

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



INTRODUCTION TO ADDITIVE MANUFACTURING

ME-413

M 2) AM for metallic materials

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Contents

1	Introduction written by Noah Studer	3
2	Direct Energy Deposition of metallic materials written by Emilien Ancey	3
2.1	Process working principle	3
2.2	Feeding materials: powder and wire feeding	4
2.2.1	Suitable metals	4
2.2.2	Powder feedstock	5
2.2.3	Wire feeding	6
2.3	Key processing parameters and their influence on the resulting part	6
2.3.1	Laser energy density: combination of laser power, scan speed and laser spot size	6
2.3.2	Powder flow rate	8
2.4	Solidification, resulting microstructure and final roughness	8
2.5	Applications, advantages and disadvantages	8
3	Selective laser melting (SLM) written by Noah Studer	10
3.1	History and development of SLM	10
3.2	Principle and functioning of SLM technology	10
3.3	Process parameters and their impact on part properties	11
3.4	Materials available for SLM technology	13
3.5	Post-processing of SLM parts	13
3.6	Advantages and limitations	13
3.7	Industrial applications	14
4	Electron-Beam Melting (EBM) written by Luka Roche	15
4.1	Background	15
4.2	Technical Details	15
4.2.1	Electron beam generation and beam control	15
4.2.2	Powder bed melting	16
4.2.3	Post-processing	17
4.2.4	Materials	17
4.3	Advantages and limitations	18
4.4	Applications	19
5	Extruded metal processes written by Adrien Borgeat	20
5.1	Material extrusion (MEX)	20
5.1.1	Screw-based MEX	20
5.1.2	Plunger-based MEX	20
5.1.3	Filament-based MEX	21
5.1.4	Material selection	22
5.1.5	Debinding and sintering	22
5.1.6	Advantages and disadvantages of MEX	23
5.2	Semi-solid metal extrusion and deposition (SSMED)	23
5.2.1	Process and material selection	23
5.2.2	Advantages and disadvantages SSMED	24
6	AM for metallic materials at Micro and Nano-Scale written by Arnaud Sansonnens	25
6.1	Micro Selective Laser Melting	25
6.2	Direct Ink Writing	26
6.2.1	Working Principle	26
6.2.2	DIW Setup	26
6.2.3	Capabilities and Geometries	27
6.3	Electrohydrodynamic (EHD) Printing	27
6.3.1	Ink Deposition Modes	27
6.3.2	Capabilities and Geometries	27
6.4	Laser-Induced Forward Transfer (LIFT)	28

6.4.1	Capabilities and Geometries	28
6.5	Focused Electron/Ion Beam Induced Deposition (FEBID/FIBID)	29
7	Conclusion written by Emilien Ancey	31
8	References	31

Abstract written by Adrien Borgeat

This literature review presents the recent advances in the field of additive manufacturing (AM) applied to metallic materials. The focus is set on different methods either in development like Semi-solid metal extrusion and deposition (SSMED) or well established like Direct Energy Deposition (DED), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and metal extrusion (MEX). Potential improvements on these methods are also presented. All these processes are categorized in three main groups: powder jet, powder bed and solid extrusion techniques. Their working principles, feeding materials and other key parameters, such as laser power or cooling rates are studied in depth. The impact of these elements on the properties and the microstructure of the printed body is also highlighted in order to present strengths and limitations of all the processes. Finally, emerging technologies of metallic AM applied to micro- and nano-scales are discussed along with their potential applications. This review highlights the complexities and capabilities of each process, showing the diversity of the additive manufacturing processes on metals.

1 Introduction written by Noah Studer

Additive manufacturing (AM), commonly known as 3D printing, has progressed from a prototyping tool to become a transformative technology in manufacturing, especially for metallic materials. Metals are the most widely used materials in the industry due to their exceptional mechanical properties making them essential for producing high-performance components that can withstand mechanical, thermal, and chemical stresses. The use of AM technology makes it possible to manufacture metallic parts with complex geometry, reduced weight, and therefore lower cost. As AM becomes more widely used in industry, it is important to identify the different techniques that can be used to produce parts for specific applications using metal as a raw material. This literature review provides a detailed exploration of the different processes for metals, examining their capabilities, advantages, limitations, and industrial applications.

The aim of this review was to delve into the three main areas of AM for metals: powder jet, powder bed, and solid extrusion. It therefore began by looking at direct energy deposition (DED) for powder bed processes, then selective laser melting (SLM) and electron beam melting were also covered in the area of powder bed solutions and, finally, material extrusion (MEX) and semi-solid metal extrusion and deposition (SSMED) were investigated for extruded solid techniques. After an overview of the processes used to produce parts by additive manufacturing from metals, it was decided to delve into the emerging AM technologies used at the micro- and nanoscales to understand the impact of the advantages of AM for producing miniaturized, high-precision components.

Through this literature review, the objective was to present the different additive manufacturing processes available for metals, to observe the different materials available for these technologies, to analyze the influence of process parameters on mechanical properties and surface quality, and to understand how the process can be tuned to meet current challenges by improving part quality, reducing defects, cost and weight to meet the requirements of advanced industrial applications such as those found in micro- and nanoscale industry or in other fields such as aerospace, medicine or the automotive industry.

2 Direct Energy Deposition of metallic materials written by Emilien Ancey

Direct energy deposition (DED) is the generic term referring to additive manufacturing of materials by deposition of material in molten state. This term can refer to the additive manufacturing of any material such as plastics for example. In our case, metallic materials will be discussed. Also, in DED, many heat source can be used such as lasers but also electron beams. In this work, only laser technologies will be discussed as they are the most common ones.

2.1 Process working principle

As briefly introduced, DED of metallic materials will be described here. It is first of all really important to note that many names are often used to describe such processing techniques of metallic materials using a laser as heating source, such as Direct Metal Deposition (DMD), Laser Engineered

Net Shaping (LENS) or Laser Based Metal Deposition (LBMD). All these techniques are referring to the same working principle that will be described further on, and are simply different machines where some key features (such as the head movement device) are changing.

DED of metallic materials usually consists of a laser beam focused on the surface of a substrate thanks to optical devices, creating a melting pool. This heating from the focused laser beam originates from the absorption of photons by the metallic substrate and excitation of atoms resulting from these interactions [1]. At the exact same time, a metal powder (or a metallic wire, feedstock will be discussed later-on) is injected into the melt pool by a single, co-axial or multi-jet nozzle (or a metallic wire feeder). In the case of powder feeding, all three types of feeding nozzles have pros and cons that will be discussed deeper in part 2.2. As the laser moves away, the pool (with an increased volume due to the material addition) solidifies, creating the part geometry. A simplified schematic in Figure 1 shows the typical equipment set-up for a metallic powder. As shown on Figure 1, "tracks" of metal are created one next to another, creating one layer. Usually, when going from track to track in one layer, track overlap is about 25%, meaning that 25% of previously deposited track width is remelted when making the new one. This impacts the microstructure and resulting properties of pieces. As layers are made, it is the surface of the added metal that is then heated and creates the melting pool.

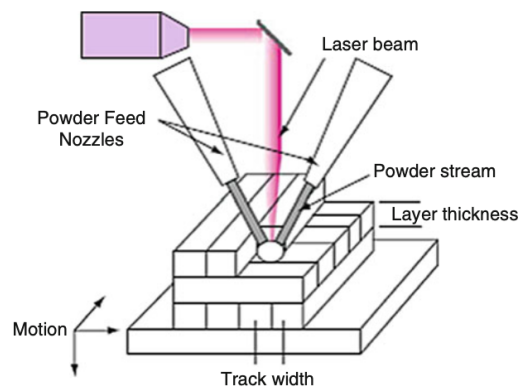


Figure 1: Schematic of the DMD process [2]

The common set-up includes a moving deposition head and a stationary part, but the contrary can be found.

Typical technical datas for this technique are as follows: build rates up to $300 \text{ cm}^3/\text{h}$. Layer thickness are generally in the order of $40 \mu\text{m}$ to 1mm . Feed rates between 4 and 30 g/min are obtained in the case of metallic powder feeding. The spot size of the laser beam varies between 0.3 and 3mm , and finally the scanning speed ranges from 150 mm/min up to 1.5 m/min [3]. Typical laser used are Nd:YAG, CO_2 lasers or fibers lasers, depending on the machine and materials used. [4]

2.2 Feeding materials: powder and wire feeding

DED of metallic materials can typically use metallic wire or powders. This section will discuss the pros and cons of each feedstock, and the typical metals used for such process.

It is crucial to previously note that the choice of either a powder feeding system or wire one is determined by many factors such as the part geometry complexity, or required dimensional accuracy. A quasi case-to-case determination is required.

2.2.1 Suitable metals

Before choosing the way we will use our feedstock, it is important to know whether or not it will be possible to use it for DED application.

For metals, typically gold and some alloys of aluminum and copper are not adapted. This mostly comes from the fact that they have a high reflectivity at typical laser wavelengths applied in such technique and exhibit high thermal conductivity. The efficiency of the laser heating is thus reduced, and the required intensity and power required are elevated, which can lead to problems that will be discussed in more details in section 2.3. Most other metals are quite straightforward to process,

even if a special care must be taken to prevent oxidation. Generally, metallic materials that exhibit reasonably good weldability are easy to process. Titanium alloys are the best example of a metal that benefit of this processing technique, being hardly machinable, it turns-out to be economically viable to make parts this way, as well as mechanically interesting. Typical titanium alloys used are α - β alloy Ti-6Al-4V used in aerospace field. Many steel alloys can be manufactured using these techniques, such as austenitic stainless steels. The list is non-exhaustive as a quasi-infinite number of alloys could be manufactured this way, but in order to really benefit from the economical and mechanical point of view, one must compare it with traditional production methods [3].

2.2.2 Powder feedstock

Most widespread feedstock for DED of metallic materials is powder feedstock. Powder size must range from 20–150 μm in order to obtain a good flowability as well as have a regular sphere-like shape in order to get a high-density packing in the melt pool, which will be beneficial for final properties of parts [2] [3]. It is very important to note that the powder fineness will also play a non-negligible role in the resolution of the process.

Powders are usually fabricated by gas-atomization. It consists of injecting a liquid metal in a zone where high-velocity gas stream (of argon or nitrogen) is moving, thus breaking the molten metal in fine droplets. It results in particles with diameter ranging from 60–125 μm . Nevertheless, it happens that contaminants (mainly from ceramic parts being in contact with the melt) impact the powder quality. Nowadays, typical method utilized are plasma melting in combination with inert-gas atomization (PIGA) where contamination are removed by changing the way the metal is melted and transported [5].

