MICROSTRUCTURAL INVESTIGATION OF SS316L FABRICATED USING POWDER BED FUSION PROCESS

A PROJECT REPORT

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BONAFIDE CERTIFICATE

Certified that this project report "**MICROSTRUCTURAL INVESTIGATION OF SS316L FABRICATED USING POWDER BED FUSION PROCESS**" is the bonafide work of "**SARAN MAGESH, SHANMUGAVEL M, SUBASH K, VISHNU C,**" who carried out the project work under my supervision.

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INTERNAL EXAMINER **EXTERNAL EXAMINER**

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ABSTRACT

Porosity is one of the major defects threatening mechanical properties in parts manufactured with Selected Laser Melting (SLM) method. Optimizing densification of materials is thus a key target of SLM as well as other similar methods to achieve the desired properties as per applications. Globally, SLM is changing the way organizations design and manufacture products. It is an emerging manufacturing technique. This technique is classified as additive layered manufacturing, as the component is built by adding material in layers. Components/parts manufactured by Selective Laser Melting (SLM) find a lot of applications in many industries like aerospace, biomedical and automobile. Proposed research work investigates the effect of various process parameters such as direction of build manufactured by the SLM process of Stainless Steel 316L [SS316L]. The literature indicates that process parameters having maximum impact on mechanical properties includes Laser Power (P), Exposure Time (T), Hatch Spacing (HS). The effect of these process parameters on Ultimate Tensile Strength (UTS) and its microstructure was investigated.

Keywords: Additive manufacturing, Selective laser melting (SLM), Mechanical properties, Laser Power, Hatch Spacing, Exposure Time

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LIST OF SYMBOLS

SYMBOLS	DESCRIPTION
σ	Tensile strength
Σs	Yield strength
E	Young’s modulus
ρ	Density
K	Thermal conductivity
c	Specific heat
C	Carbon
Mn	Manganese
Si	Silicon
P	Phosphorus
S	Sulphur
Cr	Chromium
Mo	Molybdenum
Ni	Nickel
N	Nitrogen
L	Length
W	Width
T	Thickness

LIST OF ABBREVIATIONS

ABBREVIATIONS	DESCRIPTION
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
3D	Three dimensions
2D	Two-dimensional
GE	General Electric
CAD	Computer Aided Drafting
STL	Standard Tessellation Language
G-codes	Geometric code
M-codes	Miscellaneous function code
HIP	Hot Isostatic Pressing
SLA	Stereolithography
VPP	Vat Photopolymerization
UV	Ultraviolet
DOD	Drop on Demand
MJ	Material jetting
BJ	Binder jetting
FDM	Fuse deposition modelling
MEX	Material extrusion
DMLS	Direct metal laser sintering
EBM	Electron beam melting
SLS	Selective laser sintering
SHS	Selective heat sintering
SLM	Selective laser melting
PBF	Powder bed fusion
UAM	Ultrasonic Additive Manufacturing
LOM	Laminated Object Manufacturing

CNC	Computer numerical control
DED	Directed Energy Deposition
LPBF	Laser-based powder bed fusion
SEM	Scanning electron microscopy
EBSD	Electro backscatter diffraction
LOF	Lack-of-fusion
PDAS	Primary dendrite arm spacing
PLS	Polymer Laser Sintering
MLS	Metal Laser Sintering
MJF	Multi Jet Fusion
SS316L	Stainless steel 316L

CHAPTER 1

INTRODUCTION

1.1 ADDITIVE MANUFACTURING

Additive manufacturing is the process by which digital 3D design data is used to build up a component in layers by depositing material. It is opposite to subtractive manufacturing. Additive manufacturing is also known as “3D printing”. According to ASTM F42 additive manufacturing is defined as “the process of joining material to make object from 3D model data usually layer by layer as opposed to subtractive manufacturing methodologies”. Additive manufacturing allows for mass customization, reduced material waste, lower cost, increase efficiency compared to injection moulding, extrusion. Companies like GE and Boeing are swiftly and immediately replacing older technologies, processes and assembly lines with additive manufacturing due to the immense benefits it brings. Some of the reasons for this popularity include the fact that additive manufacturing offers remarkable efficiency, affordability, and quality for many different product designs.

1.2 PROCESS CHAIN

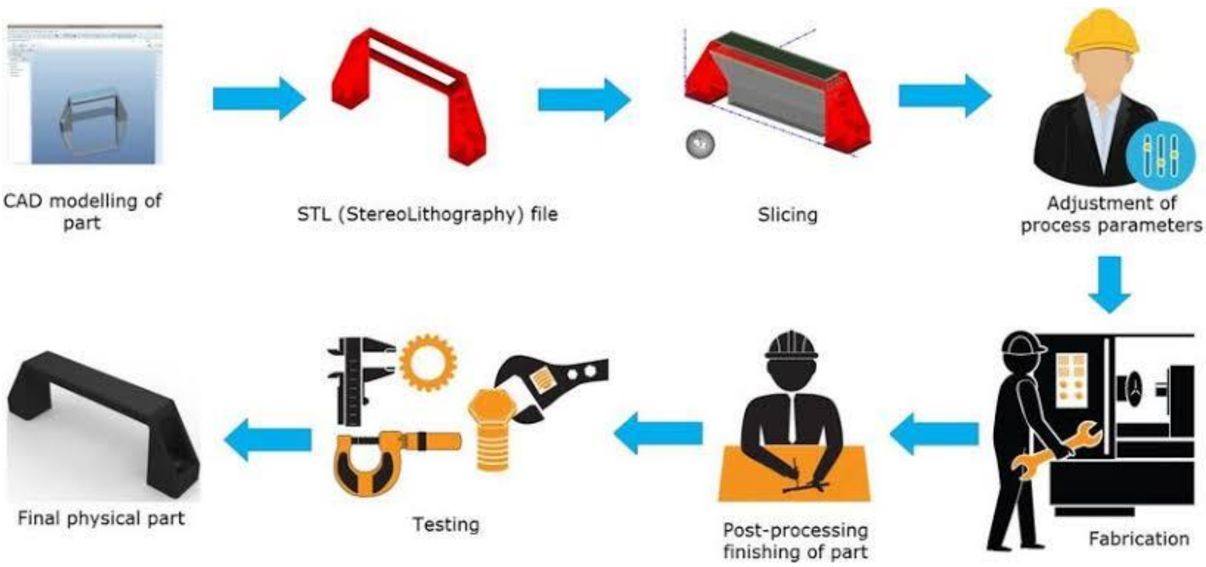


Fig.1.1 Process chain of AM

STEP 1: CAD DESIGN

CAD models that fully describe the external geometry are required for all AM parts. Any professional CAD solid modelling software can be used to create this, but the final product must be a 3D solid or surface model. To create such an image, reverse engineering equipment (for example, laser and optical scanning) can also be used.

STEP 2: CONVERSION TO STL

Upon completion of the digital model, the STL (Standard Tessellation Language) file format must be used to create the stereolithography. Nearly every CAD system supports this format, which is how AM machines communicate. The STL file serves as the basis for calculating the slices of the model.

STEP 3: TRANSFER TO MACHINE

In the third step, the STL file is transmitted to the AM machine. As a result of this step, it is possible to adjust the build so that it is positioned and sized correctly. A computer controls the AM machine. The AM machine is controlled by the computer, that computer only generates the required instruction in the form of G-codes and M-codes based on the given process parameters. It generates instructions automatically, if any correction is needed for the betterment of the part to be built it can be corrected.

STEP 4: SETUP

Before the building starts, the equipment has to be set up. The settings can constitute power, speed, layer thickness, and other several parameters related to material and process constraints, etc.

STEP 5: BUILD

The fifth step is the actual building of the CAD model, melting layer by layer. This process can be semi or fully automated but some online monitoring is often conducted, so that the machine does not run out of material or that some software error occurs.

STEP 6: PART REMOVAL

Once the part is manufactured it has to be removed from the process, which is normally done manually. This may require interaction with the machine, which may have safety interlocks to ensure, for example, that the operating temperatures are sufficiently low or that there are no actively moving parts.

STEP 7: POST PROCESSING

After the build, the part might need some post-processing before it is completely finished. Of course, depending on the material and AM process used, some parts might need machining, cleaning, polishing, removal of support structures, hot isostatic pressing (HIP), and heat treatments.

STEP 8: APPLICATION

At this stage, the part can be ready for use. Nevertheless, it could also need some additional treatments, like painting, or assembling with other components before it is fully usable. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled with other mechanical or electronic components to form a final model or product.

1.3 TYPES OF ADDITIVE MANUFACTURING

According to "ASTM F42 – Additive Manufacturing", formulated a set of standards that classify the range of Additive Manufacturing processes into 7 categories.

1. Vat photopolymerization
2. Material jetting
3. Binder jetting
4. Material extrusion
5. Powder bed fusion
6. Sheet lamination

7. Directed energy deposition

1.4 VAT PHOTOPOLYMERIZATION(VPP)

Stereolithography (SLA), the first patented and marketed AM process is a vat photopolymerization technology. Dr Hideo Kodama, a Japanese researcher, created the contemporary layered stereolithography technique in the early 1970s, employing ultraviolet radiation to cure photosensitive polymers. Chuck W. Hull invented the term stereolithography after patenting the technique in 1986 and establishing a company called 3D Systems to market it. Hull characterised the approach as printing small layers of an ultraviolet-curable substance in a series to create 3D things. The layer thickness of vat photopolymerization is 0.025-0.5mm. Material used in vat photopolymerization process is plastics and polymers.

According to ASTM "Vat photopolymerization is an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization".

1.4.1 WORKING

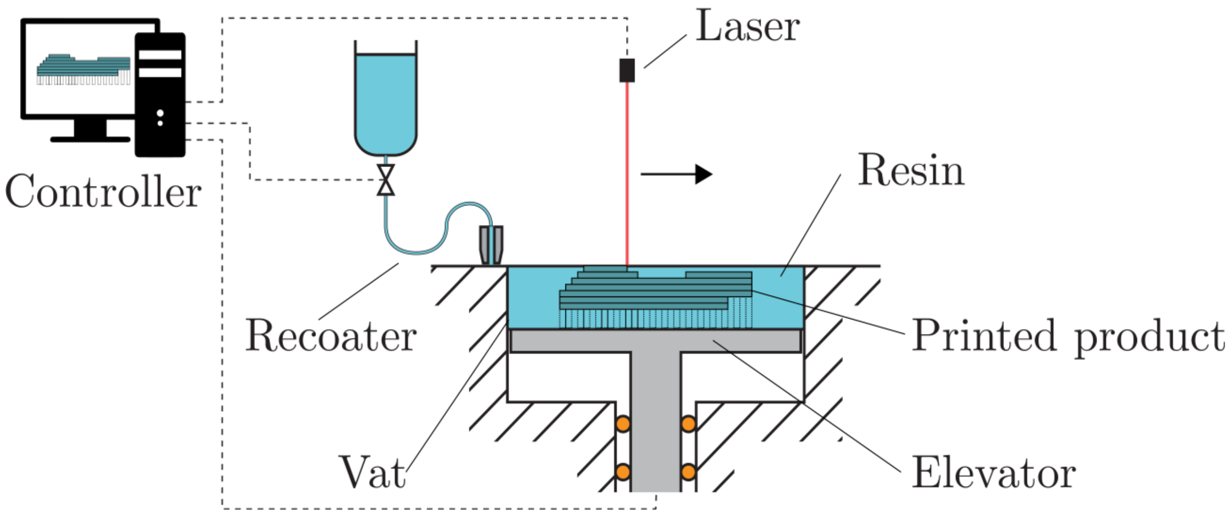


Fig. 1.2 Schematic diagram of VPP process

The build platform is lowered from the top of the resin vat downwards by the layer thickness. A UV light shown in figure 1.2 which cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous. Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on. After completion, the vat is drained of resin and the object removed. After the part removal, support structure and post processing are done.

1.4.2 APPLICATION

- ❖ Smart composites
- ❖ Soft robotics
- ❖ Bio medical
- ❖ Prosthetics
- ❖ Jewellery
- ❖ Prototypes

1.4.3 ADVANTAGES

- ❖ High level of accuracy.
- ❖ Good surface finish.
- ❖ Relatively quick process.
- ❖ Typically, large build areas.

1.4.4 DISADVANTAGES

- ❖ Costly in comparison.
- ❖ Lack 0f photo resin material choices.
- ❖ Inadequate strength and durability.
- ❖ Resins can warp and bend over time.
- ❖ Required support structure and post processing.

