

**ANALYSIS OF MATERIAL BEHAVIOR IN METAL ADDITIVE
MANUFACTURING (MAM)**

BY

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I dedicate this work to my loving family

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NOMENCLATURE

AM	Additive Manufacturing
DMLS	Directed Metal Laser Sintering
CM	Convectional Manufacturing
XRD	X-ray Diffraction
RP	Rapid Prototyping
MAM	Metal Additive Manufacturing
CAD	Computer Aided Design
LM	Layered Manufacturing
Autofab	Automated Fabrication
DM	Desktop Manufacturing
SFF	Solid Freeform Fabrication
TO	Topology Optimization
GD	Generative Design
SLA	Stereolithography
LOM	Laminated Object Manufacturing
SGC	Solid Ground Curing
FDM	Fused Deposition Modelling
SLS	Selective Laser Sintering
DSPC	Direct Shell Production Casting
LENS	Laser Engineering Net Shaping
MJ	Material Jetting

PBF	Material Extrusion, Powder Bed Fusion
DED	Directed Energy Deposition
CMB	Controlled Metal Build-up
SLM	Selective Laser Melting
DSPC	Direct Shell Production Casting
RPD	Rapid Plasma Deposition
EBM	Electron Beam Melting
BJ	Binder Jet
SEM	Scanning Electron Microscope
EDX	Energy Dispersive X-Ray

THESIS ABSTRACT

Full Name: Ibrahim Abdullah Ibrahim Al-Deheish
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Additive Manufacturing (AM) is very flexible in terms of shaping and changing the design and come up with totally new designs that cannot be achieved by traditional manufacturing. However, complex shapes do not guarantee strength, and therefore it is important for AM parts to have sufficient strength in order to be used as commercial products. Since there is a need for more in-depth studies related to the material behavior of metal additive manufacturing, this research is intended to experimentally study the material behavior of 316L Stainless Steel additively manufactured by Direct Metal Laser Sintering (DMLS) with considering the impact on changing the thickness and building orientation. The study covers the mechanical properties along with microstructure analysis of printed parts that includes tensile testing, hardness testing, surface roughness testing, X-ray diffraction (XRD), porosity analysis, and composition analysis. Therefore, the outcome elucidates the positioning of metal additive manufacturing to be compared with traditional manufacturing, which can be further analyzed for future material behavior and design optimization studies.

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التصنيع الإضافي مرّن للغاية من حيث تشكيل وتغيير التصميم والتوصل إلى تصميمات جديدة تمامًا لا يمكن تحقيقها عن طريق التصنيع التقليدي. ومع ذلك، الأشكال المعقدة لا تضمن القوة والصلابة، وبالتالي من المهم أن تتمتع الأجزاء المصنعة بهذه التقنية بقوة وصلابة كافية لاستخدامها كمنتجات تجارية. نظرًا لوجود حاجة لمزيد من الدراسات المتعمقة المتعلقة بسلوك المواد الفولاذ المصنعة بتقنية التصنيع الإضافي، فقد تم تحديد هذا الموضوع لإجراء دراسة تجريبية لسلوك مادة الفولاذ المقاوم للصدأ (316L) المصنوع بشكل إضافي بواسطة تقنية تليد المعادن بالليزر المباشر (DMLS) وهي إحدى طرق التصنيع المضاف مع مراعاة التأثير على تغيير السماكة واتجاه بناء الطباعة. تغطي الدراسة الخصائص الميكانيكية مع تحليل البنية المجهرية للأجزاء المطبوعة التي تشمل اختبار الشد واختبار الصلابة واختبار خشونة السطح وانحراف الأشعة السينية وتحليل المسامية وتحليل التركيب. لذلك، توضح النتيجة تحديد موضع تصنيع المواد الفولاذ المصنعة بتقنية التصنيع الإضافي ليتم مقارنتها بالتصنيع التقليدي، والذي يمكن تحليله بشكل أكبر لسلوك المواد في المستقبل ودراسات تحسين التصميم.