Powders are subsequently fluidized either by gas or by applying ultrasonic vibrations. Most of the time, it is made by using a gas. One can see this as turning a solid powder into a "fluid-like" material by creating a "suspension" of the powder in the gas (as it would be a suspension inside a liquid for example) and reduce contact between the particles. This way, powders flow much easier. They are then transported to the melting pool by a nozzle that usually applies a pressure drop to make the fluidized powder flow to the workpiece.

In order to make metallic alloys parts, two main routes can be followed: the use of pre-alloyed powders where powder grains are already alloyed, or use powders of pure metals, and mix them in appropriate amounts in order to obtain the wanted alloy. The second option allows for a huge versatility, even in one part, of the material composition, as if fed by two different feeder, the feed-rates can be monitored in order to get specific compositions in specific spot of the part, which is very interesting here. Typically both techniques can nevertheless be used in practice [2].

Single nozzle powder feeding Single nozzle feeding involves, as its name suggests, a single nozzle that delivers powder in the melting pool. This typical set-up is illustrated in Figure 2 right below.

The major benefit in such a set-up is that the price is lower, as it is technologically much simpler than a co-axial or a multi-jet nozzle.

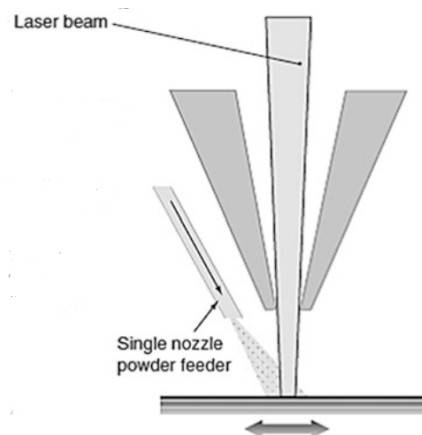


Figure 2: Single jet nozzle [2]

Co-axial nozzle Here, the powder jet is focused into the melt pool using a shielding gas, that can protect the melt pool from oxidation, which is very interesting as liquid metals are highly reactive. Also, it leads to less losses of powders. This set-up is shown schematically in Figure 3 right below.

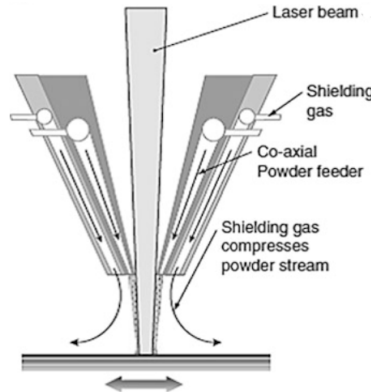


Figure 3: Co-axial nozzle [2]

Multi-jet nozzle Multi-jet nozzle, and for example 4-nozzle feeding, is made of four distinct nozzles, evenly distributed around the laser beam (discontinuous co-axial nozzle). The main benefit of a multi-jet nozzle feeding system is that it allows more precision in layers of the part, but as in the single-nozzle, no shielding gas is present.

2.2.3 Wire feeding

Wire feeding will typically be used when precision is not the key parameter of the processing, and that the part geometry is less complex, so mainly for easy geometries or surface coatings. Metal wires are easier to produce, and feeding devices are also less complex than the powder nozzles discussed earlier-on. The precision of the track deposition will depend here on the diameter of the wire.

Here, the wire (usually made by hot-rolling) is simply approached of the melting pool and melts there. A shielding gas stream is also very often present.

One advantage of wire feeding compared to powder one is that here there are no losses of material, except if vaporization of splattering happens. Also, some study have discussed of the possibility to get higher quality feedstock when using wires, being for example much less prompt to contamination than powders that have a much higher surface area [6] and could be very useful for applications requiring high repeatability. Also, higher deposition rates allow for interesting cost-effectiveness compared to powder feeding for large and not complex parts.

2.3 Key processing parameters and their influence on the resulting part

Many parameters are changing either from one type of machine to another, or need to be adapted from one type of metal to another. These parameters will be discussed and their influence on final microstructure and properties of final parts will also be discussed.

2.3.1 Laser energy density: combination of laser power, scan speed and laser spot size

It is very important to note that laser spot size, scanning speed and laser power, that will be discussed individually, are related by the following equation of laser energy density 1:

$$E(J/mm^2) = \frac{P}{v \cdot d} [7] \quad (1)$$

with:

- P laser power in W

- v the scanning velocity in mm/s
- d spot size in mm

Most of the time, it is the combination of these individual parameters that are of major relevance, as their impact on laser energy density will directly have consequences on the melt pool size and solidification rate of the deposited tracks.

Laser power Laser power P is a very important parameter. It usually ranges from few hundreds of watts to a few kilowatts for most of DED processes, but can in some cases go to higher powers [7].

It is selected knowing the material properties and the other parameters. Often, the goal is to select it in order to get the more dense part, with the less defects, and the more appropriate microstructure for its final use.

Laser power will directly impact the melt pool, and the possible microstructure of later obtained solidified grains. The larger the power is the bigger will be the pool and the smaller the solidification rate. A too high power can result in splattering and even vaporization of material, leading to defects and reduced properties. Inversely, a too low power can lead to unmelted powder because of a too low energy density, resulting again in decreased performances.

Typically, it was shown that in low-power machines (such as in LENS), columnar (directional) dendrites are usually obtained, even when changing the scanning speed. For high-power laser machines, equiaxed, mixed and columnar regimes can be achieved depending on the scanning speed associated. Thus, depending on the microstructure wanted, one can choose the power accordingly [2].

Scanning speed The effect of scanning speed v , that correspond to the speed of displacement of the head made of the laser and feeding device, is inversely proportional to that of laser power, as suggests equation 1. It usually ranges in DED between 2.5 to 22mm/s [3].

A decrease in the scanning speed will induce a larger melting pool and a smaller solidification rate, impacting the solidification regime, and consequently the microstructure and mechanical properties of the final part [7]. The precise optimization of this parameter, of power and laser spot size are of major importance for the productivity of the machine as well as the final quality of the product.

Cooling rate Cooling rate is a parameter that derives from the choice of both the laser power and scanning speed. DED processes can involve extremely high solidification cooling rates, from 10^3 to 10^5 K/s. It is shown that the higher the cooling rate, the thinner will be the microstructure, having impact on its final mechanical properties [7]. These cooling rates vary in the melting pool, for example depending on which direction the head is going, increasing dramatically the complexity of obtained microstructure.

These cooling rates are large in comparison to classical casting process for example, and will have impact on microstructure, as well as distribution of elements (segregation) or even formation non-equilibrium phases. This is one of the great interest arising from additive manufacturing of metals in comparison to traditional manufacturing techniques. It is really important to keep in mind that parts produced using DED undergo a complex thermal history in a manner very similar to multi-pass weld deposits. Every track and layer impact others (with a heat affected zone, or even remelting), leading to changes in microstructure, and even gradient in microstructure from surface layers to bulk ones. One need to comprehend this complexity in order to exploit such a manufacturing route the appropriate way.

Laser beam spot size and precision of nozzle-feeding Laser beam spot size is a key parameter for precision and resolution in laser-heating processes. It will directly determine track width, as one can see on Figure 4, thus, if details are required, it must be reduced. This value is often pretty large in DED, with minimum values of about 0.3mm reachable. This mainly comes from the fact that, in contrast with powder bed techniques such as SLM or LPBF, the powder (or wire) is delivered by the nozzle. Thus, the precision reached by the feeding nozzle (or wire feeding) also has to be taken into account, contrarily to powder bed techniques where almost only the laser spot size will be responsible for the precision. This is one of the main factors impacting and degrading the precision of DED techniques.

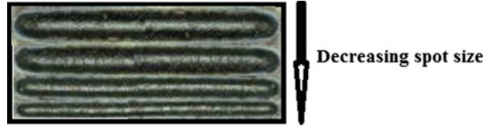


Figure 4: Effect of reduces spot size on track width and precision [7]

Modification of laser beam spot size will have the same impact on laser energy density as scanning speed, meaning the bigger it is, the smaller will be laser energy density and consequently melt pool size, with the consequences on the microstructure and properties as discussed just before. Nevertheless, in this case, the powder flow rate and its precision must also be discussed when modifying laser beam spot size, as it will also affect the efficiency and quality of the final part.

2.3.2 Powder flow rate

Only powder flow rates are discussed here, wire feed rate being more or less similar. Typical value, as mentioned in part 2.1 are between 4 and 30 g/min. This corresponds to the quantity of powder that is put in the melt pool every unit of time.

This parameter is key, as for given scanning speed and laser power, a too large value can lead to unmelted material and negative consequences on final properties of the part such as high porosity content. On the contrary, too low flow rate leads to too high power density in comparison to the one required and to vaporization of material. This rate is thus usually determined knowing the laser energy density in order to be in the good range of value and prevent problems arising from too low or large values. It will directly be related to layer thickness, as it influences the deposited volume, and the width of the tracks are related to laser spot size.

2.4 Solidification, resulting microstructure and final roughness

In the previous section 2.3, the parameters were said to have impact on the solidification rate and consequently the part microstructure. In this part, it will briefly be described how these parameters are impacting it, and their impact on final roughness of parts.

Typically, the larger the power or the smaller the beam spot size or scanning velocity, the larger columnar grains will be and the coarser the microstructure will be. Also, the lower proportion of unstable phases (such as martensite in steels) will be present. This impacts properties and potential applications, for example in reparation or manufacturing of turbine blades, where a high directional growth is required, it will be positive to increase the melt pool size and reduce the out-of-equilibrium phenomena [8]. Grain grow in layer-wise direction. It happens (only for high power machines) that depending on the parameters, fully-equiaxed grain grow in the piece, again changing the final properties. It usually is not the case in most low to medium power devices.

The effect of the parameters on surface roughness is as follows. The higher power, or smaller scan velocity or beam spot size the smaller is the final roughness obtained. This originates from the fact that at low power for example, the amount of unmelted powder particles is higher, increasing the roughness consequently [7].

2.5 Applications, advantages and disadvantages

This technique has different drawbacks compared to other similar techniques. First, the equipment is pretty expensive due to the presence of a laser, optical devices and complex 3 to 5-axis motion systems or robotic arms. Typical price for such a machine is expected to be above 500000\$ [9]. Also, the surface quality is often pretty bad, as one can see on the part shown in Figure 5, leading to near net shape blanks requiring another machining finishing step, again increasing the costs. Finally, as this process induces a phase transformation, large thermal stresses can be present, and induce cracking if undesired phases such as brittle intermetallics are present. Stress relief heat-treatment post-processing can sometimes be relevant.



