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DEVELOPMENT OF A METAL 3D PRINTING PROCESS FOR JEWELRY PRODUCTION UTILIZING TITANIUM

Examiner: Professor Heikki Handroos
D. SC. Hamid Roozbahani

ABSTRACT

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Development of a metal 3D printing process for jewelry production utilizing Titanium

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63 pages, 54 figures and 19 table.

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Keywords: Stainless-steel box, Rings, additive manufacturing, 3D printing, Powder Bed Fusion, SLM, Powder Characteristics.

The purpose of conducting this thesis is to develop a metal 3D printing process for jewelry production utilizing Titanium, Gold, Stainless Steel and Silver and to design a product to be additively manufactured for jewelry production. Possibilities of 3D printing allow the product to be printed successfully. Therefore, literature review focuses on additive manufacturing methods, which are suitable for metal printing such as powder bed fusion.

The literature review consists of six chapters, each chapter explains the process and procedures for 3d metal printing from the design on 3D software to the end of metal printing,

The case study part of the thesis is divided into two parts. Part A concentrate on finding proper geometry and parameters for support structure and rings. Part B concentrate on finding proper geometry and parameters for the stainless-steel box.

As a result, parameter, mass properties for titanium, gold, silver and stainless steel are mentioned and the cost of metal printed parts are mentioned, in addition of a comparison between powder bed fusion machine that is used in the experiment and between the available machines that exciting in market

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Cross-Section Area (mm2)
P	Density
$E_{Desnsity}$	Density Energy (Joule/Cubic Milemeter)
E_{Line}	Line energy (Joule/Milemeter)
F	Force
h_s	Hatch Distance (Millimeter)
P_{Laser}	laser power used (Watt)
γ	surface free energy
K_b	Thermal conductivity
t_{layer}	Thickness of powder bed layer (Milemeter)
V_{Scan}	Scanning speed (Milemeter/Second)
V	Scan Speed
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CJP	Color Jet Printing
DMLS	Direct Metal Laser Sintering
DMP	Direct Metal Printing
EBM	Electron Beam Melting
EOS	Electro Optical Systems
FDM	Fused deposition modelling
GE	General Electric
ICP-EOS	Inductively Coupled Plasma Optical Emissions Spectroscopy
Lf	Latent heat of fusion
MIT	Massachusetts Institute technology
MJP	Multi Jet Printing

Nd:YAG	Neodymium Yttrium Aluminum Garnet laser
PBF	Powder Bed Fusion
PLA	Polylactic acid
PSD	Particle Size Distribution
RP	Rapid Prototyping Technologies
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Surface Tessellation Language
TLS	Technik GmbH & Co
UV	Ultraviolet Resin
V	Scan Speed
W	Watt

1 INTRODUCTION

Additive manufacturing (AM) is a combination of materials to create models based on three-dimensional models. At various times, terms such as additive manufacturing, additive processes, additive methods, additive layer-by-layer production, the manufacture of solid-state products, the corresponding forms and the manufacture of products of possible forms were used.

New terms are rapidly emerging in this dynamic industry. Three-Dimensional (3D) printing, in accordance with ISO / ASTM 52900, is the manufacture of objects by applying materials to the print heads, using a nozzle or other printing technologies. In the past, this term was associated with low-cost, low-cost machines. However, this is not the case now: the terms “additive manufacturing” and “3D printing” mean the same thing (SFS-EN ISO/ASTM 52900, 2017, pp.45-50).

Advantages of 3D metal printing additive manufacturing by melting materials layer by layer and the addition of materials properties made metal AM currently highly used in many applications because of it's the ability to produce highly complex parts and to produce light-weighting products such as lattice structures shown in Figure 1 (Campanelli et al. pp. 850-857).

Figure 1. Lattice structure (Fabricating and metalworking, 2019).

Before metal AM was used in aerospace applications, the fly ratio was so high, the ratio of engine and components is 10 : 1 and 20 : 1 respectively but when AM is involved in aerospace applications, the fly ratio is reduced to 1: 1 only (GE Aviation, March 2011) so by comparing, it is shown the difference between them is big.

Some manufactured parts may require some tradition processes but parts which are produced by AM limits the use of those tradition processes and tooling, other parts can be produced just in a single step which enables mass customization that make us realize that each part produced by AM is unique and can be produced faster compared to the traditional manufacturing process (Geraedts et al. 2012, pp. 1-10) such as the fuel nozzle (GE capital 2012, pp.1-18) which is integrated by General Electric (GE), the fuel nozzle assembly parts were 20 small parts but AM had that ability to reduce parts number during assembly just into a single part, so the 20 small parts of fuel nozzle are integrated into a single fuel part, the material that was used for the fuel nozzle was cobalt chrome as shown in Figure 2 and the results were that the part is twenty-five % lighter (LaMonica, 2019) compared to the old fuel nozzle part. The benefits of printing just in a single part is that the total weight is reduced, manufacturing time and processes are reduced hence material needed is reduced which leads to reducing cost.

Figure 2. GE’s additively manufactured fuel nozzle (GE Additive, 2019).

Also, Oak Ridge National Laboratories has done the same, it has used the benefits of AM by manufacturing a robotic system (Hydraulic manifold) in a single part lightweight structure (Wohlers.T, 2016, pp.160-170) as well as Airbus bracket structure build by AM process (QMI Solutions Limited, 2013, p.4) which made it has less weight as shown in Figure 3.

Figure 3. Airbus breaks before AM (left) and after design optimization for AM (right) (QMISolution, 2013).

The main technologies used in the creation of products on additive plants:

- CJP (Color Jet Printing) - Technology for full-color 3D printing by gluing special gypsum-based.

- MJP (Multi Jet Printing) - multi-jet modelling using photopolymer or wax.

- FDM (Fused deposition modelling) -is one of the most used additive manufacturing technologies that is widely used in creating three-dimensional models, in prototyping and in industrial production.

- PBF (Powder Bed Fusion) - melting the material in a pre-formed layer, or the successive formation of layers of powder building materials and selective (selective) sintering of particles of building material.

LITERATURE REVIEW

The aim and purpose of the literature review to give the reader the information necessary to understand case study and results of the thesis. This is done by introducing work principle and history of additive manufacturing and selective laser melting (SLM), explaining the design rules for SLM and the factors effecting SLM and powder characteristics.

Literature review is consists of 6 chapters which are 3D printing, Fused Deposition Modeling, Powder Bed Fusion, Laser Process, Factors Affecting SLM and Powder Characteristic. Furthermore, the design is printed in metal with powder bed fusion. Design analysis and conclusions are presented as well.

2 3D PRINTING

Additive manufacturing is the official industry term approved by the standardization organization ASTM and ISO, but the phrase 3D printing is more common and has become the standard. It is especially widely used in the media, in the terminology of start-ups, investors and other communities.

Nevertheless, AM sets some limitations of material, resolution, and geometry. Clogging is related to FDM and 3D printing, while Stereolithography Apparatus (SLA) and Selective Laser Sintering (SLS) are costly techniques. Physical properties of the final product could be spoiled in FDM, SLS and 3D plotting. (Wang et al. 2017, p.443). In addition, it was noticed, that the SLS process is able to print from single material at one time. The building of an integrated multi-material product is possible by the connection of the part after separate printings (Melnikova et al. 2014, pp.2-29). The final decision on turning to AM from conventional methods should consider a few factors. First, the complexity of geometry, second, the customization level (uniqueness), and lastly production volume (lot size) (Conner et al. 2014, p. 64).

However, according to Hype curve of Gartner 2011 (Gartner,2011) as shown in Figure 4, 3D printing technology has been approaching to the top of the curve, more SLS machines has been building, the first self-replication printer and atom by atom printing which is used in Medical applications has been building, also in the same year the first 3D Robotic Aircraft printer and first 3D-printed car were invented as well as the first gold and silver jewelry was done using 3D printer in 2011.

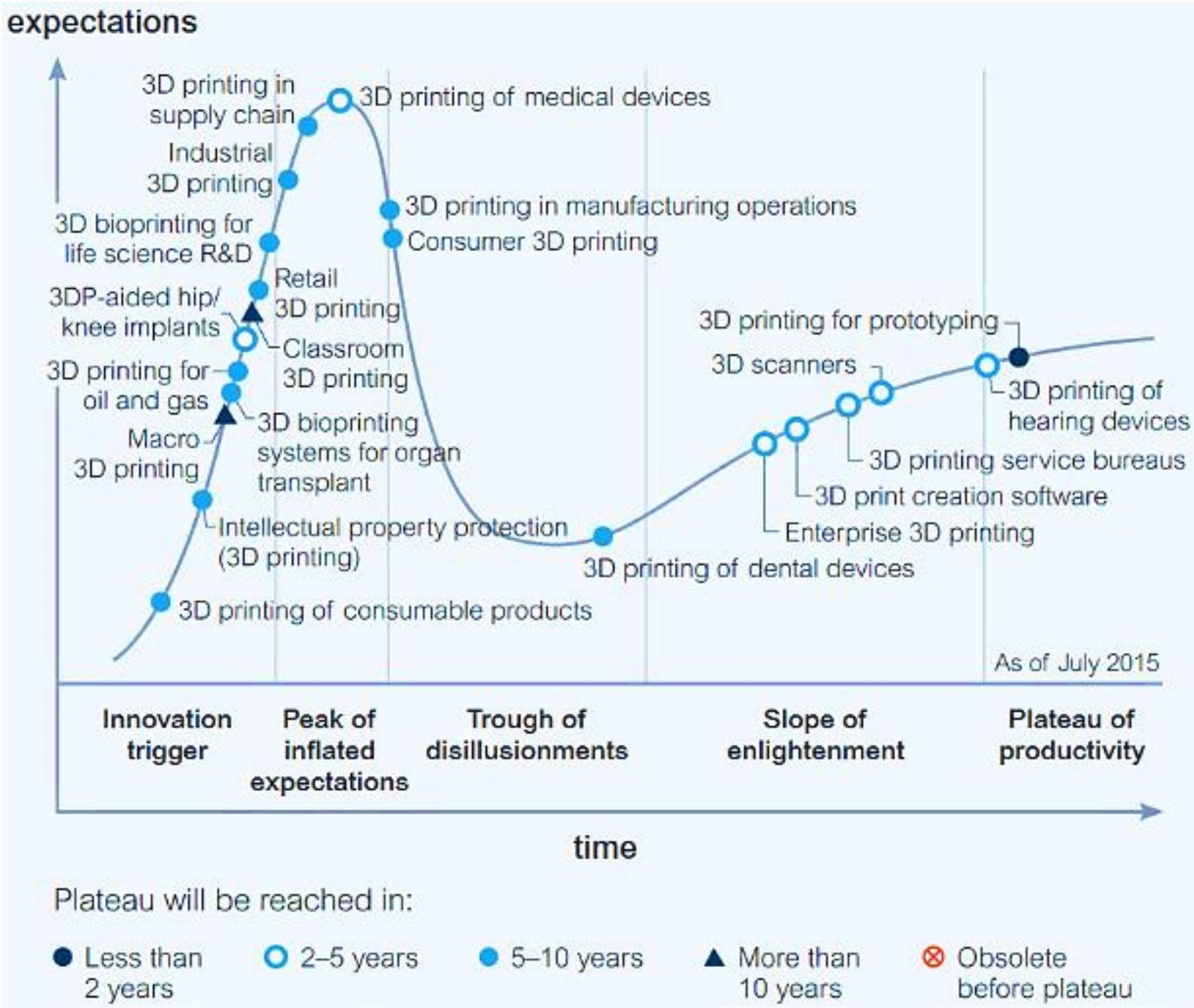

Figure 4. Hype curve of Gartner 2011 (Gartner, 2011).

2.1 History

In the 1980s 3D printing technologies took place in manufacturing, at that time it was known as Rapid Prototyping (RP) technologies (3D printing: On its historical evolution and the implications for business, 2015) because it´s aim was to create prototypes for product development fast, more cost-effective and to reduces production costs. This helped to design a more accurate model in 3D that was quite different former prototyping methods in 2D, but you can say that Charles Hull (Lipson et al. 2013, p.37) as shown in Figure 5 invented first publication for 3D printer stereolithography in. In the late 1980s, the fusion-layer printing technology FDM was developed by S. Scott Trump and introduced to the market by Stratasys since 1990 (Chee Kai, 2003 p.124).

Figure 5. The first 3D printer by Chuck Hull in 1983 (The Voice of 3D Printing / Additive Manufacturing, 2019).

2.2 Operation of a 3D printer

The first step a digital file is done by Computer-Aided Design (CAD) then send directly to the 3D printer while sending it the design is sliced into many layers. These layers will be printed one by one until we achieve our final model. 3D software such as Solidworks, AutoCAD, Inventor etc… are the software that is used for designing digital models but always those digital models have to be a solid model. (How 3-D Printing Works, 2019).

Second step four Stepper motor is highly needed for 3D printer because it requires a motor with low torque and high accuracy to move the printer head, 3 of stepper motors moving in X, Y, Z direction and the last one is needed to move the plate (3D Printing Technology,2014).

Third step 3D printers require a device that supports high-speed operating systems which is upgraded to graphics processing, the industrial interface for display support, greater efficiency and flexibility, and speed scale capability (3D Printing Technology, 2014).

2.3 3D printing process

The 3D printing process as shown in Figure 6 actually means layer-by-layer building. This type of construction usually provides no or negligible waste of material. In addition, the product could be produced hollow inside, providing the advantage of weight reduction. Model is designed beforehand by 3D software. The final STL (Surface Tessellation Language) format file provides data about mesh and 2D layers for the printer (Wang et al. 2017, p.441).

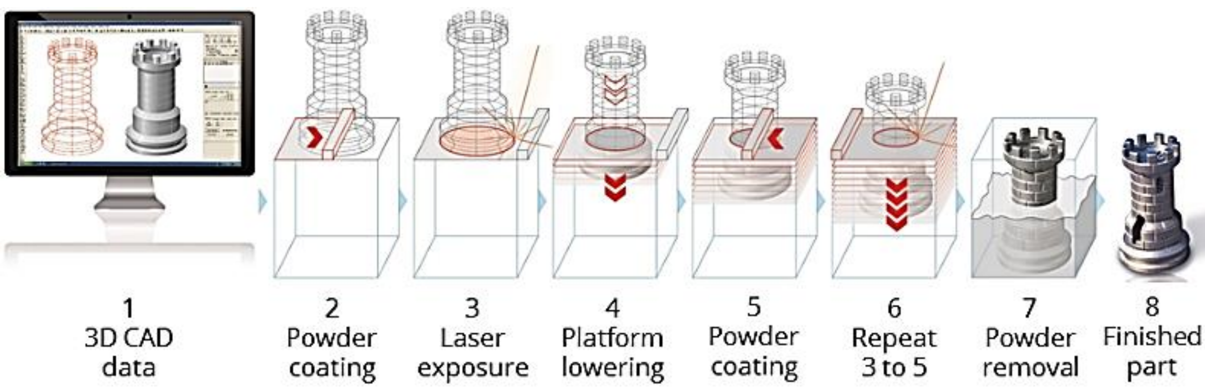

Figure 6. 3D printing process (EOS info, 2019).

2.3.1 Computer-Aided Design (CAD)

It starts when you have an idea then you start to draw a digital model of your idea, the most common method is computer-aided design (CAD). There are plenty of free and professional CAD programs such as Solidworks, AutoCAD and Inventor that are compatible with additive manufacture. The real important thing is to have a solid metal, not the surface model, this is something you should be careful about when doing design because some of the programs are doing surface model as a blender, not a solid model, then you will face some problems.

2.3.2 STL conversion and file manipulation

First STL file format was originally developed by Charles Hull in the 1980s, the name of STL is Stereolithography Tessellation Language (or simply Stereolithography) (Lipson et al. 2013, p.37). During converting, it removes the color, material, and build layers of the model and only shows the approximation of the surface or solid entities, in other words, STL is a kind of surface map of the solid model so that the surface is formed by triangular, the smaller number of triangular are, the more accurate model you will have as shown in Figure 7.

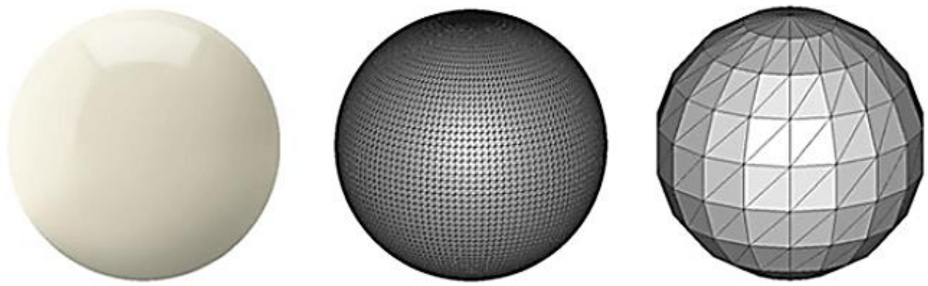

Figure 7. Converted model to STL. format (All3DP, 2019).

In Figure 7, there are a sphere with large triangular and its surface quality isn't good, so you can observe that the smaller no. of triangular are, the more accurate model is but this is something you don´t have to care about because in most of the cases STL conversion is done automatic but it is good to know what is the effect of amount of triangular for a ready product. After the STL conversion, the model cannot be easily changed also it can contain errors that make the file unusable with additive manufacturing processes or 3D printing but anyway there are different software's that can be used to remove these errors in the STL file but if you decided to change something in the model, you cannot do that change to STL form , you have to change it to original digital model. Once the file to successively converted into STL format file, it is imported into a slicer program to insert support and prepare the model for printing (Grimm et. al, 2004 pp.59-72).