1.5 MATERIAL JETTING(MJ)

Material jetting creates objects in a similar method to a two-dimensional ink jet printer. Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach. Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light. As material must be deposited in drops, the number of materials available to use is limited. Polymers and waxes are suitable and commonly used materials, due to their viscous nature and ability to form drops. Layer thickness of material jetting is 16-32 microns.

According to ASTM "material jetting is a process in which droplets of build material are selectively deposited".

1.5.1 WORKING

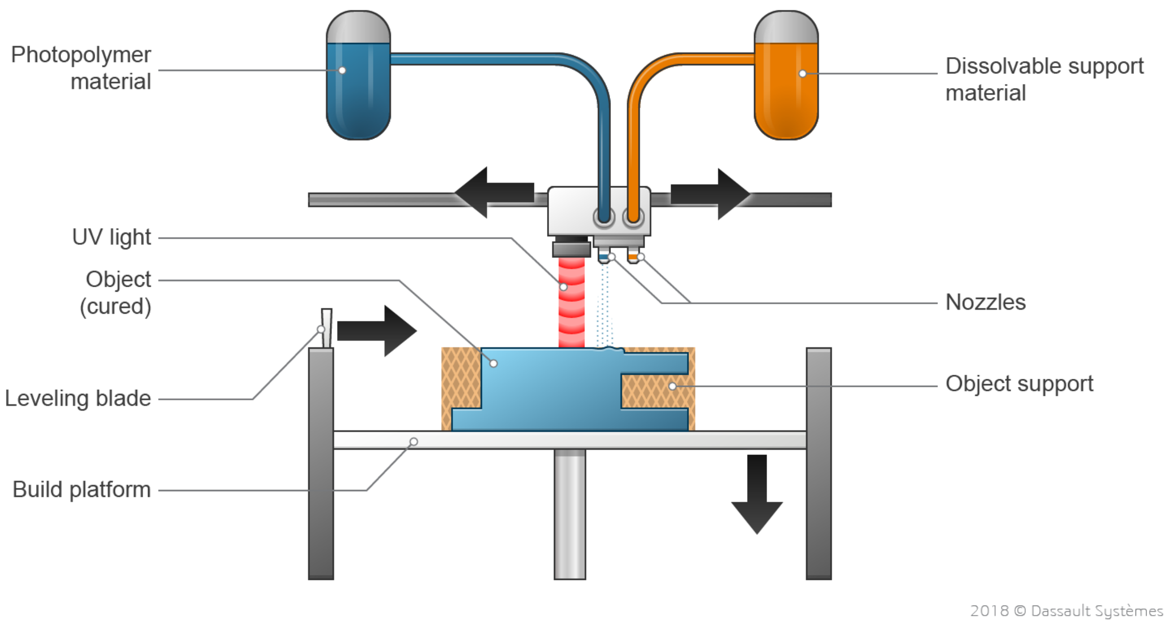


Fig. 1.3 Schematic diagram of material jetting process

The print head is positioned above build platform as shown in figure 1.3. Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method. Droplets of material solidify and make up the first layer. Further layers are built up as before on top of the previous. Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.

1.5.2 APPLICATIONS

- Light honeycomb structures
- Scaffolds for tissue engineering
- Custom anatomical models
- Biosensors

1.5.3 ADVANTAGES

- Easy operation and safe to handle owing to the absence of loose powder.
- Good surface finish.
- No need for post-curing.
- Components fabricated via MJ have homogeneous mechanical and thermal properties.

1.5.4 DISADVANTAGES

- Build volume is small.
- Material cost is higher.
- Support structure is needed.
- Build rate is less.

1.6 BINDER JETTING(BJ)

The binder jetting process uses two materials a powder-based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform. Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process. As with other powder-based manufacturing methods, the object being printed is self-supported within the powder bed and is removed from the unbound powder once completed. The technology is often referred to as 3DP technology and is copyrighted under this name. layer thickness of binder jetting is .089-0.203mm. material used in binder jetting is polymers and plastics.

According to ASTM “An Additive Manufacturing process in which a Liquid Bonding agent is selectively deposited to join powder materials”.

1.6.1 WORKING

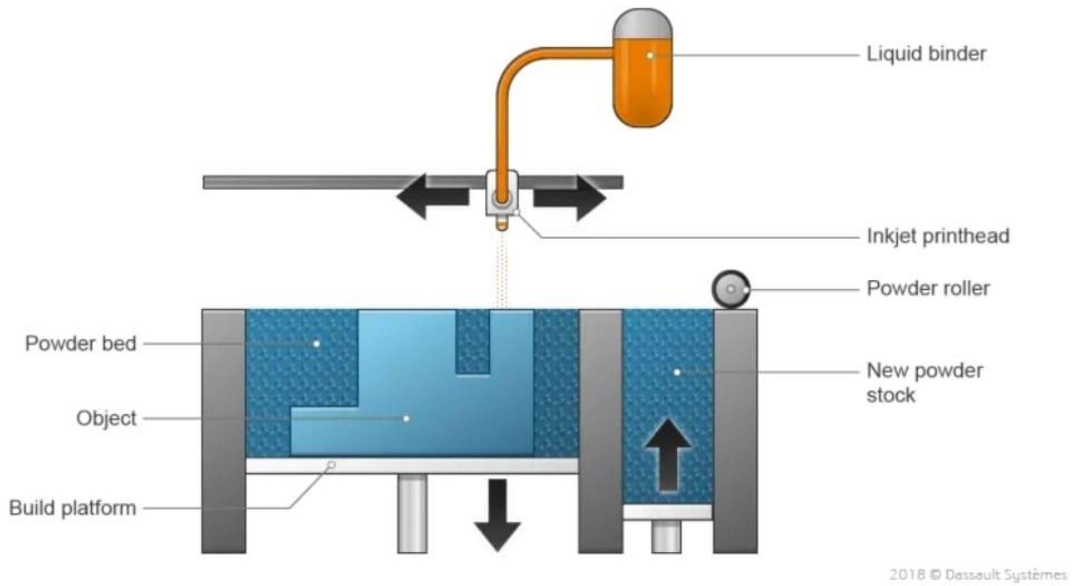


Fig. 1.4 Schematic representation of binder jetting process

Powder material is spread over the build platform using a roller. The print head shown in figure1.4 which deposits the binder adhesive on top of the powder where required. The build platform is lowered by the model’s layer thickness. Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid. Unbound powder remains in position surrounding the object. The process is repeated until the entire object has been made.

1.6.2 APPLICATIONS

- Aerospace
- Automobile
- Foundry
- Biomedicine
- Jewellery
- Sand mould for casting

1.6.3 ADVANTAGES

- Parts can be made with a range of different colours.
- Uses a range of materials: metal, polymers and ceramics.
- The process is generally faster than others.
- The two-material method allows for a large number of different binder-powder combinations and various mechanical properties.

1.6.4 DISADVANTAGES

- Not always suitable for structural parts, due to the use of binder material.
- Additional post processing can add significant time to the overall process.

1.7 MATERIAL EXTRUSION(MEX)

Fuse deposition modelling (FDM) is a common material extrusion process and is trademarked by the company Stratasys. Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited. It is a commonly used technique used on many inexpensive, domestic and hobby 3D printers. Layer thickness of material extrusion is 0.178mm-0.356mm. Materials used in material extrusion is polymer and plastics.

According to ASTM "It is an Additive Manufacturing Process in which material is selectively dispensed through a nozzle or orifice".

1.7.1 WORKING

First layer is built as nozzle deposits material where required onto the cross-sectional area of first object slice. The following layers are added on top of previous layers. Layers are fused together upon deposition as the material is in a melted state.

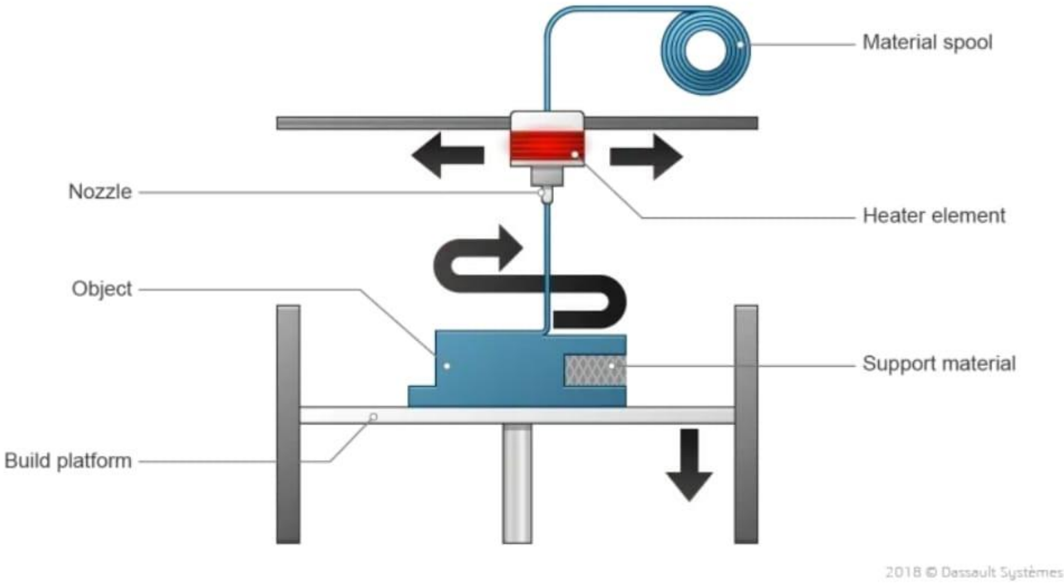


Fig.1.5 Schematic diagram of material extrusion process

1.7.2 APPLICATIONS

- ❖ Investment casting
- ❖ Injection moulding
- ❖ Prototypes

1.7.3 ADVANTAGES

- ❖ Widespread and inexpensive process.
- ❖ ABS plastic can be used, which has good structural properties and is easily accessible.

1.7.4 DISADVANTAGES

- ❖ The nozzle radius limits and reduces the final quality.
- ❖ Accuracy and speed are low.

❖ Constant pressure of material is required.

1.8 POWDER BED FUSION(PBF)

The Powder Bed Fusion process includes the following commonly used printing technique Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). Powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together. Electron beam melting (EBM), methods require a vacuum but can be used with metals and alloys in the creation of functional parts. All PBF processes involve the spreading of the powder material over previous layers. There are different mechanisms to enable this, including a roller or a blade. Layer thickness of powder bed fusion is .1mm. Material used in powder bed fusion is polymers and metal.

1.8.1 WORKING

A layer, typically 0.1mm thick of material is spread over the build platform which is shown on figure 1.6. A lase fuses the first layer or first cross section of the model. A new layer of powder is spread across the previous layer using a roller. Further layers or cross sections are fused and added.

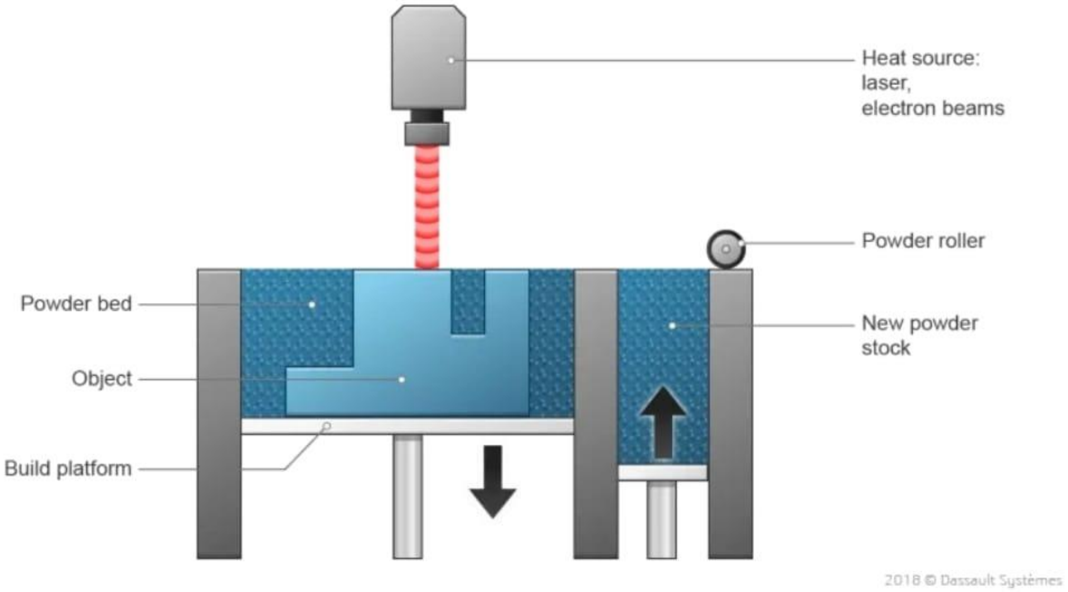


Fig. 1.6 Schematic representation of powder bed fusion process

The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing.