Figure 5: A part made by DED of metal powder [10]

Finally, many advantages and potentialities come with this technique. First of all, the material loss are very small in powder route compared to SLM for example, and close to zero in the wire route. Another big advantage is that it can be used to put a part directly on a substrate. It leads to much less joining problems in comparison to riveting of parts where, for example, large stress concentrations are presents and increasing the risk of failure of parts. The number of individual parts can thus also be reduced, simplifying the production of different assembly. This is for example of major interests in aerospace manufacturing of engines, where numerous parts are usually welded together. The large versatility of this technique is one of its major advantages: many materials can be used on the same part, in different amount at different points, meaning a tremendous designing freedom even for composites materials. This technique can be used to produce new pieces, but one major potential application is for the repairing in-situ of components. A final application is coating of parts, which can be achieved pretty fast and giving very good properties to final parts. To conclude, DED of metallic materials is a technology with a lot of potential in many fields, and this is why so much effort is put in research and development of new machines. New trends for example contain closed-loop feedback technologies allowing for a very precise control of the composition of a part and of its dimension by adapting key parameters such as laser power in real time [8]. It is a very complex method, but this complexity allows engineers to come up with very diverse properties and microstructures, which is of great interest to push the limits of materials and performances of parts.

3 Selective laser melting (SLM) written by Noah Studer

3.1 History and development of SLM

Selective laser melting also called "SLM" is an additive manufacturing process in the family of powder bed processes in competition with powder jet processes such DED. It was introduced in 1995 by scientists from Fraunhofer ILT, Matthias Fockele, and Dieter Schwarze. Their goal was to think about and develop a new 3D printing technology that could produce parts with way better mechanical properties than other technologies. Therefore, after three years of development, the first commercial machine was revealed in 1998. With this machine, using a laser of 12W, the production time of a 1x3x2cm part was equal to more than a day. Therefore, during the following years, SLM technology has been further developed to increase the volume of the build chamber to produce larger parts and reduce the production time. To compare with the first SLM machine, in 2014, the SLM 500 was revealed with a system including four lasers with a power of 700W for each leading to a total power of 2.800W. Increasing the power of lasers, the production time can be largely decreased since the powder is melted more quickly. For example, a 1x3x2cm part takes just 30 minutes to produce using a 400W laser on modern machines. In parallel, some development was made to increase the safety of employees by enclosing the system to avoid contact with metal powders or dangerous vapors.[11]

3.2 Principle and functioning of SLM technology

As with any additive manufacturing (3D printing) process, the process starts by designing the part as a 3D model using CAD software. This 3D model represents the complete shape and dimensions of the part. After that, the CAD file is processed in a slicing software to divide the part into thin, horizontal layers. These instructions are then fed to the SLM machine, guiding it on how to build the part, one layer at a time.

As it can be observed in Figure 6, the machine is made of three major parts, the laser, the build plate, and a tool to smoothen the surface of the powder. At first, the recoater spreads a thin layer of metal powder on the build plate. Next, the scanning system directs the laser beam precisely to the correct location on the powder bed. The laser heats the powder to extremely high temperatures, approximately 2000°C, causing it to melt. The laser only targets the specific areas where the part should exist, as determined by the sliced file for that particular layer. Once the metal powder melts and solidifies as it cools, the build plate lowers slightly. A fresh layer of powder, matching the thickness of the plate's downward movement, is spread on top, and the process is repeated layer by layer until the part is fully built. In order to be as precise as possible the whole process takes place in a closed atmosphere containing either air or an inert protective gas such as argon or nitrogen to avoid oxidation, remove metal vapors and particles from the building area, and protect the laser optics such as focus lenses. These particles will be captured by specific filters. This device can produce parts with edge lengths ranging from 50mm to 500mm with a layer thickness of 20 to 100µm, depending on the machine model. The precision is primarily determined by the size of the laser beam, which can range from 50 to 100µm. Additionally, the type of laser used—either a fiber laser (ytterbium-doped with a shorter wavelength) or a CO₂ laser also influences precision. These parameters enable a dimensional accuracy of 0.1% to 0.2% and surface roughness of up to 15µm.[12, 13]

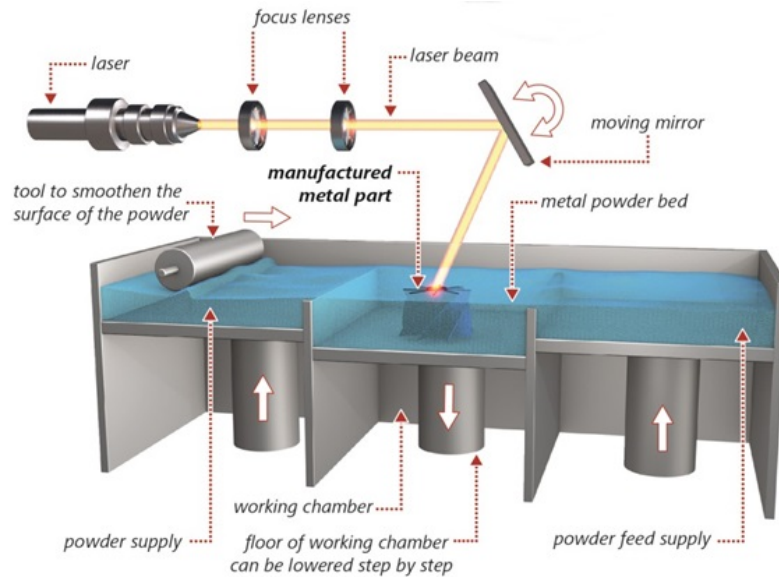


Figure 6: Selective laser melting mechanism scheme [14]

3.3 Process parameters and their impact on part properties

As discussed before, the dimensional accuracy can vary with process parameters as mechanical properties of the final part. A study focused on the influence of the different process parameters on mechanical properties [15]. Firstly, by varying the scanning speed and the laser power, as shown in Figure 7, four different cases can be observed.

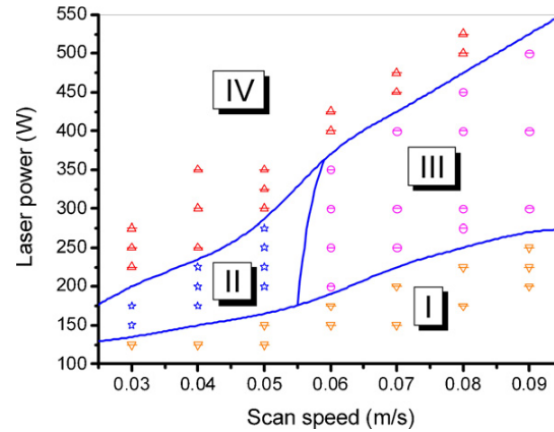


Figure 7: Influence of varying the laser power and scanning speed [16]

In zone I, the power of the laser beam is too small and no melting occurs. In zone II, the power of the laser is increased a bit and the scanning is quite low. As a result, only the surface of the powder grains is melted, which can be illustrated as balls with a solid core and a liquid surface. This allows the balls to solidify together, but because of the solid core, the cohesion between them is very weak. This phenomenon, observable in Figure 8b, is called "balling" and can have a large influence on the surface quality and stiffness of the final part. In zone III, the is still present but the fusion is sufficient to create continuous traces of fusion on the surface. However, in this case, the scanning speed is too high or the laser power is too low so the region below the surface will not be melted and the result will be a phase where lines of beads can be separated when the part is under stress or if it is subjected to an impact. Therefore, to obtain a part that is sufficiently rigid to withstand the stress and has a good surface quality, the process parameters must be set to be within Zone IV where perfect melting tracks can be observed on the surface (cf. Figure 8a).

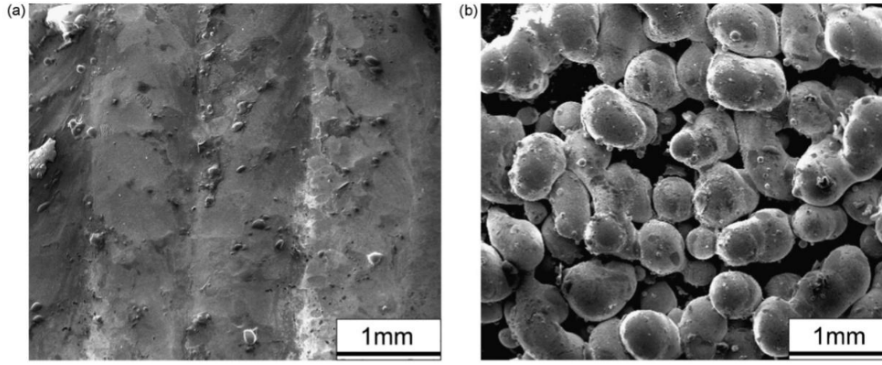


Figure 8: Different microstructures of the final part depending on process parameters ; a) Complete melted surface; b) Surface with balling phenomenon [16]

Two main other parameters can influence mechanical properties such as the yield strength, the maximum stress, or the elongation. The first is the hatch angle, which is the laser scanning direction angle between two layers. For example, if one layer "n" is scanned horizontally and the next layer "n+1" is scanned vertically, the hatch angle will be equal to 90° . This rotation between layers helps prevent defects from forming along a single direction, which can make the final part stronger and more isotropic. Searchers observed that depending on the metal used, the hatch angle can have a large influence. For example, using Inconel 625, they observed that the opening angle had no impact on the tensile strength properties. However, when using 304 stainless steel, the opening angle plays a role and must be equal to 105° to obtain the highest mechanical properties. This is certainly due to the fact that using this angle, there will be more layers with different scanning directions than if we use an angle of 90° , 120° , or 150° . As a result, the final part is more isotropic.

The second parameter is the direction of construction, i.e. the angle between the main axis of the part and the vertical axis of the construction platform. In a study based on the "tensile properties of 304 stainless steel of 304 stainless steel melted by selective laser" [17], they were able to observe the influence of the direction of construction on the mechanical properties. As shown in Figure 9, when the part is built horizontally (construction direction equal to 0°), ductility is better than in other cases. However, to obtain a good combination of ductility and strength, the part must be produced vertically. Finally, when the direction of construction is equal to 45° , the worst properties are obtained.

