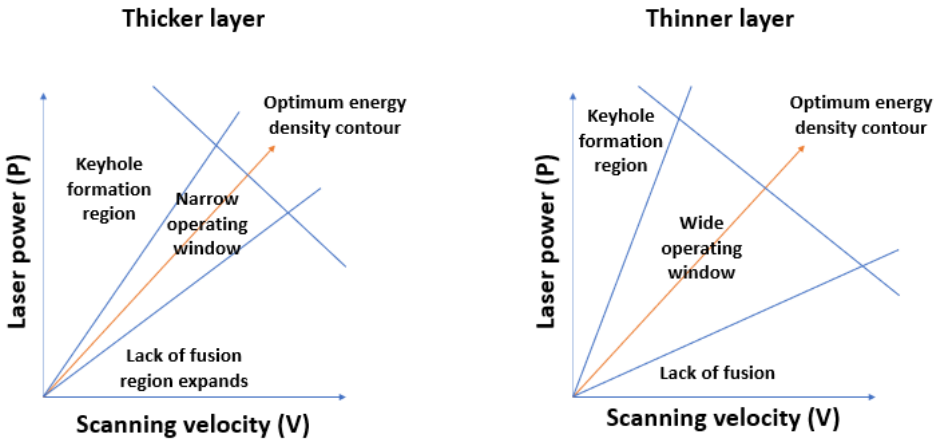


Figure 7: Operating window for thicker and thinner layer of thickness [4]

However, increasing the layer thickness can negatively affect properties of the manufactured parts. Investigations on the effects of process parameters in LB. PBF observed that an increase in layer thickness will lead to a density decrease (porosity increases), an ultimate tensile strength (UTS) decrease and a hardness decrease.

Different studies reveal almost always the same results regarding the influence of the layer thickness in several properties of the final part.

- Lower powder layer thickness results in better surface finish.
- Porosity level slightly increases with the increase in the powder layer thickness.
- Finer grain structures are achieved with smaller powder layer thickness.
- With the same power, scanning speed, and hatch spacing, the lower powder layer thickness has much higher energy density which gives rise to higher temperature

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and faster cooling rates due to thermal gradient and thus results in finer microstructure.

2.4 Dosing Factor

The powder coating dosage factor is defined as the ratio of the amount of powder provided for the coating of one layer to the amount of powder effectively deposited per layer. It addresses the excess powder that is applied by the coating system in order to form a complete layer across the build area and fill-up empty space above the part geometry caused by material consolidation. The powder excess is moved into an overflow bin.
Powder input mass per build job can be calculated tacking into account the dosage factor. For a given build job according to the following equation:

$$m_{input\ powder\ per\ job} = A_{platform} \times h_{built} \times \rho_{packing} \times f_{dosage}$$

where $A_{platform}$ is the area of the build platform, h_{build} is the height of the build job, $\rho_{packing}$ is the packing density of the powder and f_{dosage} is the powder coating dosage factor.
The thickness of the layer seems to affect the density of the fabricated parts and is often taken into account in combination with factors such as the laser power and the flowability of the powder. Further, it has a major influence when it comes to avoid delamination, defined as the separation of adjacent layers within parts. Delamination is commonly caused by incomplete melting between consecutive layers which may occur due to insufficient re-melting of underlying material. While lack of fusion defects are usually localised and can be mitigated by other post processes such as hot isostatic pressing (HIP), delamination results in macroscopic defects that cause irreversible damage to the printed object. Accurate tuning of the layer thickness can enable the melting of several material layers and achieve good adhesion between consecutive scans.
An increase in the dosed volume will mean a faster process and so a better efficiency and consequently a reduced cost. But this increase in dosed volume will make a higher power of the laser necessary to be able to correctly melt the whole thickness deposited. And we will see how dangerous it is to have a high-power laser for deformations and residual stresses on the product. So, in this case, as in many other cases, the time necessary for the project is directly proportional to the final quality of the product, and the optimum compromise should be found.

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Figure 8: Examples of possible delamination defects due to excessive dosing factor [5]

The packing factor of a powder depends on its dimensions, its segregation predisposition and consequently its flowing characteristics, and also the thickness of the layer deposited. In fact, depending on the dimension of the powders, a thin layer might not be the best for density purposes. So, the efficiency and speed of the process should not be the only parameters considered favourable for a higher thickness.

The spreader geometry is one of the factors that influence powder spreading, the most common geometries are blades and rollers. Their speed seems to have an effect on the final result. Previous studies compared roller and blade spreaders and suggested that the roller can bring better powder layer quality (characterized by higher packing density and smoother surface). They also designed a blade with a round surface and found that the performance was comparable to or even better than the roller.

The application of some packing pressure in the layer will partially disaggregate the segregated powder grains and will decrease the danger of lack of fusion in these particles.

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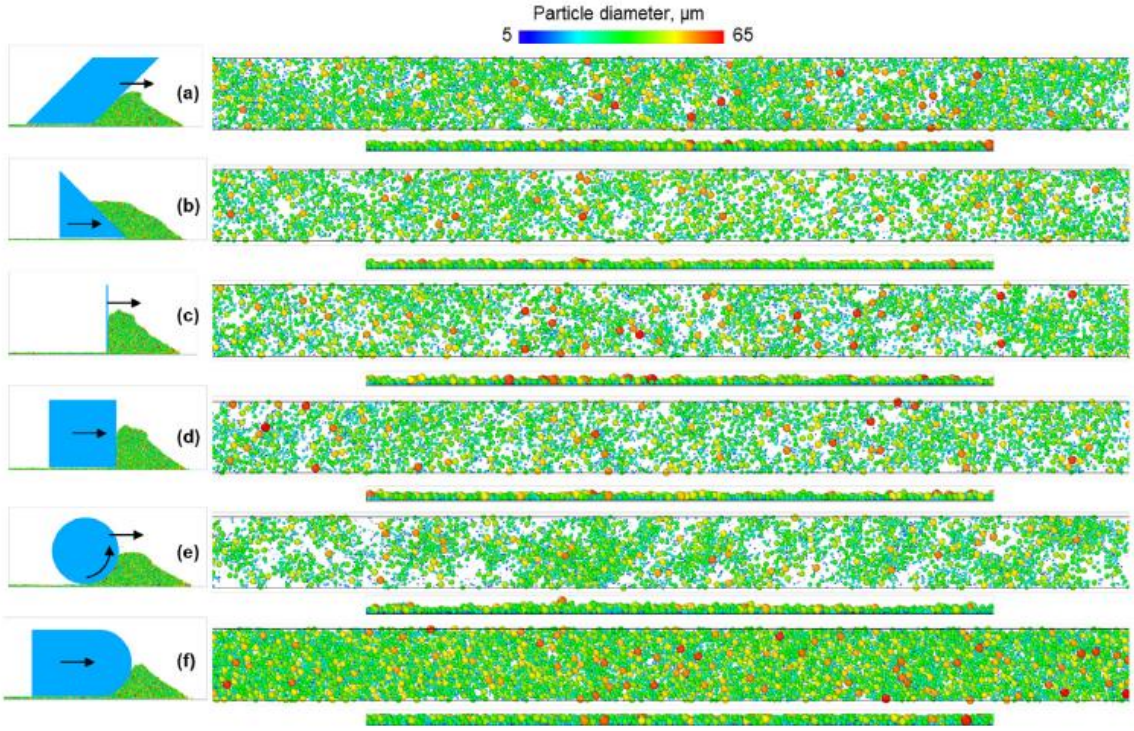


Figure 9: Different spreader geometries and their influence on particle size and distribution [6]

2.5 Interaction of Layers

The several layers created during the process Laser Powder Bed Fusion need to be interconnected. This connection is provided by an adequate melt pool. This is a result of laser radiation on the surface of the powder bed during SLM. For a detailed analysis of laser–material interactions and melt pool dynamics in selective laser melting (SLM), it is important to consider correct powder layer height and packing density in a single layer. Thus far, most experts assume that the powder layer height, which is equal to the levelling height of the build platform divided by the packing density of the powder bed, reaches a steady state after several layers. However, this assumption neglects the fact that a certain amount of powder is deposited (e.g., by spatter), and therefore, does not contribute to the molten powder layer height and that the packing density in a single layer is smaller than in “bulk”.

For an accurate modelling of the SLM process it is important to implement the correct powder layer height and packing density in a single layer. Many numerical models use the levelling height of the build platform as the powder layer height in their simulation,

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which does not represent the actual conditions during the process. The theoretical powder layer height increases in the first layers due to the difference in volume of powder and solidified material. A “steady state” is reached after approximately seven layers. This “steady state” is reached when the amount of melted powder is equal to the levelling height of the build platform. When one neglects the deposition of powder (e.g., due to spatter and denudation) and vaporization, this theoretical “steady state” powder layer height is equal to the levelling height of the build platform divided by the packing density of powder.

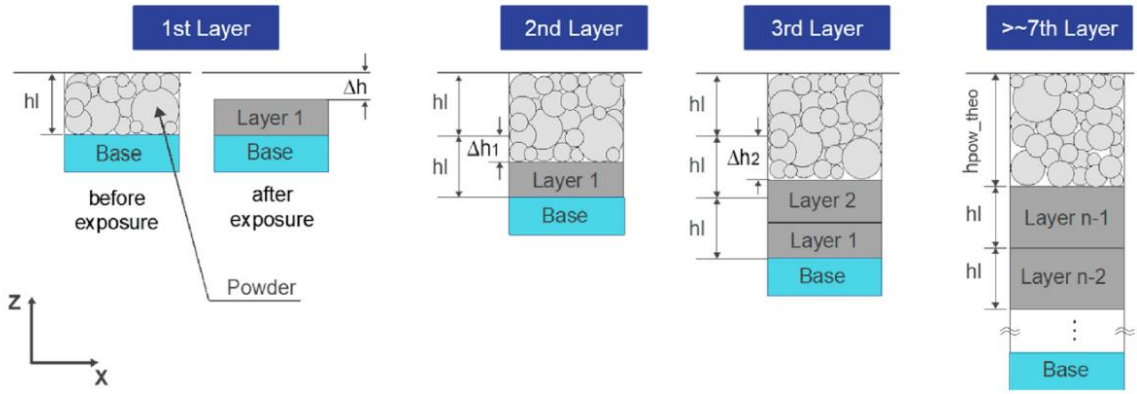


Figure 10: Difference between leveling height and powder layer height in SLM [7]

This theoretical “steady state” powder layer height is not the actual height, the powder layer height when in “steady state” is even higher than the levelling height of the build platform. It is due to the formation of spatter and denudation.