1.8.2 APPLICATION

- Tyre moulds
- Brake calliper
- Knee replacements
- Hip joint

1.8.3 ADVANTAGES

- Relatively inexpensive.
- Suitable for visual models and prototypes
- Ability to integrate technology into small scale, office sized machine.
- Powder acts as an integrated support structure.
- Large range of material options

1.8.4 DISADVANTAGES

- Relatively slow speed
- Lack of structural properties in materials
- Size limitations
- High power usage
- Finish is dependent on powder grain size

1.9 SHEET LAMINATION

Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The Ultrasonic Additive Manufacturing process uses sheets or ribbons of metal, which are bound together using ultrasonic welding. The process does require additional CNC machining and removal of the unbound metal, often during the welding process. Laminated object manufacturing (LOM) uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. The LOM process uses a cross hatching method during the printing process to allow for easy removal post build.

Laminated objects are often used for aesthetic and visual models and are not suitable for structural use. Layer thickness of sheet lamination is .150mm thick and 25mm wide. Materials used in sheet lamination is paper, plastics and sheet metals.

According to ASTM "An Additive Manufacturing process in which sheets of material are bonded to form an object".

1.9.1 WORKING

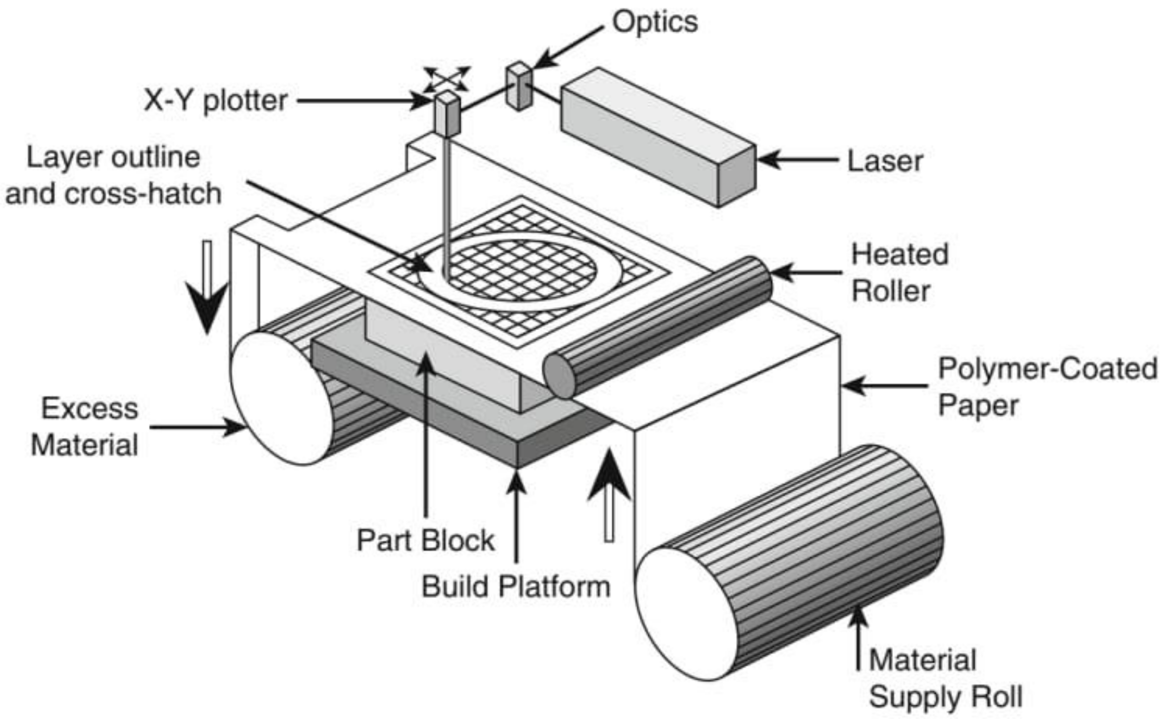


Fig.1.7 Schematic diagram of sheet lamination process

The material is positioned in place on the cutting bed. The material is bonded in place, over the previous layer, using the adhesive. The required shape is then cut from the layer, by laser or knife. The next layer is added. Process is repeated, the material can be cut before being positioned and bonded.

1.9.2 APPLICATIONS

- Education
- Medical

- ❖ Hand model printing
- ❖ Architecture

1.9.3 ADVANTAGES

- ❖ Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used.
- ❖ Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross-sectional area.

1.9.4 DISADVANTAGES

- ❖ Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect.
- ❖ Limited material use.
- ❖ Fusion processes require more research to further advance the process into a more mainstream positioning.

1.10 DIRECTED ENERGY DEPOSITION(DED)

Directed Energy Deposition (DED) covers a range of terminology 'Laser engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding' It is a more complex printing process commonly used to repair or add additional material to existing components. A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. Layer thickness of DED is 0.25-0.5mm. material used are metals.

According to ASTM "an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited".

1.10.1 WORKING

A4 or 5 axis arms with nozzle moves around a fixed object. Material is deposited from the nozzle onto existing surfaces of the object. Material is either provided in wire or powder form. Material is melted using a laser, electron beam or plasma arc upon deposition. Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.

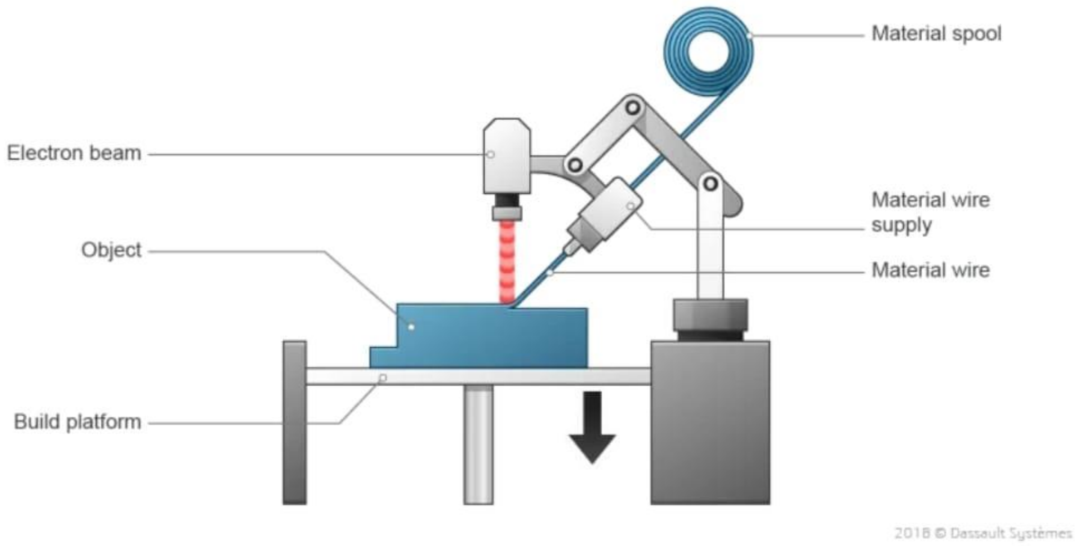


Fig.1.8 Schematic diagram of directed energy deposition process

1.10.2 APPLICATION

- ❖ Low-cost build
- ❖ Repair
- ❖ Hard facing
- ❖ Reconfiguration of forging dies

1.10.3 ADVANTAGES

- ❖ Ability to control the grain structure to a high degree, which lends the process to repair work of high quality, functional parts.
- ❖ A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure.

1.10.4 DISADVANTAGES

- ❖ Need for a support structure.
- ❖ Accuracy is relatively less.

- ❖ Surface finish is of relatively less quality as compared to contemporary AM processes.

1.11 APPLICATION OF ADDITIVE MANUFACTURING

- ❖ Aerospace
- ❖ Dental
- ❖ Jigs/fixtures
- ❖ Prototypes
- ❖ Automotive
- ❖ Jewellery
- ❖ Surgical devices
- ❖ Sports equipment
- ❖ Prosthetics and orthotics
- ❖ Tissue engineering

1.12 ADVANTAGES OF ADDITIVE MANUFACTURING

- ❖ Rapid prototyping
- ❖ Improved accuracy
- ❖ Material waste reduction
- ❖ Energy efficiency
- ❖ Reduced costs for small production runs
- ❖ Environmentally friendly
- ❖ Unique designs
- ❖ Supply chain flexibility

1.13 DISADVANTAGES OF ADDITIVE MANUFACTURING

- ❖ High cost of equipment and materials
- ❖ The need for skilled operators
- ❖ Limited choices of materials
- ❖ The slow speed of the process
- ❖ Required post processing

CHAPTER 2

LITERATURE REVIEW

H. Sohrabpoor, V. Salarvand, R. Lupoi, Q. Chu, W.Li, B.aldwell, W.Stanley, S.O. Halloran, R. Raghavendra, C.H. Choi, D. Brabazon, "Microstructural and mechanical evaluation of post-processed SS316L manufactured by laser-based powder bed fusion", describe that post-processing is one of the main ways to improve mechanical and microstructural characteristics of stainless steel 316L fabricated by the laser-based powder bed fusion (LPBF) process. In this study, optimized LPBF parameters were used to manufacture SS316L bars. For the post-processing, two main heat treatment strategies have been used, quenching and tempering, with various heating and dwelling conditions. While micro-CT scanning was used to identify the porosity inside the as-built specimen, the microstructure of both as-built and heat-treated specimens were additionally investigated by optical microscopy and scanning electron microscopy (SEM). The tensile test's wrought specimens were obtained at various strain rate of 0.1, 0.01, and 0.001 s^{-1}. A two-dimensional (2D) digital image correlation (DIC) technique and fractography analysis were used to understand the tensile behaviour further. The results show that the as-built specimen density level was in the range of 99.993–99.997%, with only extremely small pockets of pores present. The microstructure results show that temperature distribution is the most important factor in the formation of columnar grains (CG). The columnar-shaped grains formed from the edge of the melt pool (MP) in the direction of the laser motion path. The resulting dimensions and form of the cellular structures are presented. The crystal orientation of the specimens was also studied with electro backscatter diffraction (EBSD). The result shows that the fraction of directional grains <001> is relatively small due to a scan rotation and the scanning strategies adopted during the LPBF process. With heating at 1050 °C with a dwell time of 40 min, followed by quenching in cold water, smaller grain sizes were obtained, meaning longer grain boundaries and major impediments to dislocation motion, leading to better mechanical properties and fracture characteristics over wrought specimens. The results of EBSD and SEM were also correlated with the 2D DIC test results.

Xiaoyu Liang, Anis Hor, Camille Robert, Mehdi Salem, Feng Lin, Franck Morel, "High cycle fatigue behaviour of 316L steel fabricated by laser powder bed fusion: Effects of surface defect and loading mode" describe that the mechanical performances of additive manufactured (AM) material are highly dependent on the fabrication process which inevitably results in surface imperfection as well as porosity. In the present study, the high cycle fatigue (HCF) behaviour of an AM stainless steel 316L is experimentally investigated to characterize and evaluate the effect of the in-surface defects. Profilometry and Computed Tomography are used. A series of fatigue experiments is carried out under different loading modes including tension, bending, and torsion fatigue tests. For each loading condition, different surface preparations are used to investigate the effect of surface state. Fatigue tests reveal that surface treatment can improve fatigue performances the improvements observed being higher under tension/bending loading than under torsion loading. The fractographic analysis is performed for all the available tested specimens to reveal the mechanism of fatigue crack initiation. Lack-of-fusion (LOF) defects play the predominant role in the fatigue performance of SS 316L fabricated by laser powder bed fusion (LPBF). The presence of multiple LOF defects at the surface or subsurface is detrimental to the endurance under cyclic loading. By using Murakami approach modelling the relationship between fatigue strength and defect size, it is found that the multiple clustering defects act synergistically as one large virtual crack to initiate the fatigue.