2.3.3 Printing

Once the digital model is converted to STL format the consumables are loaded the printer is set up the parameters, then the printer builds the model by depositing material layer by layer, each layer may be from 0.1-0.25mm. (Grimm et. al, 2004 pp.59-72) 3D printing the model can take hours or days depending on the model, 3d printing machine itself and the material which is used.

2.3.4 Removal

Some 3D printing Methods are simple to be removed from the platform, but some other 3D printing methods require a highly technical process to remove the printed part. These kinds of methods require removal procedures and machine operators with safety precautions to avoid injury from hot surfaces or toxic chemicals.

2.3.5 Post processing

Some 3D printer technology requires a number of procedures for the printed model such as brushing powder or bathing the printed model to be much easier to remove supports but of course, it depends on the printer technology. Some technologies do not require such procedures such as FDM parts and other technologies require such as SLA machines which need a UV before handling. Nearly all parts manufactured with AM require some post-processing as shown in Figure 8 which consists of six phases such as removal from building platform and support material, surface texture and accuracy improvements and final property enhancements.

Figure 8. Before and after Post processing (3D Printing Industry, 2019).

3 FUSED DEPOSITION MODELING

The fusion-layer printing technology FDM was developed by S. Scott Trump in the late 1980s and introduced to the market by Stratasys since 1990 (USPTO, 2019). Currently, the technology is becoming more common among enthusiasts who create open source printers, as well as commercial companies due to the expiration of the original patent. In turn, the wide distribution of technology has led to a significant reduction in prices for 3D printers using this production method (Kruth. 2012, pp.357-371).

3.1 Technology description

Fused deposition modelling, or in short FDM, is a rapid prototyping technique where layers of materials are stacked on top of each other. It is seen as one of the most known principles of 3D printing and easily accessible (Taufik et al. 2016, pp.1-11). An example of an FDM printer is shown in Figure 9.

Figure 9. The newest multi-color FDM printer (Purple Platypus, 2019).

This additive manufacturing works by using usually a plastic material that is heated and thus melted. It is extruded during the deposition and build up layer after layer on a moving platform that lowers after every layer. Vertical support structures are used so as to sustain the overhanging parts; however, this printing technique is unable to create steep unsupported overhanging parts (Taufik et al. 2016, pp.1-11). The whole system is surrounded by a chamber to keep control of the thermal environment. The temperature in the chamber is maintained slightly below the melting point of the deposited material. Therefore, once the fluid material leaves the nozzle, it will harden almost instantaneously. This technique mainly uses plastics, like polylactic acid, polycarbonate, polyamide and, polystyrene amongst many other types. All types differ slightly in strength and temperature properties and can be manufactured in different colors giving an additional recognition to the 3D-printed object. The filaments look like wires, and an example is shown in Figure 10 (Wittbrodt et al. 2015, pp.110-116).

Figure 10. Typical plastic thread spools used by FDM printers (Sculpteo.com, 2019).

The thermoplastic filament is transformed into a liquid due to the applied mechanical pressure, this process is called extrusion. The viscous properties of the material are very important because this issue determines whether the liquefied thermoplastic overcomes the pressure drop so as to be released through the nozzle. Usually, the temperature is regulated by electrical coil heaters. The extruder can move in a horizontal and vertical direction and is controlled by algorithms similar to those used in numerical control machines. The nozzle moves along a predefined trajectory that is customized for the design, and usually a company's secret of how this path is defined. The extruder is driven by step motors or servo drives and usually, the Cartesian coordinate system is used to build on a rectangular three-dimensional space. A schematic overview of a typical FDM printer can be found in Figure 11 (Dizon et al. 2018, pp.45-54).

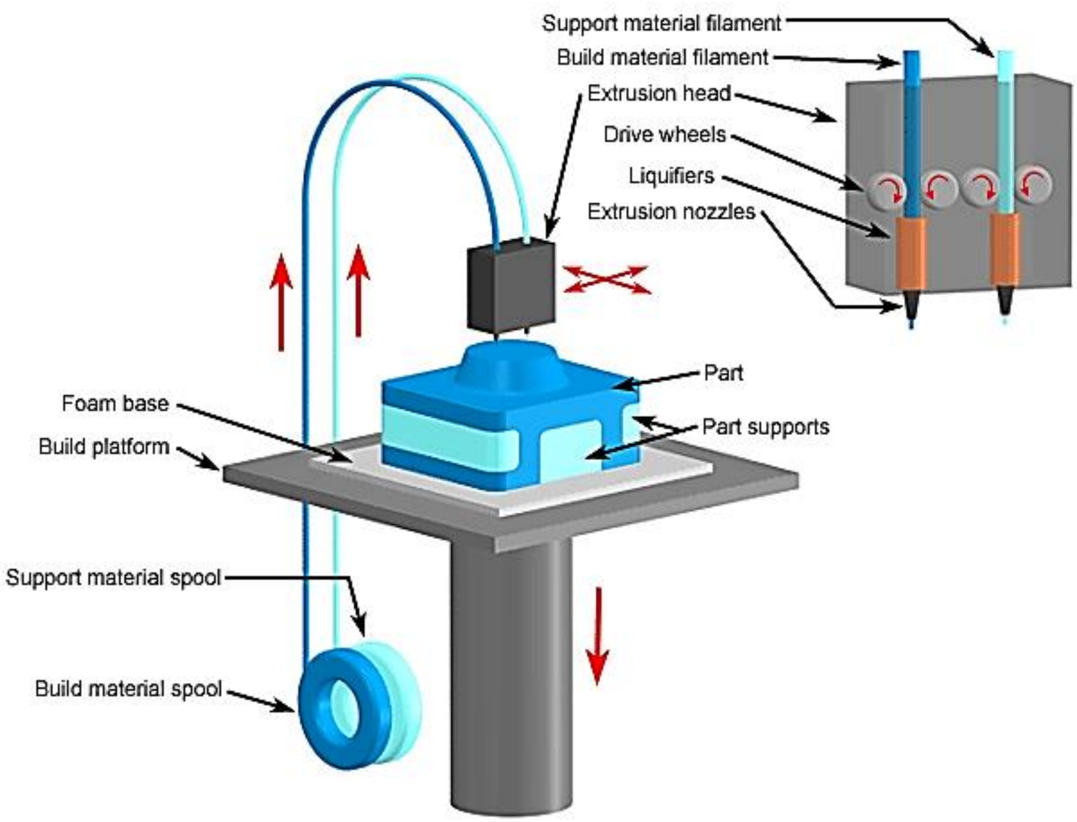

Figure 11. The scheme of the typical FDM printer Custom Partnet (2019).

The FDM technology is adaptable, but also has its limitations. It is possible to create overhanging structures, however, concerning large angles, it is necessary to use a support material that needs to be removed in the post-processing step. (Evans, 2012)

3.2 Parameters

Several parameters can be set in the FDM process. For example, it is important that the layers stick together to form one piece. Therefore, the high temperature and pressure result in melting of the previous layer, helping with a layer adhesion of the new layer to the previous. The infill and shell thickness are important parameters as well. These define the strength of the part usually, it depends on which printer is used how thin the outer layer can be in minimal millimeters. The infill is given in percentage and defines how much material is used to fill up the non-visible inside of the model. With maximum infill (100%) everything inside is plastic, creating a stronger final product. However, this also takes the longest time to make. Therefore, this must be considered carefully to get the best compromise between time, material use and strength. If possible, the support structure must be minimized. This can mainly be done by choosing a proper orientation for the model where minimum support structures are necessary.

3.3 Applications

Among the materials used are Acrylonitrile Butadiene Styrene (ABS), polyphony sulfone, polycarbonate and polyetherimide. These materials are appreciated for heat resistance. Some variants of polyetherimide, particularly, are highly refractory, which makes them suitable for use in the aerospace industry. FDM is one of the most popular consumer printers due to its inexpensive printing methods. It is easily adjustable to items used in daily life and can be used to create a various number of objects such as toys, jewelry, souvenirs, and gadgets (Wittbrodt & Pearce, 2015). Some of the disadvantages of FDM are poor accuracy and resolution. Often, the separate layers are still visible by eye in the final product. Because of these lines, post-processing is necessary. This is also vital due to the support structures, which might be hard to remove. Furthermore, there might be problems with layer adhesion, especially with overhangs or inclinations, resulting in loose pieces of filament that are not (properly) connected to the whole model.

4 POWDER BED FUSION

Powder Bed Fusion (PBF) technology is a new manufacturing process that can 3D print complex shapes that were almost impossible to manufacture before compared with traditional machining such as milling, drilling, grilling, and turning so thermal sources that is used to fuse the material in a powder to form 3D objects. Figure 12 depicts the components necessary for a particular AM process.

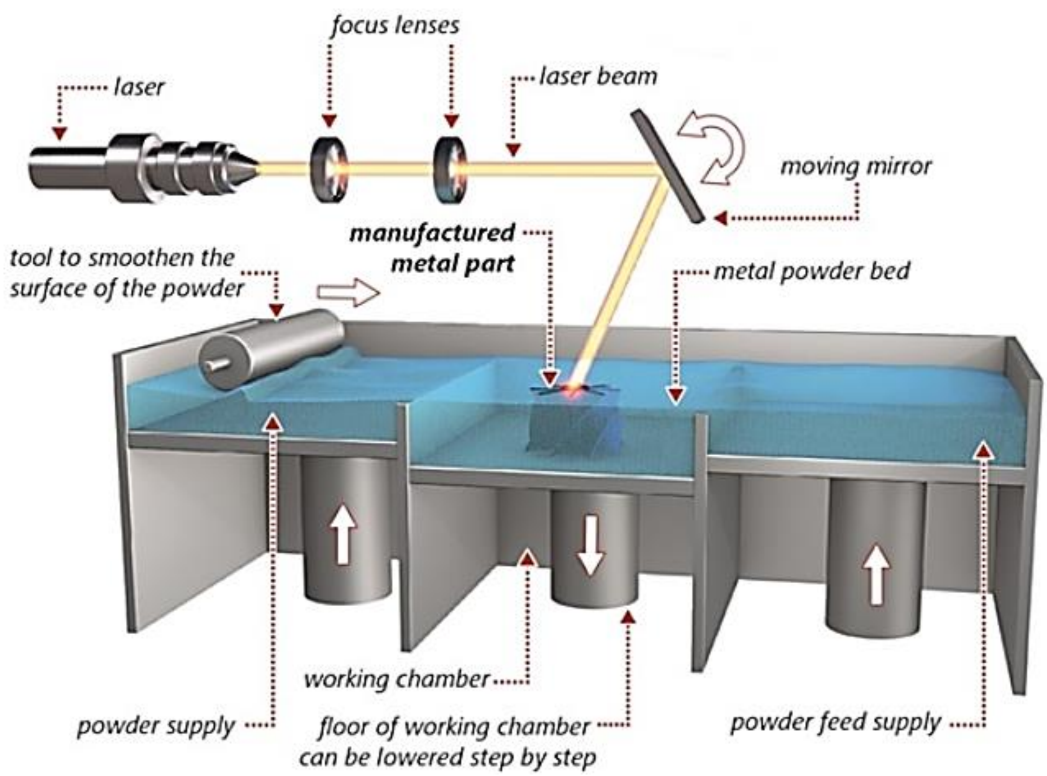

Figure 12. PBF Additive Manufacturing (Empa.ch. ,2019).

4.1 History

ISO/ASTM gives a definition for PBF technology as an “additive manufacturing in which thermal energy melts the particles of the powder layer-by-layer (ISO/ASTM, 2017, p. 29) PBF contains a lot of technologies and most of them have the same work principle but the most important three technologies are Electron Beam Melting (EBM), SLS and SLM. These founded from Texas University in the 1980s at Austin which was awarded in 1989 (Texas Education, 2019).

4.2 Technology description

Most of the 3D metal printing technologies such as SLS, Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM) technologies have the same core and work principle (Kruth et al. 2003, pp.357-371) Metal PBF technology is also known as metal additive manufacturing and laser sintering, but well-known as a PBF that can help us to have complex geometries which were impossible to be done before. The technology can build complex shapes and structures which are very difficult to manufacture before and even impossible with traditional methods such as casting and machining methods. Figure 13 illustrates the general parts of PBF.

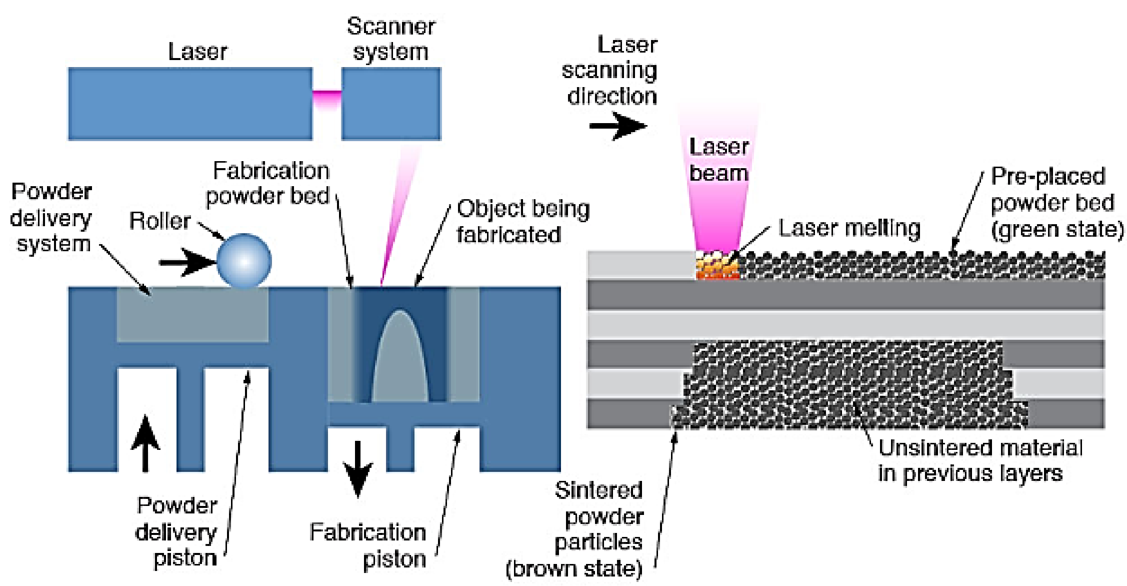

Figure 13. Powder Bed Fusion (PBF) process (Acamm llnl gov, 2019).

To produce 3D metal printed parts, it starts from sliced 3D CAD data. For each slice, a thin layer metal powder that comes from reservoir platform are spread and closely packed across the build plate by roller. The printing process starts when a powerful laser beam or a binder is used to fuse each layer together as shown in Figure 13, which is defined by the computer-generated part design data. Then, the build platform goes down by one layer thickness from (40-150 µm). The high-power laser starts to work again to metal the second layer (Fina et. al. 2018, pp.81-

84). Excess or unfused material is removed from the process by a vacuum. The density of the fused part can be altered by adjusting powder size distribution or packing, and this has a huge influence on the efficiency of the process. After each layer is fused, the build platform lowers a small amount and a new layer of powder is spread (Gibson et al. 2015, p. 107-109).

4.3 Finishing and further processing

When the printing process is completed, the whole object is covered under the powder that can be removed by using compressed air then further steps may take place, a series of post-build processing steps which includes support removal as shown in Figure 14, abrasive blasting, machining, and sometimes polishing, a compilation chart of the post-processing PBF technology is shown in Table 1. Models are almost from 90-99% done after the manufacturing process and they do not require further sintering or other infiltration process but also there are some huge objects that might need a huge range of finishing options that include materials treatment, machining, coatings and independent measurement verification (3trpd.co.uk, 2016).

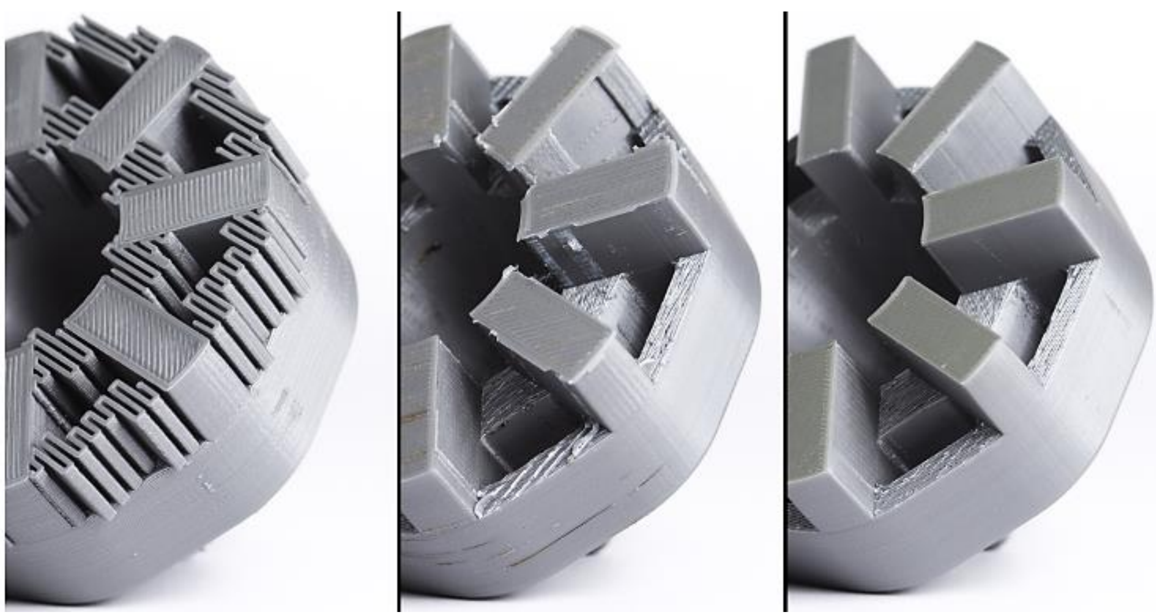

Figure 14. Original print with support attached, poor support removal and good support removal (left to right) (3D Hubs, 2019).