To understand the reason for such a powder layer height, it is important to understand that the powder layer height in the “steady state” is (only) determined by the amount of powder that is actually molten in a single layer. In the “steady state”, the amount of melted powder per layer will equal the levelling height of the build platform. When the amount of molten powder is smaller than this value, the powder layer height will increase in the succeeding layer and when it is larger than the levelling height, it will decrease. This “steady state” is therefore stable.

If one neglects the fact that a certain amount of powder is lost due to vaporization or powder disposition (e.g., spatter and denudation), this will result in a powder layer height h_{pow_theo} that is equal to the levelling height h_l divided by the packing density in a single layer. However, some powder will be deposited during the process and hence will not contribute to the molten layer height.

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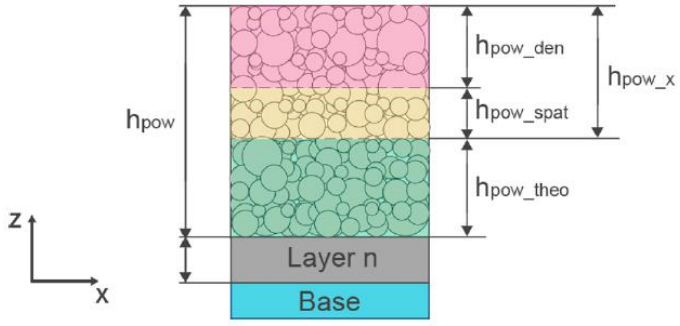


Figure 11: Overview of contributing factor to increased power layer height in SLM [7]

2.5.1 Effect of spatter on powder layer height

There are two types of spatter reported:

● Droplet spatter, which is formed by tearing and ejection of molten material directly out of the melt pool.

● Powder spatter, which occurs when non-molten powder particles surrounding the melt pool are blown away due to ambient gas flow.

Quantifying the amount of spatter is relatively complicated due to the high process speed and difficulties in capturing and measuring spatter particles. Recent publications estimate that approximately 15–20% of the powder material is converted into spatter and consequently does not contribute to the molten layer height in SLM.

2.5.2 Effect of denudation on powder layer height

The denudation zone in SLM is the area surrounding a scan track with a decreased amount of powder or complete depletion of the solidified layer underneath (see Fig. 15). Denudation is a complex phenomenon, which is mainly caused by two factors. First, particles that are wetted by the melt pool can get entrained by surface tension force. Second, the vapor jet as a result of melt pool overheating interacts with the surrounding and can sweep powder particles away with the corresponding gas flow. The energy input and ambient gas pressure have a direct influence on the size of the denudation zone. The higher the energy input, the more pronounced the denudation zone due to an increase in ambient gas flow.

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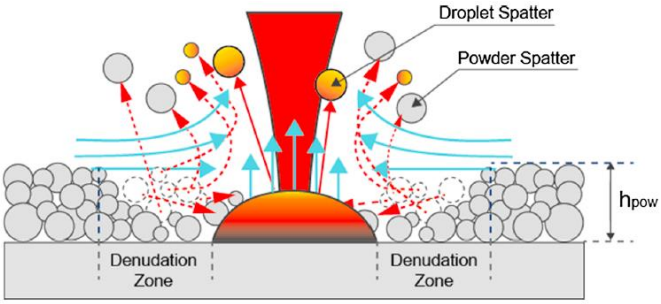


Figure 12: Overview of a spatter and denudation zone in SLM [7]

2.6 DISTORTION AVOIDANCE

During the SLM process, thermally induced residual tensions are formed. Residual stresses correspond to stresses within a plastically- or elastically-deformed material that remains within the structure after the load that deformed it is removed. Cyclic heat delivery leads to subsequent expansion and contraction of the material which creates stresses in the part during the build. These stresses can rise higher than the yield strength of the material which causes deformations in the parts either during the build or while removing the parts from the building platform when the residual stresses are released.

2.6.1 Evolution along the building process

It can be noticed that heat spreads around the melt pool only to the already solidified area of the part because of its higher thermal conductivity compared to the powder side that acts as an insulator. This has an important effect while building the object. In fact, the more solid part we build, the better heat transfer we obtain, and so we manage to better spread and dissipate heat when the object is partially built than what we can obtain at the beginning; and this also means that the temperatures reached at the beginning are higher than the ones reached with the object partially created, and they continue decreasing while the object gets to its conclusion. Obviously, all this is influenced by the geometry of the piece itself.

However, the global temperature of the part increases as the build proceeds because more heat is input to the part by every scanned hatch and layer. This leads to bigger melt pools

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since the general temperature is already much higher than previously, and subsequently the increase in temperature also decreases the cooling rate obtainable.

Higher temperature of the part lowers the yield strength of the material which increases its vulnerability to have deformations. The more heat is input to the part, the more residual stress it will gain. This means that by each new scanned layer, more stresses are generated.

2.6.2 Thermal Conductivity of Metal Powder and Surrounding Gas Effect

Thermal conductivity is an essential matter in PBF-LB as it affects the accumulation of heat in the part during the build. Lower thermal conductivity results in a larger melt pool and higher temperatures of the build. Thermal conductivity is a material related property but it can be slightly tuned by parameters such as powder packing efficiency and powder particle size. Thermal conductivity of a powder bed that consists of inert gas, such as argon, and SS 316 powder, increases with the increase in temperature because thermal conductivity of both SS 316 powder and argon gas increases with increase in temperature. Higher powder packing efficiency enables higher thermal conductivity of the powder bed. The powder particles share a larger area of contact per unit volume (specific surface area) with higher powder packing efficiency, facilitating the heat transfer between the particles, which results in higher thermal conductivity of the powder bed. Also, smaller particle size results in higher thermal conductivity of the powder bed. Smaller particle size reduces the inter particle space for shielding gas, leaving less room for shielding gas in the powder bed. Because shielding gas has lower thermal conductivity than metal powder, this results in higher thermal conductivity of the powder bed. Smaller particles also have larger specific surface area that improves thermal conductivity of the powder bed.
Powder has an insulating effect on the system and so whenever we have to create a melt pool that is completely surrounded by powder the obtained pool will be larger than normal and will take more time to cool. This is relevant for first passes/hatches.

2.6.3 Cooling Rate

The excessive heat that results from the process must be transferred out of the part as effectively as possible in order to ensure a successful build. We have already mentioned the cooling rate multiple times before.

Parameters such as scanning speed, laser power, layer thickness and hatch spacing affect the cooling rate of the part. Higher scanning speeds go through the scanning lines faster and the amount of heat input to the part is smaller . Because of lower heat input per unit

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length with high scanning speeds, the melt pool is smaller compared to lower scanning speed accompanied melt pools. A smaller melt pool cools down and solidifies quicker than a larger one. An increase in laser power results in a decrease in cooling rate because more heat is input to the part. Higher layer thickness results in lower cooling rate because of the combination of higher absorptivity of heat and lower heat transfer through thicker powder layer. As long as subsequent hatches overlap each other sufficiently, cooling rate remains nearly constant but when the hatches are too far away from each other, the surroundings of the melt pool consist more of powder. This causes reduction in the cooling rate and insufficient fusion.

2.6.4 Thermal Stresses

Response of the metal to the local temperature changes is to expand or contract whether heated or cooled, respectively, and when expansion or contraction of metal is restricted, thermal stresses occur.

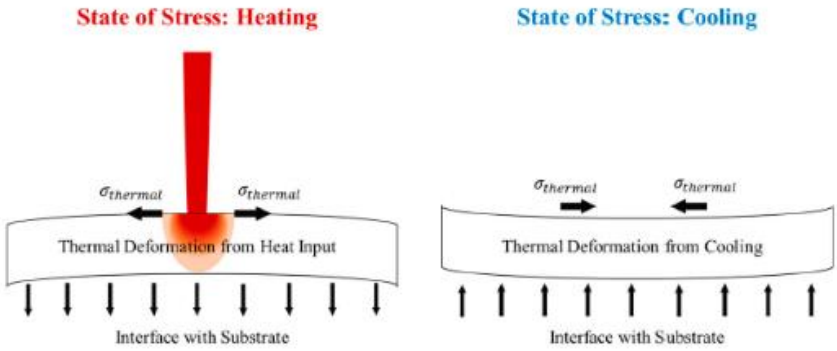


Figure 13: Stress gradientes in single layers [9]

During this heating cycle, the surface of the part pursues to expand due to strong heating but the expansion of the heated top layer is limited due to surrounding solid material, which creates compressive stress on the upper surface. When the occurred compressive stress exceeds yield strength of the material, the top surface will have plastic deformation that pursues to upset the material towards the laser. When cooling of the material begins, the material starts to contract. Now contraction of the surface is limited due to surrounding solid material, which ends up in tensile stress on the top surface. When the tensile stress exceeds yield strength of the material, the top surface pursues to bend into the opposite direction.