Xianglong wang, J.A. Muniz-Lerma, Oscar Sanchez Mata, "Microstructure and mechanical properties of stainless steel 316L vertical struts manufactured by laser powder bed fusion process", describe that Stainless steel 316 L (SS316L) vertical struts with various diameters ranging from 0.25 mm to 5 mm were manufactured by laser powder bed fusion (LPBF) process. A systematic investigation was conducted on the microstructure and mechanical properties of the produced struts. The struts possessed hierarchical microstructures consisting of cellular sub-grain structures inside columnar grains. The primary dendrite arm spacing (PDAS) of the cellular sub-grains decreased monotonically with increasing strut diameter until reaching a plateau after 1 mm. In contrast, the columnar grain width did not show a clear relationship with respect to the variation in the strut diameter. A <110> to <100> texture transition along the building direction (BD) of the struts was observed as the strut diameter decreased from 5 mm to 0.25 mm, which was attributed to the change of the heat extraction direction. Microstructure-property relations were established via Hall-Petch type correlations between the PDAS and the microhardness as well as the PDAS and the strengths of the struts, suggesting the importance of the role played by the cellular sub-grain structures in the strengthening of LPBF manufactured SS316L. Electron backscatter diffraction (EBSD) analysis confirmed that the strong <110> texture within the thicker struts promoted the twinning-induced plasticity, and thus resulted in a better strength-ductility combination compared with that of the thinner struts with <100> texture or weak <110> texture.

Andrea Avanzini, "Fatigue Behaviour of Additively Manufactured Stainless Steel 316L", describe that SS316L is the material of choice for several critical applications in which a combination of mechanical strength and resistance to corrosion is required, as in the biomedical field. Additive Manufacturing (AM) technologies can pave the way to new design solutions, but microstructure, defect types, and surface characteristics are substantially different in comparison to traditional processing routes, making the assessment of the long-term durability of AM materials and components a crucial aspect. In this paper a thorough review is presented of the relatively large body of recent literature devoted to investigations on fatigue of AM 316L, focusing on the comparison between different AM technologies and conventional processes and on the influence of processing and post-processing aspects in terms of fatigue strength and lifetime. Overall fatigue data are quite scattered, but the dependency of fatigue performances on surface finish, building orientation, and type of heat treatment can be clearly appreciated, as well as the influence of different printing processes. A critical discussion on the different testing approaches presented in the literature is also provided, highlighting the need for shared experimental test protocols and data presentation in order to better understand the complex correlations between fatigue behaviour and processing parameters.

Alexander Leicht, "Laser powder bed fusion of 316L stainless steel", describes that One of the most common additive manufacturing techniques for fabricating metallic components is laser powder bed fusion, which has demonstrated great potential in fabricating parts with properties exceeding the properties achieved via conventional methods. To fully utilize the process's potential, a more profound understanding of the microstructure and properties of the laser powder bed fusion processed material is required. This thesis aims to provide new insights into how the microstructure, mechanical properties and productivity are affected by part design and process parameters. The thesis is framed around a detailed investigation of the parts produced in stainless steel 316L. The provided results reveal that producing parts with standard process parameters leads to near full density with excellent tensile properties and a microstructure consisting of large elongated grains with predominant orientation characterized by a fine submicron cellular structure. It was demonstrated that part thickness does not influence component density, but the grain morphology and texture are affected close to the part edges. Reducing the part thickness to less than 0.5 mm reduced the predominant texture and reducing the part thickness to less than 1 mm reduced the yield strength. Altering the process parameters affected the crystallographic orientation, grain size and cell size and thus the tensile properties. Minor effects of processing gas composition (Ar, N_2 or He) on the chemical composition, microstructure, tensile strength and hardness was detected. In addition, it was revealed that a 20% faster build time could be achieved without compromising the static properties by adjusting the scan speed and hatch distance. Increasing the layer thickness to 80 µm allowed for shortening the build time by a factor of four but with a 14% reduction in yield strength and 17% reduction in ductility.

Punit Kumar, R. Jayaraj, J. Suryawanshi, U.R. Satwik, J. McKinnell, U. Ramamurty, "Fatigue strength of additively manufactured 316L austenitic stainless steel", describe that the microstructures and mechanical properties of the 316L austenitic stainless steel fabricated using binder jet printing (BJP) and selective laser melting (SLM) were investigated and compared with those of the conventionally manufactured (CM) alloy, with particular emphasis on the unnotched fatigue resistance. Results show that the work hardening behaviour, ductility, and fatigue strength (σ_f) of the BJP specimens, which contain significant amounts of pores, are surprisingly comparable to those of the CM alloy. In contrast, the SLM specimens are considerably stronger, especially in terms of the yield strength, less ductile, and far inferior in terms of σ_f although the porosity in them is relatively smaller as compared to the BJP specimens. These results are rationalized by recourse to the distinct microstructures in the two additively manufactured alloys, which stem from the different processing conditions experienced by them. The planar slip regime that prevails in the early stages of plastic deformation of the BJP alloys and a combination of other microstructural factors lead to the arrest of small cracks that nucleate at the corners of the pores, both under quasi-static and cyclic loads; as a result, neither ductility nor fatigue strength are adversely affected by the porosity in the BJP alloys. In the SLM alloy, the cellular structure, which enhances the yield strength considerably, is too fine whereas the columnar grains are minimally misoriented and coarse enough to induce any crack deflection or arrest. Implications of these results in terms of possible directions for designing AM alloys with high mechanical performance are discussed.

Jian Feng sun, Lu Shen, Weiqiang Wang, Zhu Liu, Huaming Chen, Jieli Duan, "Study of Microstructure and Properties of 316L with Selective Laser Melting Based on Multivariate Interaction Influence", describe that the selective laser melting technique is widely used in aerospace and biomedical industries, and the performance of formed 316L parts is significantly subject to the forming angle. As the selective laser melting 316L parts are constrained by multiple performance indexes, the study involves multivariate interaction influenced on the forming parameters such as the angle with the *xz* plane, the angle with the *xy* plane, laser power, scan speed, powder thickness, and hatching space on the indexes like tensile strength, density, and surface roughness with linear regression equations based on multi objective optimization to obtain the best process parameters. The study results of microstructure performance of the formed 316L parts show that the angle with the *xz* plane has significant effect on the experiment indexes, while the layer thickness has the greatest effect on the indexes. After stretching, the molten pools are obviously elongated and the microstructure of the formed 316L parts is composed of equiaxed crystals and columnar crystals with a grain width of 0.28–0.4 nm. The secondary growth of the dendrites is not obvious, and the crystallinity of the selective laser melting 316L parts is not as good as the standard parts, with the microstructure showing directional solidification due to grain refinement and microscopic distortion of crystals. As the fracture has dimples, it is a ductile fracture and typical plastic fracture. The hardness near the fracture is higher than that of the substrate, whilst the indexes regarding the selective laser melting parts are higher than the ASTM-A182 and ASTM-F3184-16 standards. Since the theoretical model built in this study has less error, the findings have practical engineering application value.

Kanwal Chadha, Yuan Tian, John G. Spray and Clodualdo Aranas Jr., "**Effect of Annealing Heat Treatment on the Microstructural Evolution and Mechanical Properties of Hot Isostatic Pressed 316L Stainless Steel Fabricated by Laser Powder Bed Fusion",** describe that in this work, the microstructural features and mechanical properties of an additively manufactured 316L stainless steel have been determined. Three types of samples were characterized: (i) as printed (AP), (ii) annealing heat treated (AHT), and (iii) hot isostatic pressed and annealing heat treated (HIP + AHT). Microstructural analysis reveals that the AP sample formed melt pool boundaries with nano-scale cellular structures. These structures disappeared after annealing heat treatment and hot isostatic pressing. The AP and AHT samples have similar grain morphologies; however, the latter has a lower dislocation density and contains precipitates. Conversely, the HIP + AHT sample displays polygon-shaped grains with twin structures; a completely different morphology compared to the first two samples. Optical micrography reveals that the application of hot isostatic pressing reduces the porosity generated after laser processing. The tensile strengths of all the samples are comparable (about 600 MPa); however, the elongation of the HIP + AHT sample (48%) was superior to that of other two samples. The enhanced ductility of the HIP + AHT sample, however, resulted in lower yield strength. Based on these findings, annealing heat treatment after hot isostatic pressing was found to improve the ductility of as-printed 316L stainless steel by as much as 130%, without sacrificing tensile strength, but the sample may have a reduced (40%) yield strength. The tensile strength determined here has been shown to be higher than that of the hot isostatic pressed, additively manufactured 316L stainless steel available from the literature.

Zhongji Sun, Xipeng Tan, Shu Beng Tor and Chee Kai Chua, "Simultaneously enhanced strength and ductility for 3D-printed stainless steel 316L by selective laser melting", describe that Laser-based powder-bed fusion additive manufacturing or three-dimensional printing technology has gained tremendous attention due to its controllable, digital, and automated manufacturing process, which can afford a refined microstructure and superior strength. However, it is a major challenge to additively manufacture metal parts with satisfactory ductility and toughness. Here we report a novel selective laser melting process to simultaneously enhance the strength and ductility of stainless steel 316L by in-process engineering its microstructure into a <011> crystallographic texture. We find that the tensile strength and ductility of SLM-built stainless steel 316L samples could be enhanced by ~16% and ~40% respectively, with the engineered <011> textured microstructure compared to the common <001> textured microstructure. This is because the favourable nano-twinning mechanism was significantly more activated in the <011> textured stainless steel 316L samples during plastic deformation. In addition, kinetic simulations were performed to unveil the relationship between the melt pool geometry and crystallographic texture. The new additive manufacturing strategy of engineering the crystallographic texture can be applied to other metals and alloys with twinning-induced plasticity. This work paves the way to additively manufacture metal parts with high strength and high ductility.

Meet Gor, Harsh Soni, Vishal Wankhede, Pankaj Sahlot, Krzysztof Grzelak, Ireneusz Szachgluchowicz and Janusz Kluczyński, "A Critical Review on Effect of Process Parameters on Mechanical and Microstructural Properties of Powder-Bed Fusion Additive Manufacturing of SS316L",describe that Additive manufacturing (AM) is one of the recently studied research areas, due to its ability to eliminate different subtractive manufacturing limitations, such as difficultly in fabricating complex parts, material wastage, and numbers of sequential operations. Laser-powder bed fusion (L-PBF) AM for SS316L is known for complex part production due to layer-by-layer deposition and is extensively used in the aerospace, automobile, and medical sectors. The process parameter selection is crucial for deciding the overall quality of the SS316L build component with L-PBF AM. This review critically elaborates the effect of various input parameters, i.e., laser power, scanning speed, hatch spacing, and layer thickness, on various mechanical properties of AM SS316L, such as tensile strength, hardness, and the effect of porosity, along with the microstructure evolution. The effect of other AM parameters, such as the build orientation, pre-heating temperature, and particle size, on the build properties is also discussed. The scope of this review also concerns the challenges in practical applications of AM SS316L. Hence, the residual stress formation, their influence on the mechanical properties and corrosion behaviour of the AM build part for bio implant application is also considered. This review involves a detailed comparison of properties achievable with different AM techniques and various post-processing techniques, such as heat treatment and grain refinement effects on properties. This review would help in selecting suitable process parameters for various human body implants and many different applications. This study would also help to better understand the effect of each process parameter of PBF-AM on the SS316L build part quality.

CHAPTER 3
POWDER BED FUSION

3.1 DEFINITION

Powder bed fusion is one of seven Additive Manufacturing techniques, in which either laser, heat or electron beam is used to melt and fuse the material together to form a three-dimensional object. Powder bed fusion process is laser-based additive manufacturing have received significant attention in the research and development of advanced engineering materials because of their higher cooling rate and better surface finish compared with other additive manufacturing processes. This chapter summarizes the recent research in the laser-based powder bed fusion process. It covers the characteristics of the process and melt pool; microstructural features including texture, residual stress and defects; and characteristics of mechanical properties of metallic parts processed by the laser-based powder bed fusion process.