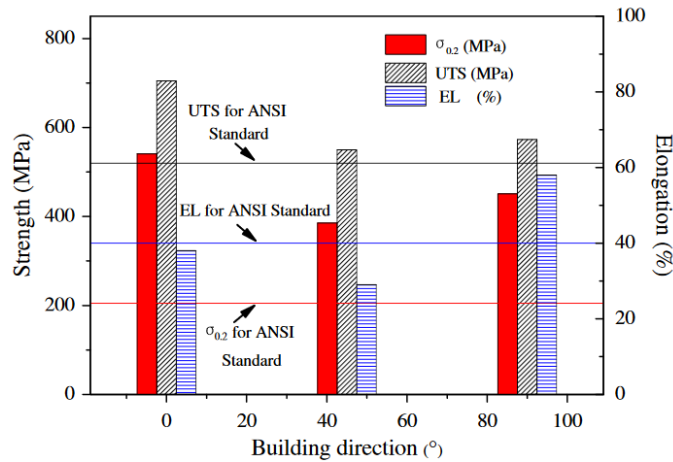


Figure 9: Mechanical properties in function of the build direction [17]

Finally, other parameters such as layer thickness or overlap rate can also have an impact on mechanical properties, but they can be neglected in comparison with the other parameters because their influence is minimal. Even if layer thickness does not have a significant impact on mechanical properties, reducing it can improve precision and surface quality and extend production time. As

for the overlap rate, increasing it ensures correct fusion between laser passes, which will increase density and strength, although excessive overlap can lead to overheating and defects.

3.4 Materials available for SLM technology

Concerning the materials that can be used to produce parts by SLM process, most weldable alloys are great candidates. The most general are stainless steels, aluminum alloys (AlSi10), titanium alloys (TiAl6V4), Nickel alloys (In 718, In 625), and Co-Cr alloys [14]. Nevertheless, some parameters reduce the selection of the material. Indeed, due to high cooling rates, problems can occur with some conventional alloys. Moreover, the metal must be available in powder form with a specific grain size. Then, each metal has a certain ability to absorb specific wavelengths of the light spectrum. It is therefore essential to ensure that the material fuses, which can be done using near-infrared lasers (such as Yb fiber lasers at $1064nm$). With this type of laser, the wavelength is well absorbed by stainless steels, titanium, nickel, etc., and allows efficient fusion. However, some metals cannot be selected if the wavelength is too high. Copper, for example, cannot be selected because the material can reflect much of the laser energy rather than absorb it, which reduces the efficiency of the process.

Finally, for large parts, a large quantity of powder will be required, which can lead to increased costs, or even more if the part requires supports during the process, as these will be discarded afterward.

Concerning the use of other materials, some studies tried to combine different materials such as metals and ceramics to produce metal matrix composites (MMCs). Indeed, a recent study reported the use of titanium carbide (TiC) and boron carbide (B_4C) particles to reinforce an Inconel 718 matrix [18]. By mixing powders together, it can be possible to form bonds between the materials in order to increase the hardness, wear resistance, strength, corrosion resistance, or high-temperature resistance of the final metal part. In addition, research is being carried out to produce intermetallic alloys that could be used to produce parts using SLM. The goal is to find optimal alloy compositions that enhance mechanical properties at high temperatures while avoiding cracking. For example, searchers try to produce an Al-La-Mg-Mn alloy, which offers high strength, work hardening, and increased ductility, along with economic benefits. Indeed, aluminum alloys are problematic due to their hot-tearing behavior. Thus, the use of other components such as silicium or zircon can provide better thermal stability resulting in higher crack resistance.[19]

Several tables are available online to give the process parameters required for each material in order to avoid residual stresses, porosity, improve mechanical properties, etc.[20]

3.5 Post-processing of SLM parts

Even if SLM has several advantages, lots of post-process steps are required to obtain a part corresponding to the initial requirements. Firstly, a kind of vacuum cleaner is used to aspirate the excess powder from the build plate and eventual supports are removed. Then, heat treatments can be applied to the part to enhance mechanical properties. These ones can be stress relieving to reduce internal stresses, hardening to increase the ductility as the hardness, or annealing to increase the toughness and ductility. After this step, the part can be removed from the plate either by hand, with a bandsaw, or by EDM (Electrical discharge machining) which is by far more precise.

Finally, to improve the surface quality and/or enhance the properties of metal parts, various techniques can be employed. Spray painting can be used to add a protective layer against corrosion. For parts requiring a smoother finish, electropolishing and tumbling can be used to reduce the roughness. Another technique, bead blasting can clean and smooth surfaces simultaneously. Additionally, brushing is a simple yet effective method for deburring and enhancing the surface texture. Lastly, anodizing enhances corrosion resistance and plasma spraying or electroplating can increase mechanical strength or wear resistance.[21, 22]

3.6 Advantages and limitations

Concerning the advantages of the selective laser melting process are multiple. Thanks to the precision of the laser beam, the parts are dimensionally accurate. Since structures are produced

layer by layer, complex structures can be produced with parts containing other geometries inside such as cooling canals, cavities, etc. Moreover, by changing the part infill, the weight can be considerably reduced keeping the same mechanical properties. Finally, costs are reduced because, with the exception of the 3D printer, the process does not involve expensive tools such as those used in conventional manufacturing processes. Additionally, contrary to pure machining, considerably less waste is produced and the unmelt powder can be sieved and reused to produce the next part. Finally, a wide range of alloys can be used to produce parts, giving a broad choice of materials.[22]

Concerning the disadvantages, due to the high laser beam temperature, residual stresses can be present in the part leading to deformations. To avoid these problems, post-processing steps are required and they can largely increase the production time if they include the increase of mechanical properties, the smoothing surfaces, etc. Moreover, given the size of the machines on the market, producing large parts can become a real challenge. In most cases, this method is used for prototype production, as the production time can quickly become substantial. Finally, the cost of the equipment can be a barrier to its use with a price between 50.000\$ and 1.000.000\$.[12]

3.7 Industrial applications

The industrial applications of selective laser melting depend on the material used. For dental and medical applications (cf. Figure 10a and 10b), titanium alloys and stainless steels can be used to produce custom-made prostheses with high precision, good biocompatibility, and corrosion resistance. These materials are also used in the automotive industry. Indeed, titanium alloys can be used to produce lightweight parts for high-performance vehicles. At the same time, stainless steel is used in complex exhaust systems (cf. Figure 10c). In the aerospace sector, Inconel and nickel alloys are used to produce parts capable of withstanding high temperatures and corrosion, which is ideal for turbine parts (cf. Figure 10d), cooling system components, or heat exchangers. Finally, in the field of tooling and molding, stainless steels and maraging steels can be used to produce molds with high hardness and wear resistance. These molds can even contain cooling channels to improve thermal control in injection molding processes.[23]

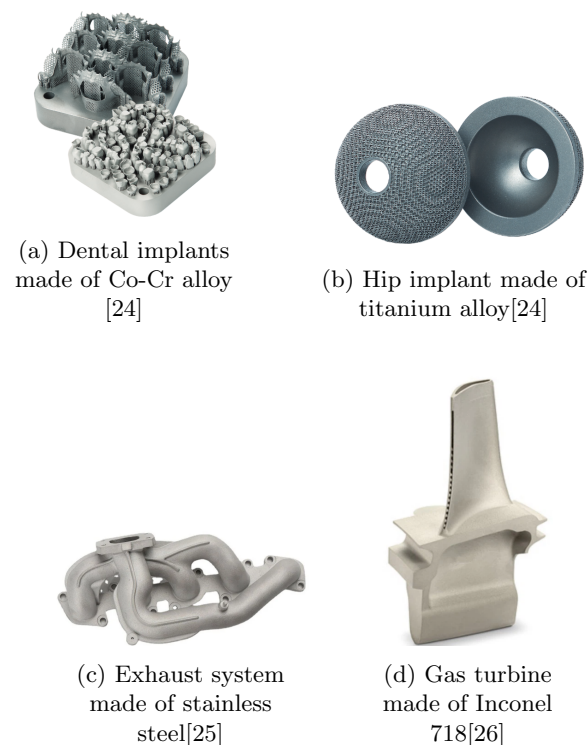


Figure 10: Different parts produced by SLM for industrial applications

4 Electron-Beam Melting (EBM) written by Luka Roche

The previous sections of this report discussed methods for additive manufacturing of metals using lasers. Another option to melt the powder is electron beam.

4.1 Background

In electron-beam melting (EBM), also called electron-beam direct manufacturing (EBDM) or electron beam powder bed fusion (EB-PBF), the heat source to melt the metal is an electron beam, produced by an electron gun. This beam is focused onto the desired positions on a powder bed, melting it locally [3]. EBM proceeds layer by layer, in a vacuum environment. While generating a vacuum has a cost, it avoids the need for post-manufacturing heat treatment, which is required for laser-based processes [27].

EBM allows for the fast production of complex and dense parts with mechanical properties comparable to wrought metals. It can produce parts destined for the aerospace and medical fields [27, 28].

The Swedish company Arcam, now acquired by General Electric (GE), is the only one marketing EBM systems. The first machine was commercialized in 2001 [29]. Their EBM machines have two main components, depicted in Figure 11: the electron-beam unit and the building chamber [27].

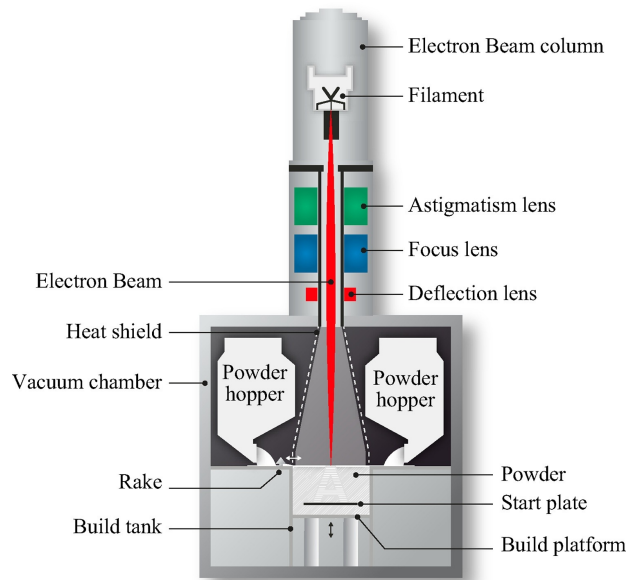


Figure 11: Components of an Arcam machine [27]

4.2 Technical Details

Similarly to other AM processes, EBM also starts with a 3D CAD model which is sliced to form 2D layers to be consecutively printed [3, 30]. The whole process is summarized in Figure 12.

4.2.1 Electron beam generation and beam control

As can be observed in Figure 11, the electron beam is generated at the top of the electron beam column by a cathode filament, generally made of tungsten. A potential of 60kV is applied between the filament and an anode to accelerate the emitted electrons to between 0.1 and 0.4 times the speed of light [27]. The beam is then controlled by three sets of magnetic lenses made of coils. The first lenses are called astigmatism lenses and aim to correct the shape of the beam. The second lenses, known as focus lenses, determine the beam size. Finally, the third ones are the deflection lenses and their purpose is to direct the beam onto the right position on the build platform in the bottom chamber [27].