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2.6.5 Solutions

2.6.5.1 Support Structure and Building Platform

One important function of the support structures in PBF-LB is to anchor the part to the building platform and to prevent the part from warping during the build, in the presence of stresses. However, the resistance for warping gains residual stress in the part. Support structures also have an important role in conducting the heat away from the part by transferring the heat towards the building platform (as seen in Fixturing, Positioning and Nesting). It is also important to remember that the residual stresses present in the final object are also partially contained by the initial attachment to the base platform and once the object is detached from the platform part of these stresses will be released giving some deformations. Deformation of metal parts is a common problem in PBF-LB due to the cyclic heat delivery and residual stresses that are unavoidable in the process. However, there are some ways to reduce the causes of cyclic heat delivery, such as by preheating the building platform which enables lower thermal gradients to occur due to lower temperature differences within the part.

Support structures have an impact on the resistance for deformations. Higher amounts of support structures have more volume to transfer heat away from the part and fix the part more strongly to the building platform, in order to avoid warping. However, support structures are removed from the part after build which limits their use as they can be challenging and costly to remove.

2.6.5.2 Scanning Strategy

Scanning strategy has an impact on the formation of residual stresses and deformations in metal parts manufactured by PBF-LB as the effect of heat can be controlled by adjusting it. The effect of scanning pattern on the vulnerability of the part to have residual stress and deformations in PBF-LB of iron based powder has been studied.

What has been noticed is that the best scanning strategy depends on the geometry that wants to be obtained. In general, it can be stated that the smallest deformations are created in the part along the scanning vector and the largest deformations perpendicular to the scanning vector.

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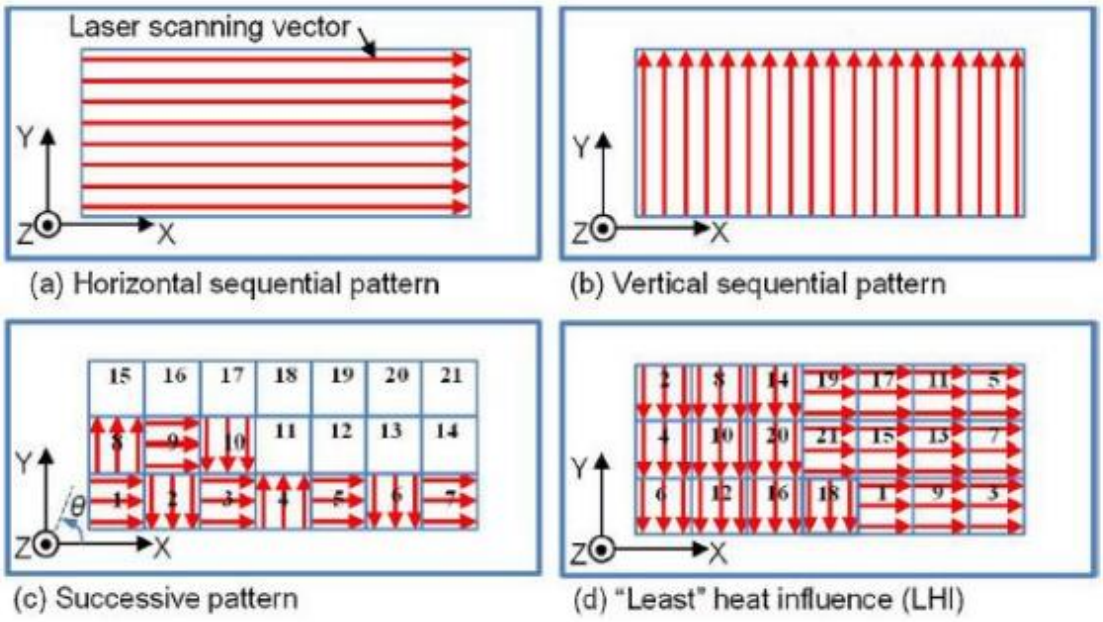


Figure 14: Scanning pattern of Iron Based Powder [9]

As it concerns the residual stresses, we can supposedly say that the behaviour of these stresses mirrors the deformation behaviour. But this doesn't always happen. The longest scanning vector results in the highest stress values and the shortest scanning vector results in the lowest stress values. This occurs because longer tracks contract more than shorter ones and when the contraction is limited, it results in higher residual stress for the longer tracks.

Overall, there will always be a level of residual stress in parts after build despite the scanning strategy used. The highest residual stresses are generated in the building direction rather than in the horizontal plane. Also, larger deformations occur more in the building direction than horizontally. The deformation shape obeys the TGM (Temperature Gradient Mechanism) and cool-down mechanism that pursues to lift the edges of parts from the building platform. Therefore, parts that are built in different orientations have different deformation shapes. Parts can be complex by shape and different scanning strategies may be required. Parts can be built with scanning patterns that are different for each layer in order to compensate for the effect of heat and generation of residual stresses and deformations in the part. For example, scanning patterns can be rotated for each new layer to achieve regular variation in the scanning direction.

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Utilizing simulation software to predict the deformation and through these predictions design the best laser path to be applied is one of the things that will permit us to optimize the system.

2.6.5.3 Building Direction and Object Orientation

It is obvious that deformation can be avoided by choosing the correct building direction and by adjusting part orientation. But it has to be noticed carefully when choosing suitable fabrication direction that the parts have different mechanical properties depending on the orientation, they are built due to the layer wise manufacturing. Tensile strength properties and surface roughness values are affected by the orientation of the part. Horizontally built parts have higher tensile strength compared to vertically built parts and sloped surfaces suffer from rough surfaces due to stair-step effect. Building time and the need and location of support structures are affected by the orientation of the part. Vertical building orientation requires more recoating time due to a higher number of layers. Capacity of the build can be affected by choosing orientation to allow building as many parts as possible in one build. Utilizing topology optimization in the design can be a way to avoid some distortions by obtaining the best object orientation and geometry.

2.6.5.4 Thermal Stress Relief

Residual stresses of parts can also be reduced by thermal stress relief that can be performed after the build, once the loose powder has been removed from the parts. When thermal stress relief is performed, the parts are still attached to the building platform. In thermal stress relief the parts and the building platform are slowly heated up and held in high temperature for several hours, allowing the metal to go through metallurgical structural change. After that the parts are left to cool down slowly in order to avoid tensions created by quick temperature change.

The effect of heat is an important aspect that should be recognized when manufacturing parts with PBF-LB. Parts can be ultimately complex by shape which creates challenges in the manufacturing as the heat transfers through the whole part towards the building platform and heat may locally accumulate strongly, inducing stresses to the part. Large areas require more scanning with a laser which induces more heat to the part. The more heat is input in the part during the build, the more it will gain residual stress and expose

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for deformations. And this also influences the possibility to apply the stress relief with success.

2.6.5.5 Post-Processing Operations

All operations applied after the build have effects on the deformations and residual stresses present and so they should be taken into consideration when defining the best process to have the least amount of final deformation of the product.

2.7 DEPOSITION RATE/PRODUCTION RATE

One of the disadvantages of the PBF-LB compared with other AM processes that produce metals such as electron beam powder bed fusion, direct energy deposition, binder jetting and sheet lamination, is the relatively low productivity. The deposition rate varies between 2 and 40 cm³/h, especially depending on the materia and The productivity of PBF-LB is approximately between 8 and 100 cm^3/h. At the same time the costs in €/cm3 are comparably high to the other processes. Due to the high costs per volume, serial production is currently not economical.

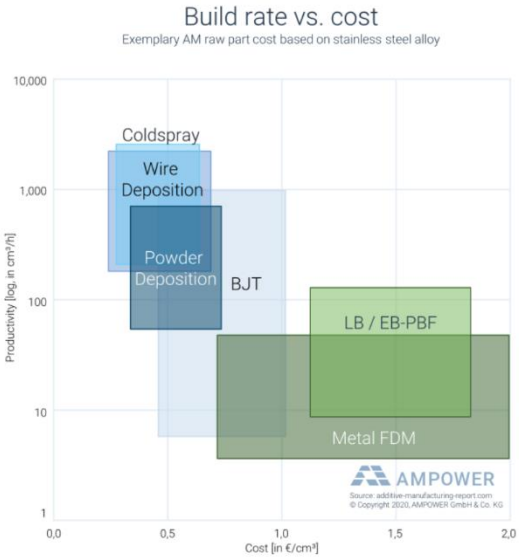


Figure 15: Build rates of different AM processes [10]

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The production time can be divided in two parts, the main time and the auxiliary time. The term main time refers to the time during which the selective melting of the powder is carried out by laser radiation. Whereas the auxiliary time refers to the time period where the SLM machine is prepared for the main time. That includes for example the preparation of the machine or the powder deposition. The powder deposition time is depending on the layer thickness *l* and the height of the part h. The deposition rate $t_{deposition}$ can therefore be calculated as followed:

$$t_{deposition}=n_{layers}*t_{layer}$$

In this equation n_{layers} is the total number of layers and is defined by n_{layers} =h/l. Whereas t_{layer} is the time to deposit one layer of powder, which is a characteristic of each SLM machine. The biggest influence on the main time is the build-up rate V. The calculation of the build-up rate is based on the process parameters layer thickness l, scanning velocity vs and the scanline spacing Δy_s.:

$$V=l*\Delta y_s*v_s$$

In order to make the process economically viable for serial production the productivity and mainly the build-up rate has to be reduced significantly. One possibility to increase the build-up rate is to increase the scanning velocity by increasing the laser power. Figure 15 shows that an increase of the laser power from 300 W up to a laser power of 2 kW results in an increase of the theoretical build-up rate to 26 mm^3/s, which corresponds to a factor of 8,9. Therefore it must be taken into account that an increase in laser power with a constant beam diameter results in a higher possibility of spattering formation. Further options beside increasing the laser power is to vary the layer thickness and a use of a bigger beam diameter. Experimental studies have shown that a bigger layer thickness will increase the build-up rate. An increase of the layer thickness from, for example, 0,6 mm to 0,15 mm at a laser power of 1 kW will increase the buil-up rate from 8 mm^3/s to 15 mm^3/s. This correlation between layer thickness and production time can be seen in the formulas mentioned above.