3.2 CLASSIFICATION OF POWDER BED FUSION

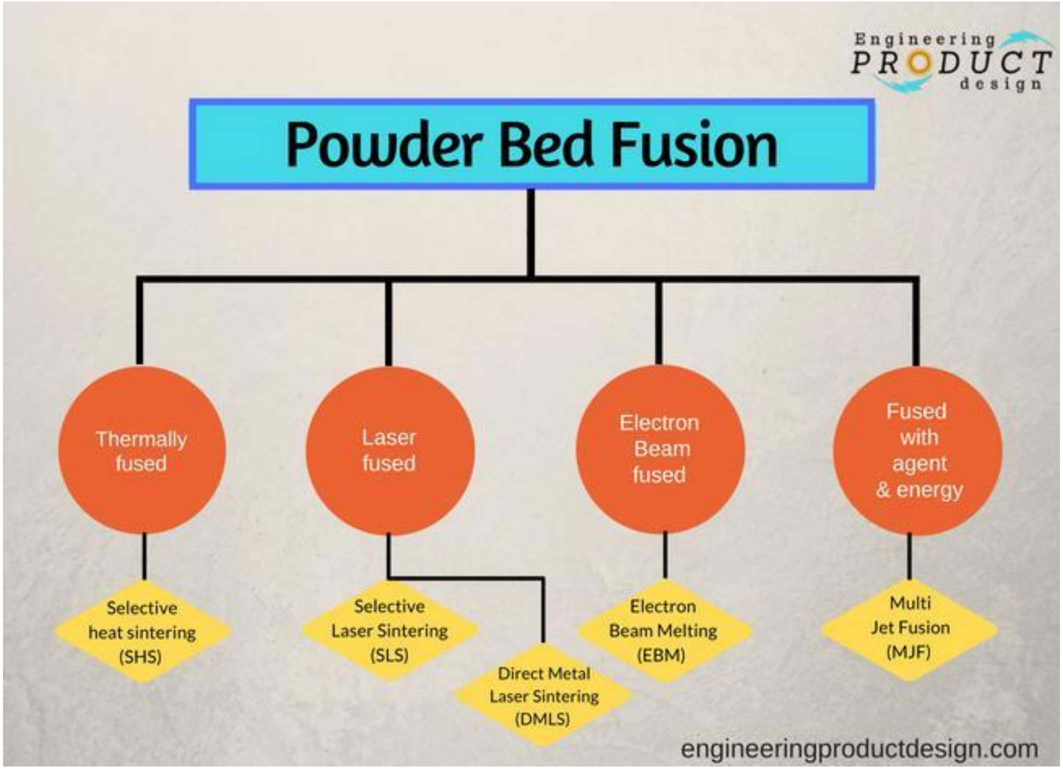


Fig. 3.1 Classification of powder bed fusion

Sintering process by laser, again classified based as polymer Laser Sintering (PLS) process and metal Laser Sintering (MLS) process. These processes were carried out by PLS machine and MLS machine. Electron Beam Melting is used to create parts with metals and alloys powders in a vacuum-built chamber. Almost all PBF methods involved spreading of powders over previous layers. This can be done by a roller or a blade mechanism. PBF techniques start from the spreading of powders and the beam scans the powders that fuses the powders and solidifies it as end components. These methods manufacture accurate and good surface finish parts for small scale production because of smaller beam size.

3.2.1 SELECTIVE HEAT SINTERING(SHS)

Plastic powder particles fuse together by a heated head. The print head shown in figure 3.2 which touches the powder and moves based on sliced STL model. This method is used for manufacturing structural parts and conceptual prototypes. The SHS technology is used in blue printer and it is a desktop 3D printer. It has a built chamber of size 200mmx160mmx140mm, printing speed of 0.078–0.118 in./hour with a layer thickness of 0.0039.

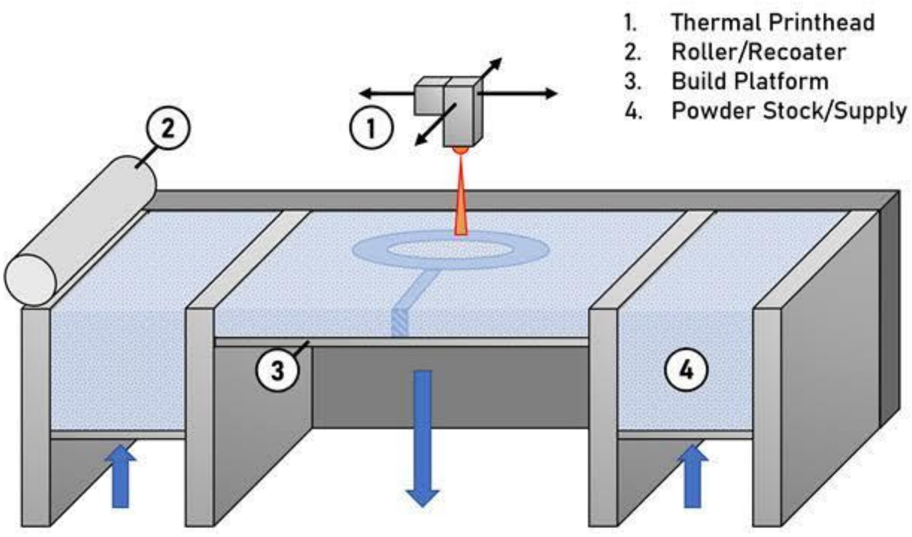


Fig. 3.2 Schematic representation of selective heat sintering

3.2.2 SELECTIVE LASER SINTERING(SLS)

The illustration of SLS method with respective to the figure 3.3 is given below. Powder can be spread on the built platform by roller mechanism, when the powder delivery piston moves up. The laser beam can scan the powders selectively and fuse/sinter the powder particles based on 3D CAD data, forming the first sintered layer. Part building bed can move down by the required thickness and second layer of powder is spread on first sintered layer. Then laser beam again scans selectively and forms the second layer by fusion onto the first layer. The process can repeat till the complete building of physical part. The part is taken from the RP machine cleaning and for secondary processes if required. Sometimes CO_2 laser beam is used. In metal SLS process a mixture powder is used. It consists of one powder having low melting point and another high melting point. During SLS process only low melting point powders can partially melt and forms the bond with unmelt high melting point powders

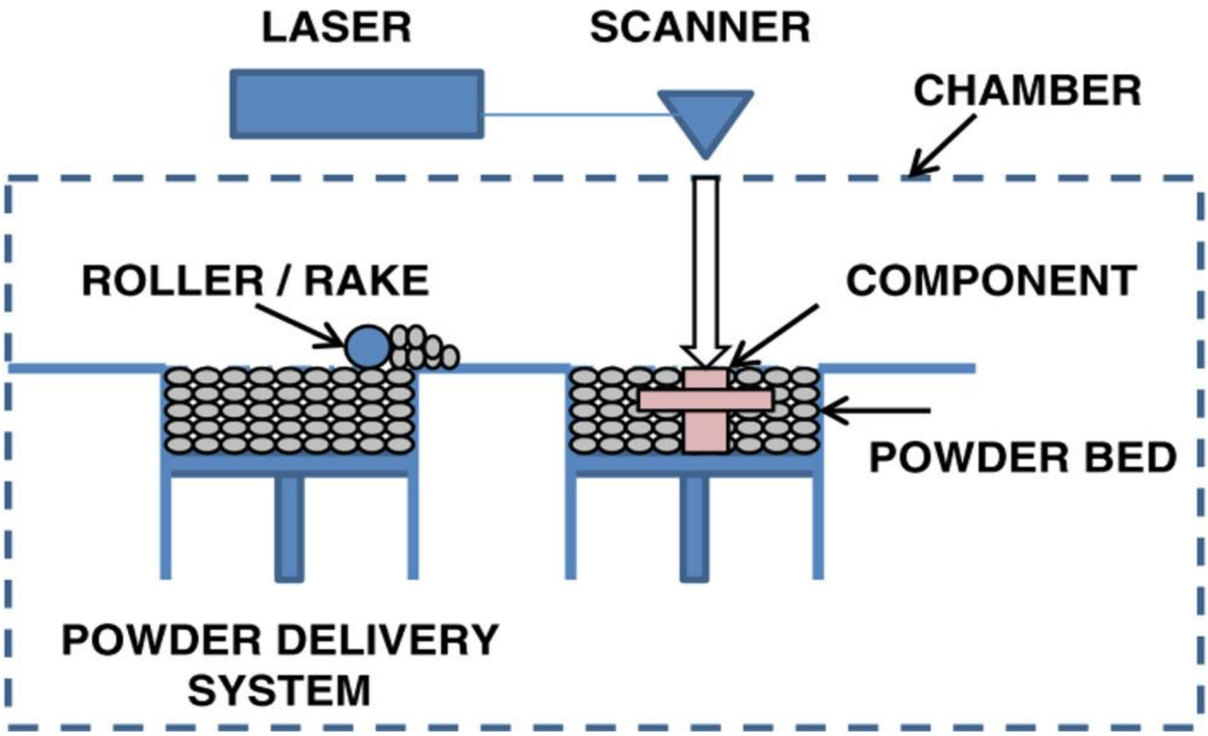


Fig. 3.3 Schematic representation of selective laser sintering

3.2.3 DIRECT METAL LASER SINTERING(DMLS)

Figure 3.4 showing the DMLS process which is similar to that of SLM process. Functional prototypes, short-run components, and functionally graded materials (FGM) are manufactured by direct metal laser sintering. Aerospace parts can be produced using less raw materials and with low cost.

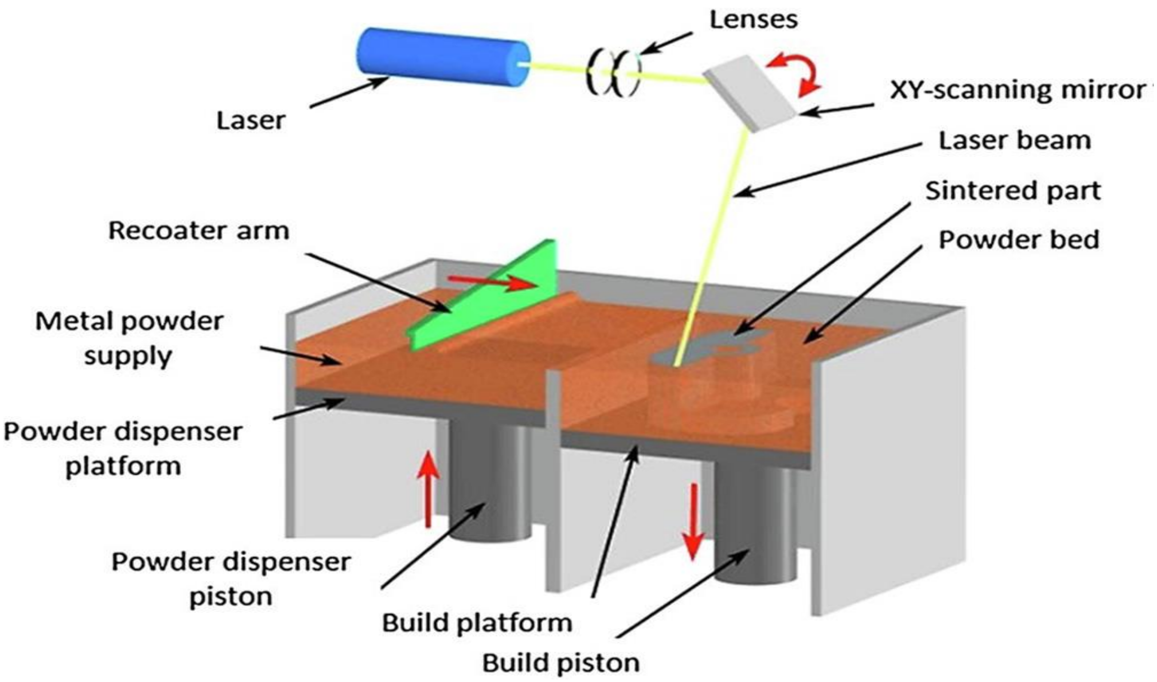


Fig. 3.4 Schematic representation of direct metal laser sintering

3.2.4 ELECTRON BEAM MELTING(EBM)

Electron Beam Melting (EBM) is another powder fusion process uses beam of electrons as heat energy source for melting metal powders as shown in figure 3.5. In EBM, electrons are emitted from a heated tungsten filament at a high speed, which can be controlled by two magnetic fields, focusing coil and deflecting coil. The focusing coil creates a thin diameter of 0.1 mm electron beam and deflecting coil deflect the focused beam at desired points for scanning the layer of alloy powder. The working of EBM is as follows. High vacuum and high temperature can be maintained in the built chamber. Powder hoppers pour a layer of alloy powders on built chamber. The powder particles melt in a small volume within the layer by a focused electron beam. The electron beam is scanned to define a 2D slice of the object within the layer. The built chamber can be moved down, and a second layer of alloy powder is poured onto the top of the previous solidified layer. The process repeats till completion of part. After removal of part from the machine, unmelt metal powders are cleaned and it can be recycled for further use. Corrosive resistance Hastelloy X can be processed by EBM and also by SLM.