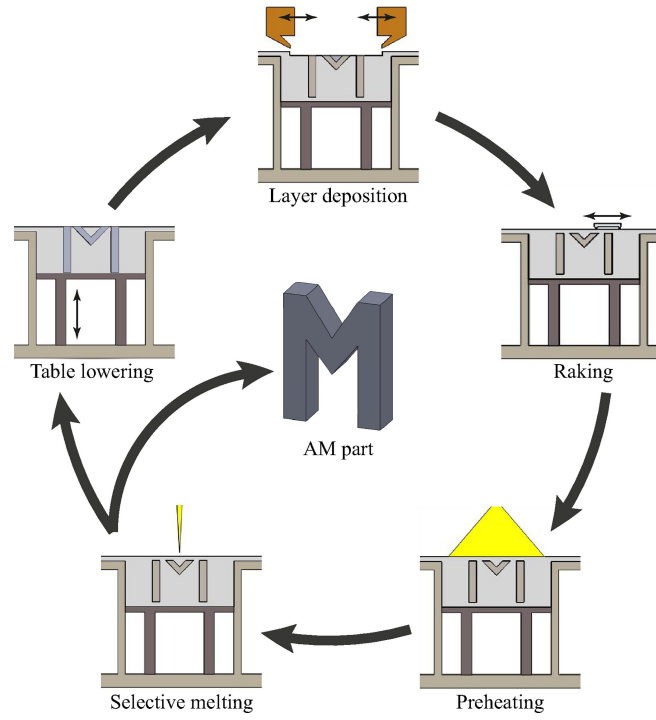


Figure 12: Steps of the EBM process [27]

Both compartments of the machine have to be under high vacuum. Reaching such a vacuum takes some time, but it is necessary to avoid the interaction of electrons from the beam with molecules in the environment [31]. Furthermore, gas flow is minimized, which allows for the reduction of internal stresses in the final part, commonly seen in processes such as SLM [27, 29]. The vacuum is generated using turbomolecular pumps and achieving pressures of about $10^{-3} Pa$ [32]. A small amount of helium is introduced into the chamber as it is an inert gas that does not interfere with the electron beam and helps dissipate the heat at the end of the printing process [33].

4.2.2 Powder bed melting

As EBM works with electrons, the powder used must be conductive. This is why EBM is only suited for metals [29]. Metal powders for this process usually have spherical particles with an average size of 45–105 μm [34].

As can be seen in Figure 11, once the electron beam leaves the column, it enters the vacuum chamber to hit the powder bed in the desired position. The powder is stored inside two powder hoppers and released onto the start plate. As an irregular distribution of the powder on the platform would cause defects, a rake is responsible for a homogeneous spreading across the plate. Each layer is between 50 and 200 μm thick [27].

The start plate, as well as each subsequent powder layer, are preheated via an unfocused electron beam. The main purpose of this is to avoid too large thermal gradients and thus thermal stresses, which can lead to the emergence of heat cracks in the final part. The preheating temperature must be adapted to the materials used. With copper, for instance, 400°C is an adequate temperature [27, 29]. Preheating also causes the powder particles to sinter, as can be observed in Figure 13, where sintering necks are visible in the preheated powder sample. This necking allows for an increased thermal conductivity between particles [35]. Moreover, sintering reduces the risk of powder spreading and makes the production of overhangs possible [27].

After the powder is preheated, it is selectively melted by the focused electron beam. Once the whole layer is built and has solidified, the build platform is lowered for the next layer to be produced in the same way. For each layer, the previous layer partially melts so it fuses with the current one [30]. The whole cycle of the process is summarized in Figure 12. The first few layers can be used as a support, to be removed from the final part.

Finally, once the manufacturing of the part is completed, the pressure and the amount of helium

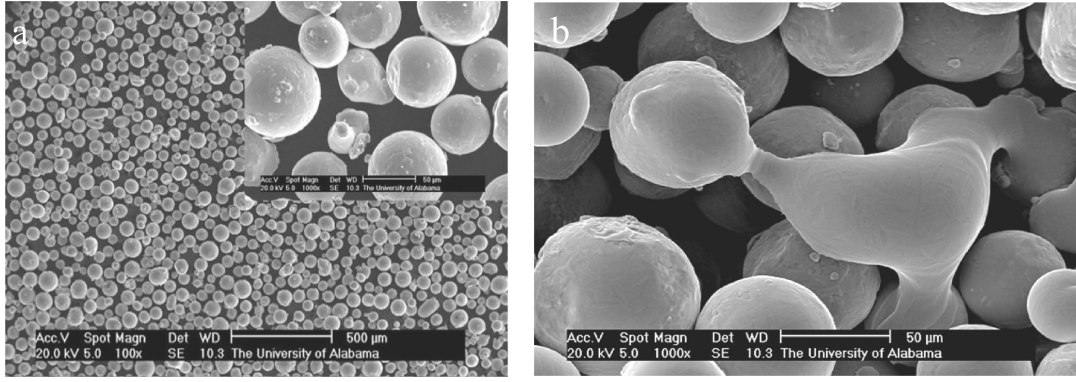


Figure 13: SEM images of Ti6Al4V: (left) raw (right) preheated, circular necks form between the powder particles [35]

inside the chamber are increased for the heat to dissipate more easily. [27]

4.2.3 Post-processing

After the part has cooled down, it is removed and the unmelted powder can be reused for the production of another part. Additionally, the powder that adhered to the part while it was hot, forming a soft agglomerate over the entire surface, can be removed through sandblasting. Using the same powder for blasting as the one used during the process allows for the recovery and reuse of all powder, including volatile and agglomerated particles [27, 35].

Unlike SLM, no further post-processing step is mandatory [36], but some treatments such as hot isostatic pressing (HIP) and vacuum annealing can increase density and modify mechanical properties [29].

The impact of these two treatments on the mechanical properties of EBM-manufactured copper tensile specimens has been investigated, with results shown in Figure 15 [37]. An expected increase in density has indeed been observed after applying either method (Figure 14).

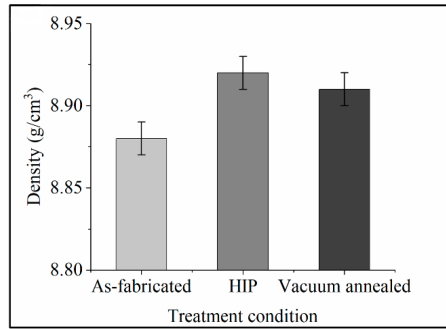


Figure 14: The effect of treatment condition on the density [37]

First of all, the anisotropy of EBM parts can be noticed, with or without post-processing treatment. In fact, there is a significant difference in ultimate tensile strength and elongation to failure for the specimens printed in the testing axis (Z) and for those printed in a direction (X) normal to the testing axis.

Moreover, both treatments cause a decrease in ultimate tensile strength, yield strength, and Vickers microhardness whereas they lead to an increase in elongation to failure [29].

4.2.4 Materials

Electron beams can heat to higher temperatures than lasers and they are far less dependent on reflectivity and wavelength. [36] This makes EBM more suited than laser-based processes for the additive manufacturing of metals such as copper, which has an absorption efficiency of only 2 to 10% in the usual infrared domain [36], and titanium, which has a higher melting point [27, 38].

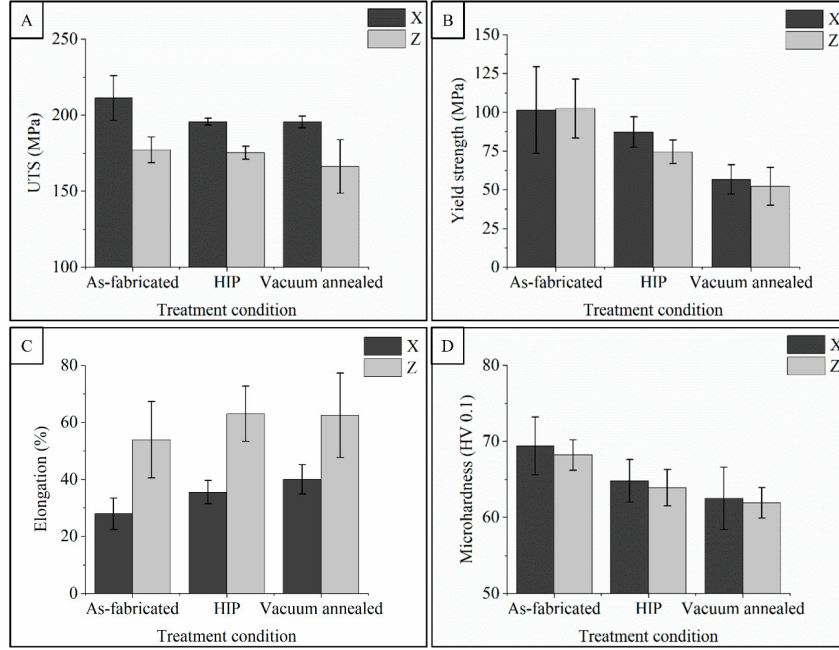


Figure 15: Mechanical properties summary and selected statistical observations; ultimate tensile strength (A), yield strength (B), elongation to failure (C), Vickers microhardness (D). Error bars indicate a 95% confidence interval based on the pooled variance of all samples. [37]

According to the laboratory tests performed by GE Additive, EBM works with, among others, the following metals and alloys: stainless steel, tool steel, nickel-based superalloys, cobalt-based superalloys, Invar, beryllium, niobium, and aluminum [39], as well as copper [29] and titanium alloys [27].

4.3 Advantages and limitations

Compared to processes such as SLM that use lasers to melt powder, EBM offers several advantages and drawbacks, summarized in Table 1.

Characteristic	EBM	SLM
Thermal source	Electron beam	Laser
Production rate	3 kg/h	0.2 kg/h
Atmosphere	Vacuum	Inert gas
Energy absorption	Conductivity-limited	Absorptivity-limited
Scan speeds	Very fast, magnetically driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals, and ceramics
Powder particle size	Medium	Fine

Table 1: Differences between EBM and SLM [29]

With electron beams having much higher energy than lasers, they heat the metal at a faster rate, making the process quicker [27]. However, the time required to create a vacuum must also be considered. The use of vacuum reduces the risk of contamination and prevents internal stresses, often making post-processing treatments not necessary.

Although SLM parts require additional post-processing costs, they are generally cheaper than EBM parts due to lower energy consumption and equipment costs [32].

EBM parts, being made with larger particle sizes, tend to have lower surface finish and feature resolution compared to SLM parts [29, 27]. The surface roughness is generally higher [38]. However,

EBM parts are denser, exhibit better mechanical properties, and can have more complex geometries [27, 29], such as cellular, meshed, and porous structures [34].

In SLM, absorption is limited by the absorptivity of the powder, depending on the reflectivity and absorption spectrum, whereas in EBM, absorption is limited by electrical conductivity [29]. Hence, producing parts with SLM from metals like copper, which has low infrared absorption, is less efficient [36].