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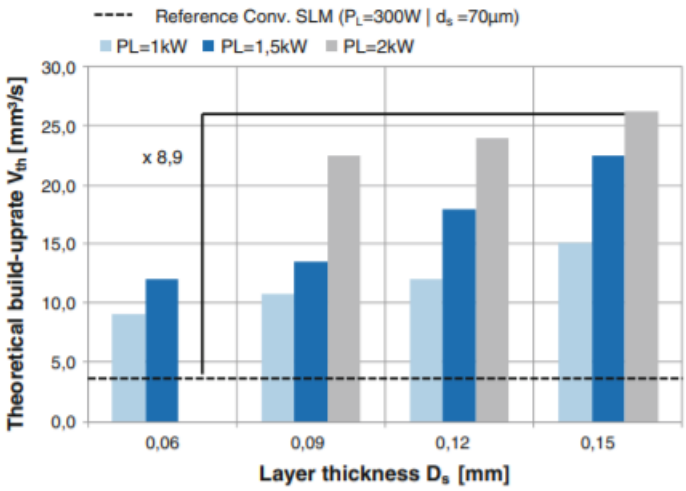


Figure 16: Influence of layer thickness and laser power on buil-up rate [11]

Besides changing the process parameters, the setup of the machine can be changed as well to improve productivity. Increasing the build volume allows to produce more parts in one build job. Thus, the number of machine setups and part removal procedures will decrease. Furthermore, productivity can be increased by using multiple laser beam sources and multi laser-scanning systems in one machine. In the figure below are two different machine concepts presented. The SLM machine X-line 1000R by Concept Lasers consists of a big build space of 630×400×500 mm^3 that can be processed with one laser-scanning-system. This scanning system is moved above the build platform. The machine is equipped with two process chambers that are rotatable. While one process chamber can be prepared for the next build job, the process can take place in the second one. In the second example, machine SLM500HL by SLM Solutions, the build volume is 500×280×335 mm^3. In this machine the process chamber can be moved inside and out of the machine. Thereby the preparation of the build space can be done outside of the chamber. Furthermore, the machine can be equipped with up to 4 laser beam sources. With these 4 laser beam sources the build area can be processed at the same time. In addition, the so-called skin-core build approach can be executed. A beam with a small diameter (d=80 µm) and up to a laser power of 400 W is used to build up the outer shape of the parts, while a laser beam with a big beam diameter (d= 700 µm) and laser power up to 1 kW is used to build the inner core of the part. With it the build up speed can be increased.

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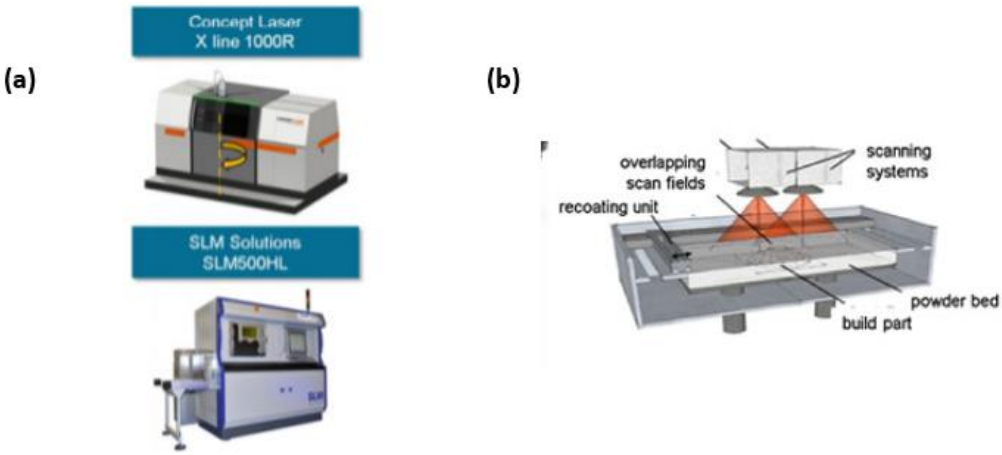


Figure 17: Different machine concepts (a) and SLM machine with parallelized scanning system (b) [11]

By using a SLM machine with two parallelized scanning systems the productivity can be increased as well. In this case, a distinction can be made between two scanning strategies. In the first scanning strategy the two laser beam sources and the two laser-scanning systems expose the same build area and the laser beams are processing one part simultaneously. In this scenario the build-up rate can be doubled. In the second strategy the laser beams will process two scanning fields, which are slightly overlapping, at the same time. This will double the build-up rate as well.

2.8 HYBRID BUILD STRATEGIES

Hybrid manufacturing is the group of processes that combine different procedures in order to cover their individual limitations and merge their benefits.
There have been various definitions regarding the term ‘additive manufacturing’ since it started to be used. In the past few years, it became consensual that the processes related with that definition could be divided into two different groups and there was a new extended classification based on an original one proposed by Bert Lauwers, which is represented down below.

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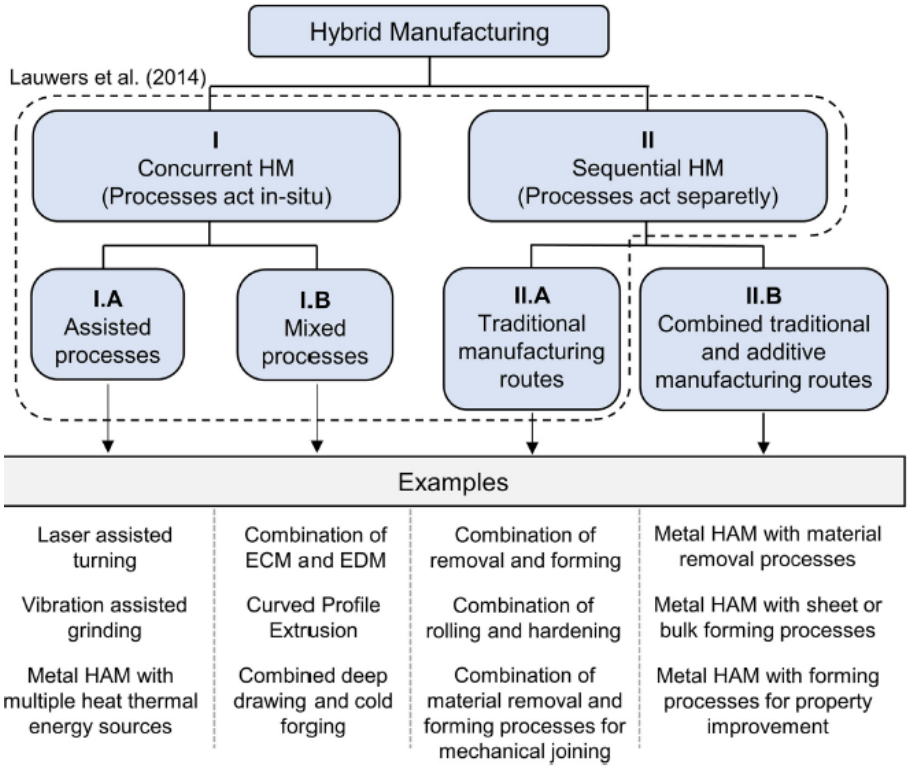


Figure 18: Classification of hybrid manufacturing processes [12]

The first group, named “Group I”, refers to processes with two or more energy sources combined, having two subgroups: Group “I.A” with assisted procedures (a secondary process is used before in order to assist the second process) and “I.B” with mixed processes (where two or more processes are employed simultaneously).
The second group, named “Group II”, includes the processes where synergetic effects are obtained with a controlled combination of separate processes, being more efficient and productive. Subgroup “II.A” includes the “controlled application of process mechanisms on primarily processed raw materials” while “II.B” regards mechanisms on additively deposited materials and is also applied to primarily processed raw materials that have been previously subjected to traditional manufacturing processes.
The second group, named “Group II”, includes the processes where synergetic effects are obtained with a controlled combination of separate processes, being more efficient and productive. Subgroup “II.A” includes the “controlled application of process mechanisms on primarily processed raw materials” while “II.B” regards mechanisms on additively

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deposited materials and is also applied to primarily processed raw materials that have been previously subjected to traditional manufacturing processes.
This hybridization's goal is to increase the range of applications and to overcome limitations related with processes individually, such as low productivity and lack of quality or precision.

2.9 PARAMETERS ADJUSTMENTS ALONG THE LAYER

All existing additive manufacturing technologies (such as SLS and SLM) use a fixed set of process parameters when scanning a part. The most relevant process parameters include the local toolpath velocity (v), system power (P), layer thickness (Lt), number of skin perimeters (n) and hatch rotation and spacing (h). The hatch refers to a series of parallel heat source trajectories used to fill the layer core. Perimeter trajectories are later specified in order to control surface finish.