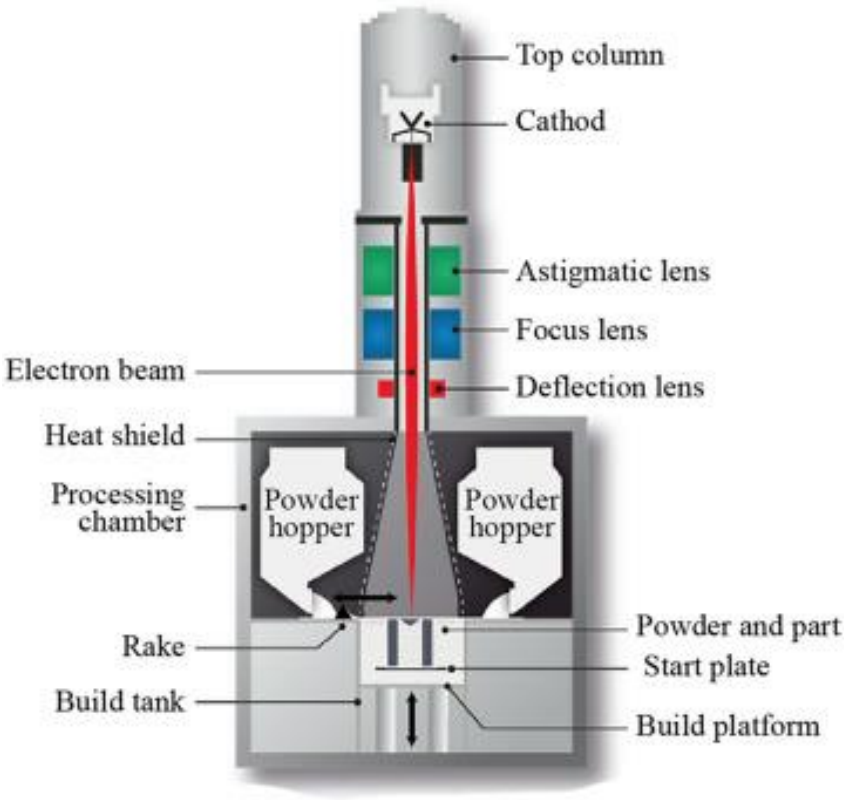


Fig.3.5 Schematic representation of electron beam melting

3.2.5 MULTI JET FUSION(MJF)

Multi Jet Fusion uses an inkjet array to selectively apply fusing and detailing agents across a bed of nylon powder, which are then fused by heating elements into a solid layer. After each layer, powder is distributed on top of the bed and the process repeats until the part is complete. When the build finishes, the entire powder bed with the encapsulated parts is moved to a processing station where a majority of the loose powder is removed by an integrated vacuum Parts are then bead blasted to remove any of the remaining residual powder before ultimately reaching the finishing department where they are dyed black to improve cosmetic appearance.

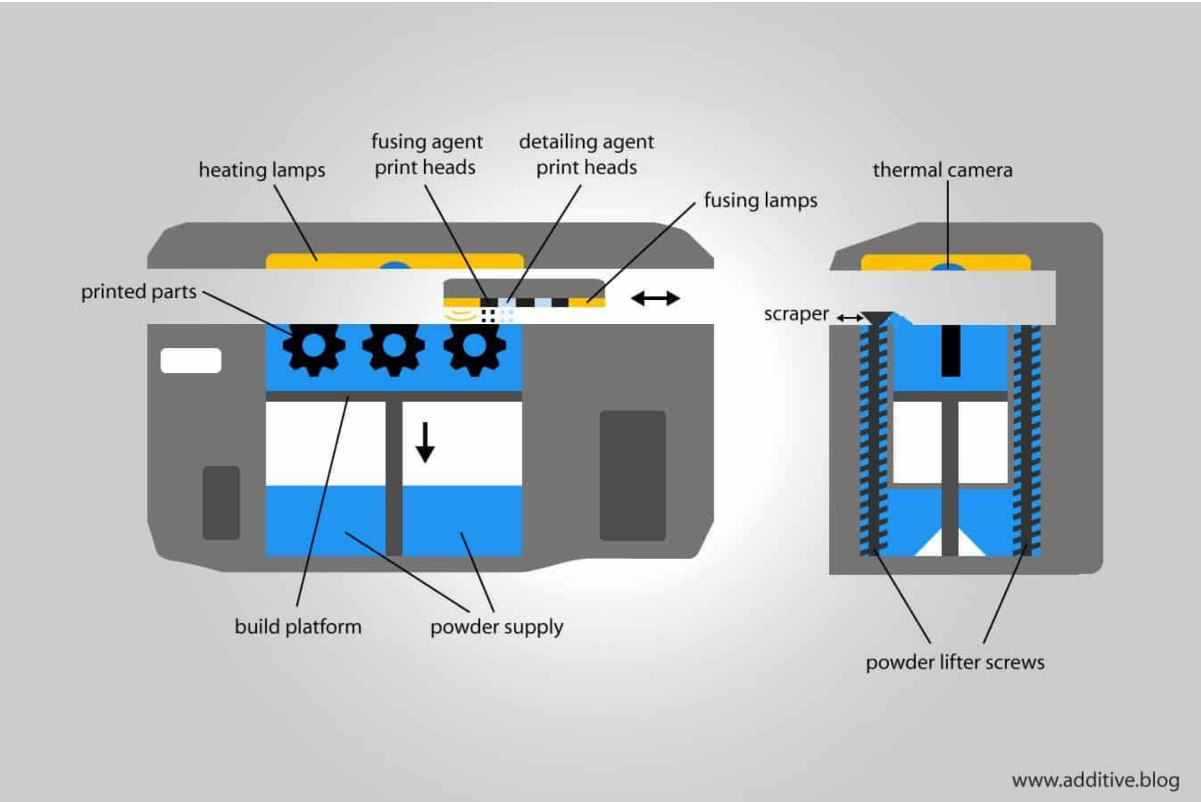


Fig.3.6 Schematic diagram of multi jet fusion

3.3 WORKING OF POWDER BED FUSION

The heat source is applied to particles contained within a powder bed, which is slowly lowered as each layer is completed and new powder is spread over the build area. A diagram of powder bed fusion is shown in figure 3.7. The powder bed is the actual build area in which feedstock, that is the bulk raw material is deposited. A thin layer of powder is spread across the completed section and the process is repeated with each layer adding to the last. After a few thousand cycles, depending on the height of the part, the built part is removed from the powder bed. When the 3D printed model is complete, unused powder is automatically or manually removed and may be reused.

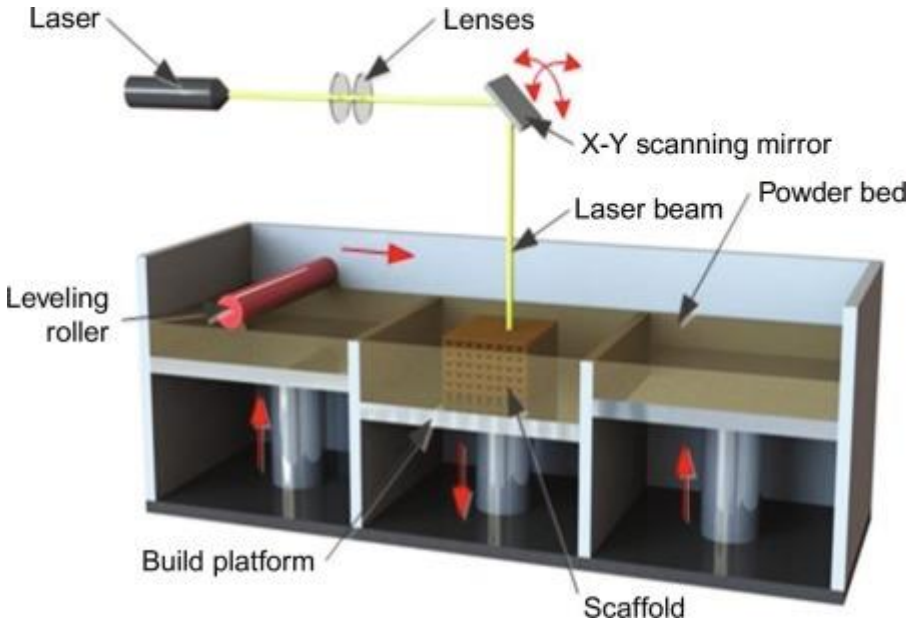


Fig. 3.7 Schematic representation of powder bed fusion

3.4 PROCESS PARAMETER IN POWDER BED FUSION

The processing parameters in the powder bed fusion processes include layer thickness (t), laser power (P), laser scanning speed (v) and scanning path strategy, hatching space (h) and laser spot size (d), particle size and distribution, platform pre-heating temperature and laser beam scanning strategy shown in figure 3.8. Laser power is applied power of laser as it scans area of each layer. Scan speed is velocity at which laser beam travels as it transverse a scan vector. Scan spacing is distance between the parallel laser scan. Scan count is number of times laser beam transverse a scan vector per layer. Scan strategy is pattern of laser as it scans over a layer in combination with the laser parameter used in each specific area. Layer thickness is distance build platform lower for spreading of new layer of powder. Build temperature is temperature of process chamber and part bed.

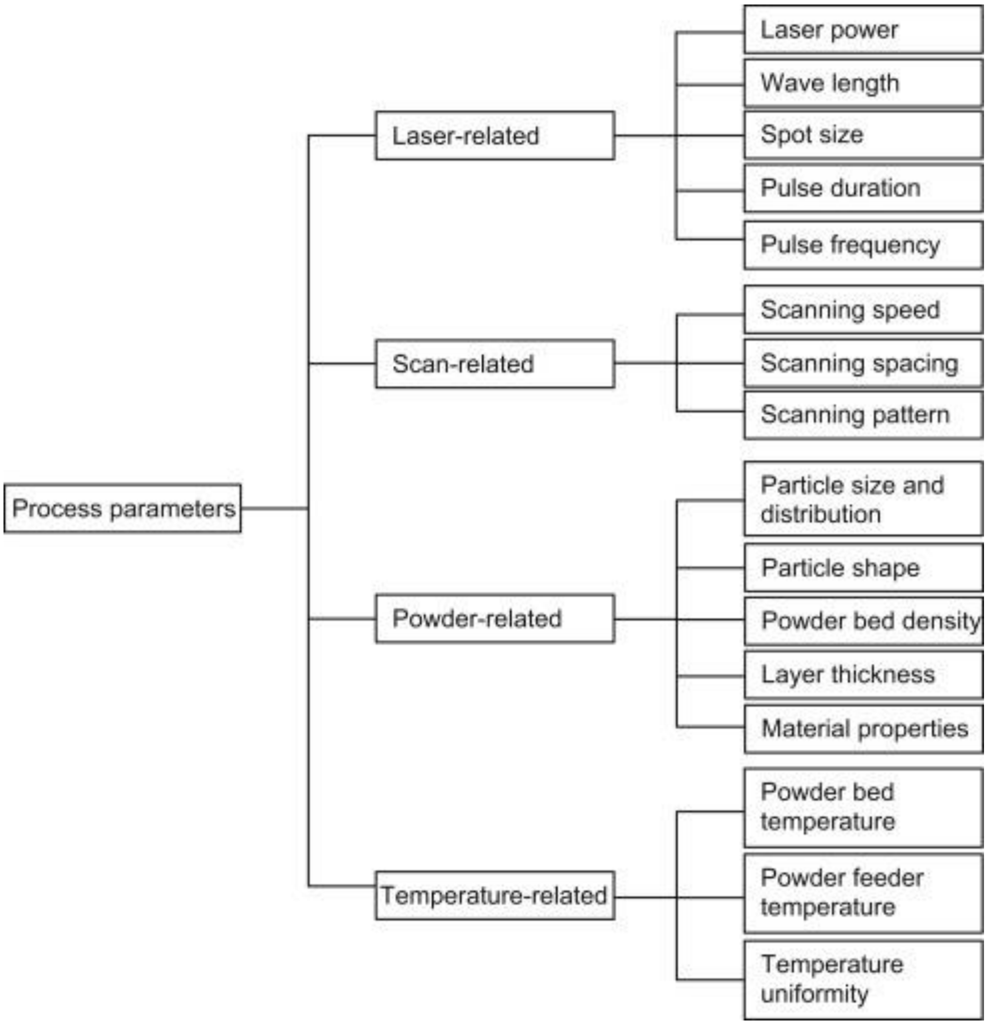


Fig. 3.8 Block diagram of process parameters

3.5 MATERIALS USED IN POWDER BED FUSION

- ❖ The Powder bed fusion process uses any powder-based materials, but common metals and polymers used.
- ❖ Metals like Titanium, Cobalt Chrome, Stainless Steel, Aluminium, Inconel and Copper are used.
- ❖ Polymers like polyamide, polystyrene are used.