Table 1. Compilation chart of the post-processing PBF technology.

Post Processing phase	Metal
Removal from the g building platform	Mechanical cutting, EDM
Support material removal	Mechanical cutting, grinding, EDM
Surface improvements	Grinding, polishing, media blasting
Accuracy improvements	Machining
Aesthetic improvements	Paint, coating
Property enhancements	Heat treatment, HIP

4.4 PBF Advantages and Disadvantages

Powder bed fusion has some common advantages and disadvantages with other AM techniques compared to traditional manufacturing methods. For example, it is possible to make complex and optimized shapes or moving parts in a single print. This furthermore gives the designer more freedom to design products. Another example of the benefits that AM simplifies the manufacturing process as there are fewer processes. AM technologies also have their own disadvantages, as large batches or heavier objects could be more expensive or time-consuming to make than with traditional manufacturing processes (Banks et al. 2013, pp.22-26). According to Gibson et al. and Ngo et al. there are also many advantages and disadvantages that are specific to PBF, although some of them also apply for some other AM techniques (Ngo et al. 2018, p. 174).

Nowadays, PBF price decreased a lot which made the manufacturing cost decrease.
Powder could be recycled in some cases. Most of the models do not need support structures but in the case to get much, more accuracy the bottom plate is used as a support and also the powder itself acts as a support structure. Sometimes, the process is slow and takes a long print time because of vacuum, powder preheating, cooling off period are added to the building time
Post-processing –Some parts might need a huge range of finishing options that include materials treatment, machining, coatings and independent measurement verification.

Unused powder can be recycled but in case of gold powder it is so expensive because to speed up the process, the powder is preheated which affects some near powder because of the heat.

The main technologies used for PBF Technology

- SLS (Selective Laser Sintering) - selective laser sintering of particles of a powdered material under laser rays until a physical object is formed according to a given CAD model;

- SLM / DMP (Selective Laser Melting / Direct Metal Printing) - selective laser melting of the metal powder according to mathematical CAD models using a ytterbium laser;

The main technologies used in the creation of products on additive plants for PBF Technologies are DMLS, EBM, SLM and SLS. (Fina et. al. 2018, pp.81-84) (ASTM, 2012, pp.1–3) (Fina et. al. 2018, pp.81-84).. Typical build size and wall thickness for most of the technologies are shown in Table 2.

Table 2. Shows the suitable typical build size and wall thickness dimensions.

PBF Technology process	Platform size	Thickness wall
SLS	300 x 300 x 300 mm Max. 750 x 550 x 550 mm	0.7mm
DMLS/SLM	250 x 150 x 150 mm Max. 500 x 280 x 360 mm	0.4mm

5 LASER PROCESS FOR 3D METAL PRINTING

Most of the 3D metal printing technologies such as SLS, DMLS, and SLM technologies have the same core and work principle (Mercelis et al. 2006, pp.254–256). SLS was the first process invented at Texas University, developed by Carl Deckard and Joe Beaman in 1980 (Deckard, 1989). After that, similar process as SLS has been created such as SLM and DMLS. SLS is one of the PBF processes used to 3d print model by melting the particles of the powder layer by layer in the chamber (Gibson et al. 2015, p.107).

Most of technologies use fiber laser, the laser power range from 200 watt to 1000 watt to the particles of the powder layer by layer in the chamber. The chamber is first filled with inert gas to minimize the oxidation of the metal. EBM is also one of powder bed fusion processes based on AM. Its work principle is to melt powder particles together, similar to most of the PBF technologies but by using an electron beam, it was announced in 1997 by ARCAM from Sweden. (Gong et al. 2014, pp.1-3). Those technologies made metals be processed and optimized for different applications that include bio-compatible metals and high performance for example in 2007 Gu and Shen processed copper powder to inquire into the cause of the balling phenomenon in the DMLS process (Gu et al. 2007, pp.163-166).

Mumtaz used high power pulse laser system Neodymium Yttrium Aluminum Garnet laser (Nd:YAG) as shown in Figure 15 in 2008 to process on superalloy based on nickel (Mumtaz et al. 2008, pp.77-87) and with the same (Nd:YAG) high power pulse laser system. Fischer has used it in (2003) to felt commercially pure titanium powder (Fischer et al. 2003, pp.467–474). All these materials that have been found are used in various fields for example titanium (Ti) is used in medical implants, nickel-based superalloys and stainless steel are used in aerospace because of their high performance.

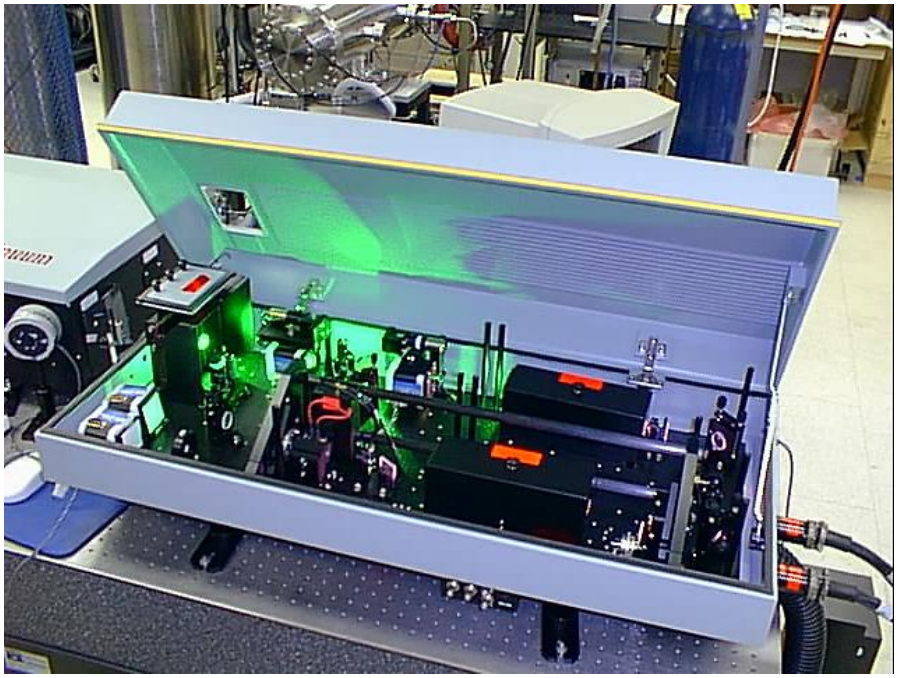

Figure 15. Neodymium Yttrium Aluminum Garnet laser (Wikipedia, 2019).

5.1 Selective laser sintering (SLS)

SLS was the first process invented at Texas University, developed by Carl Deckard and Joe Beaman in 1980, after that similar process as SLS has been created such as SLM and DMLS. SLS is one of the PBF processes used to 3d printing model by melting the particles of the powder layer (Deckard,1989). In Figure 16 shows the work principle for SLS process as a polymer laser sintering process where a powder material is spread on a platform in thin layers from (0.075–0.1 mm) in a closed chamber filled with Nitrogen (N2) to minimize the oxidation of the powder thick with a counter-rotating powder leveling roller and a laser beam or a binder is used to fuse each layer together. Excess or unfused material is removed from the process by a vacuum. The density of the fused part can be altered by adjusting powder size distribution or packing, and this has a huge influence on the efficiency of the process. After each layer is fused, the build platform lowers a small amount and a new layer of powder is spread. (Gibson et al. 2015, p. 107-109).

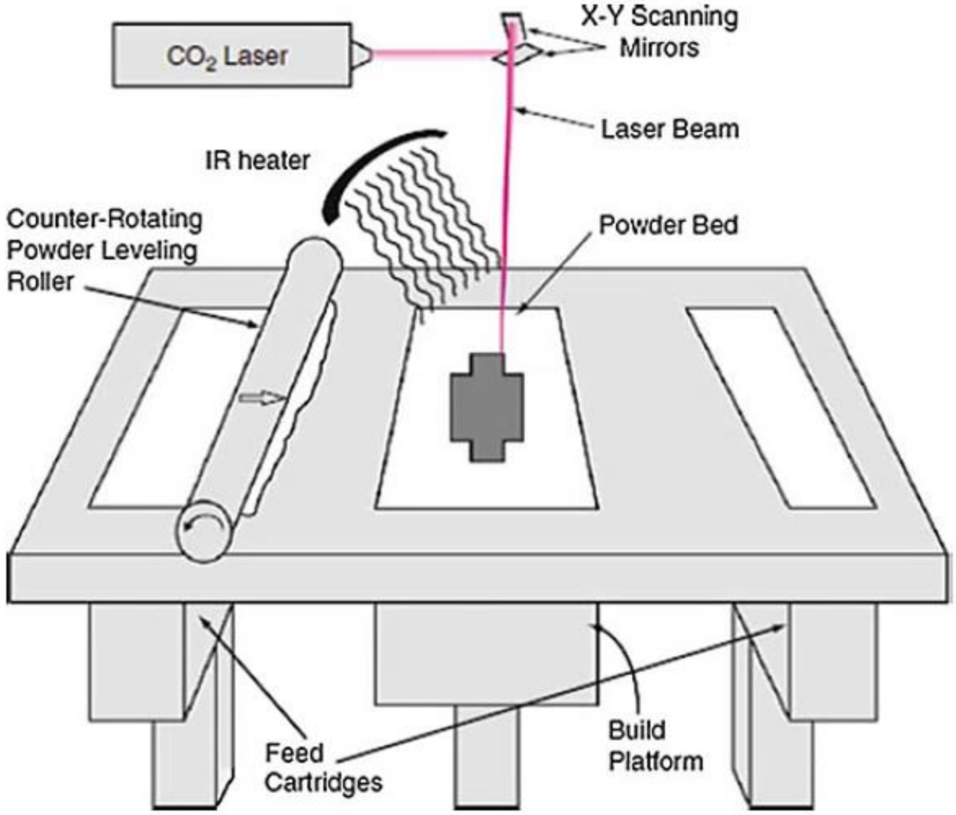

Figure 16. Selective laser sintering (SLS) (Gibson et al. 2015, p. 108).

5.2 Direct Metal Laser Sintering (DMLS)

Direct Metal Laser Sintering (DMLS) is one of the PBF technology and commonly used to 3D print metal, in 1994 Electro-Optical Systems (EOS) in Munich patented DMLS machines. After being patented by one year, EOS created the first DMLS machine called EOSINT M250. In 2004, EOS has launched another model called EOSINT M270, its thickness layer was 20 mm to improve metal printed model quality and it was the first machine with fiber laser. In 2007, EOS introduced EOS Titanium Ti64 it was the first commercial DMLS process for titanium. The cost of DMLS EOS machines starts from $500,000 besides that it requires many maintenance. DMLS work principle as shown in Figure 17 is similar to the SLS process, both of them use laser beam to fuse each layer together, but the only difference is that SLS uses plastic powder material while DMLS uses a metal powder. DMLS pieces are grainy and the metallic support structure removal and post-processing is time-consuming and requires machining (Fictiv, 2019).

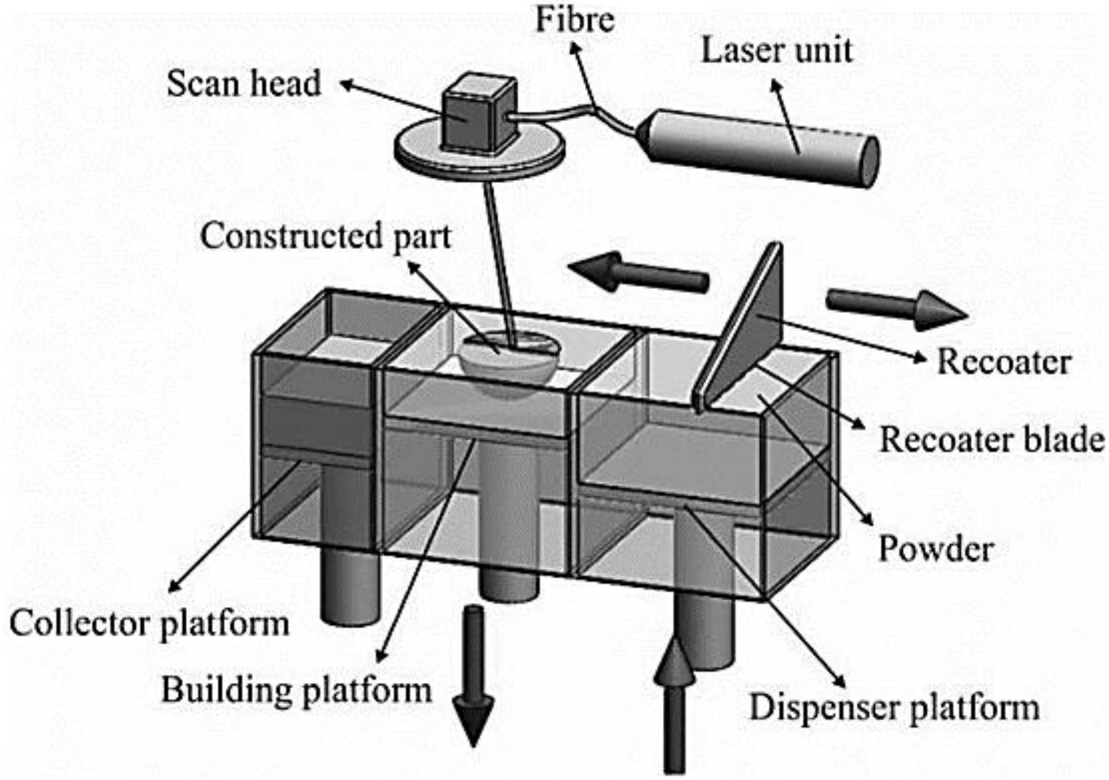

Figure 17. Direct Metal Laser Sintering (DMLS) (Fictiv, 2019).

5.3 Selective Laser Melting (SLM)

SLM laser is one of the main technologies used in the creation of products on additive plants and one of the PBF process as I have mentioned that SLM has the similar process as SLS as shown in Figure 18. Using multi-lasers can improve the building rate of the SLM process. It was started in 1995 and developed.in.1999 by Fockele and Schwarze in Fraunhofer Institute ILT in Aachen, Germany, of laser technology and then commercialized 2004 (Wikipedia.org, 2019). Comparing SLS with SLM, we will learn that SLM is faster, but it requires an inert gas that acts as a poor energy efficiency (from 10 to 20 %) and cost. Work Principle is similar to the BJG process but slower where for each slice a new thin layer metal powder which comes from the reservoir platform is spread across the build plate by roller or blade over the previous layer as dictated by the CAD data. The process happens when it is filled Nitrogen (N2) or Argon (Ar) gas to minimize the metal oxidation in a closed chamber. Choosing between Nitrogen (N2) or Argon (Ar) depends on the reactivity, for example, Argon gas for reactive materials and Nitrogen gas for non-reactive materials. (Gokuldoss et al. 2017, pp.1-12). Also, sometimes the minimization of the cooling rate is needed so substrate plate heating is used, in which it's temperature range from two hundred to five hundred Celsius is required in order to prevent a possible break down during solidification (Prashanth et al. 2015, pp.1-18). SLM is the most process which is used in AM industries, because of the various materials that can be used by it as Al-TI-Fe-Ni-Co-Cu based alloys and other composites plus its ability to produce amorphous materials (Prashanth et al. 2015, pp.1-18). Some other reports clarified that mechanical properties are directly affected by the parameters (Prashanth K.G. et al.2017 pp.25–35) and showed that powders can be reused (Ardila L.C et al. 2014, pp. 99–107) which leads to reducing the raw materials and cost and the raw materials. Compared to the BJG process, SLM is slower but can be improved by using more than one laser beam.

5.3.1 Advantages and drawbacks of using SLM

Vary materials can be used, during the process the properties can be changed, increased performance and almost low cost. SLM is almost a slow process compared to other's technologies, size is restricted, high power usage and initial costs, time-consuming for optimizing the parameter process and rough surface may occur on the printed model.

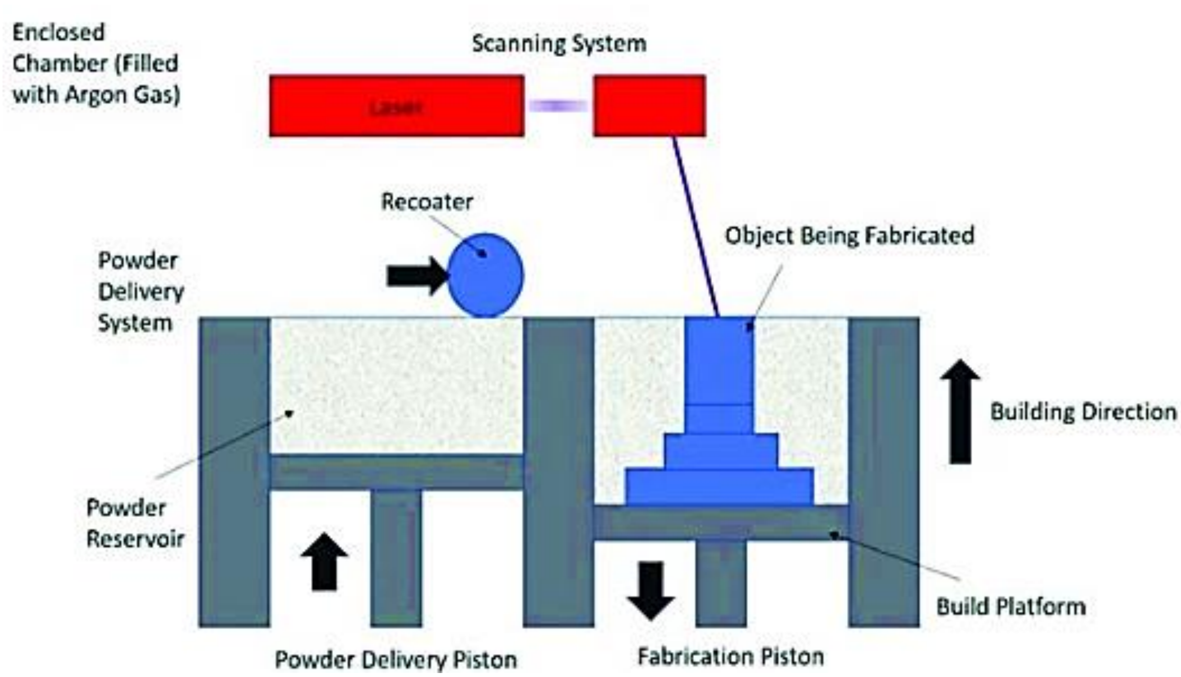

Figure 18. Selective Laser Melting (Lishi et al. 2018,p.2).

