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UNDERSTANDING ADOPTING SELECTIVE LASER MELTING OF METALLIC MATERIALS

Evren Yasa*

*Mechanical Engineering, Faculty of Engineering and Architecture,
Eskişehir Osmangazi University, Eskişehir, Turkey

Abstract

Additive manufacturing, considered as the future of manufacturing or the new industrial revolution, presents many advantages over conventional manufacturing. These include manufacturing integrated parts, eliminating joining processes, shortening lead times from design to testing, lightweight structures, being able to produce very complex geometries at almost no added cost, etc. Therefore, many industrial sectors such as aerospace, defense, biomedical and automotive, are getting more excited about adopting these technologies into their production lines. However, the shortage of experienced personnel in the field of Additive Manufacturing may make the transition period difficult and troublesome. Since AM technologies are rather new and immature compared to conventional manufacturing, many issues in terms of safety, environment, materials, process development, design guidelines as well as testing and validation arise. This paper will address and review lessons learned as a result of implementing selective laser melting for industrial applications as well as for research and development purposes so that this valuable outcome can be used as a guideline by beginners in this field.

Introduction

Additive Manufacturing (AM) is a fast growing market in terms of services and products, especially in the last 10 years [1]. The revenues from AM services and products has increased 5 times from 2010 to 2016 whereas the sales of metal AM system market has spiked almost 18 times, which shows a dramatic growth. Moreover, additive manufacturing technologies once almost only used for rapid prototyping has increasingly been used for functional part production. From 2003 to 2016, the percentage of using AM for production has increased from almost nothing to 60.6% [1]. Many leading companies in aerospace and defense industries are adopting AM technologies for increasing their product performance. Low buy-to-flight ratios, ability to build highly complex geometries which are impossible by conventional techniques, lightweight structures including lattice structures or customized density, integrated parts eliminating joining processes, no need for tools or molds are the most significant advantages of AM leading to a shortened lead time from design to testing [2-4]. For example, General Electric's hurry to get in the AM business by buying Morris Technologies and Rapid Quality in 2012 was a step forward for the industry to realize the potential. GE has continued to invest in AM by recently buying Concept Laser and Arcam to develop new Selective Laser Melting and Electron Beam Melting machines (see Figure 1 for the expected worldwide growth of the AM). Thus, AM is believed to create a new industrial revolution by eliminating the design borders set by conventional manufacturing for several industries, aerospace leading the way. However, adopting these new and comparatively immature technologies especially for metallic materials meeting very high industrial standards, are not straightforward. Moreover, the shortage of skilled and experienced personnel in AM, which is a significant barrier for wider adoption, makes it more difficult. Therefore, the experience of more than 10 years in research and development in Selective Laser Melting as well as industrial hands-on experience are documented in this paper. The lessons learned in adopting selective laser melting of metallic materials not only for rapid prototyping but also mainly for functional part production are summarized to be used as a guideline for beginners. The guidelines, not widely available in the open literature, address various process aspects spanning from design for AM to process development for new materials and to post-processing and safety.

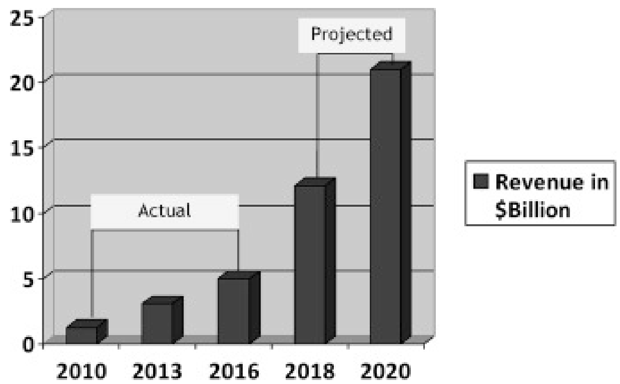


Figure 1: Worldwide revenue from AM [4]

Selective Laser Melting

Selective Laser Melting (SLM) process, as demonstrated in Figure 2, is an additive manufacturing process whereby metallic powder particles are fused together with the energy of a focused laser beam by selectively scanning a powder bed layer by layer in a successive way to create 3D objects from CAD model [5]. Unlike conventional manufacturing processes, pre-processing starts directly with the CAD model converted to a special file format (.stl) to represent the geometry with triangles and special algorithms are used to slice the 3D model into very thin layers, typically of about 20-40 µm. After allocating process parameters such as scan strategy, laser power and scan speed for each layer, the SLM equipment software gets this information and scans every layer on top of each other until the part geometry is completely built [5].