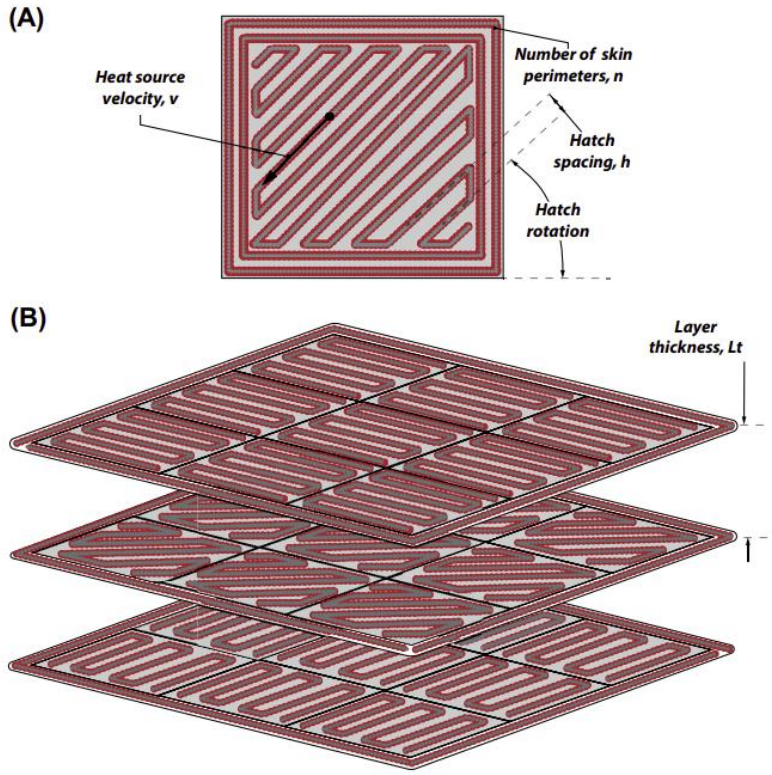


Figure 19: Relevant process and toolpath parameters, including (A) toolphat nomenclature and, (B) island strategy. For clarity, the meltpool witdh was undersized [13]

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From these characteristics, various processing parameters can be generated. Such as, energy density that is defined in linear (El), surface (Es) and volumetric (Ev) terms.

$$E_l = \frac{P}{v'}\left[\frac{J}{m}\right]$$

$$E_s = \frac{P}{vh'}\left[\frac{J}{m^2}\right]$$

$$E_l = \frac{P}{L_t vh'}\left[\frac{J}{m^3}\right]$$

These parameters are commonly registered and serve as a way of comparing various input conditions. However, one should be mindful of the fact that the parameters are subjected to error in calculation the actual absorbed energy. For example, the power reported is typically the net value emitted at the energy source, however, the actual energy received is lower due to reflection and other energy dissipation mechanisms. Of the energy density measures mentioned above, the volumetric energy density is the most commonly found in literature for PBF. The only limitation of this measure is the fact that assumes that thermal energy is deposited within a precisely defined volume of depth (Lt) and this is not what is typically observed in practice. The use of constant process parameters throughout the entire build process does not guarantee consistent quality across the whole part because SLM requires the processing of very different geometric features that have a variable influence on the behaviour of the melt pool. An example of such features are protruding structures, i.e., areas in a layer that are completely built up with loose powder

The values of energy density usually observed in PDF processes causes near instantaneous melting of the input powder. This results in rapid and directional heat transfer which is crucial to the PBF metallurgical response. Differently from traditional casting, the solidification occurs very rapidly due to high cooling rates and thermal gradients found in PBF systems. This promotes the creation of unique melt pool boundaries and anisotropic orientation of crystallographic grains in the build direction.

Most commercial applications of PBF can possess multiple length scales in the same part. Therefore, macroscopic components consist of many hundreds or thousands of unique melt pool passes. The number of parallel laser passes to fuse a layer is represented by N. Each pass is associated with a rapid solidification and consequently, the observed microstructure along the part is much more like micro-welded structures than that of cast specimens. One of the most relevant challenges for PBF certification is the control of potential defects that can occur along this extensive network of micro-fused tracks.

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The effect of the effect of the process parameters on the characteristics of the final manufactured product is intensively studied with the objective of quantifying the process that results in robustly formable materials. Distortion is a very relevant issue in PBF techniques because the process used creates high levels of residual stresses in the part. Every time a new layer is added, heat is introduced into the underlying material and this typically requires the newly melted material to reach a very high temperature in relation to the layers below. As result, large and very localized thermal gradients appear combined with non-uniform shrinkage cause the development of residual stress and distortion.

A typical sample SLM processing map is represented below. The effect of the processing parameters system power and scanning speed can easily be understood by looking at the graph. In order to obtain formable geometries one must combine high system power with low scanning speed. Low values of manufacturing power or high values of scanning speed will lead to obtaining distorted or even deformed final products.

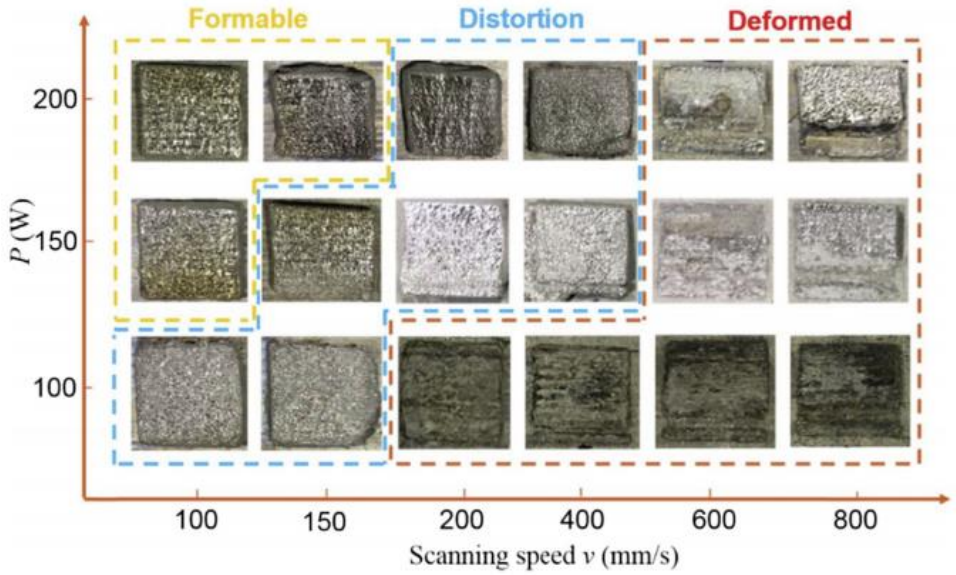


Figure 20: Sample SLM processing map [13]

Different combinations of process parameters will generate different defect morphologies on the final part. The morphology of the defects provides clues for the origin of the observed failures. The various types of defects that can generally be found include:

- Balling – Generated by incomplete fusion.

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- Gas-entrapped porosity – Associated with gas entrapped in the powder during manufacture.
- Keyholing porosity – Porosity cause by deep laser porosity.
- Lack of fusion defects - Planar defects are induced due to incomplete fusion.

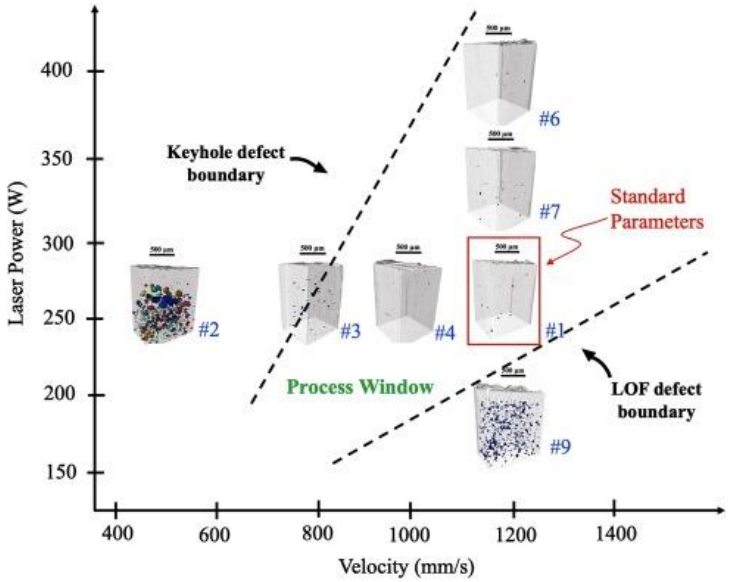


Figure 21: Defect structure process map showing how the combination of process parameters velocity and laser power influence the presence of keyhole and lack of fusion defects [14]

2.10 SCANNING STRATEGY

One of the important parameters in PBF-LB technique is the scanning strategy, which significantly affects the mechanical properties, residual stresses, and microstructural quality of the final product. In the figure below the important parameters in the scanning process are shown, including the scanning speed, hatch distance and the focus diameter.

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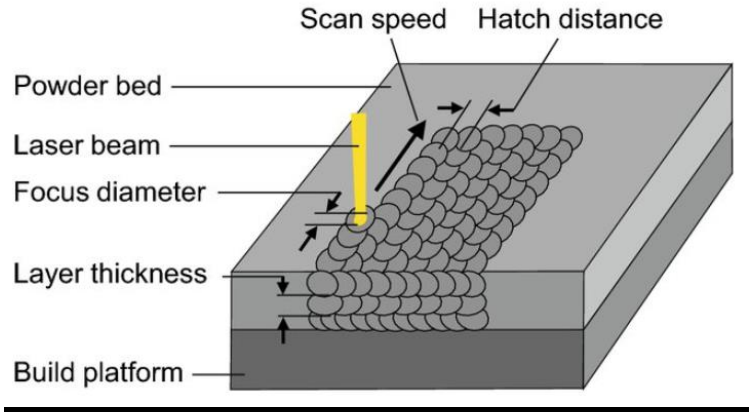


Figure 22: Parameters for the scanning strategy [15]