CHAPTER 4
FABRICATION OF SS316L COMPONENT

LPBF 3D printers use high-powered lasers to selectively melt a metal powder. The melted parts fuse together layer-by-layer on a molecular basis until the homogenous model is complete.

4.1 SPECIFICATION

Third-generation machine designed for production environments. Featuring multiple lasers, closed-loop powder handling and upgraded process control ideal for demanding applications requiring high productivity.

- ❖ 280 x 280 x 365 mm build envelope
- ❖ Multi-laser (twin)
- ❖ Dedicated material
- ❖ Automated powder handling
- ❖ Permanent filter

Fig. 4.1 Schematic representation of SLM machine

Table 4.1 Specification of SLM machine

Build envelope(L*W*H)	280*280*365 mm 11*11*14 in (Reduced by substrate plate thickness)
3D optics configuration	• Single (1*400W or 1*700W) IPG fiber laser • Twin (2*4000W or 2*700W) IPG fiber laser • Dual (1x 700 W and 1x 1000 W) IPG fiber laser
Build rate	Up to 113 cm^3/h (Twin 700 W)
Variable layer thickness	20 µm - 90 µm (more upon request)
Minimum feature size	150 µm
Beam focus diameter	80 µm - 115 µm
Maximum scan speed	10 m/s
E- connection	400 Volt 3NPE, 63 A, 50/60 Hz, 3.5-5.5 kW
Compressed air requirement/ consumption	ISO 8573-1:2010 [1:4:1], 60 l/min @ 6 bar
Dimension(L*W*H)	4150 mm x 1200 mm x 2525 mm (includes PSV)
Weight	1700 kg dry 2600 kg with powder

Average inert gas consumption in process	13 l/min (argon)
Average inert gas consumption purging	160 l/min (argon)

4.2 PROPERTIES OF SS316L

4.2.1 COMPOSITION

The chemical composition of SS316L is discussed in table 4.2.

Table 4.2 Composition of SS316L

Grade		**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Ni**	**N**
316L	**Min (%)**	-	-	-	-	-	16.0	2.0	10.0	-
	Max (%)	.03	2.0	.75	.045	.03	18.0	3.0	14.0	.10

4.2.2 MECHANICAL PROPERTIES

The mechanical properties of SS316L are discussed in table 4.3.

Table 4.3 Mechanical properties of SS316L

Properties	**Description**
Tensile strength (MN/m^2)	650
Yield strength (MN/m^2)	280
Elongation at fracture	45
Vickers hardness (Hv)	190
Young's modulus (GN/m^2)	211
Fatigue limit (GN/m^2)	028

4.2.3 PHYSICAL PROPERTIES OF SS316L

The physical properties of the SS316L material are shown in table 4.4.

Table 4.4 Physical properties of SS316L

Properties	Description
Density(g/cm^3)	7.90
Melting range(°C)	1390-1440
Thermal conductivity (w/mk)	14.6
Specific heat(J/kgK)	450
Modulus of elasticity (GPa)	200

4.3 MANUFACTURING PROCESS

The manufacturing process start from designing the model in software. It has been shown in fig.4.2. Software, we used for designing the model is Solidworks and AutoCAD.

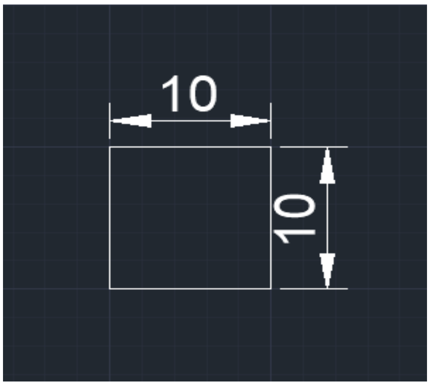


Fig.4.2 Schematic representation of plate

After designing the model, the file is converted to STL file format. STL file format of fatigue and plate specimen is shown in fig.4.4 and fig.4.5. Slicing of model are made. STL file format is transferred to SLM machine for building the model. Before the building of model, the settings can constitute power, speed, layer thickness, and other several parameters related to material and process constraints are setup.

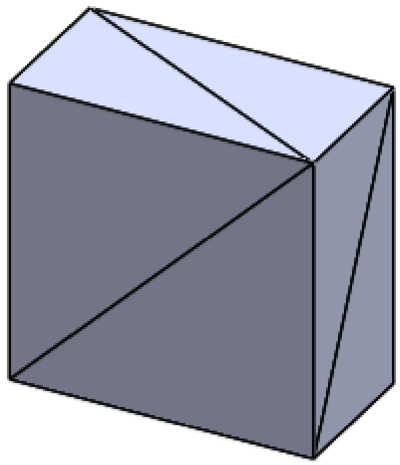


Fig.4.3 STL format of plate

Actual building of model is made melting layer by layer. Once the part is manufactured, it is removed from build platform. Fig.4.4 shows the gas atomized powder particles of SS316L in spherical structure which is used to fabricate the specimen as shown in fig.4.5 by using the optimized process parameters such as laser power, scanning speed and layer thickness in SLM 280 machine.

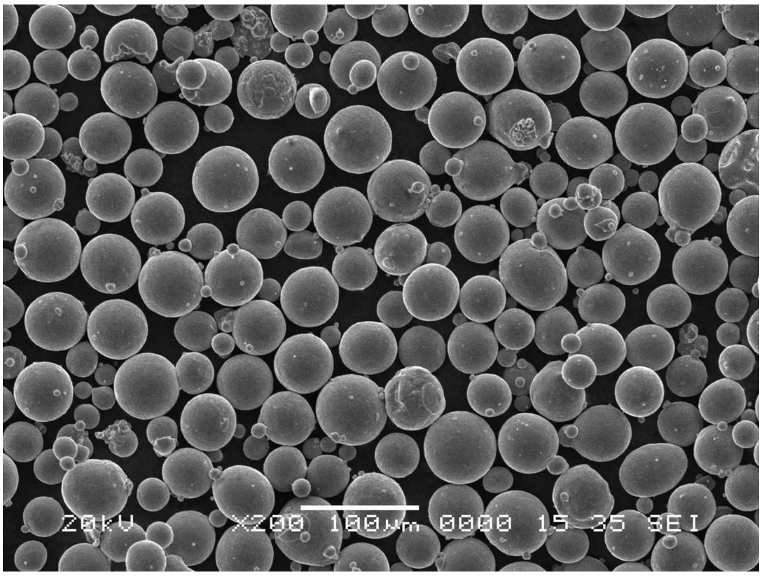


Fig.4.4 Image of gas atomized SS316L powder

Fig.4.5 As fabricated Specimen

4.4 WIRECUT EDM (Electrical Discharge Machining)

Wire Electrical Discharge Machining (EDM) shown in fig.4.6 is a process of metal machining in which a tool discharges thousands of sparks to a metal work piece. A nonconventional process, though hardly a new one, wire EDM works on parts resistant to conventional machining processes, but only if these parts are electrically conductive; usually, they are non-ferrous, and include steel, titanium, super alloys, brass, and many other metals. Instead of cutting the material, EDM melts or vaporizes it, producing comparatively small chips and providing a very accurate cut line. Industry-wide acceptance has led to a wide variety of EDM applications, as it is highly versatile, can cut hard metals, and utilizes a relatively compact amount of workspace.

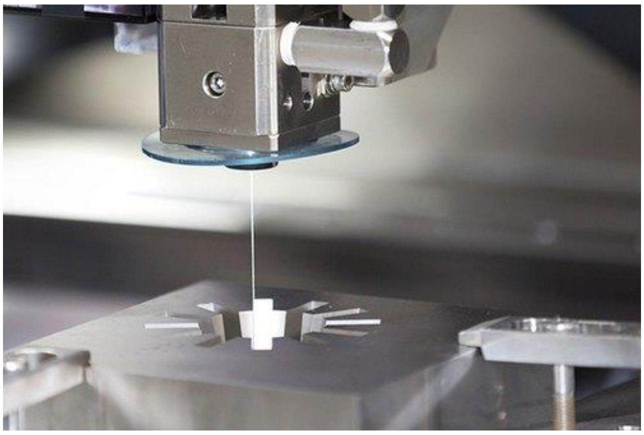


Fig.4.6 Wire Cut EDM

The final products produced by wire cut EDM process is shown in the fig.4.7 and the components produced by rolling process is shown in the fig.4.8.

Fig.4.7 Components produced by Wire Cut EDM

Fig.4.8 Components produced by rolling process

CHAPTER 5

MICROSTRUCTURAL INVESTIGATION

5.1 PERFORMING MICROSTRUCTURAL EXAMINATION

Examination of the microstructure of a material provides information used to determine if the structural parameters are within certain specifications. The analysis results are used as a criterion for acceptance or rejection.

Microstructural examination is generally performed using optical or scanning electron microscopes to magnify features of the material under analysis. The amount or size of these features can be measured and quantified, and compared to acceptance criteria. These examinations are often used in failure analysis to help identify the type of material in question and determine if the material received the proper processing treatments. Metallurgical examinations may evaluate:

- Extent of decarburization and carburization, grain size, inter-granular attack or corrosion
- Depth of alpha case in titanium alloys
- Percent spheroidization
- Inclusion ratings
- Volume fraction of various phases or second phase particles in metals.

5.2 SAMPLE PREPARATION

In order to identify and evaluate the microstructure of material, it is very important to prepare the test sample carefully and properly. The various steps in sample preparation for microstructural examination include:

- Selecting a representative sample of the materials
- Sectioning the sample to avoid altering or destroying the structure of interest
- Mounting the section without damage to the test sample
- Grinding to achieve a flat sample with a minimum amount of damage to the sample surface

- Polishing the mounted and ground sample
- Etching in the proper etchant to reveal the microstructural details.

5.3 STEPS IN SAMPLE PREPARATION

SELECTING

Selecting a representative test sample to properly characterize the microstructure or the features of interest is a very important first step. For example, grain size measurements are performed on transverse sections, whereas general microstructure evaluations are performed on longitudinal sections. Therefore, it is important to provide the laboratory with information about the orientation or the rolling direction of the test specimen.

SECTIONING

Test samples are carefully sectioned to avoid altering or destroying the structure of the materials. If an abrasive saw is used, it is important to keep the sample cool with coolant or lubricant so it doesn't burn or overheat. However, no matter how carefully abrasive sawing or electric discharge machining is performed, a small amount of deformation occurs on the sample surface. This deformation must be removed during subsequent preparation steps.

MOUNTING

After the test sample is sectioned to a convenient size, it is mounted in a plastic or epoxy material to facilitate handling and the grinding and polishing steps. Mounting media must be compatible with the sample with respect to hardness and abrasion resistance. Typical mounting materials are thermosetting phenolics such as Bakelite, and thermoplastic materials such as methyl methacrylate (Lucite). Mounting involves putting the sample in a mold and surrounding it with the appropriate powder. When the mold is heated and pressurized at the correct levels, setting or curing of the media occurs. The mounted sample is removed from the mold which is used for micro examination in optical microscope as shown in fig.5.1. If the use of heat or pressure might alter the structure of the sample of interest, then castable cold mounting materials such as epoxies are employed.

Fig.5.1 Specimen prepared for micro structure study in optical microscope

GRINDING

Grinding is used to remove the surface damage that occurred during the sectioning step and to provide a flat surface. Grinding generally involves the use of water lubricated abrasive wheels and the use of a series of progressively finer abrasive grits. This procedure provides a flat surface that is nearly free of the disturbed or deformed metal that has been introduced by the previous sample preparation steps.

POLISHING

The polishing step removes the last thin layer of the deformed metal. It leaves a properly prepared sample, ready for examination of the un-etched characteristics such as inclusion content or any porosity that may exist.

ETCHING

The final step that might be used is etching to show the microstructure of the test sample. This step reveals features such as grain boundaries, twins and second phase particles not seen in the un-etched sample. The etchant used is aquaregia solution.

5.4 MICROSTRUCTURE OF SS316L BASE PLATE

Fig.5.2 a) shows the optical images of equi axed grains morphology observed in the matrix. The microstructure austenite grains along the grain boundaries are carbide precipitates. The matrix found observed with some twin grains.