ANALYSIS OF MATERIAL BEHAVIOR IN METAL ADDITIVE MANUFACTURING (MAM)

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Additive Manufacturing (AM) as a definition is the manufacturing technique to make an object from three-dimensional model into a final product by the process of constructing materials in a layer-by-layer method. There are alternative names of Additive Manufacturing that are famously known, which are 3D Printing, Rapid Prototyping (RP), Layered Manufacturing (LM), Automated Fabrication (Autofab), Desktop Manufacturing (DM), and Solid Freeform Fabrication (SFF). Additive manufacturing becomes more common to be used as one of the important manufacturing techniques in the industry since the technology is really promising to change the way of manufacturing wide range of applications. Examples of applicable applications nowadays are and not limited to, aerospace, automotive, electronics and robotics [1]. It is actually a technology that has a high potential for innovation and expanding business growth of critical and complex products. Additive Manufacturing was developed with time to be more than just a rapid prototyping technology, but to produce accurate and complex product that is impossible or hard to be manufactured by using the traditional conventional manufacturing [2]. The methods of Additive Manufacturing have been expanded and developed with different processes that utilize the main

technique of the layer-by-layer which includes sheet lamination, material extrusion, material jetting, directed energy deposition, and powder bed fusion [1]. Each process has its advantages and limitations, and selection of the process depends on different factors, such as the targeted material and quality of the final product. The swift development in technologies of Additive Manufacturing with open-sources lets designers and non-designers to use the AM even as a hobby [3]. This research starts by understanding the basic principles and techniques of Additive Manufacturing and its advantages in developing customized products especially for Metal materials with obtaining its positioning and importance in the industry and be knowledgeable about how and when this technique can be utilized.

1.2 MOTIVATION

Traditional manufacturing or conventional manufacturing might require several stages during the process of producing and manufacturing complex parts that makes the cost of the complex part to be very high. Alternatively, Additive Manufacturing is very flexible when it comes to shaping and changing the design with initiating totally new designs by unlocking new methods in the design and manufacturing with achieving cost-effective and weight reduction results that cannot be achieved by traditional manufacturing. Therefore, the utilization of design optimization with Computer Aided Design (CAD) programs can be very beneficial and maximized in AM technologies, such as topology optimization, lattice optimization, and generative design.

However, complex shapes do not guarantee strength, and consequently it is critical for AM parts to have sufficient strength in order to be used as commercial products especially for metal parts. Since there is not much work related to the material behavior of metal additive manufacturing, this

topic was selected to experimentally investigate the material behavior of metal additive manufacturing in order to compare it with the traditional manufacturing. Therefore, the expectation after this work is to know where the metal additive manufacturing stands in terms of replacing it with traditional manufacturing, which can be a guide for future design optimization industry.

1.3 OBJECTIVE

The objective of the thesis has been selected based on the gap found in the literature review. The utilization of Additive Manufacturing (AM) is generally known for manufacturing complex parts and customized products. Therefore, the literature review covers an overview of AM with Metallic components along with brief about design optimization techniques that can maximize the utilization of AM with complex parts, which includes Topology Optimization (TO) and Generative Design (GD) approaches. It also covers previous studies related to material behavior of metal AM with more focused on 316L Stainless Steel material.

Utilizing design optimization in AM can be a great method for weight reduction of parts with cost-effective solution; however, it is important to analyze especially for complex parts with considering creating special shapes of surfaces and new shapes of inner structures. Previous studies have been conducted on experimenting the effect of changing the thickness and building orientation with 316L Stainless Steel material, but each study has been investigated separately with different process parameters. Hence, it is critical to investigate both effects with the same process parameter and build plate when considering printing a complex part as one piece.

Therefore, the aim of this thesis is to study the material behavior in the metal additive manufacturing with the effect on changing the orientation and size on parts printed with the same

process parameters and building plate. Consequently, 316L Stainless Steel material with different thicknesses and building orientations have been selected in order to get an experimental data that can be analyzed and compared with the material behavior of the traditional manufacturing. Therefore, the journey of the project is as follows:

Phase 1: Understanding the basics of additive manufacturing and what can be done with additive manufacturing especially in metal products, and where is the current market in this field.