6 FACTORS AFFECTING THE SLM PROCESS

SLM process parameters in Figure 19 are material characteristics, laser, scan, and environment. Material characteristic depends on physical properties and chemical composition of the powder that consists of density, thermal conductivity, latent heat of fusion, particle size distribution (PSD), particle morphology and melting point and evaporation point. In the case of laser, it depends on what type of laser (Pulse or Continuous Wave Laser) and laser wavelengths. Also, the scan is one of the parameters that have a high effect on the laser process, there are 3 kinds of scans are done during the process such as Scan Parameters Scan Speed Scan Strategy and Hatch distance is one of the parameters also. Finally, the last parameter is the environment where the process takes place. All these parameters are mentioned in this chapter (Maarten Van Elsen, 2007, pp.31-41).

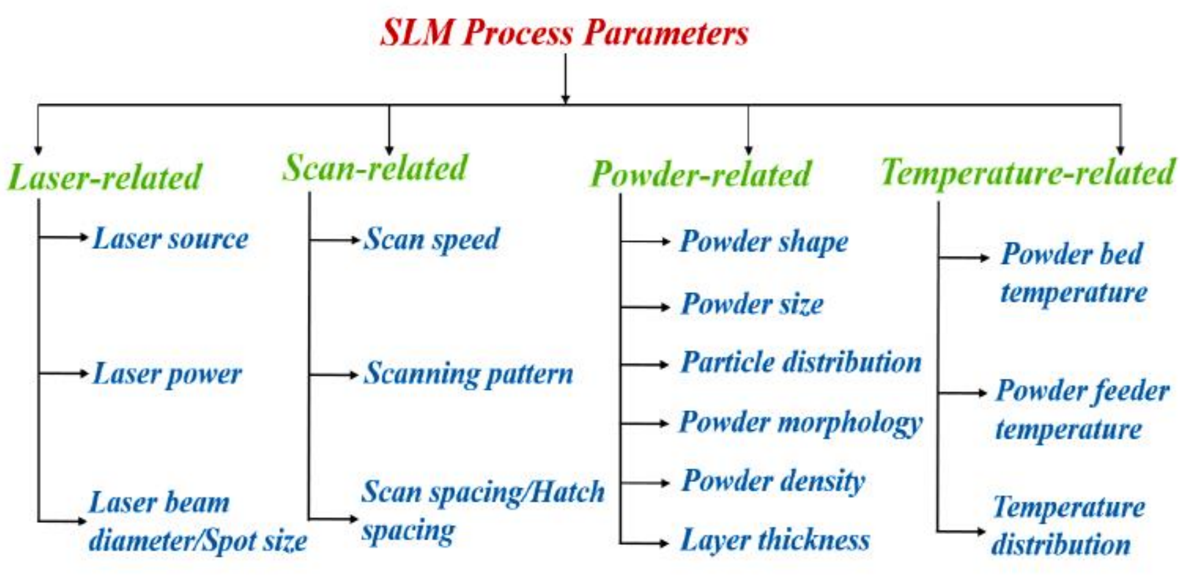

Figure 19. SLM process (Gausemeier,2016).

6.1 Material

Material characteristic depends on physical properties and chemical composition. Physical properties of any material mean to know its density, thermal capacity and latent heat of fusion.

The main factor of this heat balance and thermal expansion determined by melting enthalpy of the metal is because of thermal conductivity which determines the stresses which are caused during re-solidification of the melted metal. While checking the chemical composition behavior that affects shrinkage and wettability (Singheiser et al, 2001 249-259).

6.1.1 Density (ρ)

There are two types of densities of any powder individual particle density and the packing density, particle. Density depends on the type of material, while the packing density is known as packed density and depends on particle morphology. (Maarten Van Elsen, 2007, pp.31-41)

6.1.2 Thermal conductivity (kb)

The thermal conductivity at a specific thickness of the powder depends on the number of connected particles. Some particles are directly proportional to powder pressure that means that as compaction increase, the number of connected points will increase which leads to high heat transfer occurs across the powder layer. (Van Elsen M, 2007, pp.31-41)

6.1.3 Latent heat of fusion (Lf)

The latent heat of fusion is also one of the parameters that have a high effect, it is the energy that changes the material mass from solid to liquid without considering the temperature. It is also used in heat balance determined by melting enthalpy of the metal (D. F. De Lange et al. 2004, pp.154-162) (M. Van Elsen et al. 2007).

6.1.4 Melting and Evaporation point

The melting point happens when the states are changed from one state to another (solid into liquid) at a specific temperature. While evaporation point and melting point have many similarities but the only difference is that evaporation point happens when the material changes from liquid to gas state not as a melting point from solid to liquid state (Van Elsen M, 2007, pp. 31-41).

6.1.5 Particle Size Distribution (PSD)

PSD is one of the parameters that as a high effect on powder characteristics, it is important for the process and final quality of the parts (German, 1989) because it shows the size of the powder particle. While wider PSD is used to increase density to fill the empty spaces between the particles in Figure 20. Then agglomeration phenomena can occur when a powder has a lot of small particles, this occurs because the Van der Wall forces makes the deposition process more difficult (Simchi.A, 2014, pp. 937-948) the number of small particle’s increases, the energy needed to melt them decrease and it improves the quality of the surface (Karapatis, N. P et al. 1998. pp.77-89) (Sears, J. W. et al. 1999 pp.1-16) (Syvanen, T et al. 2000 pp.21-29). Therefore, the best solution is that the powder should consist small particles to fill the empty spaces between the particles and to increase the density of the used powder (Zhu, H. H. et al. 2007 pp 294-298).

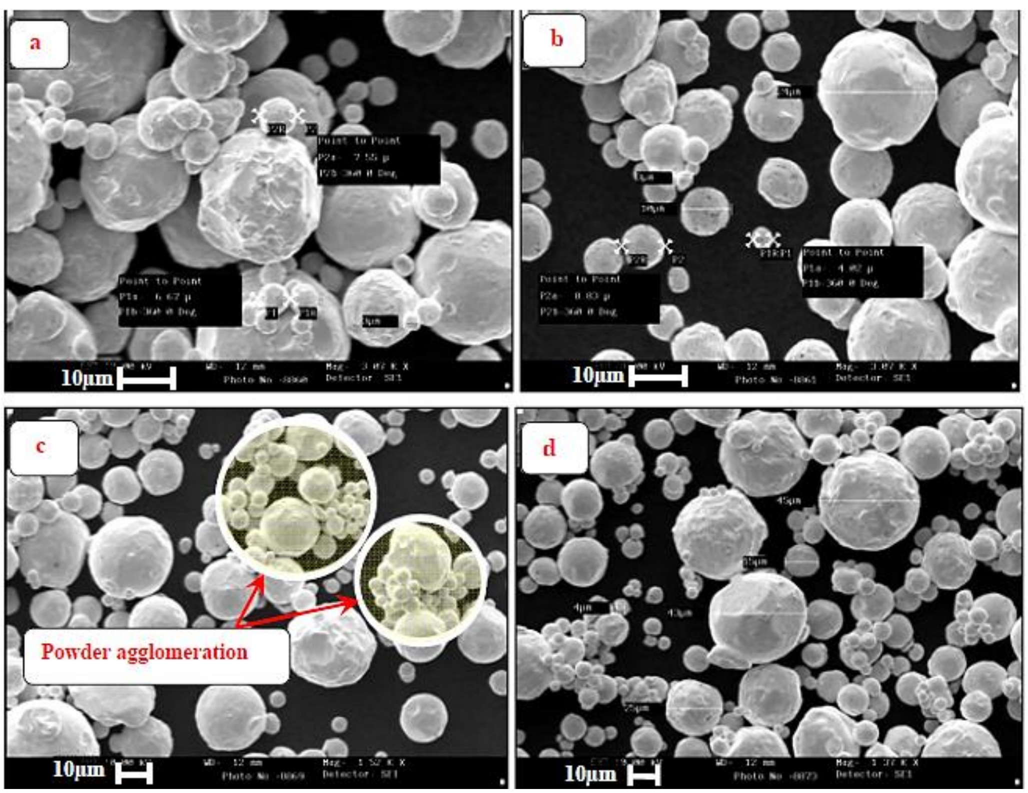

Figure 20. Image's gold (Au) powder PSD (M. Khan et al. 2008, pp.278-286).

6.1.6 Particle morphology

Powder morphology means the shape of the particle and it is directly affected by the preparation method in Figure 21 for a titanium powder. More spherical particles are produced by atomization gas technique which function is to improve powder flowability, improve layer quality and the final product in SFF technologies (Niu, H. J. at al. 1999 pp. 25-30).

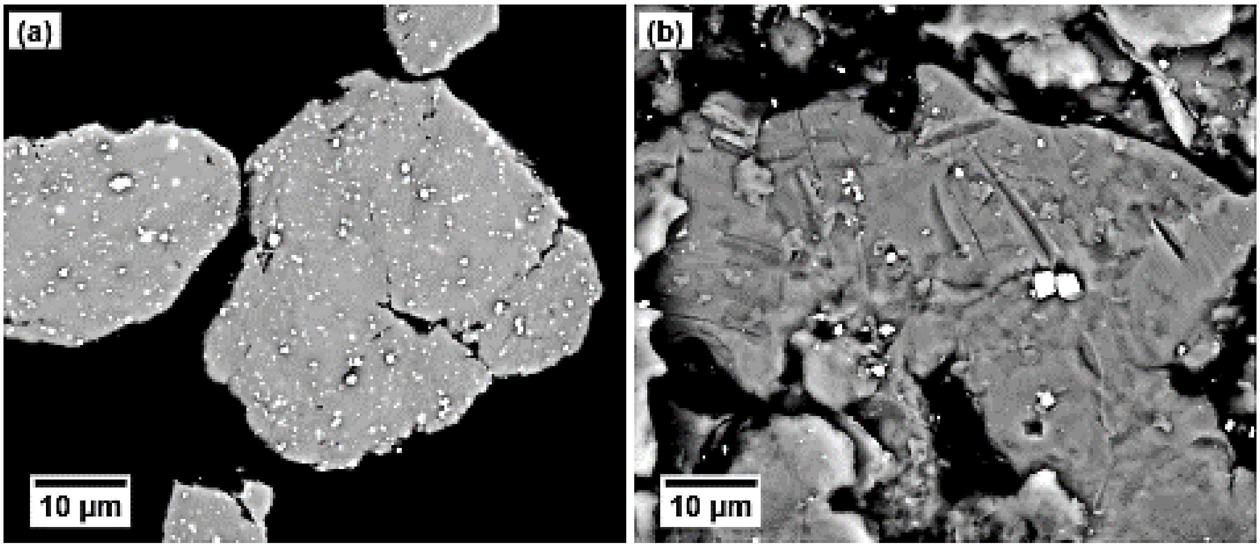

Figure 21. Titanium Powder (a- Inside Titanium Powder), (b- on the particle surface) (Jiˇrí Kozlík et al. 2018, p.12).

6.2 Laser

SLM process work principle is by melting the powder by laser. The properties of the laser are spot size, wavelength, laser power and the form of energy (continuous and pulsed). Only difference between continuous laser and pulsed laser is that continuous laser parameters are laser power and spot size and those are the only parameters that can be changed (Deckers, J. 2008, pp.1-12) while pulse laser parameters are pulse frequency, spot size, pulse duration and peak power and those are the parameters that can be changed in case of pulse laser. The spot size as mentioned before is one of the laser properties that is usually modified and set before building the part and it cannot be changed during the process. In addition to the laser properties, laser parameters are also important parameters that effects on the final model. Laser parameters are wavelength, beam quality and minimum spot size. These two laser types are explained in detail below (R. Poprawe et al. 2004, pp.47-54).

6.2.1 Pulse and Continuous Wave Laser

Pulse laser work principle is by using a small blast of energy to melt the material (Yevko. V et al. 1998, pp. 168-184). A pulsed laser scans a by a straight line and more parameters are needed to control pulse energy, pulse duration, repetition rate and energy control. As well as pulse shaping which is ramp-up pulse and ramp-down also effects on the building part and helps improve top surface roughness (Mumtaz et al. 2008, pp. 77-87). The continuous laser is generated by a continuous excitation with almost constant output energy. The continuous lasers work principle is to heat and melt the powder homogeneously (Fischer et. al. 2002 pp. 467–474). Due to the limitations of parameters to be set for continuous laser, we can observe that the build part production has fewer variables compared with the pulse laser. Difference between pulsed and continuous wave laser is shown in Figure 22.

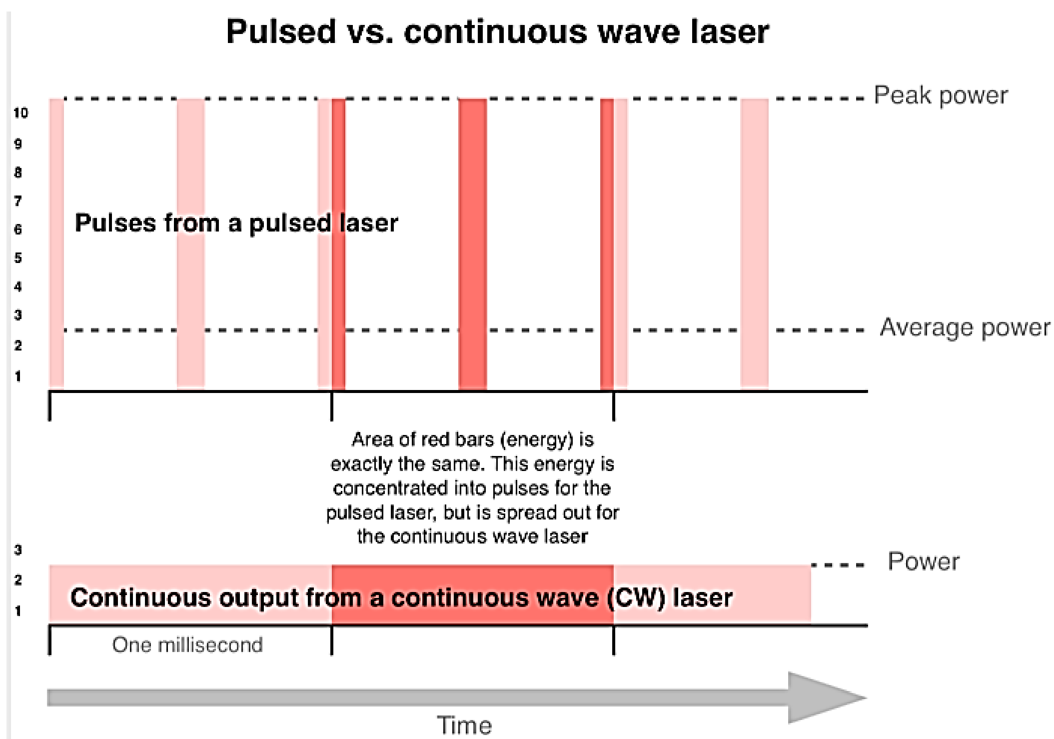

Figure 22. Difference between pulsed and continuous wave laser. (International Laser Display Association, 2019).

6.2.2 Laser Wavelength

Direct metal fabrication of metals uses different laser sources, the most two broadly laser sources that are used are Carbon Dioxide (CO_2) lasers which operating wavelength 10.6µm and

Neodymium-Doped Yttrium Aluminum Garnet (Nd:YAG) lasers which operating wavelength 1.06µm. Nowadays a new type called Ytterbium fiber laser that is more used and more progressively, used for processing metals, its operating wavelength is from 1.07 µm to 1.09µm. (IPG photonics YLR-50). Therefore, in 2000 Laeng clarified that at shorter wavelength leads to make the metal absorb incident radiation that make the processing easier (Laeng et al. 2000, pp. 3973-3996). By comparing between Nd:YAG laser and fiber laser we find that fiber laser has the highest beam quality but in general most metals use from twenty to thirty % Nd:YAG and fiber laser wavelengths (Kruth et al. 2003 pp. 139-142) (N. K. Tolochko et al. 2000, pp.155-166).

6.3 Environmental Effects

The environment which happens to metal powder during the process (to get melted and re-solidify) is one of the important factors that highly effects on the building part. Those factors are bed pre-heating, oxidation and inert gases.

6.3.1 Oxidation

Many lasers which are used has a common problem is called oxidation as shown in Figure 23, In case of SLM laser process, the oxidation increases with the increase of the temperature and overheating the metal (M. Rombouts et al. 2006 pp. 187–192). This unwanted phenomenon is fixed by using a shielding gas (Grevey et al, 2005, pp. 647-651). There are 2 methods which are used for shielding, the first method is to fill the evacuated chamber with inert gas and its drawback that it cost a lot and requires more setup time, the second method is called nozzle feed method. In case of nozzle feed method work, the principle is that inert gas is straight directed from laser nozzle to molten metal (done by laser), this method advantage is better than the first method because it highly protects the melt pool from oxidation.