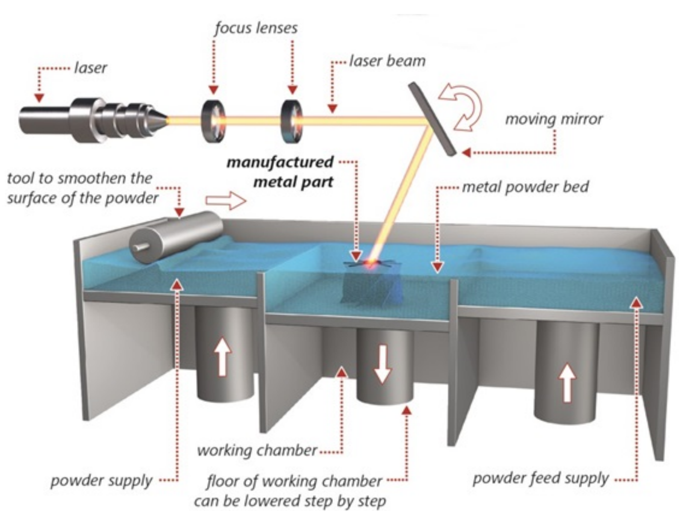


Figure 2: Schematic demonstration of the SLM process [6]

Regarding the SLM process, there are many issues to be tackled to meet high industrial standards such as reliability and traceability. The very first question to be raised is on the selection of a suitable equipment. Unlike Electron Beam Melting (EBM) process where Arcam is currently the only equipment vendor, there are various vendors offering a wide range of SLM machine capabilities. An incomplete list of the main machine vendors and their different models are listed in Table 1. As seen, the range of build volume spans from 50x50x50 mm (Concept Laser Mlab Cusing 200R) to 800x400x500 mm (Concept Laser XLINE 2000R). Although GE Additive has announced a larger build volume (1 m^3) for their ATLAS project in FormNext 2017, it has not yet been commercialized [6]. All the machines utilize a continuous fiber laser with a power in the range of 20 W (min) to 4 x 1000 W (max). Although all machine vendors give different trade names for the same process such as Selective Laser Melting, Direct Metal Laser Sintering/Melting, Laser Cusing and others, they all address the same working principles. Moreover, different models of different brands distinguish from each other to a negligible extent. Yet, there are many factors that could potentially influence the decision on the machine other than cost. First of all, the build volume is a major decision criterion. Not only the part size is effective on the build volume, but also the expensive powder that should be used to fill the build volume and nesting effect to decrease operational costs per part shall be taken into account. Moreover, available validated materials from the machine vendor and their application experience with these materials, reactivity of the material, contamination issues, production speed (not the speed of galvo mirros stated in many machine catalogues as 7000 mm/s), minimum feature size depending on minimum layer thickness and laser beam size in focus as well as automation of powder handling processes. Moreover, many process monitoring systems are being commercialized on these SLM machines to provide traceability and reliability. Although many other technical details are similar on the machines, such systems may be distinguishable. For example, optical tomography (OT), developed by MTU and EOS, is quite different than its competitors and has the potential to avoid defects of type lack of fusion in final parts [8].

Depending on the application, many other technical specifications for the SLM machine can be listed. A benchmarking study almost always give convincing results as presented in [9]. Four different machine vendors were asked to build the same benchmarking design from the same material as shown in Figure 3. The quality of the obtained parts in terms of tolerances, density, ability to produce fine details, etc. was very different from each other. One of the machine vendors, even did not use the specified material but another alloy; Inconel 718 in place of Inconel 625, was used (see the contradictory density results shown in Figure 4). Thus, a customized benchmarking design where the key characteristics of the equipment can be compared is highly recommended in the procurement stage. Moreover, the vendor’s experience in a specific industry may also be a key parameter for the selection.

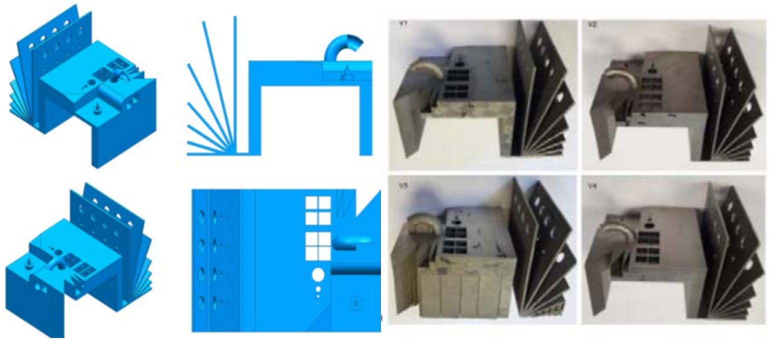


Figure 3: The benchmark design and obtained physical parts from 4 machine vendors presented in [6]

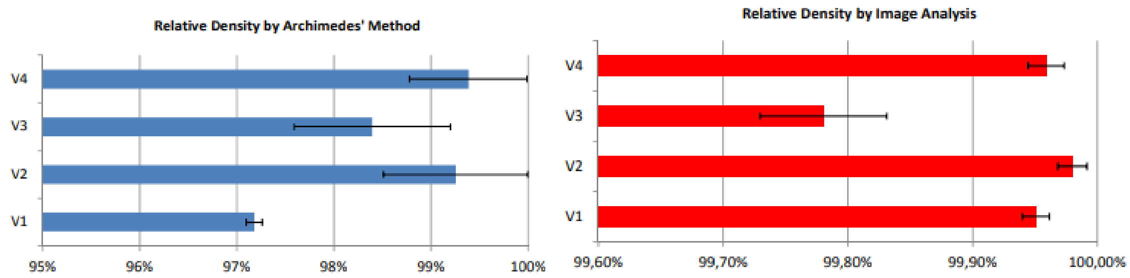


Figure 4: The specimen taken from the benchmark which was made by the Machine Vendor 1 (V1) presents very low Archimedes density compared to image analysis for the same specimen [6]