Phase 2: Selecting a specific topic in this field to be experimentally studied. Identifying the requirements for the study with considering all the existing challenges and limitations.

Phase 3: Designing the specimen to be printed by additive manufacturing and selecting the process parameters.

Phase 4: Print the parts which is tensile test specimen with different dimensions and building orientation.

Phase 5: Experimental tests for printed parts that includes tensile, hardness and surface roughness to followed by looking at the microstructure of the materials.

Phase 6: Analyzing the databased on the experimental results.

1.4 METHODOLOGY

The methodology of the work is initiated by identifying the optimal design of a part that can be manufactured by MAM utilizing the process of Directed Metal Laser Sintering (DMLS) within the specification of the machine in terms of the building volume and applicable materials. The process starts by selecting parts to be printed by metal additive manufacturing with the material of

316L Stainless Steel with considering different parameters, orientations and dimensions. Five parts are considered to evaluate two scenarios, which are the effect of changing the thickness along with changing the building orientation. All parts are tensile test specimens, and each part is to be printed with three samples in order to validate the experimental data. These parts are to be experimentally studied to understand the material behavior in metal additive manufacturing by applying tensile tests, hardness tests, surface roughness, X-ray diffraction, and optical microscope. The parts are printed by GE Concept Laser M1 machine.

Therefore, the experiments should provide insight into the microstructure side as well as mechanical properties. Also, it should be able to understand the reasons behind what is being observed and provide hypothesis for the observed results. If microstructure is a bit challenging to get acceptable results, which can be expected, the surface roughness and hardness results should also be enough. The process is summarized as follow:

- **Material Selection:** 316L Stainless Steel has been selected since it is one of the main materials that can be used in various applications.
- **Design of Part:** the selected design for parts is the tensile test specimen in order to be able to perform tensile test to obtain the mechanical properties of additively manufactured 316L Stainless Steel considering the effect of changing the geometry and printing orientation followed by microstructure analysis.
- **Printed Parts:** the printed parts are tensile test specimens using Directed Metal Laser Sintering (DMLS).
- **Tensile Test:** the tensile test has been conducted in a machine with load up to 50kN in order to reach the required load of all printed parts.
- **Hardness Test:** hardness test is conducted by using Rockwell B.

- **Surface Roughness:** analysis of surface roughness has been conducted for all parts.
- **X-Ray Diffraction (XRD):** XRD has been conducted for all parts to evaluate the printed material behavior pattern among all parts.
- **Optical Microscope:** Parts have been on the optical Microscope to measure the effect of geometry change and building orientation in porosity.
- **Composition Analysis:** Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray (EDX) has been conducted to identify the chemical composition of the printed parts.

CHAPTER 2

LITERATURE REVIEW

2.1 BACKGROUND OF ADDITIVE MANUFACTURING

The procedure of making a three-dimensional object was started and developed in the early 1980s to manufacture an object by the technique of building a layer by layer with the name of rapid prototyping (RP). The primary raw materials used in rapid prototyping were liquid, solid and powders [4]. The technology of Additive Manufacturing becomes a focus area in academic researches as well as in the manufacturing industry because of the potential capabilities that can be achieved to manufacture very complex and functional parts from 3D CAD design, which is hard to be manufactured by the traditional conventional manufacturing process. Additive Manufacturing also has the potential of minimizing current constraints in terms of design geometry, reducing cost of manufacturing, and increase production time [1]. Large scale manufacturing companies from different industries started to think about producing critical parts by Additive Manufacturing since the potential growth of the technology is not only limited to rapid prototyping and customized products. Therefore, the technology of AM can be utilized in producing parts that is difficult to be produced by conventional manufacturing [2].

The development of Additive Manufacturing technologies and processes are on-going since the start of the technology up to now. Several Additive Manufacturing methods and processes have been industrialized that includes Sheet Lamination, Material Jetting (MJ), Material Extrusion,

Powder Bed Fusion (PBF), and Directed Energy Deposition (DED). One of the most common processes to be used for metal components by AM is the PBF [1].