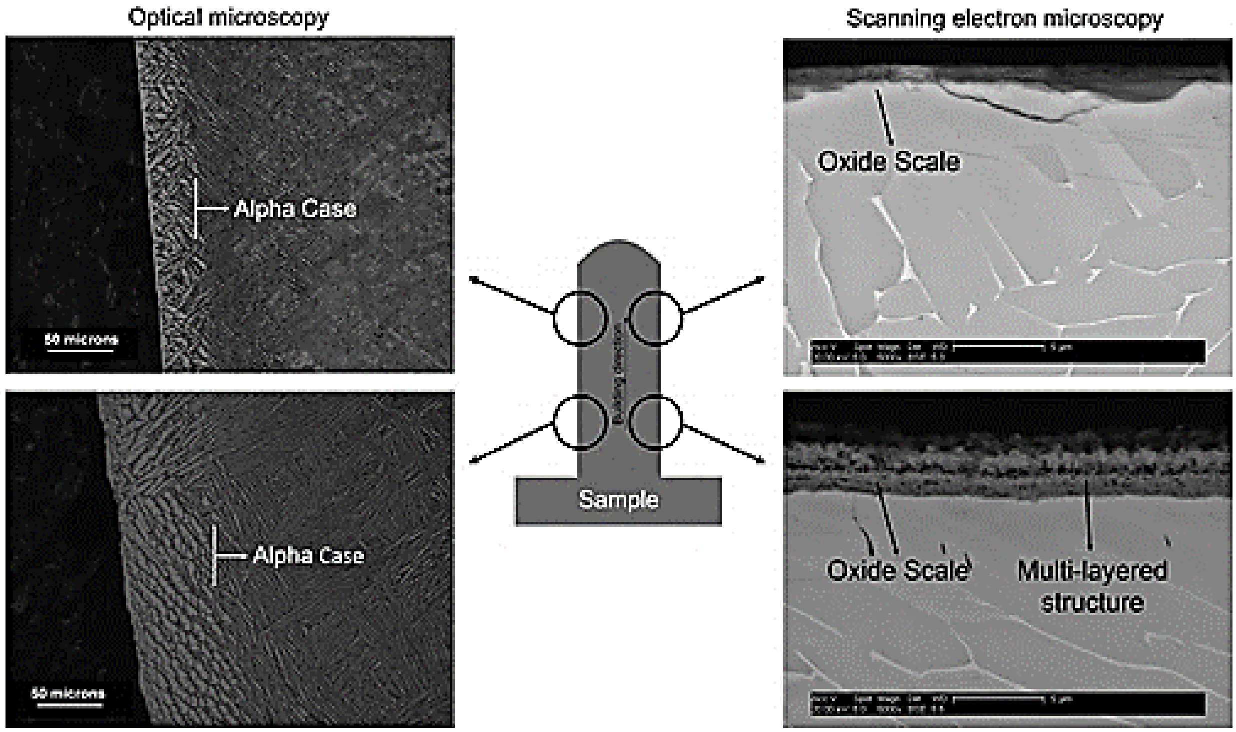

Figure 23. Metal oxidation by Optical microscopy and Scanning electron microscopy (Flipboard, 2019).

6.3.2 Inert environment and gases

As mentioned before that inert gas is the solution for oxidation problem, there are different inert gases that are used such Helium (He), Argon (Ar) and Nitrogen (N2). Helium gas is a light gas, it is even lighter than O2 that make us face the same problem of oxidation because of the small percent of oxygen in it, so it is difficult for Helium gas to protect the molten metal from oxidation. In case of Nitrogen gas, nitrogen gas as the ability to react with some important metals which are used in a lot in additive manufacturing industries such as Ti, Chromium (Cr) and Magnesium(Mg), so it might react on the surface of the object which leads to a direct effect mechanical properties of the model (Kou et al. 2003 pp.70-73). In case of Argon gas is a heavy gas, even heavier than O2 which make Argon gas better for shielding purpose (Messler, 1999) [107]. Many of the commercially uses argon gas for shielding such as MTT Realizer, EOS M290

6.4 Scan

Laser scans that occur during the process with SLM is shown in Figure 24. All those parameters are mentioned in this chapter.

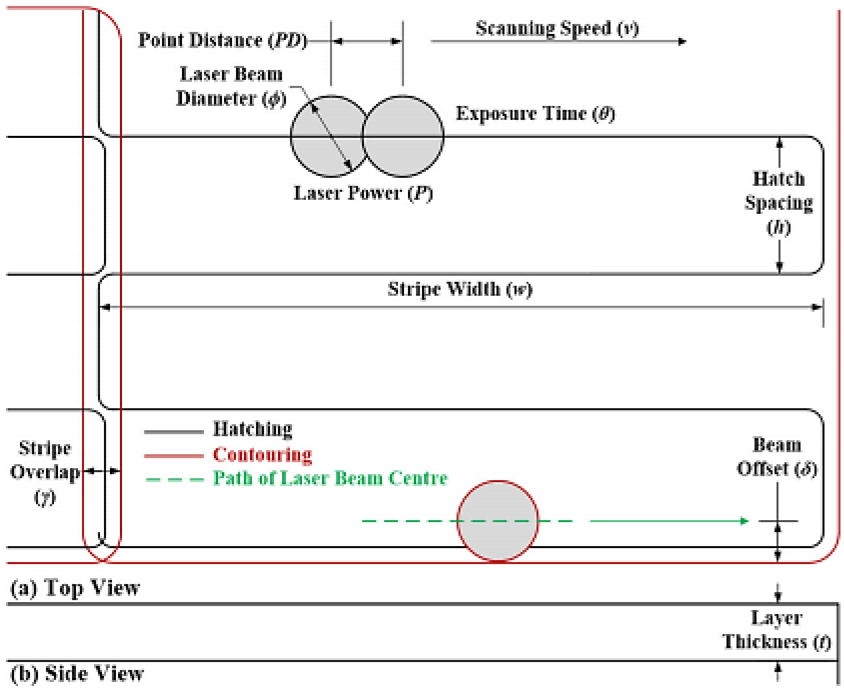

Figure 24. All Laser scans parameters (Yakout M et al. 2017 pp.5-8).

6.4.1 Scan Parameters

The scan parameters are the scan speed, the hatch spacing, percentage overlap and scan strategy, those parameters are one of the main things to have a success printed part because those parameters have highly effect on the build rate such as its surface roughness and model quality.

6.4.2 Scan Speed (V)

Scan speed is the laser speed to scans the part, it also one of the factors that as I highly direct effect on the final model.

6.4.3 Scan Strategy

The most commonly used strategies for laser scanning in SLM are meander, stripe, chessboard, and spiral as shown in the Figure 25 respectively (J.-P. Kruth et al. 2004, pp.616-622).

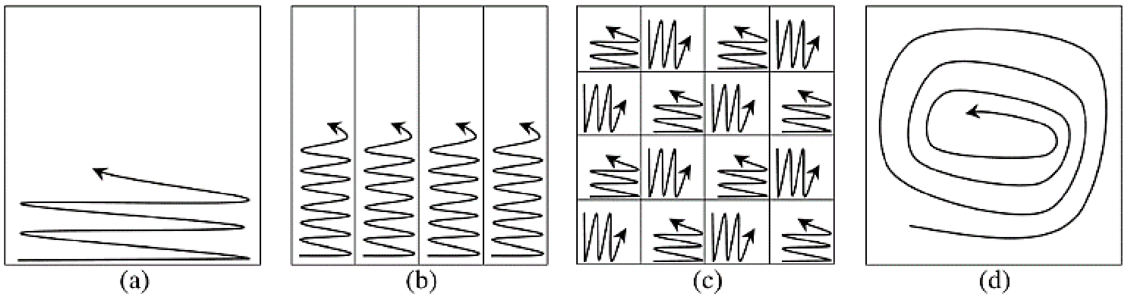

Figure 25. Laser scanning strategies. (a) meander (b) stripe (c) chessboard and (d) spira.

6.4.4 Scan Spacing

Is the connection between two scan tracks, the space between the two scans should be slow to have a good accuracy which leads to decrease the processing speed (W. Meiners et al. 1999) (M. Van Elsen et al. 2007).

6.4.5 Hatch distance (h_s)

Hatch distance is the distance between two successive scan tracks. A certain amount of overlap is important between hatch lines as shown in Figure 26 because it avoids porosity and provides better layer integrity. The rule of hatch distance always has to be smaller than laser beam diameter, otherwise, the process will not work well (Antti Salminen, 2019).

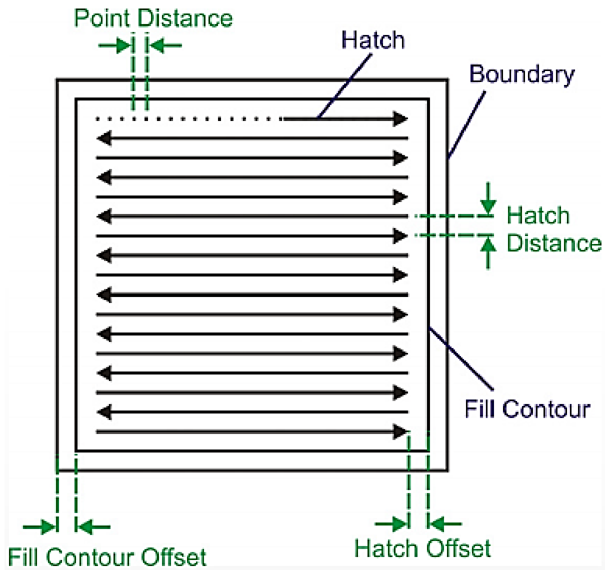

Figure 26. Hatch distance for two consecutive beads (Antti Salminen, 2019).

6.4.6 Power Density (Intensity)

Usually, in PBF we use laser and the main laser parameter is Power (watt), so it is so important to know some calculations of laser power which are Power Density (Intensity), Line Energy and Energy density. It means how much energy we are bringing into a certain cross-section area that means that the power of the laser is divided by the cross-section area of beam (Yakout M et al. 2017 pp.39-41).

6.4.7 Line Energy

It means how much energy is brought into the surface for melting, it can be calculated by (Yakout M et al. 2017 pp.39-41).

$$E_{Line} = P_{Laser}/V_{Scan}$$

Where: E_{Line} = line energy (J/mm)

P_{Laser} = laser power used (W)

V_{Scan} = scanning speed (mm/S)

6.4.8 Energy density

It means how much heat energy is brought to a volume of PBF, where the volume of PBF can be calculated by multiplying hatch distance and thickness of powder bed layer (Volume of powder in one track). The most important condition is that laser beam has to be bigger than the hatch distance, otherwise we will have bad quality and line energy component is used used in energy density equation (Yakout M et al. 2017 pp.39-41)

$$\mathrm{E_{Desnsity}} = \mathrm{P_{Laser}}/\mathrm{V_{Scan}} \,.\, \mathrm{h_s} .\, \mathrm{t_{layer}}$$

Where: $\mathrm{E_{Desnsity}}$= Density Energy (J/mm3)

$\mathrm{P_{Laser}}$ = Laser Power (Watt)

$\mathrm{V_{Scan}}$ = Scanning Speed (mm/s)

$\mathrm{h_s}$ = Hatch Distance (mm)

$\mathrm{t_{layer}}$ = Thickness of powder bed layer (mm)

7 POWDER CHARACTERISTICS

The characteristics of the powder do not only depend on the density of powder material, but powder characteristics are also divided into basic properties and secondary properties. Basic properties such as particle size, particle shape, particle porosity, particle microstructure, while secondary properties are specific surface, apparent density, tap density, flow rate, compacting characteristic and sintering characteristic. The important properties are particle shape, particle size distribution, amount of small and large particles in the powder, powder surface free energy, powder particles and container walls fraction, presence of antistatic agents and agglomeration phenomena (German, 1989), height and type of fall and shielding (Santomaso et al. 2003 pp. 2857-2874). The surface free energy (γ) is defined as the change of force [F] with area [A] at a constant temperature, pressure and composition (German, 1989). Van Der Waals attractions, electrostatic charges and magnetic forces phenomenon can occur if the particles size less 0.05 microns (German, 1989), while bulk density is defined as mass divided by the volume, the volume includes the space between particles and volume particles (Svarovsky et al. 1987). Poured bulk density that is known also as apparent density and it is the most used to measure bulk density while tap density is the bulk density can be defined as the density of the powder after it has been tapping or vibrating.

7.1 Effect of SLM on gold powder (24 carat)

In this section, the results of an experiment have been done by the SLM machine for a single layer of gold powders. Fiber laser power installed in SLM was used in different power watt from minimum power which is ten watts to the maximum is fifty watts. Ten-watt power was not enough to melt the powder shown in Figure 27. Different scan speeds ranges did the experiment from 15 to 500mm/s. The first experiment parameters were from 15 to 200mm/s scan speed and laser power from 10 to 50 Watt, by analyzing the first experiment results, the good melting happened in unstable melt region, although the gold powder was completely melted in the unstable melt region (Mushtaq Khan et al.2016, pp.97-101).

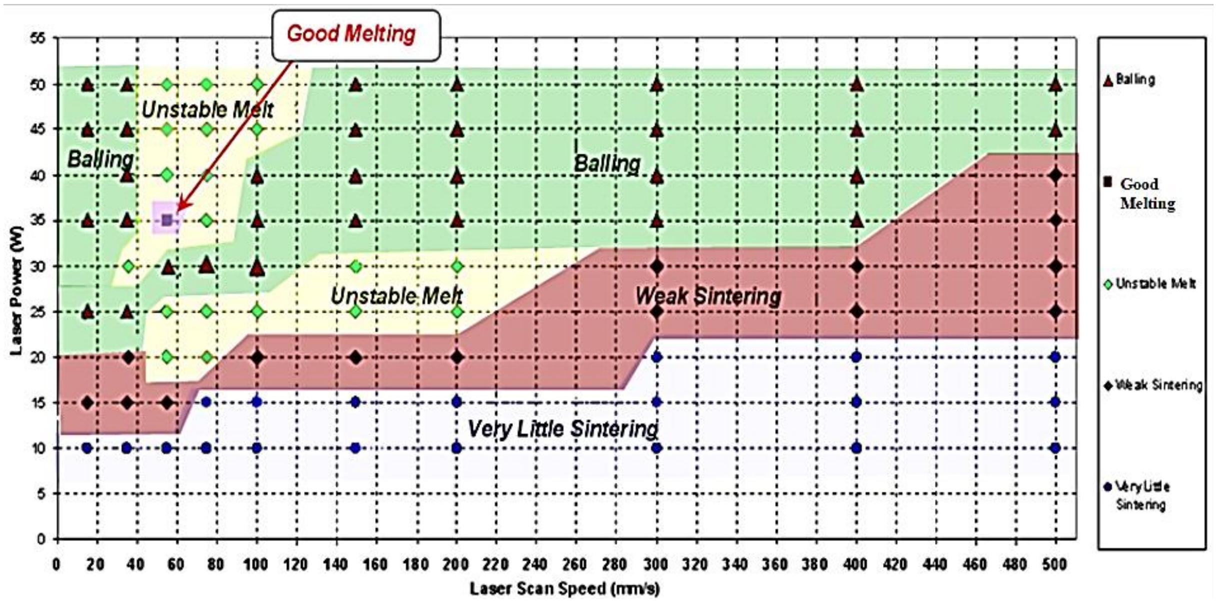

Figure 27. SLM used in different power from 10w to 50w on gold powder (Mushtaq Khan et al.2016, pp.97-101).

The second experiments were for further understand these regions, the parameters which are used in the second experiment was varying parameters (10, 25, 45, 65, 130 and 160mm/s) and for laser power was from 25 to 50W, the second experiment was done in a way to fill the large gaps between the points. Laser power and scan speed various values in the first and second experiment was done by a way to obtain detailed processing and for further understand these regions. In addition to the first and second experiment, a third experiment has been done and it was the most useful experiment in obtaining further detailed processing as shown in Figure 28. By analyzing Figure 28 , there are five different regions appeared which are balling region, good melting region, unstable melt region, weak sintering region and very little sintering region. Balling phenomena may occur in case if small spherical balls that are created by the molten material spreads. If the ratio between length and diameter greater than 2.1 so the molten transfer into small droplets (J.P. Kruth et al. 2004 pp.142-147). Balling phenomena can make molten metal destabilizing and to split to droplets by high and low scan speed respectively, so in case of high scan speed balling can be found due to the increase of L/D ratio 2.1 which caused by the increase of metal pool length and decrease for its width. Molten may have time melt because low-speed scan leads to high input energy and more time to be molten and then to droplets before it could be re-solidify. As in shown Figure 29, the balling phenomena is clearly appearing at 50-watt power and 25mm/s scan speed, the large spacing between these droplets as in Figure 29 is an increase in the break-up time (M. Rombouts et al. 2006, pp.50-57).