Table 1. Available machine vendors and model with a comparison of main properties

Vendor	Model	Building Volume	Laser Type	Focus Diameter
3D Systems				
	ProX DMP 100	100 x 100 x 100 mm	50 W/Fiber laser	
	ProX DMP 200	140 x 140 x 125 mm	300 W/Fiber laser	
	ProX DMP 300	250 x 250 x 330 mm	500 W/Fiber laser	
	ProX DMP 320	275 x 275 x 420 mm	500 W/Fiber laser	
CONCEPT LASER				
	Mlab Cusing 200R	100 x 100 x 100 mm3 70 x 70 x 80 mm3 50 x 50 x 80 mm3	Fibre laser 200 W (cw)	approx. 50 µm
	M1 Cusing	250 x 250 x 250 mm3	Fibre laser 200 W (cw), optional 400 W (cw)	50 µm
	M2 Cusing	250 x 250 x 280 mm3	Fibre laser 200 W (cw), optional 400 W (cw)	50 µm, optional variable focus move (50 µm – 500 µm)
	M LINE FACTORY	400 x 400 x up to 425 mm3	Fibre laser 4 x 1,000 W	50 µm – 500 µm (dynamic focus adjustment)
	X LINE 2000R	800 x 400 x 500 mm3	Dual laser, 2 x 1,000 watt	approx. 100 – 500 µm
EOS				
	PRECISION M 080	Ø 80 mm x 95 mm	Yb-fibre laser; 100 W	less than 30 µm
	M100	Ø 100 mm x 95 mm	Yb-fiber laser; 200 W	40 µm
	M290	250 mm x 250 mm x 325 mm	Yb-fiber laser; 400 W	100 µm
	M400	400 mm x 400 mm x 400 mm	Yb-fiber laser; 1 kW	approx. 90 µm
	M400-4	400 mm x 400 mm x 400 mm	Yb-fiber laser; 4 x 400 W	approx. 100 µm
ORLAS				
	Creator	Ø 100 mm x 110 mm	Yb Fibre Laser / 250 W	min. 40 µm
REALIZER				
	SLM 50	Ø70 mm x 40 mm	Fibre Laser 20-120 W	
	SLM 125	125 X 125 X 200 mm	Fibre Laser 100-400 W	
	SLM300i	300 x300 x300 mm	Fibre Laser 400-1000 W	
RENISHAW				
	RENAM 500M	250 mm x 250 mm x 350 mm	500 W ytterbium fibre laser	
	AM250	245 x 245 x 300 mm (X, Y, Z) (360 mm Z axis by request)	200 or 400 W	70 µm diameter at powder surface
	AM400	250 mm × 250 mm x 300 mm	400 W	70 micron focal spot size
SLM Solutions				
	SLM125	125 x 125 x 125 mm³	Single (1x 400 W) IPG fiber laser	70 µm - 100 µm
	SLM 280 2.0	280 x 280 x 365 mm³	Single (1x 400 W), Twin (2x 400 W), Single (1x 700 W), Twin (2x 700 W), Dual (1x 700 W and 1x 1000 W) IPG fiber laser	80 - 115 µm
	SLM 500	500 x 280 x 365 mm³	Twin (2x 400 W), Quad (4x 400 W) Twin (2x 700 W), Quad (4x 700 W) IPG fiber laser	80 - 115 µm
SODICK				
	OPM250L	250 x 250 x 250 mm	Yb Fiber Laser 500 W	

Safety, Health and Environmental Issues

There are various types of hazards related to this process to be thoroughly considered such as chemical, mechanical, electrical and thermal hazards as listed in Figure 5. The machines generally employ very high energy laser beams as the energy source for melting the powder particles. The lasers utilized are considered as Class IV unless operated inside the machine with many redundant safety switches and infrared-blocking glass window in the build chamber. With all precautions, the safety level becomes to the one of a Class-I. Generally, the laser working depends on the oxygen level to be lower than 1-2% and the chamber's door being closed. To avoid oxidation, normally much lower oxygen levels are preferred since the mechanical properties vary differently with the change of oxygen concentration [10]. The SLM machines are operated under protective atmosphere such as nitrogen or argon gas to avoid oxidation at elevated temperatures. Only special instruments can detect an oxygen deficiency when working with these odorless, tasteless and colorless gases. Preventive measures shall be taken against the asphyxiating effect of inert gases. For example, the room where the SLM machine is installed shall be ventilated adequately. The waste gas from the machine shall preferably be emitted via a non-return flap to outside and not to the room back. Once the process is completed, the operator shall be sure that the chamber is ventilated enough before he/she puts his/her head inside the chamber to start removing the part. Generally, stationary oxygen sensors are recommended to be installed in the risky areas around the machine.