However, there are some challenges and limitations of each process. One of the main challenges in Additive Manufacturing technologies is to confirm the designed part is able to be manufactured by Additive Manufacturing in order to be more robust with cost-effective solution. It mainly considers two properties, which are fragility and printability. The fragile of manufactured component means the capability of the part to withstand the process of post printing along with the normal use. On the other hand, the printability of the part means the capability of the AM process to build the correct design and geometry of the part [2]. Also, the main challenge in terms of the quality in AM is the mechanical properties, which has limited repeatability and stability of the manufactured part. In general, the quality of the part is directly affected by the microstructure of the material in the processes of Additive Manufacturing. The expected defects that might occur in Metal parts by using the Powder Bed Fusion (PBF) process such as cracks, porosities and residual stresses is due to several factors that includes laser power, laser scanning speed and hatch distance [1].

The diversity in application of Additive Manufacturing processes along with the expanded usage of materials allow for manufacturing metallic components directly with meeting the customer's needs and requirement with regards to mechanical properties and accuracy of geometry. For production of custom parts, it is critical to fabricate complex geometries with maintaining high precision and accuracy. Therefore, the technology of Metal Additive Manufacturing (MAM) is used extensively in order to add value to the manufacturing industry with wide range of creativity and new opportunities. The recent developments of manufacturing, materials and modelling

changes the concentration of Additive Manufacturing from only rapid prototyping to be more into an industrial production of metallic components.

2.2 EVOLUTION OF METAL ADDITIVE MANUFACTURING (MAM)

The advantages of Additive Manufacturing processes are remarkable in rapid production of parts as well as the freedom of design with the capability of fabricating single or multiple parts from large diversity of materials available in the market. The evolution of Material Additive Manufacturing (MAM) was briefed by Tim Gornet and Terry Wohlers which the commercialization of the technology of Stereolithography (SLA) was used to manufacture industrial parts, and the method is to solidify thin layers of liquid polymer that is sensitive to ultraviolet (UV) light by using laser. The primary use is for fabricating prototypes [5]. The first development of commercialized SLA system in the world was SLA-1 by 3D Systems company in 1987 [6]. Other companies later on had developed other commercialized SLA systems in the market. Two leading companies in SLA are 3D Systems and EOS. EOS developed STEREOS 400 in 1990s, and system of Mark 1000 SL by Quadrax also entered the market at the same time [7].

The development of metallic in Additive Manufacturing started in the early of 1990s. It started by an agreement between Electrolux RD and EOS to develop the technology of Direct Metal Laser Sintering (DMLS). The collaboration concluded by commercializing EOSINT M 160, and it was the first AM of metallic parts [7]. Subsequently, in the year of 1991, three different processes in Additive Manufacturing were commercialized, which were Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC), and Fused Deposition Modelling (FDM) by the companies of Helisys, Cubital, and Stratasys, respectively [8]. The process of LOM starts from binding metal

foil or sheet material in a layer-by-layer by the source of digital guide laser to build 3D metal object. The process of SGC is similar to SLA technique, which structure of 3D is built by liquid photopolymers. The process of FDM starts with extruding the material of thermoplastic in a filament form to fabricate the part in layer-by-layer technique.

The Selective Laser Sintering (SLS) was introduced by DTM, bought by 3D System, and Solidform in 1992. SLS utilizes the heat source of laser beam to fuse the powder material [9]. The technique of Direct Shell Production Casting (DSPC) was patented by MIT in 1993 and marketed by Soligen technologies [10]. In 1994, the machine of EOSINT M160 was introduced to the market for prototyping using the technique of DMLS. In the following year, EOS developed the system named EOSINT M250 that is capable to produce metallic parts. Around the year of 1996, 3D printer of Z402 was launched by Z-Corp in order to build 3D model by powder material of plastic-based with liquid binder of water-based. AeroMet company established in 1997 created laser AM system to process a wide range of powder materials, particularly Titanium Alloy powder, by utilizing the source of high-power laser. The development of metal powder technology named Laser Engineering Net Shaping (LENS) was by Sandia National Labs in the United States of America in 1998 and was commercialized after that by Optomec [11]. The Additive Manufacturing system of powder laser interaction was introduced in 1998 by Optomec that utilizes the technique of powder feed laser energy deposition. Later, DMG and Trumpf were the leading in the development of DED system [4].