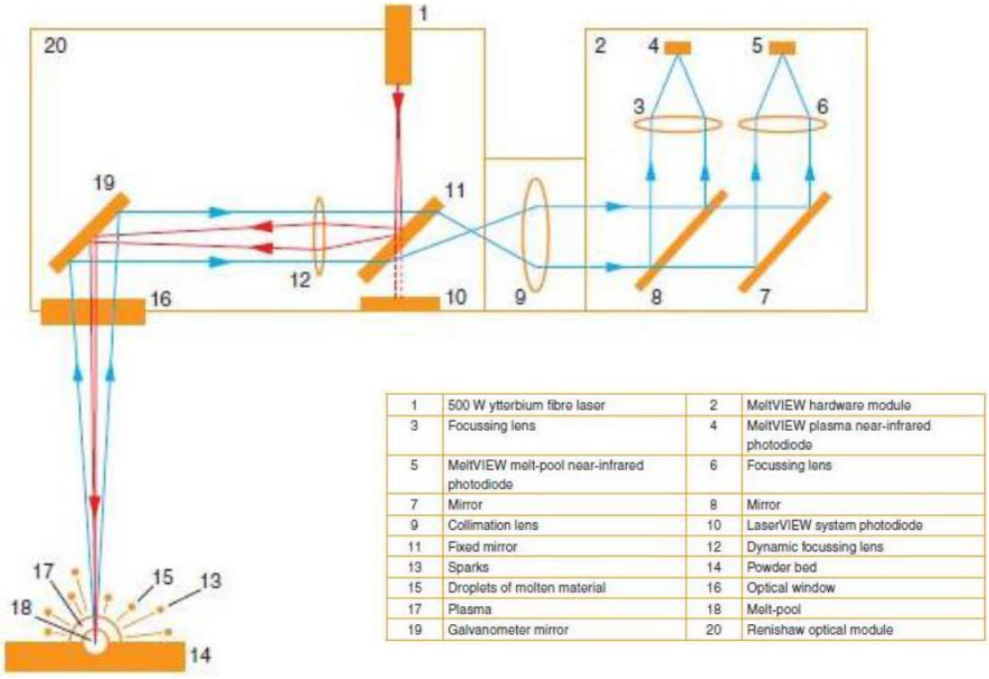
Hatch distance is the distance between two successive laser beams, being directly proportional to the production speed. A large hatch distance means that it takes less time for laser to scan the layer. On the other hand, several scanning needs to be executed in order to process the whole layer if there is a small hatch distance. A small hatch distance is also needed if the purpose is to make thin products.
With a large scan spacing, a large laser spot is required, since there remains a gap between two consecutive scans if that is not verified, resulting in porous products. Large spot sizes are achieved with high laser power.
This results in the need to establish a maximum scan spacing. Some overlap is made to avoid porosity deformation at the boundaries of scans, since the power is higher at the center of the beam, with overlap compensating the heat difference. It is possible to calculate and apply an optimal hatch distance, which results in the reduction of the overall porosity of the product.

3. EQUIPMENT AND ACCESSORIES

3.1 Optical System

Among the building systems of PBF LB technique, the optical system plays an important role in delivering the Laser beam for the melting of the powder. The picture below shows an example of the laser beam delivery setup with the components.

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1	500 W ytterbium fibre laser	2	MeltVIEW hardware module
3	Focussing lens	4	MeltVIEW plasma near-infrared photodiode
5	MeltVIEW melt-pool near-infrared photodiode	6	Focussing lens
7	Mirror	8	Mirror
9	Collimation lens	10	LaserVIEW system photodiode
11	Fixed mirror	12	Dynamic focussing lens
13	Sparks	14	Powder bed
15	Droplets of molten material	16	Optical window
17	Plasma	18	Melt-pool
19	Galvanometer mirror	20	Renishaw optical module

Figure 23: Example of Laser beam delivery setup with the components [16]

In this type of machine, the lasers used are usually fiber lasers, as they have a lower cost of purchase and maintenance than other lasers, are energy efficient, and provide better beam quality.

3.2 Powder Feeding System

Powder Feeding systems use the same feedstock as power-bed systems, however the way the material is added layer by layer is very much different. The powder flows through a nozzle being melted from a beam right on the surface of the treated part.
This system is also known as Laser Metal Deposition, Laser Cladding, or Directed Energy Deposition. The process is very precise and based on an automated deposition of a layer material with a thickness that varies between 0.1mm and some centimetres. This process has various features that include the absence of undercutting and the metallurgical bonding of the cladding material with the base material. In this welding technique, the substrate is penetrated by a low heat undercutting.

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3.3 Powder Handling System

Several different systems for powder delivery in PBF processes have been developed. The lack of a single solution for powder delivery goes beyond simply avoiding patent embodiments of the counter-rotating roller first used in SLS machines. The development of other approaches has resulted in a broader range of powder types and morphologies which can be delivered.

Any powder delivery system for powder bed fusion must meet at least four characteristics.

- It must have a powder reservoir of sufficient volume to enable the process to build to the maximum build height without a need to pause the machine to refill the powder reservoir.
- The correct volume of powder must be transported from the powder reservoir to the build platform; sufficient to cover the previous layer but without wasteful excess material.
- The powder must be spread to form a smooth, thin, repeatable layer of powder.
- The powder spreading must not create excessive shear forces that disturb the previously processed layers.

In addition, any powder delivery system must be able to deal with these universal characteristics of powder feeding.

- As particle size decreases, interparticle friction and electrostatic forces increase. These result in a situation where powder can lose its flowability. Thus, any effective powder delivery system must make the powder flowable for effective delivery to occur.
- When the surface area to volume ratio of a particle increases, its surface energy increases and becomes more reactive. For certain materials, this means that the powder becomes explosive in the presence of oxygen; or it will burn if there is a spark. As a result, certain powders must be kept in an inert atmosphere while being processed, and powder handling should not result in the generation of sparks.
- When handled, small particles have a tendency to become airborne and float as a cloud of particles. In PBF machines, airborne particles will settle on surrounding surfaces; which may cloud optics, reduce the sensitivity of sensors, deflect laser beams, and damage moving parts. In addition, airborne particles have an effective surface area greater than packed powders, increasing their tendency to explode or

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burn. As a result, the powder delivery system should be designed in such a way that it minimizes the creation of airborne particles.

- Smaller powder particle sizes enable better surface finish, higher accuracy, and thinner layers. However, smaller powder particle sizes exacerbate all the problems just mentioned. As a result, each design for a powder delivery system is inherently a different approach to effectively feed the smallest possible powder particle sizes while minimizing the negative effects of these small powder particles.

3.4 Gas System

The SLM processes are performed in general in a closed build chamber filled with shielding gas. This shielding gas is recirculated in a closed circuit with a filter which results in a shielding gas flow that can be either direct or indirect. Figure 23 show the schematic circulation of the shielding gas in a SLM chamber.

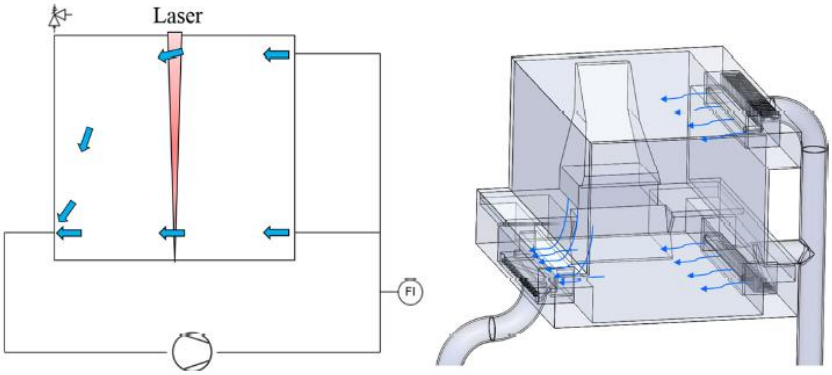


Figure 24: Gas flow configuration in a SLM machine, showing the schematic circulation of the shielding gas [17]

In the selective laser melting process, the characteristics of the shielding gas atmosphere and the implementation of the gas flow are factors that influences the stability of the process and therefore the part quality and consistency. On one hand, inert atmosphere protects the process zone from reactive gasses in order to prevent chemical reactions like oxidation or nitration. On the other hand, the gas flow removes process by-products from the process zone, which prevents the process from being disturbed.

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These by-products, represented down below, may significantly disturb the melting process. They can induce laser attenuation by absorbing incident laser energy when they stay in the laser path. In addition, scattering and thus a shift of the focal point can also be a consequence. Condensate, ejected powder and spatter can also be deposited on the surfaces causing material accumulation, thickening of the powder layer, among other problems that this entails.

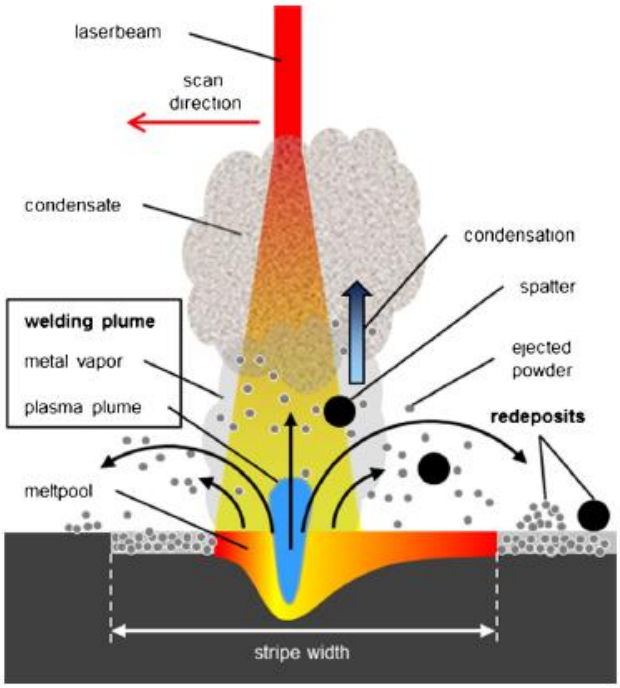


Figure 25: Schematic representation of possible process by-products [18]

3.5 Deposition Direction

Powder deposition represents an important factor which influences the quality of the final product. In order to obtain good surface quality, uniform spreading and smooth deposited layers should be guaranteed. One should also be concerned about the quantity of powder. Surplus powder is important to ensure complete coverage but may also lead to increased weight. This can cause friction between the new layer and the solidified layer and lead to "misalignment" of layers. Using a mesh to bond to first layer may help minimize this problem.