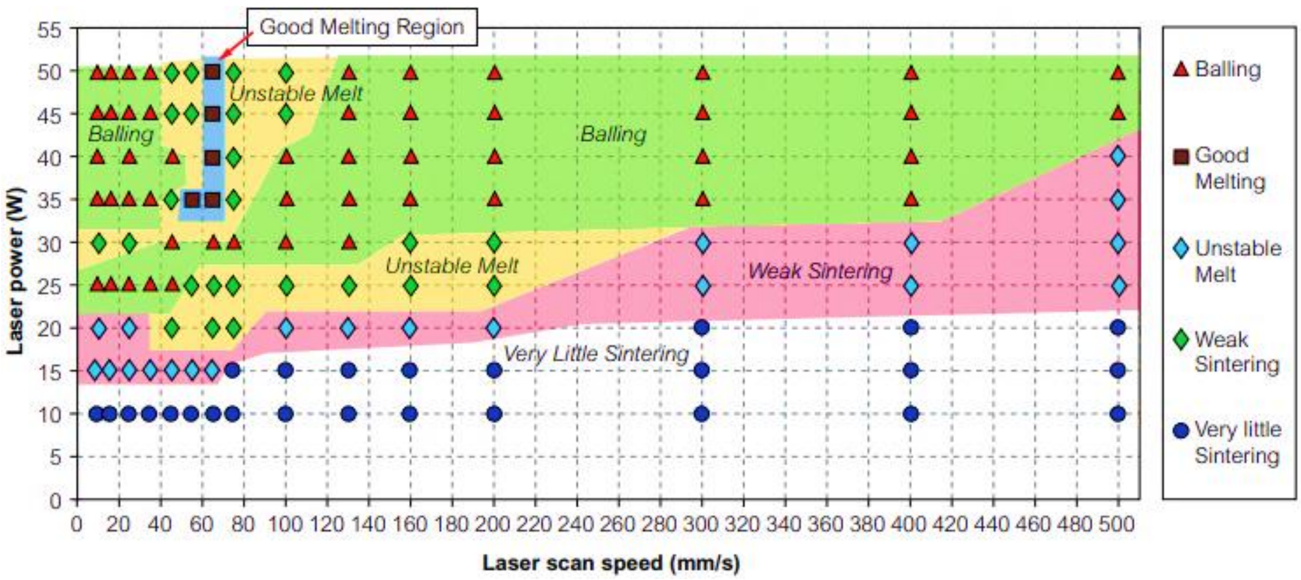

Figure 28. SLM used in different power on gold powder (Mushtaq Khan et al.2016, pp.97-101).

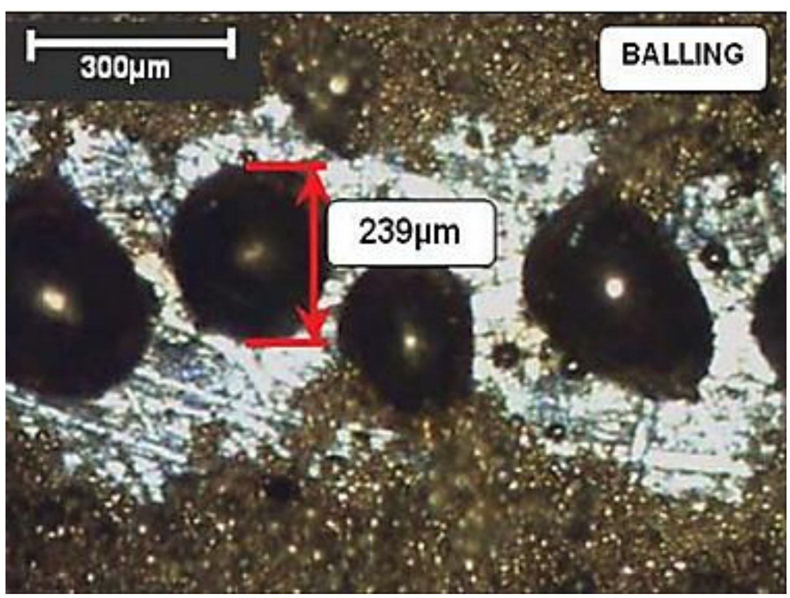

Figure 29. Balling phenomena during SLM of gold (Mushtaq Khan et al.2016, pp.97-101).

A,b,c and d in Figure 30 shows an example for a good melting, unstable melt, weak sintering and very little sintering scans and shows us that gold powder is well melted but in unstable melt region and in case of the weak sintering it couldn’t be completely melted.

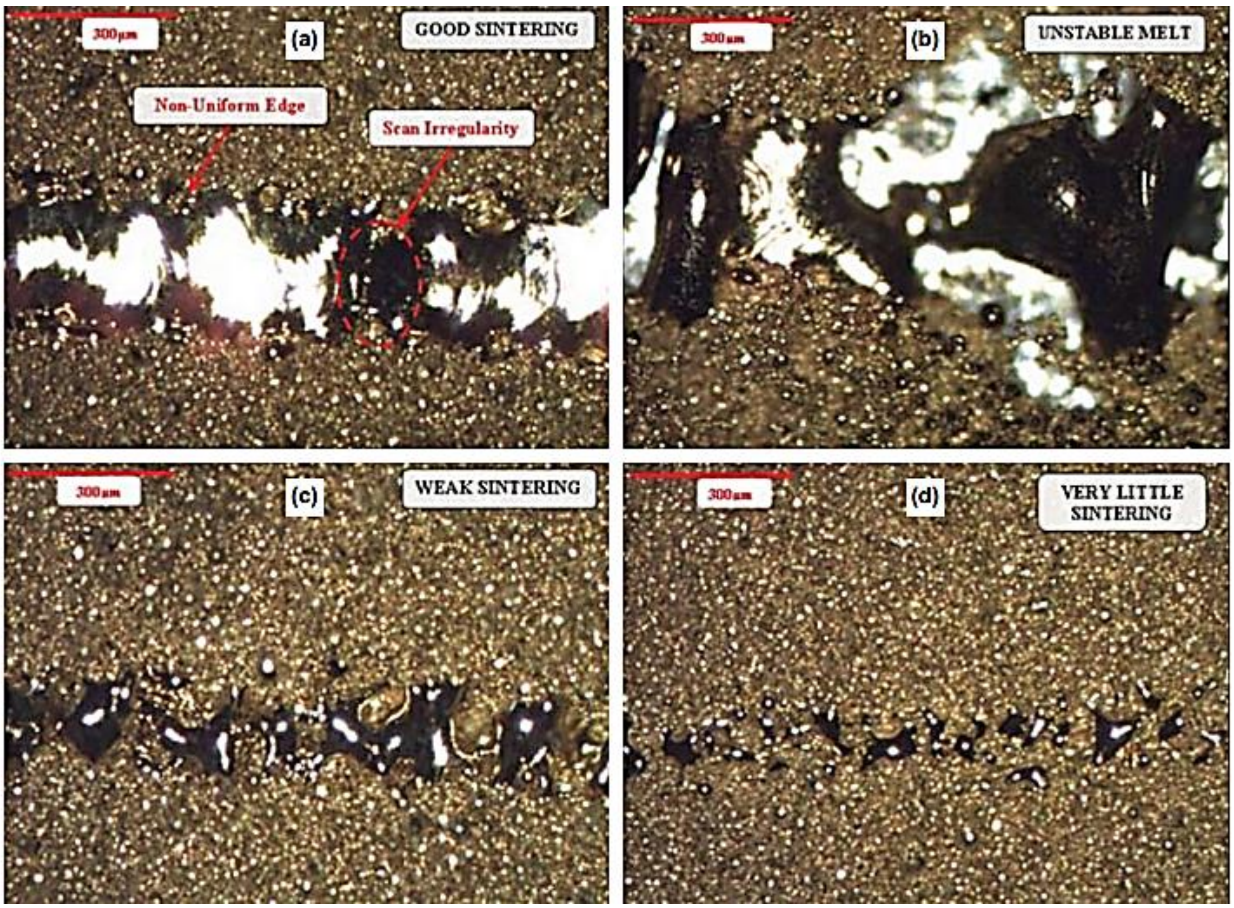

Figure 30. Effect of SLM of gold (Mushtaq Khan et al.2016, pp.97-101).

By analyzing Figure 30 (a) At fifty watt and sixty five mm/s scan speed the melting of the gold powder is good (b) at fifty watts and forty-fifth mm/s scan speed, melt is unstable (c) at fifteen watts and twenty-five mm/s scan speed, the sintering is weak (d) at ten watts and ten mm/s scan speed, very little sintering occurs.

7.2 Effect of SLM on Titanium powder (Ti-6Al-4V)

In this section, the SLM homemade machine, made by Mound Laser & Photonics Center, has done the results of an experiment. Ytterbium fiber laser is installed in SLM homemade machine, its wavelength is 1064 nm and a maximum laser power it can reach is 500 W. The experiment took place at constant laser beam diameter and layer thickness, bed is not preheated, closed chamber is filled with argon to minimize the oxidation and a 50 μm thin layer of metal powder is used for the experiment. The results of an experiment have been for 2 cases, powder case and no powder case. The experiment was done for a single layer for Ti-6Al-4V alloy by melting the layer of powder deposited on the substrate. Parameters for powder case and no powder case is shown in Table 3 and the effect of SLM on titanium powder shown in Figure 31,32 (Chandrakanth Kusuma, 2014, pp.41-53).

Table 3. Parameters for powder case and no powder case.

Parameters	Powder case	No Powder Case
Laser power	91, 194, 297, 400	276, 318, 360
Scan speed	200, 500, 800, 1100	20, 60, 100
Laser beam diameter	100	115
Layer thickness	70	none

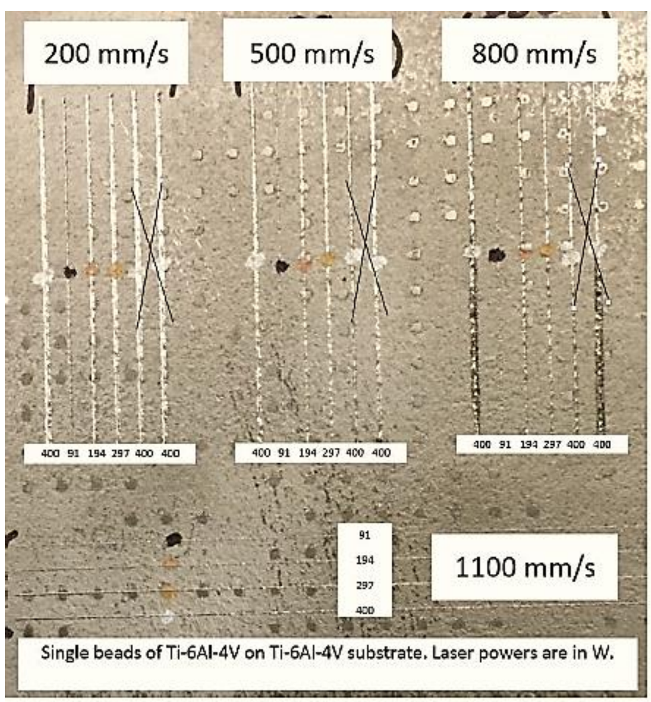

Figure 31. Effect of SLM on silver at different scan speeds for (no powder case) (Chandrakanth Kusuma, 2014, pp.41-53).

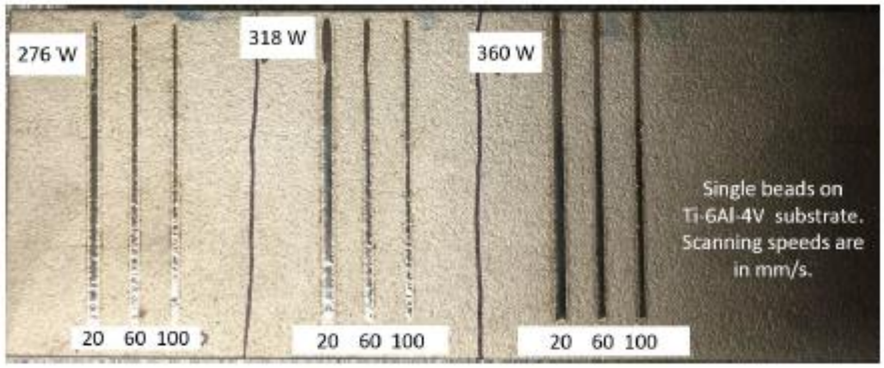

Figure 32. Effect of SLM on titanium at different scan speeds for powder case (Chandrakanth Kusuma, 2014, pp.41-53).

As results, it is shown that Start and end line shape of the powder and balling in the melt pool as shown in Figure 33 ,34

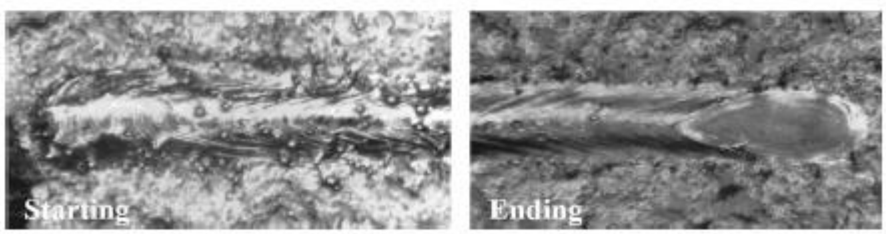

Figure 33. Start and end points of Ti-6Al-4V at laser power (400 W,200 mm/s) (Chandrakanth Kusuma, 2014, pp.41-53).

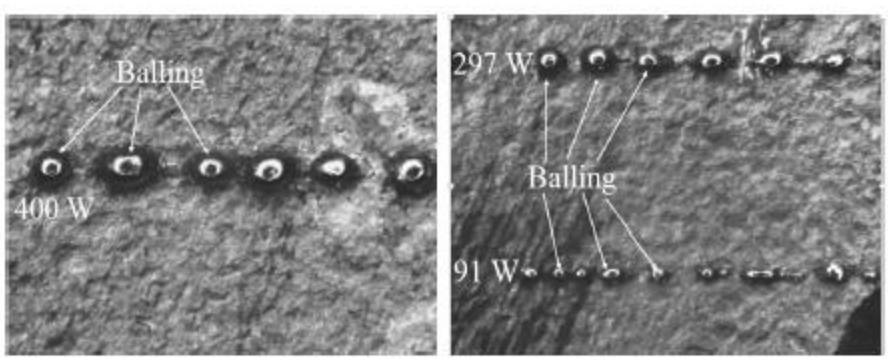

Figure 34. Balling in the melt pools of Ti-6Al-4V sample (1100 mm/s). (Chandrakanth Kusuma, 2014, pp.41-53).

7.2.1 Titanium Powder Characteristics

The ti-6al-4v powder was gained from TLS Technik Germany and the first published results of particle size distribution which is measured by MICROTRAC SI/S3500 laser scanner are done by (Thejane et al. 2016, pp.161-171). Chemical composition for TiAl6V4 is shown in Table 4

Table 4. Chemical composition for TiAl6V4.

Ti	Al	V	C	O	N	Fe	H	Total
Bal.	5.50-6.50	3.50-4.50	0.08	0.13	0.03	0.25	0.0125	0.5

Powder elemental and inert gas fusion are the important factors because powder elemental analysis and inert gas fusion are used to determine metallic composition and to measure the composition of gas respectively. The oxygen concentration in the powder is 0.082, 0.092 and 0.096. Material characteristics of TiAl6V4 are good corrosion resistance, high specific strength, high cycle fatigue strength and toughness. Mass characteristic of the powder is shown in Table 5 and typical application areas aerospace, automotive and medical energy.

Table 5. Material Properties of ti-6al-4v powder.

Elastic Modulus	104800.31 N/mm^2
Poisson's Ratio	0.31 N/A
Tensile Strength	1050 N/mm^2
Yield Strength	827.37088 N/mm^2
Thermal Expansion Coefficient	9e-006 /K
Mass Density	4428.78 kg/m^3
Hardening Factor	0.85 N/A

7.3 Effect of SLM on Silver powder (pure silver)

In this section, the results of an experiment have been done by the SLM machine for a single layer of silver powders. Yb:YAG fiber laser power installed in SLM was used in different power watt that delivers 100 W, the wavelength is 1070 nm, spot size is ≈15 µm and thickness is 25 µm (A Gebhardt et al. 2014). The First experiment was done by different scan speeds ranges from 80, 125, 250, 375 to maximum 750 mm/s (from left to right), as shown in Figure 35 that created high line density and balling phenomena occurred at scan velocity 250 mm/s.. Effect of the energy input on single tracks effects with scan speed 250 mm/s. As a result, the optimized scanning velocity for a laser power of 100 W was found to be 250 mm/s. The resulting track-width reaches a value of 70 μm (A Gebhardt et al. 2014).

Figure 35. Effect of SLM on silver at different scan speeds (80, 125, 250, 375 to maximum 750 mm/s) respectively (A Gebhardt et al. 2014).

The second Experiment was done at constant scanning velocity and different laser power to study the effect of the laser power on the density of the tracks. As shown in Figure 36, laser powder range are 50, 80, 90 and 100 W. The results of the second experiment could not be investigated because of the high laser power (100 W), therefore the particle size distribution and the thermal conductivity of the powder at 100 W cause an unstable melt pool and a poor surface quality (A Gebhardt et al. 2014). The third Experiment a preexposure strategy has been developed to have a much higher thermal conductivity of the material and to attain a stable melt pool because of the better head conductivity high density of lines that leads to having a stable melt pool and the amount of semi-melted adherent particles are reduced. In Figure 37, a pre-exposure laser power range from 50, 60, to maximum 70 Watt. At laser power, 50 watts but also less semi-melted but also it shows the best uniformity of the melt pool occurs and highest density (A Gebhardt et al. 2014). Material Properties of pure silver powder is shown in Table 6.

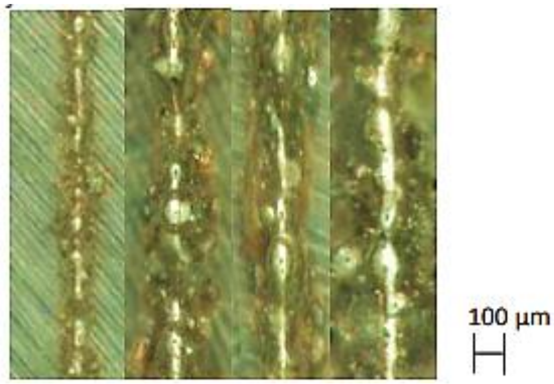

Figure 36. Effect of SLM on silver at different laser power (50, 80, 90 and 100 W) (from left to right).