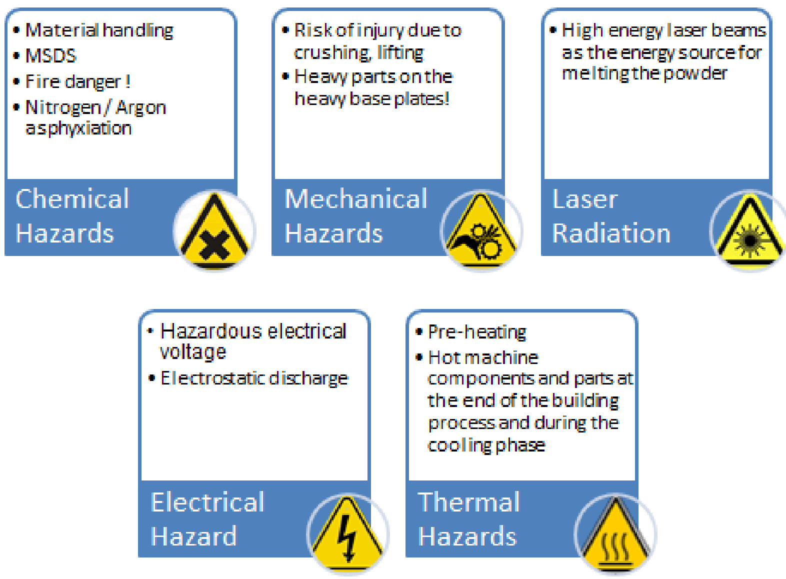


Figure 5: Different types of hazards related to the SLM process

Regarding the safety handling the material, although micro-sized particles are used in SLM rather than nano-powders, it is still important not to inhale, to smoke and of course to eat these powders. Most metal powders are considered as carcinogenic. Moreover, direct skin contact is not recommended because it may cause irritation. Material Safety Datasheets (MSDS) shall be visible near the machine so that they can be referred to for material handling. Moreover, metal powders are flammable and potentially explosive, especially when dispersed and exposed to ignition. Therefore, it is important not to swirl up the powder in the process chamber. Especially the metal condense material, dark-brown or black in color, which is a by-product of the SLM process deposited in the filter, is very dangerous. This vaporized metal powder can cover chamber walls, f-theta protection glass (if any) and filter unit. This condense material is very dangerous for the operator especially during filter change. It is highly flammable and can immediately ignite when swirled up and exposed to air. Thus, using/wearing protective equipment including respiratory mask, face mask, gloves, inflammable clothes, googles, static electric mat, etc. while handling the machine is very critical and should be a strict part of operational instructions for safety. Keeping no sources of ignition near the machine, avoiding electrostatic charging, using suitable protective gas while processing, avoiding swirling up are commonly applied prevention measures to avoid fire risk with metal powders. The fire extinguisher, which should be kept very close to the SLM equipment, used for metal powders is classified as Class-D and utilizes a very fine dry powder. After its use, this powder may lead to severe corrosion in electronic devices if not cleaned up very sensitively. Therefore, having and applying suitable written procedures for all risky activities is crucial for operating an SLM machine.

Mechanical and thermal hazards may occur due to some overlooked safety issues related to the build chamber. There are few moving parts inside the chamber such as the powder coater, build platform, powder dispenser and excessive powder platform. Colliding the coater blade with an incorrectly positioned build platform where some parts are built is a common mistake and can lead to significant wear of the blade as well as breaking of built parts. Generally, when there is a harsh collision of the recoater blade, the coating system is stopped due to load limit. In addition, the operator of the equipment shall keep in mind that the building platform and the base plate connected to it after the process is complete may be hot due to preheating to a temperature generally less than 200 °C. Not all machines utilize base plate heating but many have this property mainly to eliminate the humidity at least from the very first layers of powder so that a good connection is provided between the base plate and the first layers leading to a good anchorage during the build. Some customized machines also utilize higher temperature pre-heating to reduce the temperature difference during the process and thus leading to lower residual stresses [11]-[14].

Some new EHS concepts are recently presented such as the pre-fabricated turnkey solution of AddUp's FlexCare System which is a containerized metal production room built to related standards for working with metallic powders in the 3D printing process. This cell, shown in Figure 6 consists of the machine or machines, sifter, inerted vacuum cleaner, powder handling equipment, extinguishers, powder containers, etc.

Figure 6: AddUp's FlexCare System [15]

Pre-Processing, Process and Post-Processing Steps

Once the CAD file is sliced into thin layers and process parameters are attributed to the job file, it can be loaded in the machine computer where relocation or orientation of the parts are possible. Depending on the machine model and the experience level of the operator, pre-processing after loading the layers until the start of the build may take 1-2 hours for a medium-size SLM machine. This time of pre-processing is needed mainly for:

- Pre-heating of the base plate up to a temperature depending on the material (up to 200°C): The success of the build highly depends on the strength of this connection. A loose fusion of the very first layers (typically 10 layers) will prevent the anchorage effect and may lead to failures. The alignment of the base plate with respect to the coater shall be completed after this step so that expansion of the base plate due to given heat is taken into account.