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Three methods of deposition mechanisms are generally utilised: rotating/counter-rotating roller, wiper blade and slot feeder. Two conditions must be kept in mind for a good deposition: the deposited powder cannot be compacted by a scraper blade and this blade must touch the powder along a fixed line, so ay scratch in the blade leads to irregularities along the layer.

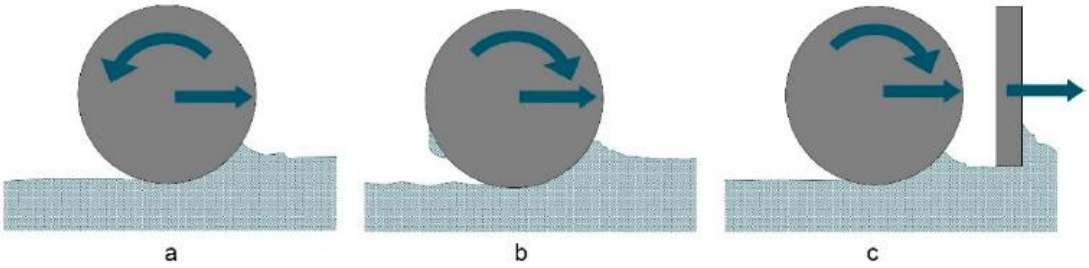


Figure 26: Deposition mechanisms, (a) Counter-rotating Roller, (b) Foward-rotating roller, (c) combination of balde roller [19]

It is generally accepted that the best strategy is to use the combination of two approaches of the hopper (slot feeder) and rolling. This way the two conditions for good deposition considered above are guaranteed and only the height (vertical dimension) needs to be controlled. It can be seen from Figure 25 that the forward-rotating roller is causing defects in the powder bed as some of the powder is sticking to the roller.

Powder specifications like particle size and shape should be monitored as they significantly affect the powder fluidity. If the particles are too small and their shape is too irregular, they will impede the smooth deposition of layers. Usually, finer particles produce the best surface finish if melted under ideal melting conditions. Although, a decrease in powder size may increase some weak forces such as Van Der Waals, magnetic forces, electrostatic charges, and capillary forces. The presence of this forces will reduce the fluidity of the powder. It is also worth mentioning that spherical-shaped particle generally led to ideal flow properties. A flat bottom geometry provides the lowest roughness of the surface, which is good because it guarantees minimal surface finish. This is due to the higher compression of the powder bed, which is related to the two-dimensional contact zone. For a round or sharp blade, it was found that the effective vertical compression was subpar, which generated higher surface roughness.

Lastly, the translational speed of the rollers also showed to influence over the quality of the final product. It was found that higher translational speeds were responsible from higher compression forces which lead to a increase in the specimens density. On the other

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side different research reached the conclusion that lower translational speeds created higher powder quality.In addition, rollers with large contact areas proved to be the best choice as they provide better support between the particles and roller.

A hopper system delivers powder to the powder bed from above rather than beneath. The powder reservoir is typically separate from the build area, and a feeding system is used to fill the hopper. The hopper is then used to deposit powder in front of a roller or doctor blade, or a doctor blade or roller can be integrated with a hopper system for combined feeding and spreading.

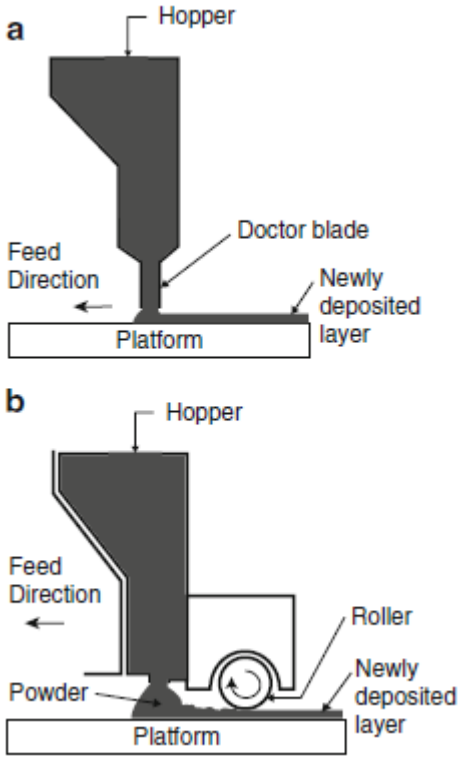


Figure 27: Examples of hopperbased poder delivery systems [20]

3.6 Sieves and Filters

The PBF-LB process has a major advantage associated with the ability to recicle all unused powder during fabrication, which is a big benefit since it allows considerable cost savings. There is a large quantity of powder that can be reused because it is not consolidated during fabrication. However, the material must have its quality as close to

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the virgin material as possible, which makes it necessary to implement a process that can minimize any changes regarding the “original” material.
The powders need to have a strictly controlled and homogeneous size, they have to be homogeneously mixed and homogeneously spread, and they need to not suffer aggregation due to residual electric charge or magnetization or any other parameter that can give agglomeration.
Other particularitie that should be considered in the PBF-LB process is that it can reach very high temperatures and is able to generate big cooling rates, something that can cause instabilities, which leads to the formation of spatter particles, condensate plumes and ejected powder. With each reutilization, there is more undesired agglomerated particles and an increase of oxygen, which can affect the powder quality and requires the implementation of strategies to preven it from happening.
An effective solution to this problem is the introduction of a sieving stage, where the powder is mechanically sieved, after being removed from the machine. This can help to maintain the right size range for the powders and help avoid possible contaiments such as ejected material and/or agglomerated particles.

Apart from the sieving system, filters can also be used to assure the powder quality.

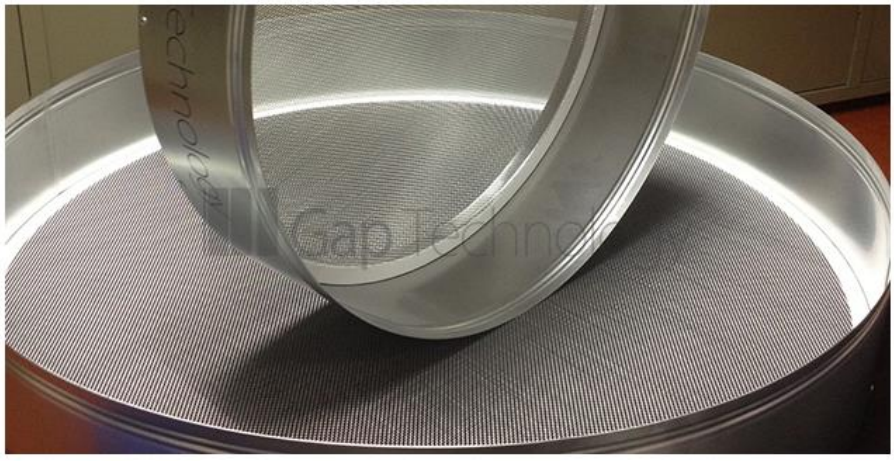


Figure 28: Exemple of a sieve to use in PBF-LB [21]

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4. DEFECTS

The mechanisms of formation of PBF-LB defects have been under investigation in recent years. Several publications have discussed various types of defects in metal AM and described the mechanism of their formation. However, the analysis techniques could also apply to all other AM process defects.

These defects are induced to the AM parts during the manufacturing process. The localized heating and rapid cooling along with consuming powdered material as the feedstock create a favorable environment for defect formation by leaving small cracks, unmelted particles, LOF (Lack of Fusion) regions, or creating gas bubbles.

4.1 Sources of Defects

Feedstock Material → can be the first source of defect formation based on its atomization process and whether it carries a high amount of entrapped gas.

Energy input → another main source for defect formation which should be optimized based on the material and other process parameters to maintain a low defect producing process. The energy density per unit volume is a parameter commonly used. This parameter incorporates the beam speed, power, and offset between melt tracks. The energy supplied to the melt pool should be optimized to only partially melt the previously deposited layer in order to create a perfect bond between the two sequential layers. Any deviation from this optimized amount of energy could create insufficient melting or vaporization and a highly unstable melt pool. Having insufficient energy will cause compromised bonding between layers and create LOF defects. Having excess energy, on the other hand, will cause violent convection currents and significant vapor recoil forces, which can lead to ejected spatter and instability

LOF (lack of fusion) defects → These defects usually have sharp edges and are elongated between the layers and also laser tracks. Generally, large LOF defects are formed around and contain unmelted power particles.

Voids and Gas Bubbles → This type of defect is common when the heat input is too high, and occurs mainly in the melt pool. They are generally spherical in shape due to the dominance of surface tension in the liquid metal. The entrapped gas content of these pores depends on whether a shielding gas was used, the type of feedstock powder, and the original gas entrapped in the powder particles. These gas pores might be hard to remove

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by post-processing treatment depending on the solubility of the contained gas. Round pores are also formed when the high applied energy causes the melt to vaporize locally and become entrapped in the melt pool. Due to re-melting while depositing the next layer, there is a possibility for gas bubbles created on top of the melt pool to escape as opposed to the gas bubbles deeper in the melt pool which makes them more detrimental. High power and low scan speed strategy should be avoided to prevent the formation of these detrimental defects. This kind of porosity is sometimes referred to as keyhole induced porosity.

4.2 Defect Control

Variability in AM machines, beam source/material interactions, and geometry can cause inconsistency in the microstructure and defects, and consequently variability in the mechanical performance even for the same processing conditions. Characteristics of defects such as size (volume, area, diameter), shape, location, and distribution have shown to play key roles in mechanical properties and specifically fatigue performance of the AM metals and should be thoroughly studied in order to evaluate and quantify their effect.
The object can be analysed by:

- Cross section analysis
- Bulk density
- Archimedes method
- Gas pycnometry
- X-ray micro-CT (extremely precise but also expensive and complex)

The first two methods are traditional destructive methods. Since the parts manufactured by AM process are relatively expensive, the non-destructive methods of defect characterization are of great interest. The most common are the last three in the list.