The system of Controlled Metal Build-up (CMB) was introduced by a German company called Roders in 1999. At the same period, RTS-300, which is Pro-metal rapid tooling, was developed by Extrude Hone, which is now ExOne, to fabricate metal components as well as high-value tools. Fockele & Schwarze company in Germany developed the system of steel powder Selective Laser

Melting (SLM) in the year of 2001. Technique of laser curing to fabricate 3D objects with minimum wastage of material was developed by Concept Laser. Moreover, Swedish company called ARCAM developed the technology of electron beam PBF that utilize high power source from electron beam to manufacture customized metal components. On the other hand, Trumpf developed the technique of PBF in the year of 2003 to melt the metal alloys directly by the source of laser energy. After that, the system of T612 was introduced by Solidscape to produce wax patterns for the process of investment castings [4].

EOSINT M270 system was introduced in 2006 by EOS with the possibility to construct parts with powder of cobalt chrome. Later, technique of Rapid Plasma Deposition (RPD) was developed by Norsk Titanium in 2007 that was an adapted method of Additive Manufacturing from conventional arc welding of plasma. The main applications of RPD are aerospace and aircraft. Also, ARCAM launched A2 Electron Beam Melting (EBM), and EOS launched Formiga P100 Laser Sintering. Connex500 is a multi-material machine was introduced by Object Geometries in the year of 2008 that works based on the technology of polyjet matrix. SLM250-300, which is a Selective Laser Melting (SLM) technique, was commercialized by MTT. After that, EOS-M was developed in 2012 by EOS to produce accurate metal alloys in order to manufacture jewelries. There was a drop of the market value of several Additive Manufacturing companies in 2015 even though the systems of metal PBF continued to be robust in different industries, such as energy, oil&gas, and aviation [4].

In 2016, HP company along with Desktop Metal joined the market with commercializing the technology of Binder Jet (BJ) for metal. Later on, large corporations realized the potential and invested in improving the technologies to resolve the existing concerns. Figure 1 summarizes the above in a simple process.



Figure 1: Evolution of Metal Additive Manufacturing processes [4]

2.3 BASIC PRINCIPLES OF ADDITIVE MANUFACTURING TECHNOLOGIES (OVERVIEW)

The customer's requirements and demand in the market have enlarged to produce products with specifications that includes size, quality, shape, and lead time of manufacturing, in which the main requirements are to produce customized parts with high quality and minimum time of production. Therefore, these requirements directed the market to swiftly develop technologies of Additive Manufacturing and advanced later on to enter the metal market. Then, the development of Metal Additive Manufacturing (MAM) has continued up to now. The classification of processes and technologies in Additive Manufacturing is based on the raw material that is used to manufacture the part. As the focus area in this research is metal, there are four categories of technologies and processes in Metal Additive Manufacturing, which are:

- 1- Liquid
- 2- Solid
- 3- Wire
- 4- Powder

Figure 2 lists all categories of raw material and sub-category for the technologies of each raw material.