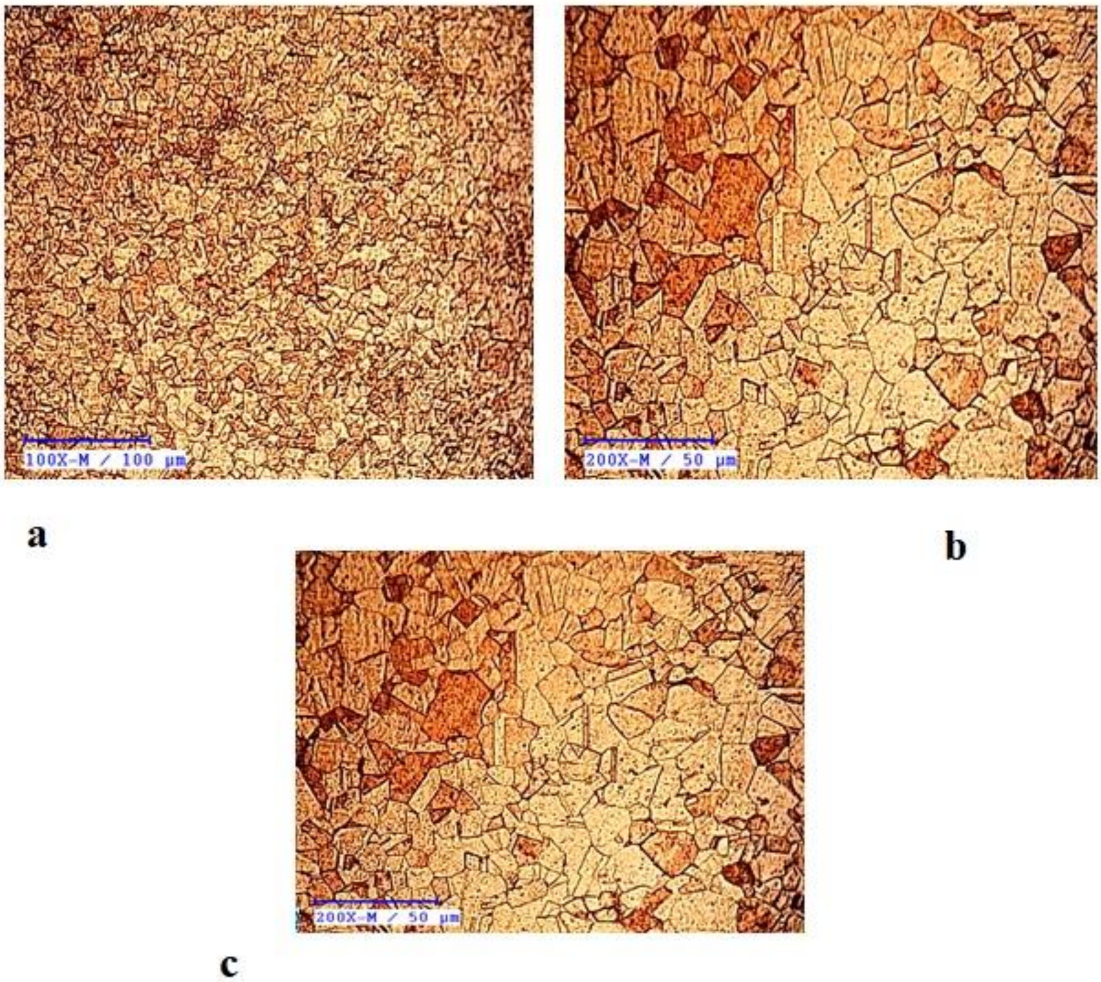


Fig.5.2 Optical images of rolled SS316L specimen

Fig.5.2 b) shows the micrograph higher magnification to resolve the grain boundaries and fig.5.2 c) shows the 500X magnification clearly indicates the grain boundaries are observed. The carbide precipitates to resolve high magnification.

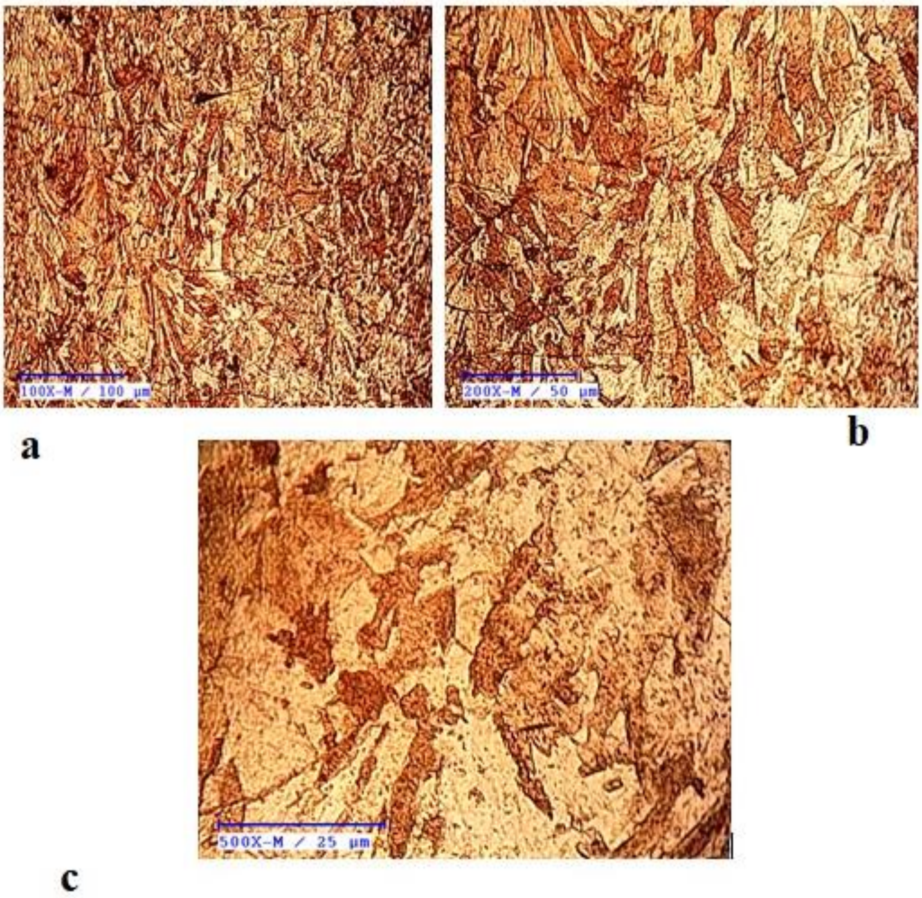
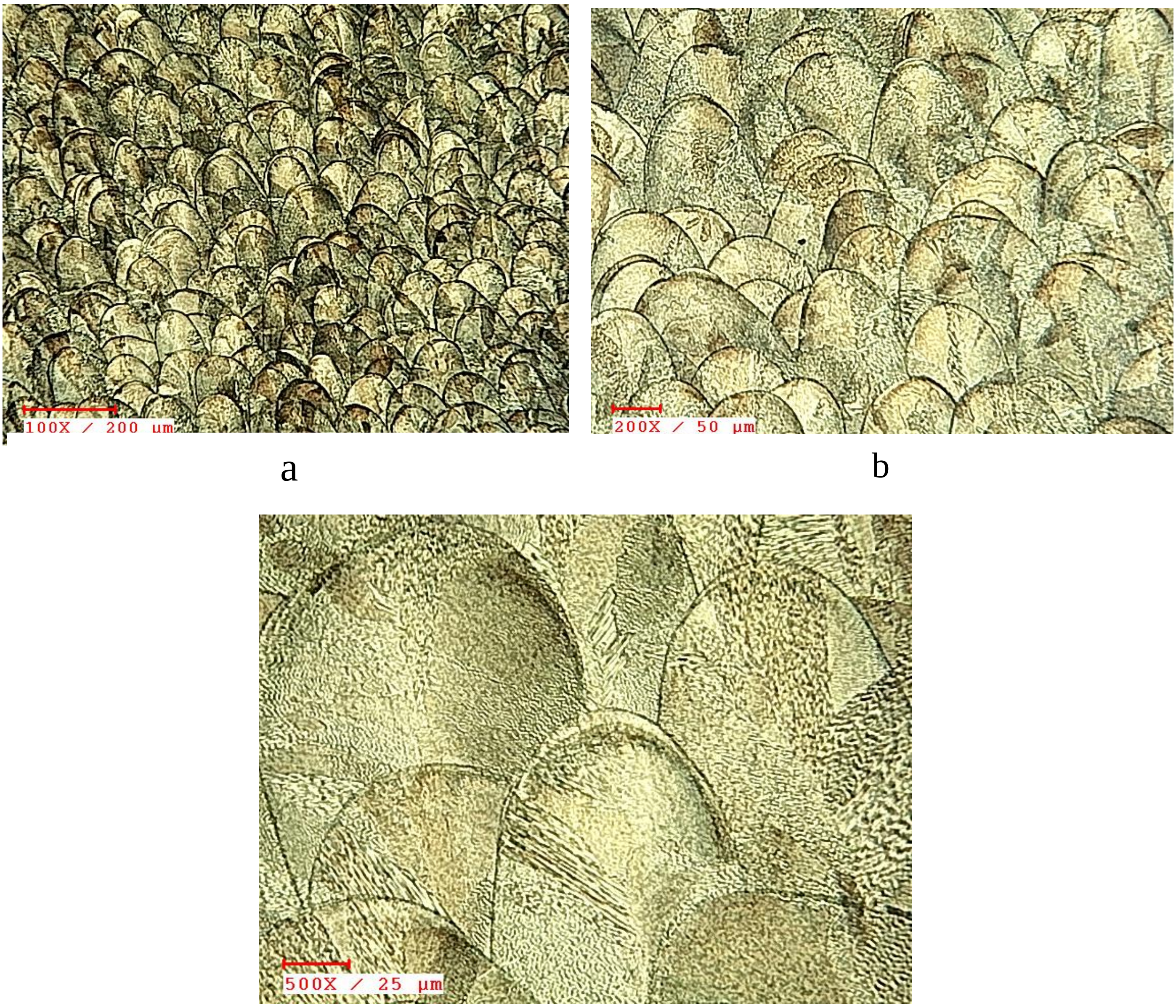


Fig.5.3 Optical images of SLMed (AM) SS316L specimen

Fig.5.3 a) shows the micrograph fish scale morphology observed in the matrix. The matrix columnar grains along the grain boundaries with molten pool observed. The layer of the angle orientation is 48 degrees onwards more over fig.5.3 b) shows the micrograph higher magnification to resolve the columnar sub structure and fig.5.3 c) shows the 500X magnification clearly indicates the grain boundaries are observed fish scale structure. The fish scale structure remains the grain flow at the grain orientations.



a b

c

Fig.5.4 Optical image of SLMed + Heat Treated specimen

Fig.5.2 (a, b & c), fig.5.3 (a, b & c) & fig.5.4 (a, b & c) shows the micrographs of Base and SLMed (AM) specimen respectively. The non-spherical pores were found to be mainly formed at the interlayer boundaries and are mainly located near the bottom of the melt pools. These types of pores are usually formed due to the excessive energy input and unstable melt low behaviour. Some elongated pores can also be observed. It is also noted that the morphology of the solidified melt pools changes with energy density.

CHAPTER 6
CONCLUSION

This work investigated the influence of different SLM and SLMed Heat treated devices on the microstructure and the resulting material properties. The steel powder from the same powder batch was used for all tests so that only the influence of the different SLM machines becomes visible. From the obtained results, the following conclusions can be drawn. The SLM-built SS316L possesses a hierarchical microstructure. The microstructure consists of grains with a size of 10– 50 μm and fine sub grains within single grains. No significant influence of the employed SLM machines on the microstructure was observed, which indicates similar thermal conditions during each build-cycle. However, specimens built using different SLM machines were found to have a considerably different porosity. Pronounced differences in terms of mechanical strength were detected between the specimens produced on the two employed SLM devices, although optimized process parameters were used for each individual device. Therefore, the influence of different SLM devices has to be taken into account when producing structural parts. In this context, the influence of the powder-supply system appears to be important and has thus to be investigated more deeply in the future.

CHAPTER 7
FUTURE SCOPE

In future investigations, especially the influence of the specimen size on the Weibull modulus has to be investigated. Further research is required with regard to the influence of the recoated system, the characterization of the applied powder layers (local packing density, reusability of powders, homogeneity) and the influence of further post processing (heat treatment, HIP post-compression) on the mechanical, chemical, and cyclical material properties. There is also the question of whether the results obtained for SS316L stainless steel can be transferred to other material systems.

CHAPTER 8
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