- Cleaning and alignment of the base plate attached to the build platform: The base plate creates a flat platform for the part to be built on. As said above, the success of the whole build highly depends on the connection of very first layers to the base plate. If the alignment of the base plate is not appropriately carried out, the thickness of these layers will not be homogenous everywhere on the base plate which is undesired. A proper deposition of the very first layer of powder is shown in Figure 7 where it can be seen that the powder layer is almost transparent and the base plate can be seen. If the first layer is very thick, a good connection to the base plate is difficult to provide. A schematic demonstration of a homogenous powder laid for the first layer is shown in Figure 8a. If the base platform is not perfectly aligned with respect to the coater blade, the case shown in Figure 8b is possible where the thickness varies along x-axis of the machine. This is also possible among y-axis. To avoid this, proper grinding of the base plates shall be conducted for re-using of base plates. The parallelism and the flatness of the base plate after the grinding operation shall be no more than a layer thickness (typically less than 20-30 µm) so that it can be compensated in one layer. Provided that the coater blade is well aligned, a proper grinding of the base plate is the only measure to be taken for most of the machines except some models of EOS. For example, on EOS M290, two alignment buttons (along x and along y) are available on the front of the build chamber to orient the build platform to avoid such misalignments which is very useful (see Figure 9). Otherwise, if the base plate cannot be aligned well with respect to the coater blade, it has to be changed or re-ground resulting in time loss. The linear displacement error of the building platform for many machine models is given to be less than 5 µm. However, a detailed measurement and analysis given in [16] shows that straightness, yaw and pitch errors on the other hand were significantly higher and may contribute from 20 to 30 µm of form and orientation tolerances over a large size build.

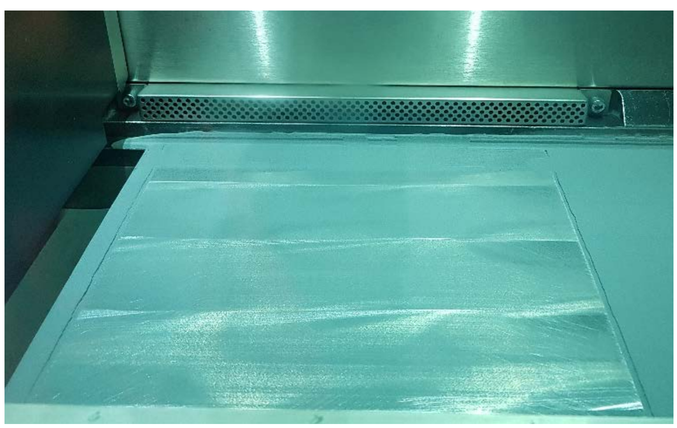
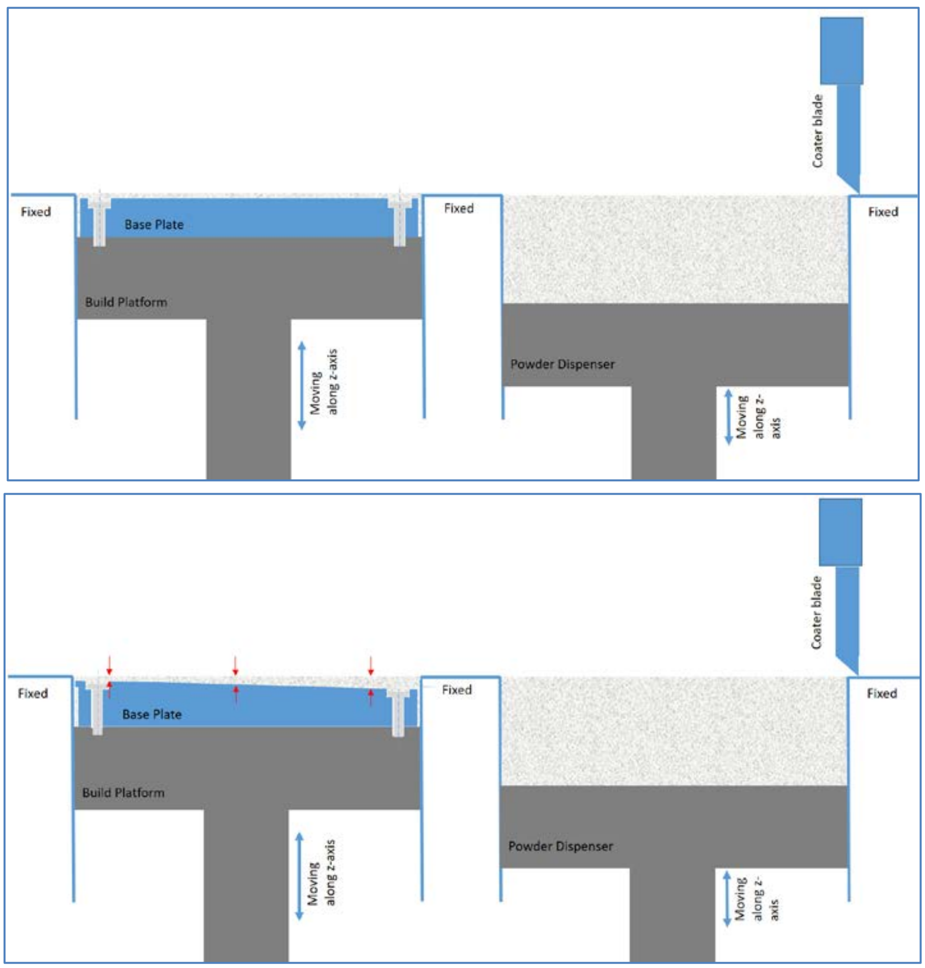