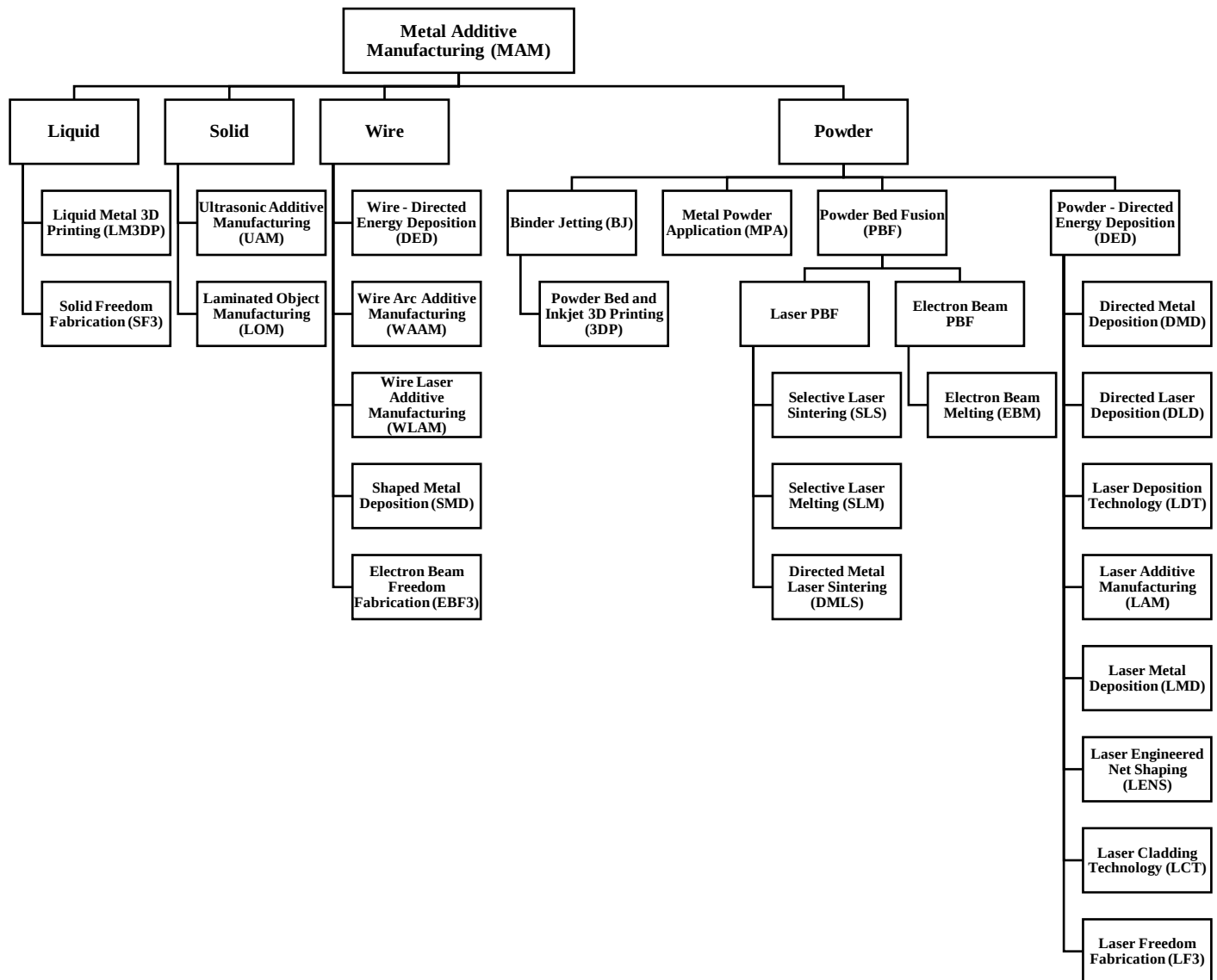


Figure 2: Classification of Metal Additive Manufacturing processes based on raw material [4,12]

Pratheesh Kumar et al. [4] summarized the comparisons of the processes of Metal Additive Manufacturing in a table as shown in Table 1 to cover different aspects that includes the nature of the process, principle, and technology along with advantages, limitation and uniqueness.

Table 1: Comparison of process nature in Material Additive Manufacturing processes [4]