Both processes have the advantage of recyclability of unused powder [27, 32].

4.4 Applications

EBM-manufactured parts have more applications than prototyping only. Orthopedic metal implants are frequently manufactured using EBM due to its capability to create complex geometries [40]. This includes components such as acetabular cups with outer porous mesh structures, femoral knee implants, and intramedullary rods [40], as well as dental implants (Figure 16) [41]. However, post-processing surface finishing is necessary to avoid rough surfaces [40, 42].

EBM is also a suitable process for producing titanium aluminide parts for the aerospace industry, notably due to its ability to build dense and complex components [27, 43]. The enhanced mechanical properties and reduced risk of heat cracking, as mentioned in previous sections, enable the manufacturing of high-performance components such as aircraft engine blades and automotive turbocharger wheels (Figure 17) [43].



Figure 16: Ti mandibular framework fabricated using EBM technology [41]

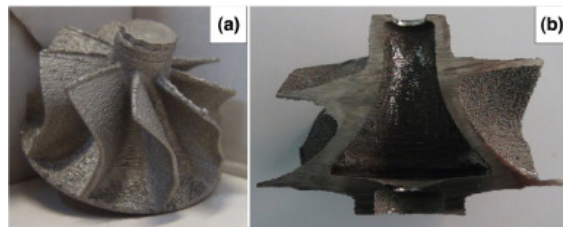


Figure 17: (a) TiAl turbocharger wheel produced by EBM; (b) cross-section of a hollow TiAl turbocharger wheel [43]

5 Extruded metal processes written by Adrien Borgeat

After discussing additive manufacturing processes of metals based on powders, solutions using wires are studied. These processes present pros and cons really different than the powder-based ones, making their study relevant.

5.1 Material extrusion (MEX)

The metal material extrusion (MEX) is an additive process that can be compared to metal injection molding (MIM) because of their similar procedures to obtain finished parts. Indeed, both of them include the manufacturing of green bodies, a debinding step and a final sintering step. The major difference is that the green body is formed layer by layer with the help of a printer and no mold is needed. MEX can be applied to various metals such as stainless steel, titanium, nickel or aluminum alloys. First, three different methods used to obtain the green bodies are discussed. Then, the debinding and sintering steps are presented [44]. In all these cases, selectivity is achieved by carefully tuning the printing parameters such as nozzle velocity or layer thickness. Of course, a general rule cannot be applied as a major dependence on the printed material properties is observed [45].

5.1.1 Screw-based MEX

To begin with, the screw-based metal MEX is presented. Here, feedstock under the form of 3 – 5mm granules is used. Their composition will be discussed in section 5.1.4. As presented on figure 18, the feedstock is transported by a screw through a heater where it melts and a wire is formed exiting through a nozzle [45].

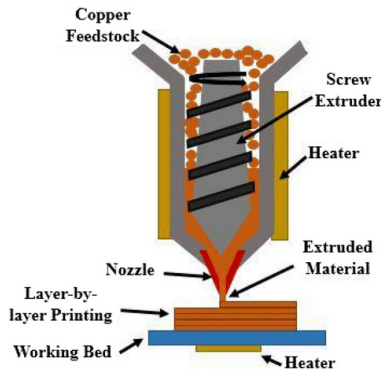


Figure 18: Setup of screw-based MEX [45]

This process presents many important advantages. First, the granules used as a feedstock are the same than in the case of MIM. Therefore, many different alloys are already on the market under this form allowing a more complete selection of materials. Moreover, it is possible to fill the printer continuously. Therefore, no time is lost in re-heating the printer for new compounds and the printer is never stopped before finishing the production of the sample. It is also possible to crush defective parts and add them once again in the printer. Finally, the granules are directly used and don't need to be further prepared as filament for example, which allows time, infrastructures and cost savings. Nevertheless, this system is not perfect. The main remaining challenge is the control of the flow rate. Indeed, some air is trapped in the exiting wire leading to fluctuating flow rates. Moreover, the head of the printer is complex in this system, leading to important costs [44],[45],[46].

5.1.2 Plunger-based MEX

This method is quite similar to screw-based MEX but is supposed to be an improvement. Indeed, this new method does not use any screw as that process requires a complex (and expensive) print head. The goal is to keep using MIM feedstock, which allows a great variety of printable alloys. Therefore, plunger-based MEX can be used with either granules (like in screw-based MEX) or bars. Figure 19 presents the setup for this process. It is shown that a plunger replace the screw

but the rest is very similar. In their study, Waalkes *et al.* estimated the price of these printers to 5k to 10k€[46].

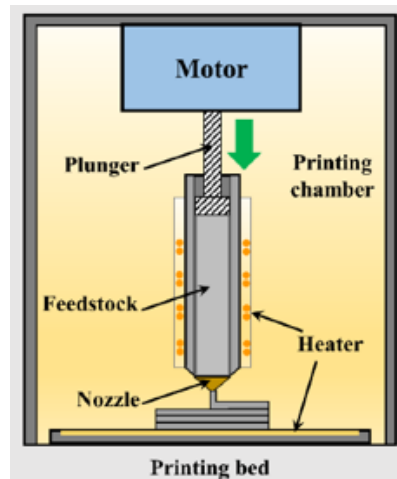


Figure 19: Setup of plunger-based MEX [44]

If this method is supposed to be an improvement compared the screw-based process, some disadvantages appear. First, the printer cannot be continuously fed. Therefore, some discontinuities appear in the printed body as well. Moreover, if bars are used as feedstock, their production requires a supplementary step. Nevertheless, the solution with the granulated feedstock is nowadays mainly preferred [44].

5.1.3 Filament-based MEX

Contrarily to the two previously discussed method, filament-based MEX use directly wires as feedstock. They are heated in a nozzle to be fluid enough for printing. Figure 20 presents how this process works [47]. The diameter of the filaments varies between 0,4 and 1mm [48].

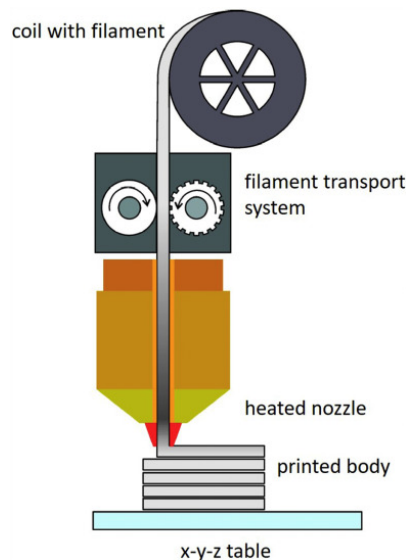


Figure 20: Setup of filament-based MEX [47]

This process is the most popular in terms of MEX. Therefore, the literature concerning this technique is important and the system has already been well developed. Originally, this method was implemented with polymer wires and printer used for this material are sometimes used with metal wires. Moreover, the printers are cheaper (the price is around 1000 €) than in the case of the two other methods. Nevertheless, the nozzle must in general be adapted because it suffers important wear rates [47]. Concerning the disadvantages of this method, one will note that the

fabrication of the wire is a quite complicate step. As it will be discussed in the next section, the amount of metal in the feedstock is also smaller as more polymers are needed in order to obtain filaments that are flexible enough and don't break during handling. Finally, some companies such as BASF are now commercializing metal wires at a quite big scale. This will favor a standardization of the process and make metal additive manufacturing at lower costs [47].

5.1.4 Material selection

The feedstock for MEX is generally composed of a major fraction of metal powders to which two polymers are added. Concerning the metallic fraction, many different elements can be used. Indeed, copper, titanium alloys or nickel alloys can be processed through MEX. However, the main part of the market is dominated by stainless steels as roughly 60% of the existing feedstocks were made of this material in 2022, according to Suwanpreecha and Manonukul [44]. The only requested quality needed to produce MEX feedstock is that the metal must be sinterable (ie. having a high diffusion coefficient in itself and a high surface energy). Regarding the powders, better results are obtained with spherically shaped and small particles (below $20\mu\text{m}$ for stainless steels) as the final part is denser. Furthermore, small particles allows the printing of thin layers, which favors a good surface finishing. As a comparison with MIM, the powders must be smaller and more spherical for MEX. Indeed, the pressure is smaller during the fabrication of the green body which leads to lower density for MEX processes. Smaller and more spherical particles allow to overcome this issue. In general, the fraction of metal in the feedstock oscillates between 60 and 69% for screw- and plunger-based processes. In the case of filament-based MEX, only 50 to 60% of metal are found in the feedstock as more polymers are needed to reduce the brittleness [44].

The feedstock contains also some polymers of two types. First, a plasticiser is needed. Its role is to give fluidity to the feedstock. In the case of MIM, it ensures to completely fill the cavity. For MEX, it reduces the viscosity of the filament allowing a better freedom in geometry design and ensuring that the filament won't break, keeping a continuous printing. In general, a low molecular weight polymer like carnauba wax, paraffin or polyethylene glycol are chosen as plasticiser, which counts for 50 to 90% of the polymer content of the feedstock. The second polymer, called backbone polymer, presents a higher molecular weight. Here, polypropylene or polyethylene are often used. This polymer gives strength to the feedstock and helps keeping the shape of the body after the elimination of the plasticiser and before the sintering [44].

5.1.5 Debinding and sintering

When the green body is printed with any of the three methods presented above, two more steps are needed to obtain a final sample: debinding and sintering. These steps are exactly the same than in the case of MIM. As this process is better documented, a book about MIM is used as reference [49]. The debinding is made in two steps. First, the plasticiser is eliminated. To do so, different methods exist. The most common one is solvent debinding. Indeed, the green body is placed in a liquid that dissolves the plasticiser. Nowadays, the most common solvents are hexane or acetone, particularly efficient to dissolve wax. Another solution is to melt the plasticiser. Nevertheless, this method is only scarcely used as it is really difficult to avoid evaporation of big bubbles that would damage the material when exiting. Of course, both the solvent or the temperature must be carefully chosen in order to eliminate only the plasticiser (no harm must be done to the backbone polymer) [49]. Concerning the secondary debinding, it is generally done through melting of the second polymer. This time, the formation of bubbles is not an issue anymore. Indeed, the first step of debinding creates porosity that go through the piece, allowing the melted backbone polymer to flow out of the sample without damaging it. In general the debinding temperature amounts to 450 to 500°C if the backbone polymer is polypropylene. In the case of polyethylene, the temperature is in the range of 500 to 600°C. Of course, this is often done under controlled atmosphere to prevent metal oxidation [49].