5. POST PROCESSING

Defects occurring in the part produced by PBF process are often similar to the welding defects. One of the most common factors for these defects is wrong heat input rates or segregation issues during high temperature solidification. Surface defects or surface roughness is also one of the major defects of the PBF process. These defects occur because of high cooling rates and repeated thermal loading.

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In the heat treatment process, it is very important to discover the concluding microstructure. Usually, they affect the mechanical properties of metal to a great extent. The thermal treatment is required to heat-treat the material to reduce the porosity and other defects. When material comes out of an AM process, there are some steps that are used to develop a fabricated part into an end. In general, the heat treatment processes include:

- Hot Isostatic Press (HIP)
- Stress relief
- Alloy specific solutions
- Quench
- age-tempering processes

Solution, Quench, Age and Temper Heat Treatments: For precipitate hardened material, a solution heat treatment is required to dissolve the material with as usual quenching is required. These steps are required, where the processing of material does not result in an optimum structure for meeting the requirements for the part which is in use. The solution treatment should be long enough to dissolve the precipitate but at the same time should be short enough to limit the grain growth. These processes (Solution, Quench, Age and Temper Heat Treatments) tend to be alloy specific, but give the different starting condition of AM materials relative to cast and wrought materials even for the same alloy, where a standard wrought and cast material heat treatment already exists. If the material is solutionize, the matrix of material is ‘‘reset”.

Hot Isostatic Press (HIP): Most of the metals are heat-treated by this method called HIP. This method is used to close down the pores and crack developed in the material. When pores develop on the surface, they are known as ‘open’ pores, the internal cracks can also be treated by HIP. This process includes a process by which the pressure and high temperatures both work simultaneously and engage in heat treatment of AM parts to close the non-surface pores or porosity that may lead to poorer tensile and fatigue performance.

Most of the post–processing parts of AM can be performed this way. Although it is not necessary to use it for all AM parts, many users with high performance or safety critical applications have included HIP in the standard process for a wide variety of materials to control and reduce porosity and defects that create from non-optimal process conditions. The use of HIP may examine the grain structure of the AM parts.

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Stress Relief: Stress relief includes the recovery of material at an elevated temperature. The atomic diffusion rate increases the atoms present at regions of higher stress, which start to move towards the region of lower stress which results in relief of internal strain energy. PBF produces a high thermal slop layer by layer, which generates a high degree of localized residual stresses throughout the part. It is not possible to remove the part from the build platform without any distortion. A stress relief step is necessary to equalize the stress gradients that are caused by the process of thermal gradients to enable the removal of the part from the material without any distorted shape or part cracking.

6. CONSUMABLES

6.1 Feedstock

There are a wide variety of alloys processable by PBF-LB including:

- Steels (316L, 304, 17-4PH, etc.)
- Nickel base alloys (In718, In625, In713C, Nimonic 90, MP35N)
- Cobalt base alloys (F75 Co-Cr)
- Titanium based alloys, such as (CP Ti, Ti-6Al-4V (grades 5 and 23)
- Aluminium base alloys (AlSi10Mg, etc.)
- Precious metal alloys, based on gold, silver and platinum
- Copper base alloys
- Magnesium base alloys
- Refractory metals (Mo alloys, W alloys, WC, and Ta)
- Metal matrix composites (MMCs) and nano-dispersoid reinforced materials

The feedstock should be chosen based on requirements and user needs, consider the manufacturability of the materials and in accordance with the build plate material and feedstock, in order to be compatible, with a similar thermal expansion. Feedstock should be handled and stored carefully to prevent cross contamination. Powder should be climatized (temperature & humidity) before introduced to the machine. If required by the customer, powder containers can be filled by inert gas (argon or nitrogen) to provide a protective atmosphere. There are some risks involved with neglected handling and storage. Dust explosion and powder contact and inhalation are serious problems that should be highly avoided.

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Morpohlogy: influences flowability and packing density. Should be spherical without agglomerates and satellites.

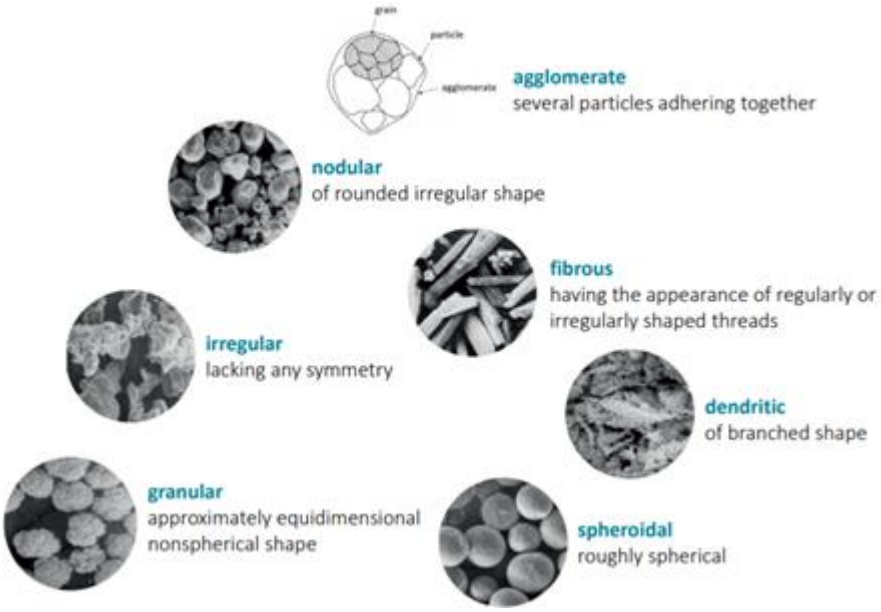


Figure 29: Possible types of morphology of diferent powders [22]

Particle size distribution: influences flowability, due to cohesive and gravitational forces, and packing density. Particle range should be between 10 - 45 µm.

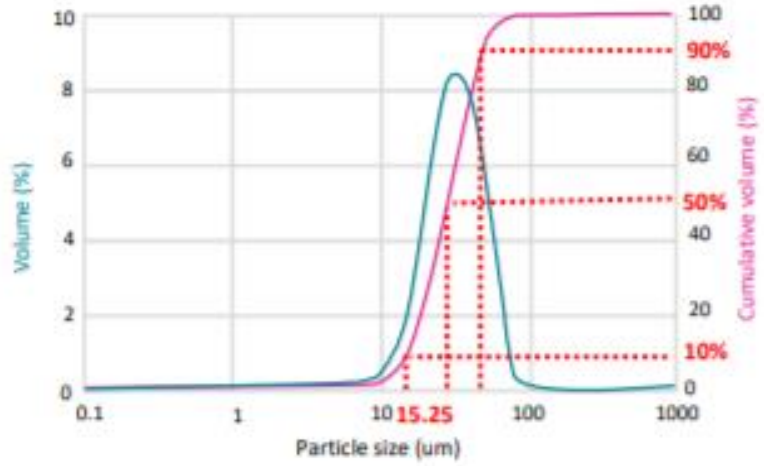


Figure 30: Influence of a particle size on a packing density [23]

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Flowability: it's the ability of a powder to flow. It's a function of powder size and size distribution, powder morphology and surface, and cohesive strength by adsorbed water on the particle's surfaces. Influences the uniformity of the powder bed and the powder delivery in system piping.

Spreadability: ability of the powder to be spread uniformly during the process.

Chemistry: takes into account the composition and the contamination of the powder. Influences the quality of the parts.

6.2 Process Gas and Gas System

In the majority of the applications of PBF-LB we are referring to the Melting PBF-LB, a certain degree of protection from oxidation needs to be assured in the system. In this case though, we have to create protection but we also have to consider that we are working with powders so the calibration and positioning of the gas system needs to be carefully studied. The solution has been found with a regular flow of inert gas above the powder layer, horizontal to the system in order to create a protective sublayer over the powder layer deposited. The correct amount of gas then needs to be calibrated in function of the powder dimension and the packing of the layer itself.
The gas flow system doesn't just have this function though. We can see in the following image that the process in absence of gas is subjected to vapour creation and intensive spatter.

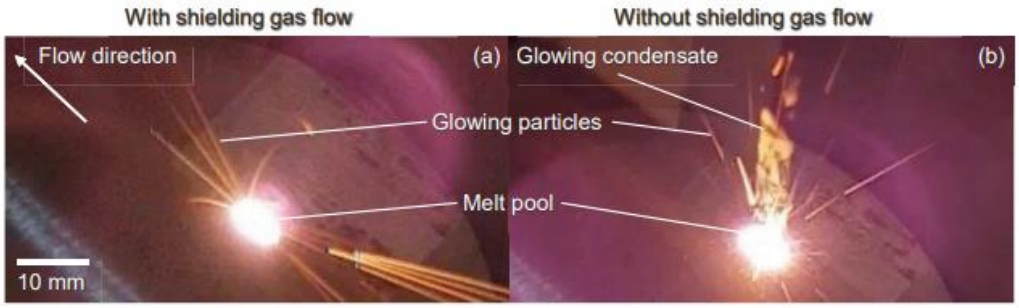


Figure 31: In-situ images of the exposure of stripes with (left) and without (right) shielding gas flow support. The process without shielding gas flow is forming a glowing pillar out of condensate and vapor [24]

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In absence of gas flow these are the main problems that can be observed in the process:

- increased laser beam attenuation and/or scattering by the small condensate particles in the vapor plume ejected from the keyhole
- large spatters and/or denuded powder particles landing on the unprocessed powder bed when the gas flow is insufficient to remove the vapor plume and/or the spatters
- oxidation of the melted metal

The gas flow mainly solves all these problems as it can be noticed in the figure. Different gases will have a varying effect on part properties and only noble gases can be used with reactive metals. Slight changes in flow pressures can have a strong effect on part quality and a good understanding of the impact of flow on part properties across the build plate is critical.

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