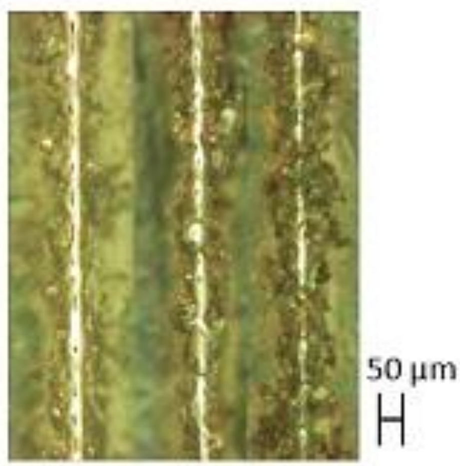

Figure 37. Effect of SLM on silver at different laser power (50, 60, 70) watt (from left to right).

Table 6. Material Properties of Pure Silver Powder.

Elastic Modulus	71000 N/mm^2
Poisson's Ratio	0.37 N/A
Shear Modulus	25000 N/mm^2
Mass Density	11000 kg/m^3
Tensile Strength	125 N/mm^2
Thermal Expansion Coefficient	2e-005 /K
Thermal Conductivity	420 W/(m·K)

7.4 Effect of SLM on Stainless Steel Powder (316L).

In this section, the Renishaw AM250 machine for 316L powders was used for the experiment. Ytterbium fiber laser installed in Renishaw AM250 machine with a 200 watt. The stainless steel powder is supplied by Renishaw Canada and manufactured using a gas atomization process and its material composition is shown in Table 7, the powder particles and grain size are 15–45 µm (Yakout et al. 2017, pp.1953-1974).

Table 7. Material composition of stainless steel 316L powder.

Fe	Cr	Ni	Mo	Mn	Si	N	O	P	C	S
B/	6–18	10-14	2–3	< 2	< 1	< 0.10	< 0.10	< 0.045	< 0.03	< 0.03

The laser power is from 50 to 400 W, scanning speed from 100-1600 mm/s, layer thickness from 40 to 60 µm and hatch spacing from 80 to 130 µm. Based on those values, at laser power (200 Watt) , scanning speed (750 mm/s) which was controlled by exposure time (80 µs) and point distance (60µm), layer thickness (50µm) and hatch spacing (110µm) are recommended (Yakout et al. 2017, pp.1953-1974). As results, a list of SLM process parameters producing stainless steel 316L is shown in Table 8 as well as the material mass characteristic of 316L powder is shown in Table 9 (Yakout et al. 2017, pp.1953-1974).

Table 8. SLM process parameters producing stainless steel 316L.

Laser power	Scanning speed mm/sec	Layer thickness µm	Hatch spacing	Laser energy density J/mm3
50	100	0.04	0.07	179
50	120	0.04	0.12	87
100	300	0.03	0.081-0.126	88-137
100	300	0.03	0.112-0.125	89-99
85-105	300	0.02-0.06	0.112-0.125	38-156
150	400	0.035	0.08	134
190	50-800	0.05	0.15	32-507

The SEM analysis on the side surface as shown in Figure 38. The analysis showed that Figure 38-a is large particles (250μm) on the surface of some samples, Figure 38-b vertical lines perpendicular to the scanning direction, Figure 38-c surface voids and partially melted powders, Figure 38- d cracks between subsequent layers.

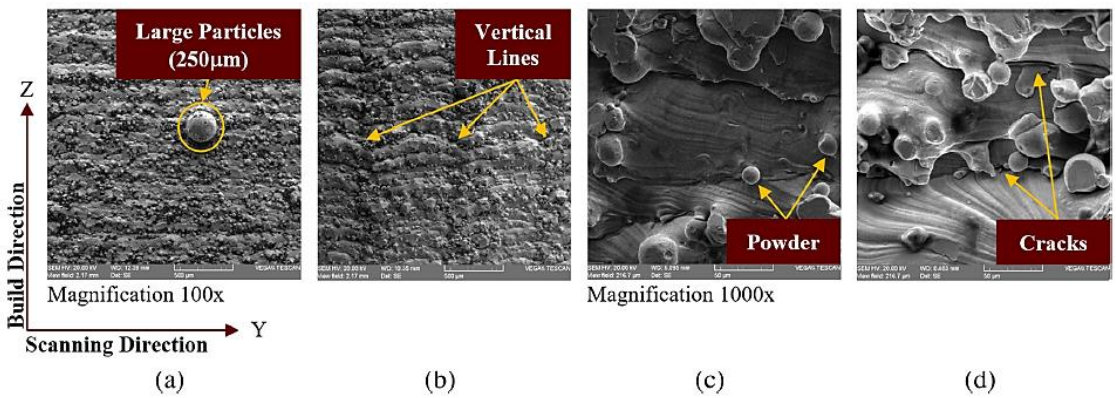

Figure 38. The SEM analysis (Yakout et al. 2017, pp.1953-1974).

Table 9. Material Properties of 316L powder.

Elastic Modulus	192999.9974 N/mm^2
Poisson's Ratio	0.3 N/A
Tensile Strength	50.0000017 N/mm^2
Yield Strength	37.8951459 N/mm^2
Thermal Expansion Coefficient	1.6e-005 /K
Mass Density	8000 kg/m^3
Hardening Factor	0.85 N/A

8 CASE STUDY

The case, study chapter aims to show the difference between tradition jewelry manufacturing and 3D printing additive manufacturing and to 3D metal printing rings and box for jewelry production as shown in Figure 39. The goal of this study is to develop a metal 3D printing process for jewelry production utilizing gold and Stainless Steel by reducing the amount of powder required. Based on the data collected, CAD designs will be considered, the difference between a cross-section area of tradition jewelry manufacturing and 3D printing additive manufacturing and most of the parameters of the ring will be considered due to major problems faced during printing complicated designed rings and low specifications of the PBF machine. All test pieces were manufactured by PBF observing the general AM process chain that was discussed earlier.

The process has been done in the Lappeenranta-Lahti University of Technology LUT. The 3D CAD software used for modelling was SolidWorks 2018 3D CAD software and Dassault Systems 3DEXPERIENCE Platform (DELMIA Additive Part Preparation). The equipment that was needed to complete the experiment was 3d metal printing PBF machine, and a polishing machine (Benchtop Polisher) to avoid having rough surfaces.

Figure 39. 3D metal printing rings and stainless-steel box made in LUT laboratory.

8.1 Rings

Several rings model has been designed most of them were the newest fashion rings but the simplest ring was the model which was manufactured due to major problems faced during printing complicated design. The simple ring after designing has been 3D printed by utilized Gold and Stainless Steel as shown in Figure 40.

Figure 40. Rings utilized by Gold and Stainless Steel powder.

8.1.1 Ring Design

The first step was to define the geometry and dimensions of the rings and stainless-steel box. The main important terms to have a successfully 3D metal printed rings and stainless-steel box is to have a physically and typically size ring so it can be printed successfully by PBF machine. The important terms that must be taken in considerations are curved surfaces, wall thickness and physical size, therefore simple ring will be designed to fit the specification of PBF machine in LUT laboratory. Table 10 shows the suitable typical build size and wall thickness dimensions for PBF machine that is used in Lappeenranta-Lahti University of Technology laboratory.

Table 10. Shows the suitable typical build size and wall thickness dimensions.

Technology process	LUT PBF Machine
Platform size	25.13 cm^3
Thickness wall	0.4
Focal length	400mm

The initial design of the ring was designed in SolidWorks as presented in Figure 41 and an additional design on the surface of the ring as shown in Figure 42.

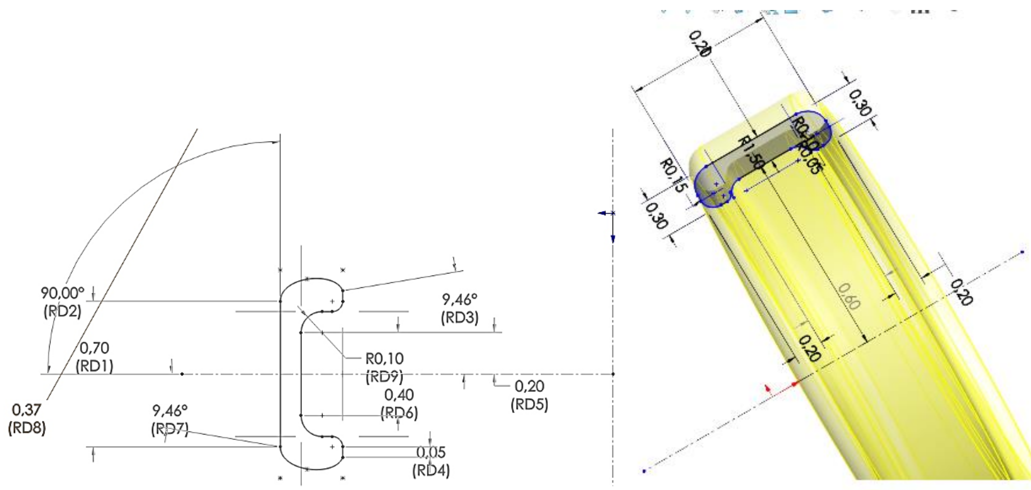

Figure 41. The initial dimension of the ring.

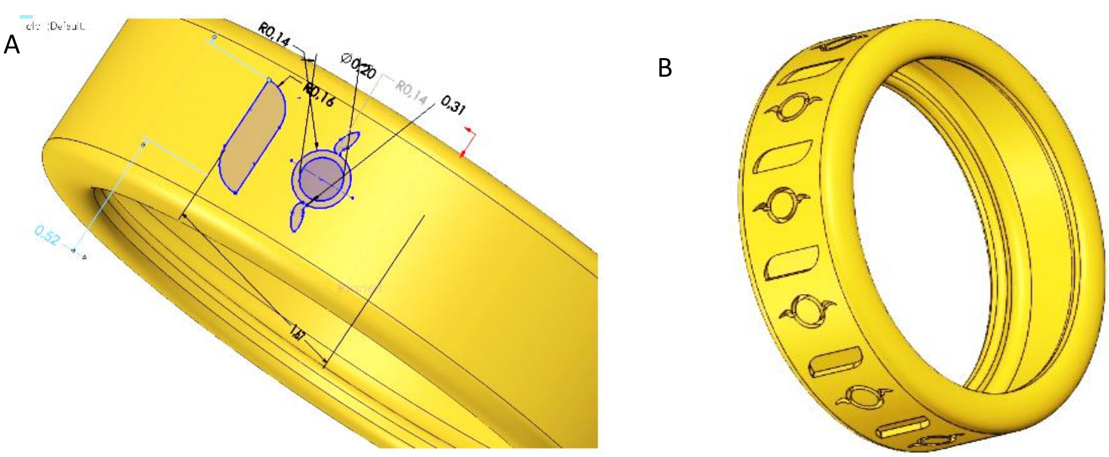

Figure 42. Ring CAD (A: design on the surface of the ring), (B: Final design).

8.1.2 The manufacturing process of ring version 1 utilizes SS316L powder

To 3D print metal ring utilizes SS316L powder, the characteristic of the powder is mentioned such as its material properties and genetic data. The material properties of SS316L powder are high hardness, toughness and corrosion resistance, and can be highly polished, generic data of the powder are density 7.99 g/cm³, thermal conductivity is 16.2 w/mk, melting range from 1371 °C to 1399 °C, coefficient of thermal expansion at temperature range of 0 °C to 100 °C is 16 (10^-6) K.

8.1.3 Support Structures

As mentioned before that PBF of metal requires support structures in order to avoid collapsing and excessive warping also it helps to transfer heat out of the part during build. Therefore, the second step was to build support for the ring, which is created in Dassault System 3DEXPERIENCE Platform, DELMIA Additive Part Preparation as shown in Figure 43.

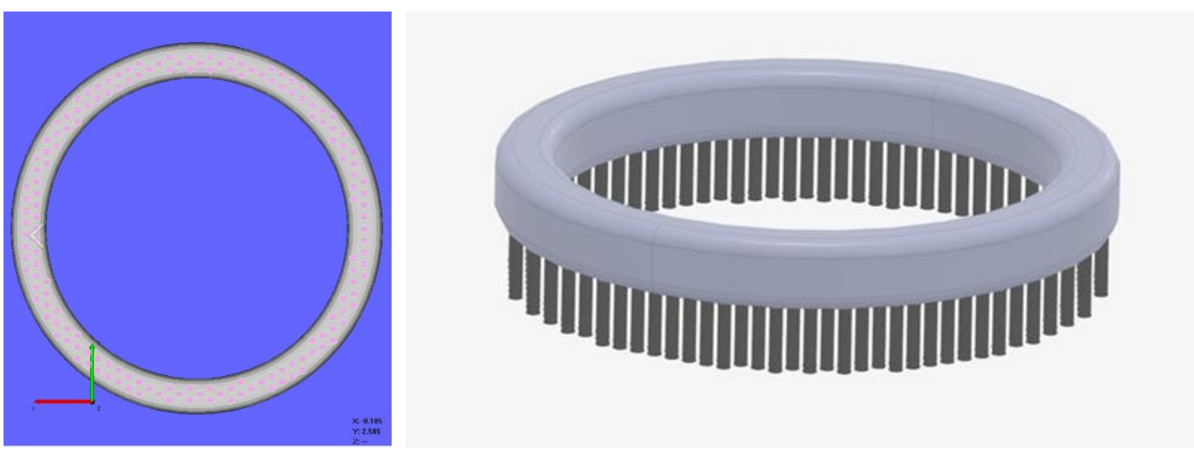

Figure 43. Support structure created by in Dassault System 3DEXPERIENCE Platform.

8.1.4 The manufacturing process of ring utilizes stainless-steel powder (L316)

Next step is to set support structure and Stainless-steel ring parameters shown in Table 11 and Table 12 respectively, after building the supports structure of rings, converting files to STL format and uploading the model design to PBF machine as shown in Figure 44.

Figure 44. PBF machine for 3D printing rings.

Table 11. Parameters of building support structures.

Speed	1200 mm/s
Power	75%

Table 12. Parameters of the ring utilized by SS316L powder.

Distance	0.10 mm
Speed	1000.0 mm/s
Power	100.0
Beam offset	0.065
Hatching	X, Y, Alternating, Rotated are selected

First 3D metal printing results for utilizes SS316L powder was not properly the results that is needed as shown in Figure 45 and 46. Because the parameters shown in Table 12 was not the proper parameters and the design of the ring shown in Figure 42 was also not suitable. Because it is important that the CAD model describe completely the external geometry of the part in order to be suitable for the machine, therefore the sharp internal corners dimensions were not suitable for PBF machine.

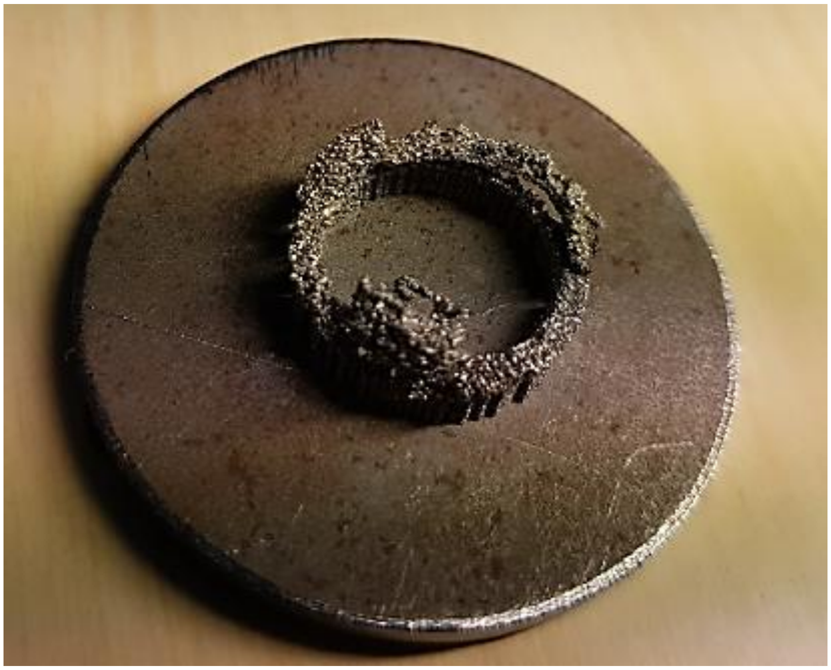

Figure 45. First 3D printed ring utilizes SS316L powder.

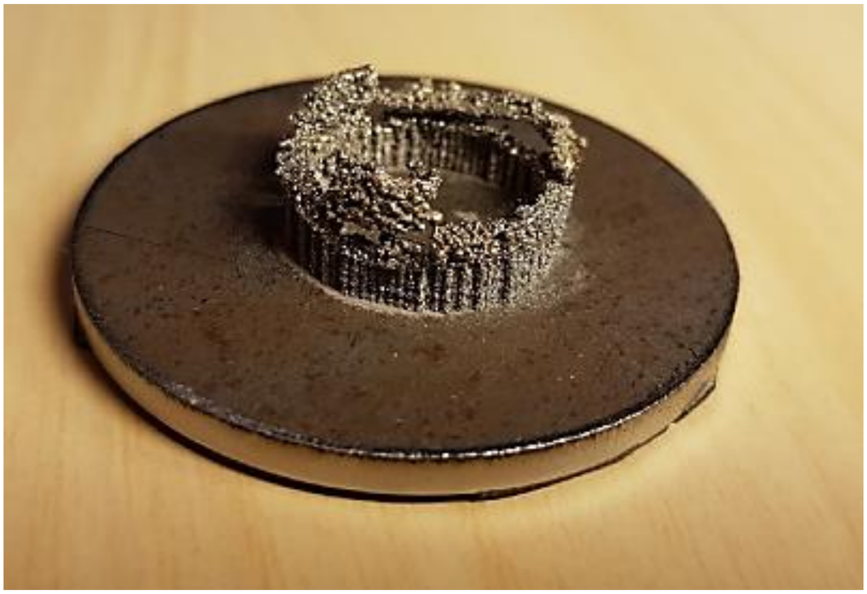

Figure 46. First 3D printed ring utilizes SS316L powder.