Figure 7: The very first layer of powder deposition on a DMLS machine ready to start a new job

- Compacting and levelling of the powder dispenser: This is needed to increase the packing density of the powder in the dispenser so that the amount of powder laid in one layer is greater leading to a higher density in the resulting part. Research conducted by various researchers by experimental and simulation studies shows that a higher packing density leads to a smoother surface quality [17][18]. Moreover, a higher packing density plays a significant role in the formation of the powder bed influencing density, mechanical and physical properties of the built parts [19]. Different measures are taken to increase the packing density of the powder filled in the dispenser. Some are related to the powder characteristics. For example, a Gaussian distribution of the powder particle size distribution is recommended to maximize the packing density. If the powder particles only consist of very fine or very coarse particles, it is impossible to fill in the gaps to a great extent [18][20]. Other than the powder characteristics, there are some measures to be taken during pre-processing such as using a spatula for stabbing powder particles and compress them more. Some other solutions can be used like making a dead weight from a non-magnetic material with a geometry having the same cross-section of the powder dispenser and compressing the powder particles with this weight [21].

- Cleaning of the lens and filling the chamber with the protective gas.



a)

b)

Figure 8: Inside the build chamber showing the main components (base plate, build platform, powder dispenser, coater blade) (not to scale) a) homogenous thickness of the first powder layer b) heterogeneous thickness of the first powder layer (see red arrows for the change of the thickness)

Figure 9: Two alignment buttons (along x and along y) are available on the front of the build chamber on EOS M290

Due to the nature of the process, very high cooling rates, from melting temperatures of metals to pre-heating temperatures of most 200 °C, are encountered in SLM. The cooling rate is proportional to the temperature difference and inversely proportional time to cool down. Some R&D machine use a high pre-heating temperature for the base plate up to 600°C for decreasing the temperature difference [12,13] but this brings new problems such as caking of the powder particles which are supposed not be melted as well as to be sieved and reused. Thus high cooling rates leading to thermal residual stresses and deformations are considered as a natural consequence of this process. The bulky parts having a large area to be scanned have a higher energy input and may lead to warping and even warping the entire base plate. To avoid such cases, the base plates shall have adequate thickness, of at least 3-4 cm. The base plate thickness has a clear influence on the residual stress distribution as shown in [22]. Before part removal from the base plate, a higher base plate thickness results in a lower stress level in the base plate itself and a more uniform stress level in the part. Thus, a thick base plate results in a smaller deformation due to part removal, compared to a thin base plate. The thermal deformations occurring after the part is removed from the base plate can partially be avoided by stress relief heat treatment but cracking or warping during the build is irrevocable.

Another critical point to be considered to eliminate or reduce warping and cracking is the design of support structures. These supports are used for different purposes in SLM such as anchorage of overhang surfaces to the base plate and effective heat transfer so that no excessive heat input is accumulated on a local spot. The importance of the design of support structures is generally underestimated. The effect of process parameters or the design of support structures on thermal deformations are studied by various geometries which are expected to deform easily without sufficient anchoring [24] [25]. As shown in Figure 10a-c, there are many design parameters for the support structures defining the strength of the connection. Depending on the geometry and the material, the support structures shall be defined to avoid undesired deformations during the build [27]. Generally software available on the market for pre-processing .stl files automatically creates the support structures according to the rules defined by the user. The recommended support structures are basic block structure (as shown in Figure 10) yet for some geometries these may not be sufficient to avoid deformations. A very interesting study by Cooper et al. suggests to use completely contactless support structures [28]. Figure 10d demonstrates the difference between a long overhang surface with and without contactless support beneath. As evident, the one with a contactless support below shows lower deformations proving that the effect of supports as heat sinks are helpful.