The final step to obtain the final sample is sintering. Here, strength is given to the piece and (almost) all the porosity is suppressed. During this step, mass transfers occur at high temperature (in general between 1200 and 1400°C depending on the metal). Powders get connected and the final piece is obtained [49]. Once again, the atmosphere must be controlled to avoid unexpected

reactions. For stainless steel, nitrogen or hydrogen atmosphere are used depending on the precise composition of the alloy. The sintering time depends on the final density expected and the temperature but, in general, it amounts to 2 to 4 hours. As bulk mass transfer occurs, the size of the sample is decreased. This phenomenon called shrinkage keeps the shape of the sample but a size reduction of 12 to 20% is observed. Of course, this has to be considered when the green body is printed to ensure that the final piece will present the expected size. Furthermore, small powders induce a more important shrinkage. As these powders are used for MEX, the importance of shrinkage is increased [49].

5.1.6 Advantages and disadvantages of MEX

Many advantages are reported for MEX compared to other additive manufacturing processes for metals. First of all, no loose metal powder are involved in the process as they are trapped in the feedstock. This reduces the risk of inhaling this particles and protect the health of the users' lungs. The second great advantage of this method is its flexibility and accessibility. Indeed, lower power sources are needed as the metal does not need to be completely melt during the printing nor the sintering. Moreover, as the feedstock of MIM can be used, many different materials are already on the market. Multi-material printing is also possible by using a printer with multiple heads. Finally, MEX is not used only for prototyping but also in bio-engineering, where the mechanical properties obtained are sufficient. It is particularly useful for implants as the shape can be precisely designed [44].

But MEX is not a perfect method and some defects must be highlighted. First, the nozzles suffer from an important wear because of the contact with metal and must be often replaced. Second, as explained in the sintering section, the shrinkage is very important because small particles are used. Moreover, the mechanical properties obtained with MIM are better than the one of MEX. Because of the time required for debinding and sintering, MEX is also a quite long process [44]. Finally, the x-y resolution of this method is found between 250 and 400 μm according to Desktop metal (a major fabricant of printer for MEX). This is less precise than other methods such as SLM for example [50].

5.2 Semi-solid metal extrusion and deposition (SSMED)

Finally, a process that does not involve any powder at all is studied. Semi-solid metal extrusion and deposition (SSMED) is not completely scaled at an industrial level yet but presents some advantages that makes research valuable. It is interesting to compare SSMED with fused deposition modeling (FDM) as they work on a same way [51].

5.2.1 Process and material selection

The main idea of SSMED is to use semi-solid wires meaning that they are not fully melted during the printing. According to Jabbari & Abriani the solid fraction has to be set between 30 and 50% when the feedstock exits the nozzle [51]. In comparison to FDM, it allows to work with lower temperature or alloys with a higher melting point, increasing the range of possible materials. This applies particularly for alloys with a phase diagram presenting a wide biphased liquid-solid region. The main alloys that can be used with this method are based on aluminum, iron, titanium or nickel, allowing a quite wide choice. In order to improve the quality of printing, the microstructure of the feedstock is important. Indeed, globular grains lead to better rheological properties meaning that the printability is increased. To reach this microstructure, two solutions are presented: rheoforming (which consists to form the feedstock from melted metal) or thixoforming (which requires a pretreatment of the material to avoid a dendritic microstructure) [51].

Concerning the process itself, it is really close to what is done with FDM. As the rheological properties of semi-solid metal are different to those of polymers or completely molten metals, the nozzles must be adapted. Indeed, the authors reported to use Prusa i3 FDM machine (which is one of the most common machine for FDM worldwide) with a changed head. As shown on figure 21, the filament enter the printer through a tube. After crossing a heat sink, it enters the hot chamber. The melting front was designed to be located at an intermediate point between the enter

of the chamber and the nozzle. The distance between the exit of the nozzle and the last printed layer is kept at 1,1 times the diameter of the nozzle to maximize the printing quality. Regarding the filament, diameter around 3 mm are chosen [51].

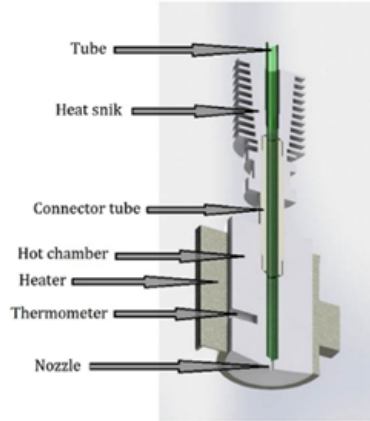


Figure 21: Setup of SSMED [51]

5.2.2 Advantages and disadvantages SSMED

Even if SSMED is a process under development, it shows many advantages. First, it does not use any metal powder which reduces the cost and protect the health of users. The deposition rate and the repeatability are also known to be better than in powder based processes. In opposition to MEX, the samples do not present any porosity leading to better mechanical properties. No de-binding nor sintering steps are needed, leading to much faster processes. Moreover, the shrinkage is reduced as lower temperature are needed. This advantage holds in comparison to standard FDM of liquid metal. Moreover, low temperatures reduce the cost and allows the selection of materials not available for standard FDM. Finally, the contact between layers is really efficient, avoiding local weaknesses at the interfaces [51].

The main issue of this method is the understanding of the rheological properties of semi-solid metal, which are reported to be crucial. As the solid fraction modifies a lot these properties, many researches are needed to produce an optimal printer. As discussed earlier, the crystal structure of the feedstock also plays a major role on the quality of the printed samples. To ensure the globular microstructure, complicated processes need to be applied to the feedstock, leading to increased cost and production time. Moreover, the x-y resolution of SSMED is estimated to be close to the one of MEX, which is far from the precision achieved with SLM for example [51].

6 AM for metallic materials at Micro and Nano-Scale written by Arnaud Sansonnens

Metal in microstructures is often essential for enhancing properties like conductivity, strength, and corrosion resistance. Traditionally, these enhancements have been achieved through coating methods, such as electroplating and physical vapor deposition (PVD), which apply thin, uniform metal layers to surfaces. While effective for simple, planar structures, these 2D coating techniques fall short in creating the complex, three-dimensional (3D) geometries increasingly required in advanced microsystems.

Emerging 3D additive manufacturing (AM) methods are addressing this gap by enabling precise, layer-by-layer fabrication of intricate 3D metal structures at the microscale. Unlike traditional coating processes, 3D AM techniques can produce freeform geometries, internal channels, and lattice structures, providing greater design flexibility and functionality in miniaturized parts. This leap forward is particularly transformative in fields like microelectronics, soft robotics, and biomedical devices, where there is a growing need for complex, application-specific microstructures with enhanced mechanical resilience and multifunctionality. By unlocking new capabilities for metal fabrication at the microscale, 3D AM is expanding the design possibilities for robust, high-performance microsystems tailored to specific applications.

6.1 Micro Selective Laser Melting

Micro-Selective Laser Melting (micro-SLM) is a specialized form of Selective Laser Melting (SLM) adapted to produce fine, high-resolution metallic parts on a microscale. In micro-SLM, a focused laser selectively melts metal powder layer by layer to build up the final structure, a process particularly suited for creating small, intricate components that require high mechanical strength and precision. Key to this adaptation are enhanced laser optics and smaller powder particles, which enable the precise control necessary for microscale resolution. This enables micro-SLM to achieve feature sizes and tolerances on the order of tens of microns, making it highly valuable for industries that need miniaturized, robust components, such as medical devices, microelectronics, and aerospace applications.

In conventional SLM, powder particle sizes typically range from 20 to 50 μm , and layer thicknesses are generally between 20 and 100 μm . For μSLM , it is possible to use powder particles smaller than 1 μm , layer thicknesses below 10 μm , and achieve a structural resolution of approximately 15 μm [52].

One of the most advanced commercialized machines for μSLM is the DMP74 from 3Dmicro-PRINT. The main characteristics of this machine are presented in Table 2.

Table 2: Specifications of DMP74 [53]

Parameter	Specification
Build Volume (L x W x H)	60 x 60 x 40 mm
Laser Source	IR Fiber laser 50 W / 200 W
Precision Optics	High speed galvo scanner
Layer Thickness	$\leq 5 \mu\text{m}$
Optical Resolution	5 μm
Surface Roughness	Down to 2 μm (Ra)
Laser Spot Diameter	$\leq 30 \mu\text{m} \leq 20 \mu\text{m}$
Process Atmosphere	Argon: ≤ 20 ppm (O_2 ; H_2O)
Inert Gas Consumption	≤ 3 l/h Argon
Machine Size (L x W x H)	2,494 x 1,452 x 2,506 mm
Machine Weight	Approx. 1,800 kg

Recent advances in μSLM technology [54] have demonstrated the potential for sub-5 μm feature resolution and production rates exceeding 60 mm^3/hour , significantly enhancing its application potential in high-throughput manufacturing environments.

6.2 Direct Ink Writing

Direct Ink Writing (DIW) is a well-established technique for additive deposition at the microscale, commonly applied to materials such as metals, polymers, and ceramics. In the context of metals, DIW is a process using concentrated metal nanoparticle inks to print fine, complex structures. DIW operates similarly to macroscopic filament extrusion but on a much smaller scale, enabling the creation of 3D structures by extruding ink layer-by-layer through a micrometer-sized nozzle. This process allows for precision in printing microscale parts due to its unique material handling and extrusion capabilities. To improve performance, Laser DIW incorporates a laser to anneal the metal nanoparticle ink immediately upon deposition, enabling faster solidification, enhanced structural stability, and the creation of more complex freestanding structures.

6.2.1 Working Principle

DIW relies on the viscoelastic properties of its inks, which must exhibit shear-thinning behavior—a decrease in viscosity under applied shear stress. This property enables a consistent flow of ink through the nozzle, producing a filament with:

- A solid core that retains shape.
- A fluid shell that allows for layer fusion.

As the ink exits the nozzle, the stable core retains the shape, while the sheared outer layer enhances adhesion between layers. This dual-layer filament structure allows DIW to print self-supporting and spanning structures, enabling the creation of complex shapes.

6.2.2 DIW Setup

A typical DIW setup includes:

- A glass pipette with a micrometer-sized nozzle (1–10 μm).
- A pump to regulate ink flow.
- A translation stage for precise movement.

The nozzles are typically produced by laser-pulling a glass capillary, achieving precise diameters. The metal nanoparticles ink, often composed of silver nanoparticles around 20 nm in diameter, is dispersed in water and ethylene glycol. These inks are highly concentrated (around 75% by weight [55]), which maintains the required shear-thinning properties. Too few it will spread on the substrate, too much it will clog the nozzle.