After submitting version 1 of the design, the following observations were made to further improve the design:

- Modifying the design such that it can be printed as one piece while keeping its functionality.
- Modifying the internal parts that need to be moving such that minimal support structure can be used in this section to avoid melting while keeping its functionality.
- Avoid overhangs during printing.
- Thorough consideration of built orientation.

In that case, another simple ring has been designed shown in Figure 47 by using SolidWorks 2018 3D CAD software which was more simple and lighter compared with designed ring and with no draws on its surface compared to the old model. The dimension of the modified ring is shown in Table 13.

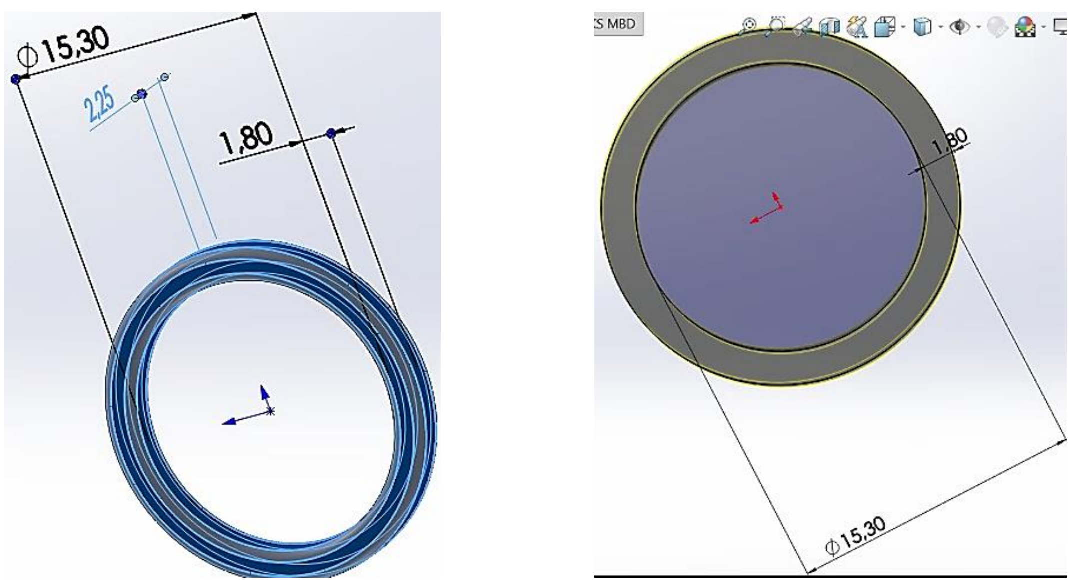

Figure 47. Modified Ring.

Table 13. Dimension for the second ring.

Inner circle	18.90 mm
Outer circle	15.30 mm
Fillet radius	0.5 mm

The support structures are required to hold it while printing, the support parameters are the same parameters that are used with the old model shown in Table 11, and they were mainly stock values of the machine setup. After using different parameters shown in Figure 48, removing support structure and polishing the ring, a successively 3D metal printed ring utilizes SS316L powder by PBF machine shown in Figure 49

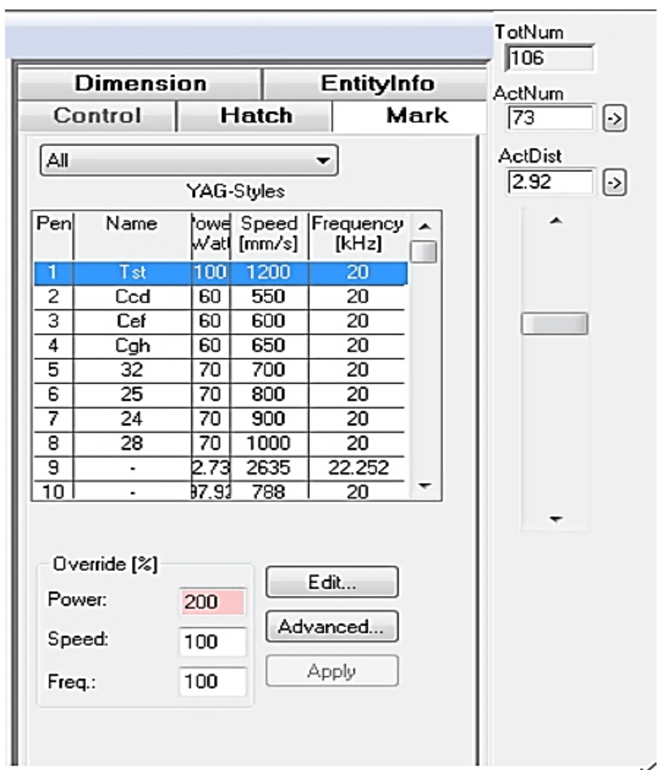

Figure 48. Ring parameters utilized by SS316L powder.

Figure 49. Successively 3D printed ring utilizes SS316L powder.

8.1.5 The manufacturing process of ring utilizes gold powder

By using the same modified ring in Figure 47, same PBF machine shown in Figure 44 and using a different parameter for manufacturing a gold ring, a successively 3D metal printed ring utilizes 24-carat gold powder shown in Figure 50 and gold ring parameters are shown in Table 14

Table 14. Parameters of the ring utilized by 24 carat gold powder.

Laser Power	50W
Scan speed	100 mm/sec
Hatch distance	80 µm
Layer thickness	10 µm
Bed Tempersure	100ºC

Figure 50. Manufactured gold ring after polishing.

8.2 Stainless-steel box

In this chapter, the design of stainless-steel box created in Solidworks, parameters used for 3D metal printing box and the specification of PBF machine that is used are going to be mentioned in this chapter

8.2.1 Design for stainless-steel box

As mentioned before that, the first step was to define geometry and dimensions of the stainless-steel box. The main important terms to have a successful 3D metal printed model is to have a physically and typically size, so it can be printed successfully by the PBF machine. The stainless-steel box in Figure 51 created in Solid works 2019 software and its dimension is shown in Figure 52.

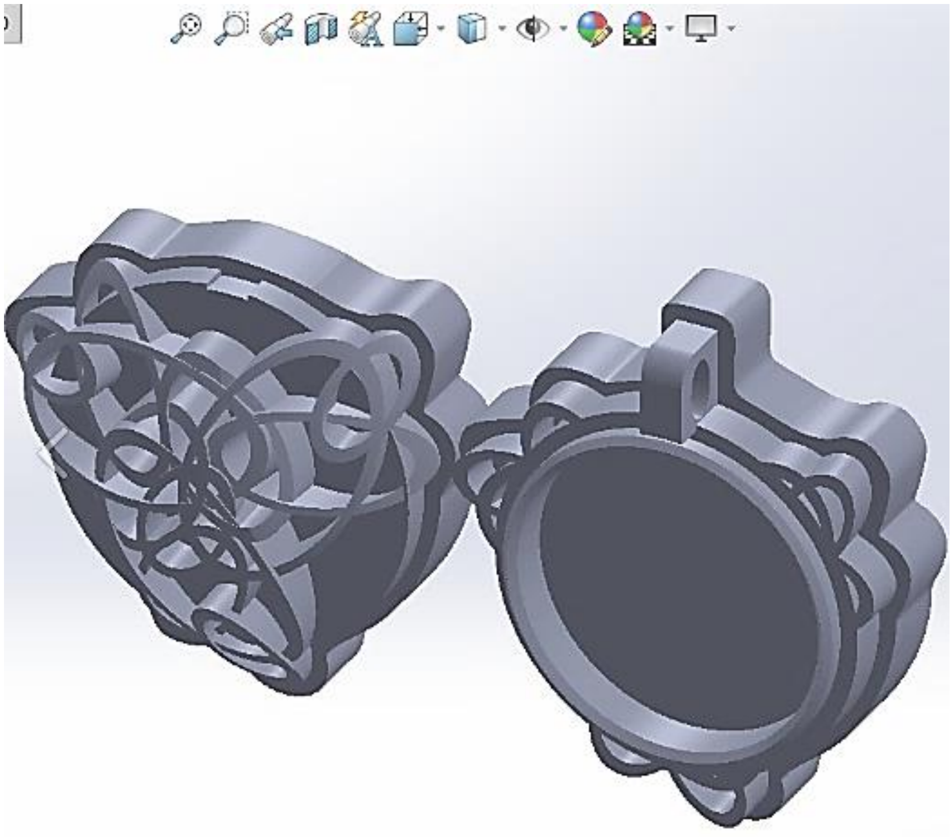

Figure 51. Stainless-steel box created in Solidworks 2019 software.

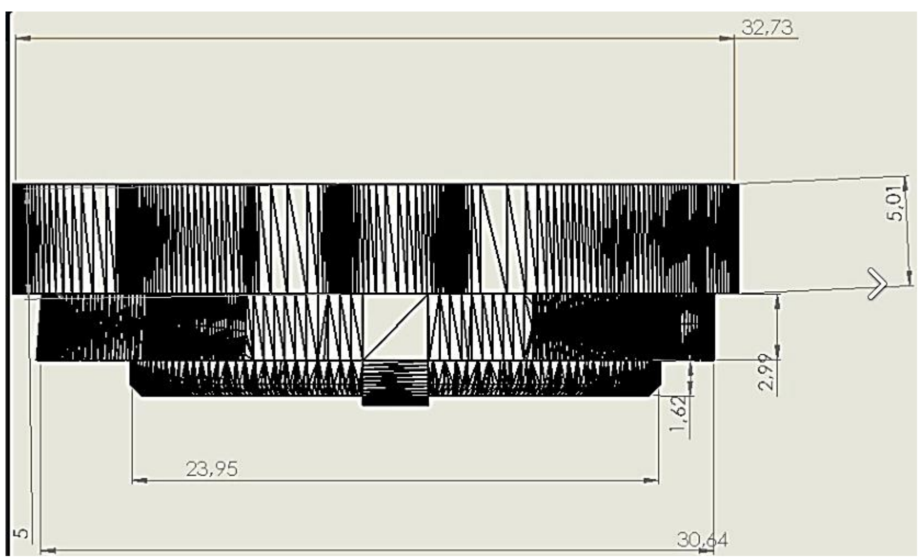

Figure 52. The dimension of the stainless-steel box.

8.2.2 The manufacturing process of Stainless-steel box

Stainless-steel SS316L is the powder that is used for 3D metal printing the box, the stainless-steel box has been printed by EOS 290 machine

8.2.3 EOS M290

EOS M 290 in Figure 53 works with many different metal powder materials, such as steel, aluminum, titanium and nickel alloy (EOS, 2019 pp.1-5). In this study, EOS Stainless-steel 316L is used, which corrosion resistant material ideal in many applications from the aerospace, turbine and automotive industries to consumer products such as decorations, watches, and jewelry. The EOS Stainless-steel 316L can be machined, polished and shot-peened, but solution-annealing if not required because of the good mechanical properties of the as-built state. As the DMLS is a layer-by-layer technique, some of the mechanical properties are anisotropic. As mentioned, parts made of EOS Stainless-steel 316L have great mechanical properties, for example, they typically have a hardness of 89 HRB and yield strength of 540 ± 55 MPa in the vertical direction and 640 ± 50 MPa in the horizontal direction. (EOS, 2014 pp.1-5). EOS M290 specification is mentioned in Table 15.

Figure 53. EOS M 290 metal additive manufacturing machine (EOS 2019).

Table 15. EOS Specification.

Build	20312.5
Laser power	400 W
Min. Beam spot size	100 µm
Mechanical properties	850-950 MPa (7 %)
Bulk Hardness	400 VHN
Used inert gas	nitrogen or argon
Scanning measure	Galvanometers
Surface finish	Very good
Resolution	Good
Used materials	Light metals, stainless and tool steel, superalloys

After modelling the box as shown in Figure 54, converting it into STL. Format and uploading it into EOS 290, then next step is to set the parameters needed to 3D metal print the stainless-steel box. The parameters of the box in Table 16.

Table 16. Parameters of the box utilized by SS316L powder.

Layer thickness Laser Power	200W
Speed scan	1000.0 mm/s
Layer thickness	20µm
Hatching distance for the bulk material	0.1 mm

After a successively printing, then removing support structure and polishing, the stainless steel box is been successively printed as shown in Figure 54.

Figure 54. Successively 3D printed stainless steel box.

9 RESULTS

One of the thesis goals is to reduce the amount of powder required during 3d metal printing parts, some materials are so expensive such as, gold powder, in addition to the build sizes for most of PBF machines are so huge. Build size or build volume determines the maximum space-capacity of the 3D printer for a PBF machine, it directly effects on the amount of powder needed and cost. Builds size values can be calculated by length X width X height, Arcam, EOS, Concept Laser and X Liner are huge machines with a huge build size so it will cost a lot to 3D print a jewelry production.

In the results section, a comparison between the PBF machine that is used in the experiment, and most of PBF machines that already exists in the market. In addition to parameters of rings, stainless-steel box and support structure are already mentioned in the case study section. The Comparison will be between power, machine price, the material used, built platform and the cost of powder used in each PBF machine, also material characteristics of the 4 metal printed rings are mentioned, such as the density, volume, surface area, mass for each ring.

Table 17. Material Characteristics of the 4 metal printed rings.

Properties	Gold ring	Stainless-steel ring	Titanium ring	Silver ring
Density	0.02	0.01 gram/mm3	0.00 gram/mm3	0.01 gram/mm3
Mass	3.91	1.65 grams	0.91 grams	2.27 gram
Volume	206.04	206.04	206.04	206.04 mm3
Surface area	389.03 mm2	389.03 mm2	389.03 mm2	389.03 mm2
Powder cost	2.3 gram	0.55 gram	1.2 gram	1.75 gram

Comparison between PBF machines used in experiment and PBF machines in nowadays market

Table 18. SLM Solutions 500 HL.

Power	Machine Price	Material Used	Build platform
1000+1000 +400+400	700000 €	316L, 17-4PH, H13, Al-Si-12, AlSi-10, AlSi7Mg, Ti6Al-4V, Ti-6Al-7Nb, Hastaloy X, cobalt-chrome, Inconel 718/625	500 x 280 x 320 cm3
Titanium density	Titanium mass	Titanium price per gram	Cost euro
4.429 g/cm3	198419200 gram	1.2	213814753.12
Stainless-steel density	Stainless-steel mass	Stainless-steel today’s price per kilo	Cost euro
7.90 g/cm3	353920000	0.55 per kilo	174799635.42

Table 19. LUT PBF Machine.

Power	Machine Price	Material Used	Build a platform
400	N/A	stainless steel, titanium,gold, Silver	25.132 cm3
Titanium density	Titanium Mass	Titanium Today’s price per gram	Cost euro
4.429 g/cm3	111.0309628	1.2	133.571
Stainless-steel density	Stainless-steel mass	Stainless-steel today’s price per gram	Cost in euro
7.90 g/cm3	198.54	0.55	109.197
Gold density	Gold mass	Gold today’s price per gram	Cost in euro
19.32 g/cm310.49	485.55 263.634	2.31.75	1116.765
Silver density	Silver mass	Silver today’s price per gram	Cost in euro
10.49 g/cm3	263.634	1.75	461.3595

10 CONCLUSION

This master thesis title is “Development of a metal 3D the printing process for jewelers production utilizing Titanium” initially illustrates the main principles in AM and PBF processes. It has successfully taught about the process of designing and manufacturing a 3D printed model by taking the consideration and opportunities of additive manufacturing and settled on creating an object with a simple design. Feedback from LUT’s 3D printing representatives gave us important hints to make the design simple as possible and then the model is been modified to follow that advice. I was aware from the start that producing a complex model will be hard to be printed by PBF machine.

Throughout the design process, the newer versions of the model were consistently improved to suit printing in LUT PBF machine. The first model turned out in a bad condition because sharp internal corners dimensions weren’t a suitable PBF machine and the significance of reducing the number of support structures was brought more to the design. While further reducing the amount of material to be used in the model was making the model more suited, the improvements did not touch the glaring difficulty. Printing a well-functioning model in metal will be difficult due to the support structures that must be printed inside the model between moving components. The difficulty of metallic printing of stainless-steel box was made clear after the design process had reached its end.

11 FURTHER RESEARCH

The development of metal 3D printing process for jewelry production utilizing gold, stainless steel, silver, and titanium can be improved more until the amount of used powder can be reduced to the minimum that leads to reducing the cost.

A new platform could be built or developed by increasing bed temperature above 150 ºC hence overall energy required to melt the powder will decrease which leads to an improvement for the powder characteristic such as its density.

Some other developments can be done by fixing a high-speed camera in PBF machine, so our knowledge may increase more about the powder characteristic in different temperature and learning more about melt dynamic and balling phenomena for all powders.

Build volume rate and design can be improved especially for low production and complex that will decrease a lot the required powder hence reducing cost, as well as new software can be programmed to analysis such as EDX analysis which is used to check the presence of oxide films which causes layer delamination.

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