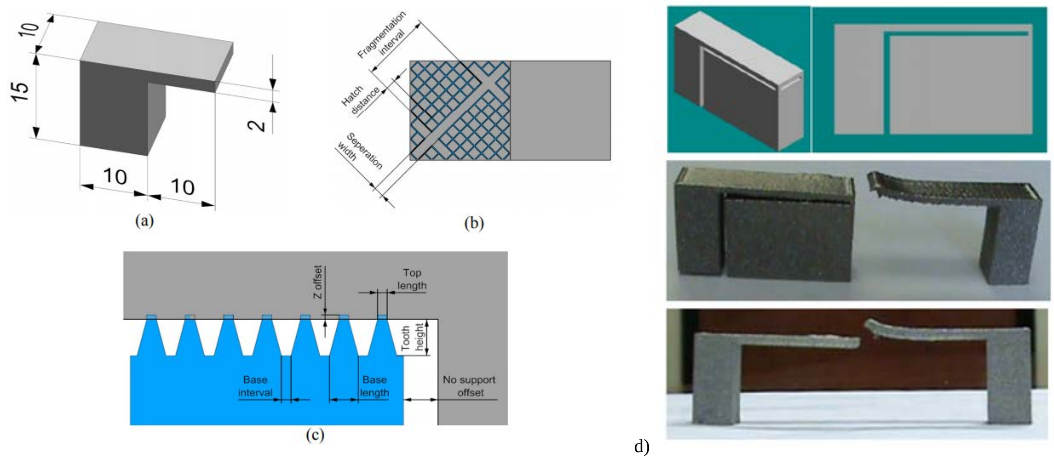


Figure 10: Designed part and dimensions for experiments (a), definitions for block supports (b), tooth dimensions (c) [25] contactless support structures and resulting geometries (d)

Moreover, solid supports which do not contact the part to be built may be added to play a role as a railway to guide the coater with a metallic blade (see Figure 11). These solid supports are needed to avoid first contact and collisions of the coater blade with intricate features of the part to be built and consequent dents or marks. With these rail type supports, the coater meets first with these solid structures and start sliding on them rather than colliding with the thin wall of the part. Moreover, when the coater exits the rails, it already loses contact with the part leaving no mark. The reason behind such need is called as “edge-effect” and explained in detail in [29].

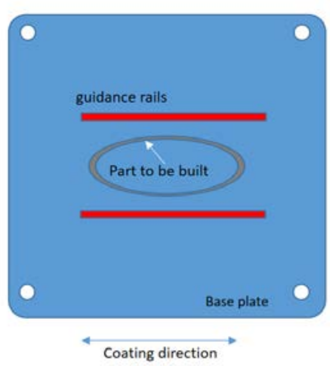


Figure 11: Rail type support structures to avoid tight contact between the part to be built and the coater leading to deformations and local dents (from top view of the base plate)

The edge effect due to the nature of the process results in contact between the edges of the layer and the coater blade. If non-metallic blades are used, this does not present any problems. However, for the metallic blades, this may lead to early and unexpected failures of the builds. Therefore, some precautions are needed to be taken during pre-processing. First of all, the contact shall ideally start from 0 and gradually increase to its maximum meaning that no long parallel contacts shall be allowed. To avoid maximum contact at one single position of the coater, the part shall be oriented with some angles around z-axis. An example is given in Figure 12. On the left of the figure, the coater needs to collide with the long side of the rectangle along x-axis during the coater’s move in an undesired way: sudden and long contact. On the right of the figure, the parts are oriented so that the coater's contact with the coater increase from zero to its maximum gradually. Moreover, if anything goes wrong with the first part, this will not have any influence on the second one unlike the case shown on the left. This will lead to successful build for the second part even the first one is not possible to be built. Another important issue to be taken into consideration in part positioning on the base plate is the overhangs' inclination being towards or backwards from the coater direction of powder deposition. Naturally, all these explanations are valid if the coater is only uni-directionally depositing powder. When met with the coater, the inclined wall shall be pushed towards the base plate so that the resulting force is not acting to separate the part from the base plate. Many different options are available for selecting the part orientation and support design. **Figure 13** clearly demonstrates the influence of these on the build space, heat transfer, area to be supported, manufacturability, etc. Thus, it is generally an optimization problem of multi-criteria.

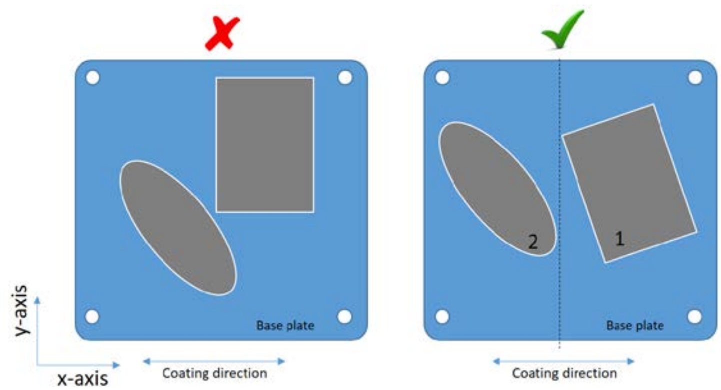


Figure 12: How to position the parts on the base plate a) a wrong positioning of 2 parts b) preferable positioning of the same parts