Raw Material	Manufacturing Process	Process nature	Principle	Technology	Advantages	Limitations	Unique Features
Liquid	LM3D	Metallic wire is fed continuously into the inert gas chamber surrounded by coil winding, which melts the metallic wire, based upon the table motion, molten metal gets added up layer-by-layer.	Magneto hydrodynamic droplet generation	Acoustic ejection droplet	1) High arbitrary shapes can be fabricated 2) Unique metallic grain structure can be obtained with improved mechanical properties	1) Processing cost is high 2) Energy and time required to fabricate a parts is also high	1) Maximum deposition rate can be achieved (540 g/hr) 2) Droplets range 50–500 μm diameter
	SF3	Ultra violet rays are used to cure photo sensitive polymers forms a layer. With the CAD data, table will move to achieve required geometry	Selective curing of photo polymer (resin) using a UV laser	Photopolymerization	1) Smooth and high quality surfaces can be obtained 2) High dimensional accuracies can be achieved	1) Limited mechanical and thermal strength 2) Complex geometry parts cannot be fabricated	1) Layer thickness can be achieved up to 25 μm and minimum feature sizes 50–250
Solid	UAM	Sequential bonding of metal foil together by using ultrasonic metal welding in a layer-by-layer fashion. It also integrated with CNC machining facility to remove a material, thereby forming component	Plastic deformation and recrystallisation of metallic foils by the frequency of ultrasonic sonotrode	Embedding of various components into the metal matrix	1) Alloys can be directly fabricated	1) The time required to cool the component is high, so net time required to fabricate component is high	1) Embedded sensitive- functional component between the foil layers and bond the structure into the dense metallic structure
	LOM	The object is fabricated by successively layering sheets of build material, bonding them together by heat and pressure. Furthermore, cutting them into desired shape by carbon laser	Utilisation of localised energy source (Ultrasonic/ laser) to bind a stack of metallic sheets precisely	Selective deposition and lamination	1) Raw materials are readily available 2) Large parts can be made	1) More complex geometries cannot be fabricated 2) Dimensional accuracy is less 3) Solidity depends upon curing and resins used	1) it is independent of materials, thus metals and ceramics can be fabricated. The ceramic tape thickness 190–200 μm can be fabricated
Wire	WAAM	It uses electric arc to melt the metallic wire. WAAM is controlled by robotic arms. The melted clad over the substrate will be in the form of beads, which will stick together to form a layer.	Formation of melt pool when the energy source melts the rod	Extrusion of molten metal into beads	1) Cheaper process and raw materials 2) Can be used for repair process	1) residual stress and distortions. 2) requirement of shielding gas	1) Deposition rate (1 kg/hr–4 kg/hr) can be achieved 2) Large components weighing above 10 kgs can be fabricated
	WLAM	The high power laser source is used to melt the continuous metallic wire to produce 3D metallic parts.	Formation of melt pool when the energy source melts the continuous wire	Extrusion of molten metal in the form of beads	1) High degree of freedom for designing a part with manufacturing the near net shaped components with higher accuracy. 2) Reduced material wastage	1) Quality of parts manufactured by this method is affected by the process dynamics.	1) Laser beam diameter 1.35 mm and maximum laser power of 400 W
	SMD	It is a process by which the metallic wire is continuously melted and deposited along a predefined path until required thickness to achieve final component.	Formation of melt pool when the energy source melts the continuous wire	Multi-pass welding technology	1) Reduced of lead time, 2) Less material wastage, less inventory costs.	1) Irregular liquation, rapid change in thermal cycles 2) Induced cracks on HAZ	1) This process will reduce the lead time by 60% for fabricating new part as well as prototype 2) Reduces the cost of manufacturing by 40%