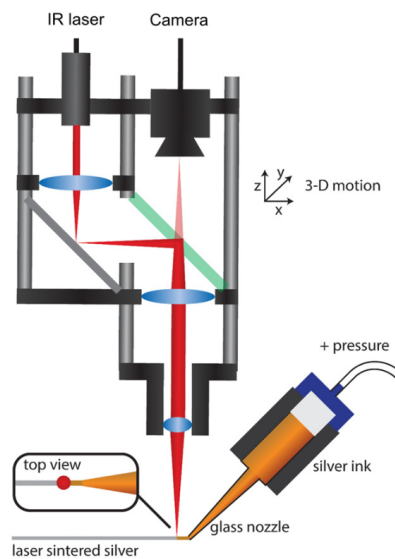


Figure 22: Setup of Laser DIW [56]

Figure 22 illustrates the setup of a Laser DIW system. The schematic highlights key components, including the optical path that aligns the laser, camera, and printed part, ensuring precise in situ annealing and monitoring during the printing process.

6.2.3 Capabilities and Geometries

DIW excels at creating continuous filaments, individual traces, and self-supporting structures. The solid filament core allows for the creation of out-of-plane arcs and spanning wires. Recent advancements in laser-assisted DIW (laser-DIW) enable in situ annealing, which solidifies the ink more rapidly, allowing the fabrication of nearly arbitrary geometries:

- Traditional DIW achieves minimum diameters around $2\text{ }\mu\text{m}$ [55]
- Laser-DIW enables finer features, with diameters as small as 600 nm [55]

DIW for metal was principally performed with silver nanoparticles, but could certainly be extended to other material. The extrusion speed is in range of $20\text{-}500\text{ }\mu\text{m s}^{-1}$ for conventional DIW and is in range of $0.5\text{-}1\text{ mm s}^{-1}$ for the laser-DIW [55].

6.3 Electrohydrodynamic (EHD) Printing

Electrohydrodynamic (EHD) printing is a high-precision additive manufacturing technique that leverages electrostatic forces to eject tiny droplets of conductive ink from a nozzle onto a substrate. In this process, a high-voltage electric field is applied between the nozzle and the substrate, inducing a charge within the ink. As the electric field strength increases, the ink at the nozzle tip deforms into a cone shape (known as a Taylor cone), eventually overcoming surface tension and releasing a fine jet or droplet. This enables precise deposition of materials at microscale or even nanoscale levels.

6.3.1 Ink Deposition Modes

- In Cone Jet Mode, EHD printing maintains a continuous jet of ink from the nozzle, which can be controlled to produce a consistent line or path on the substrate. This mode is particularly useful for creating continuous conductive traces, fine lines, or patterns with high accuracy, as it allows for a steady, uninterrupted deposition of ink.
- In Microdripping Mode, tiny, controlled droplets of ink are released from a nozzle under the influence of a pulsed electric field. In this mode, the electric field is carefully adjusted to form a small, stable Taylor cone at the nozzle tip, which periodically releases droplets rather than a continuous jet. This allows for high-precision placement of individual droplets at specific locations.

6.3.2 Capabilities and Geometries

EHD printing achieves high resolution and precision in metal deposition. This method can create feature sizes of :

- few μm for Cone Jet ($8\mu\text{m}$ [57])
- few tens of nm for Microdripping (50nm [58])

few μm for Single Jet, for example and The metals often used as deposits are Gold, Silver, Copper or Cobalt. [59]

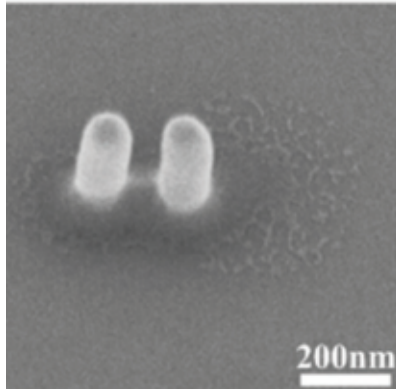


Figure 23: Gold Pillars obtain by EHD printing [59]

The technique is used to create both wire-like structures and dot patterns, making it particularly valuable for quantum applications, where precise nanoscale features are essential for functionality and performance. Figure (23) shows two Gold Pillars create by EHD printing. The conductivity of Gold attract the dropping particle and allows a better precision.

6.4 Laser-Induced Forward Transfer (LIFT)

Laser-Induced Forward Transfer (LIFT) is an additive manufacturing technique that enables the precise deposition of materials by using laser ablation to transfer material from a donor layer to a substrate. In LIFT, a laser pulse is focused onto a thin metal film, which is coated onto a glass slide (carrier). The laser energy heats and melts a small area of the metal, creating pressure that ejects a droplet of molten metal from the donor layer onto the substrate below. This droplet then cools and solidifies, building up the desired pattern or structure.

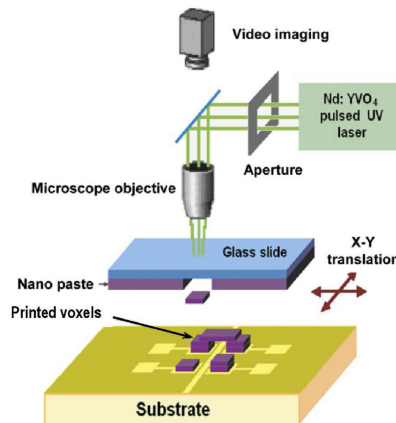


Figure 24: Lift Setup [60]

The LIFT setup typically includes an XYZ-stage for precise positioning of both the carrier and substrate. The laser is directed through the carrier glass slide to strike the metal donor layer from behind. A small, controlled gap between the donor layer and the substrate ensures accurate droplet placement. By moving the substrate and using multiple laser pulses, LIFT can deposit droplets in a sequential layer-by-layer fashion to create 3D structures. Flat, thermally conductive substrates are preferred to ensure adhesion and avoid splashing. Often, surfaces require pre-treatment to improve metal droplet adherence.

6.4.1 Capabilities and Geometries

LIFT enables the creation of structures with minimal feature sizes of $0.5\mu m$ [60]. The technique supports a wide range of metal. In terms of geometry, LIFT is particularly effective for building vertical and layered structures. More complex geometries, such as free-standing shapes, are possible by incorporating sacrificial supports

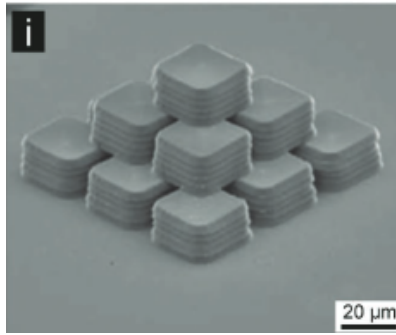


Figure 25: Square Silver Structure obtain with LIFT [60]

Figure (26) shows a typical 3D structure produced by LIFT. In this image, each "block" reveals distinct layers, with each layer formed by a single droplet deposition. The square shape of each droplet is a result of the laser beam being shaped as a square, demonstrating how the laser geometry directly influences the deposited structure's form and layering precision.

6.5 Focused Electron/Ion Beam Induced Deposition (FEBID/FIBID)

Focused Electron Beam Induced Deposition (FEBID) and Focused Ion Beam Induced Deposition (FIBID) are the most precise additive manufacturing techniques. In both methods, a precursor gas is introduced, which adsorbs onto the substrate surface. When the high-energy beam (electron or ion) interacts with this layer, it releases secondary electrons that cause the precursor molecules to break down. The resulting solid, non-volatile components of the precursor stay on the surface to form the desired structure, while any volatile byproducts are released into the surrounding area.

The equipment used for FEBID and FIBID differs slightly. FEBID typically takes place in a scanning electron microscope (SEM) equipped with a gas injection system, whereas FIBID often employs a dual-beam setup that combines an SEM with a focused ion beam (FIB) source. FIBID offers a higher deposition rate but can cause substrate damage or contamination due to the ion beam (often gallium ions), while FEBID generally has lower deposition yields but avoids such damage. The choice of precursor plays a critical role, as it determines the purity and composition of the deposited material.

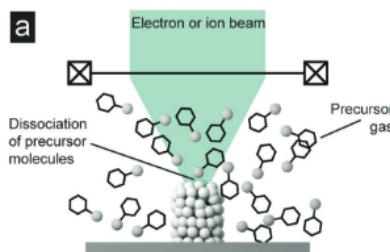
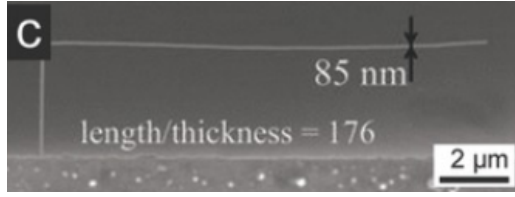


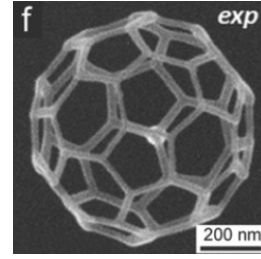
Figure 26: FEBID or FIBID Principle [55]

FEBID and FIBID enable extremely precise patterning, with resolution determined not only by the beam diameter (1–10 nm for FEBID and 10 nm for FIBID) [55] but also by the interaction volume between the beam and substrate, which is typically several times larger than the beam size. This interaction volume broadens the area of precursor dissociation, imposing a resolution limit and highlighting the importance of substrate choice and beam control for achieving fine detail.

There are methods to minimize the interaction volume in FEBID and FIBID. In [61], researchers successfully achieved deposits with feature sizes between 0.7 and 2 nm.



(a) Standing Wire [55]



(b) Platinum Icosahedron [55]

The SEM can be used to provide real-time feedback, adjusting the beam power based on the structure's growth, which enhances deposition precision and allows 3D structures to conform closely to a predefined model. Figure (27a) shows a standing wire with a length of $15\,\mu\text{m}$ and a thickness of $85\,\text{nm}$ —a remarkable achievement in structural control. Figure (27b) displays a 3D icosahedron (similar to a football) constructed using feedback control; without this feedback, the 3D loop might remain incomplete due to deposition inaccuracies.

7 Conclusion written by Emilien Ancey

Metal additive manufacturing, encompassing techniques like direct energy deposition, selective laser melting, electron beam melting, extrusion and even micro and nano-scale additive manufacturing, is transforming the landscape of modern manufacturing processes. Each method has its own strengths; direct energy deposition offers effective solutions for repairs and refurbishments, while selective laser melting and electron beam melting allow for precise, complex geometries that are critical in high-performance applications. Extrusion processes add further value with their potential for efficient, scalable production. Finally, the micro and nano-scale techniques enable for complex and intricate development of metallic parts at a very low scale, which was completely unthinkable with traditional processing methods, and is of great interest in order to improve micro components mechanical and physical properties. As alloy development, control over microstructures, and multi-material capabilities continue to advance, metal additive manufacturing is becoming a viable alternative to conventional methods in industries like aerospace, automotive, medical, or microtechnology.

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