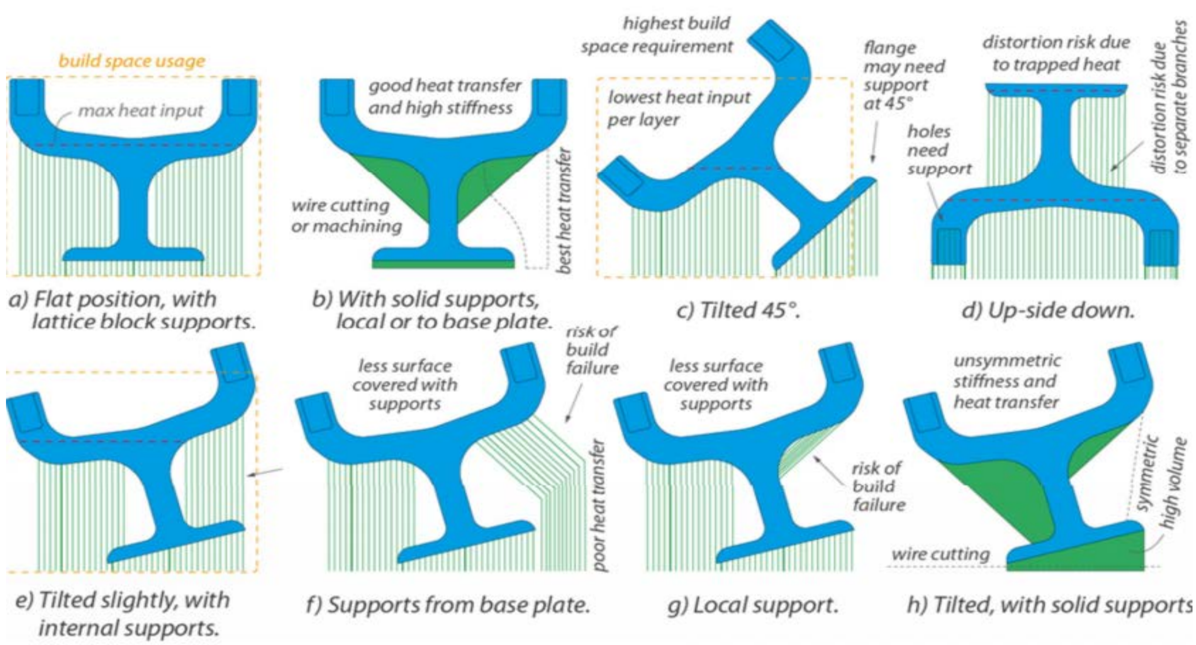


Figure 13: Different types of supports in various orientations of the same part leading to different manufacturability, laser scan area per layer, surface roughness, build height, etc. [30]

Another underestimated aspect of the SLM process is the need for post-processing. The general understanding of "plug and play" for SLM machines imposes that the part built will be ready to be used directly after the process is completed. However, this is far from the reality. Depending on the application, requirements generally call at least for stress-relief heat treatments and surface finishing. The first operations to be conducted after the process is completed is to remove the part attached to the build platform from the machine followed by cleaning. All the powder particles, even the ones stuck in the internal channels need to be removed if any heat treatment will be applied. Otherwise, these powder particles sinter even at stress-relief heat treatment temperatures and will almost become impossible to be removed afterwards. After cleaning the loose powder particles, shot peening is recommended. This will not improve the surface quality to a significant extent even if applied for several minutes but rather it will expel the loosely connected powder particles from the surface. The media choice in shot peening depends on the material of the part. For example, ceramic media is used for titanium alloys to avoid any contamination with metallic media. After shot-peening, the part is heat treated depending on the requirements. The optimal recipes for the heat treatments may be different for SLM parts from conventionally produced equivalents [31]. Titanium alloys for example exhibit a different microstructure after the SLM process due to very high cooling rates and generally need heat treatments to enhance the ductility. After the heat treatment, the part needs to be removed from the base plate and support structures. The support structures thus also need to be optimized for easy removal. Wire-Electro Discharge Machining (EDM), band saw or manual deburring tools may be used to remove the supports, each having own advantages and disadvantages. The positioning of the parts on the base plate and design of support structures shall take removal process into account. For easy handling of the build platform generally for making small parts on large build platforms, a small base plate is generally very handy. Using a large base plate as an adapter, a small base plate can be fixed on the build platform making grinding and EDM operations easier. The selection criterion of the base plate is also an important topic which is not discussed in open literature. For titanium alloys, only titanium alloy of the same type is used as the base plate. But for most of the metals, AISI 1045 steel is used even for nickel superalloys. The reason for such a selection is the crystal structure of the material. The crystal structures of the base plate shall be compatible with the material that is used in the process. The surface of the base plate is rather demagnetized and shot-peened after grinding so that back-reflections into the optical system of the machine are avoided.

Conclusions

Selective Laser Melting is one of the most promising AM techniques to produce functional metallic parts with good mechanical properties presenting many advantages especially for highly demanding sectors like aerospace and defense. However, the adoption period for AM techniques bears some difficulties due to the fact that these manufacturing technologies are very much different than conventional machining and requires experienced personnel. The open literature gives a very comprehensive overview of the research and development in the field but almost no clues can be found for beginners. Against the general understanding of "plug-and-play" for AM technologies, this paper underlines the tips and tricks that can be used and appreciated in the initiation phase of technology adoption. Moreover, the lessons learned given in this paper can be helpful to understand the unexpected issues that will be encountered such as the importance of safety and post-processing issues. Yet, it should be noted that the given information is not sufficient to cover all aspects of the SLM process. For example, the process failure mechanisms and issues in process simulation are not addressed and needs further reporting.

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