Raw Material	Manufacturing Process	Process nature	Principle	Technology	Advantages	Limitations	Unique Features
	EBF3	A continuous thin wire is forced and focussed over an electron beam. The platform is lowered, and the process is repeated until the required thickness of component is achieved.	Formation of melt pool when the energy source melts the continuous wire	Cross cutting rapid manufacturing Technology	1) Consumes less electricity and material 2) Improve the endurance of the component	1) The large components can't be produced by this process, expensive process	1) About 90% complete utilisation of feed stock material 2) Deposition rate 330–2500 cu.cm/hr, power usage can be 95% efficient.
Powder BJT	INKJET 3DP	The recoating blade will move and evenly spreads the powder over the bed. Then, the carriage that carries bonding materials as well as coloured ink will moves over the bed. This carriage will selectively spray the bonding material and coloured ink over the powders	Drop- on– demand inkjet printing technology	Powder bed and inkjet head printing	1) Very large parts and complex metal geometries can be fabricated 2) Excellent for low to medium batch production	1) Lower mechanical properties than DMSL/SLM parts 2) Only rough details can be printed	1) Droplets diameter around 80 µm can be achieved 2) It produces metal parts and full-colour prototypes at a fraction of the cost compared to DMLS/SLM and Material Jetting respectively
Powder Bed	Fusion	SLS	A process to form 3D solid part by combining the powder material with the application of heat and pressure	A layer of powder spread on the bed is selectively sintered by CO2 laser in a 2D cross section	layer by layer 3D printing technology	1) Very fast and accurate process 2) Superior surface finish can be obtained 3) Material wastage is minimum	1) Highly skilled operators are required 2) Cool down is almost equal 50% of part fabricating time, leads to long production time 3) Post processing is required
	SLM	(minimum ± 0.3 mm) 2) A minimum layer thickness of 0.08 mm Similar to the SLS process, A process to form 3D solid part by combining the powder material with the application of heat and pressure in a inert gas atmosphere		A layer powder is melted on the bed instead of sintering with the help of high energy laser beam	layer by layer 3D printing technology	1) A high precision and high quality metal parts can be fabricated 2) Composites and ceramics can be also fabricated	1) Relatively new technology, very huge cost of machine and materials, inert gas supply is required.
DMLS	thickness- 20 µm A 3D object is fabricated in a layer by layer manner with a help of computer controlled laser technique.	Application of high power laser source is directly supplied on the entire layer of bed, thereby metal powder fuses together to make a product		layer by layer 3D printing technology	1) Porosity can be controlled to the maximum extent	1) An expensive process compared to other process 2) Offers small build volume technologies	

Raw Material	Manufacturing Process	Process nature	Principle	Technology	Advantages	Limitations	Unique Features
EBM	An electron beam is used to melt the powder material which is emitted by a tungsten filament controlled by coil	A 3D object is fabricated by melting and fusing the layer of metal powder with a help of computer controlled electron gun	layer by layer 3D printing technology	1) High density parts can be obtained (above 90%) 2) Good mechanical properties can be obtained	1) Compared to laser melting parts 2) Slow and Expensive process 3) Applicable to limited set of metals	1) A layer thickness of 0.1% of titanium and its alloys give a better results in faster time reduces the cost of 35% compared to other techniques	
Powder	MPA	A process where metal powder is applied by kinetic compacting to build completely sealed materials, in a Hermle five-axis machining centre to create parts with highly complex inner geometries.	A thermal spraying process for metal powders in which material is uniformly dispersed by kinetic compacting and micro forging	Thermal integrated with Metal powder application technology	1) Complex material can be fabricated 2) Multiple materials can be fabricated simultaneously	1) High initial investment for machines	1) Powder particles having grain size 25–75 μm can be easily processed
Powder DED	DMD	The moving head which contains the energy beam and powder feed nozzle. The powder from the feed nozzle is propelled to the point where the energy beam and powder can actually meet, then the powder material starts melting and deposits over the substrate.	The melted layer of clad will be formed with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) No wastage of powder material	1) powder materials cannot be reused like SLM and SLS process	1) The deposit width is between 0.6 and 2.4 mm while the layer thickness lies between 0.2 and 0.8 mm.
	DLD	Powder jet and laser source will be either coaxial or non-coaxial. But the laser beam used in this process provides high stability to the process, because of its flexibility, the beam focus can be narrowed over wide region over the substrate.	The powder material is melted by laser source will be formed to required shape with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) High density and complex parts.	1) Large parts cannot be fabricated	1) Highly stable and beam focus can be narrowed over wide region over the substrate
	LDT	Under highly controlled atmosphere, the high powder laser beam is focussed over the powder metal jet, this melts the powdered metal over the base material. The material gets added up in a layer by layer manner	The powder material is melted by laser source will be formed to required shape with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) Highly slender clads can be produced, so it is suitable for coating applications	1) High geometric curvatures cannot be coated because of traverse system	1) The layer thickness is around 0.125–1 mm and layer width are around 1–4 mm.

Raw Material	Manufacturing Process	Process nature	Principle	Technology	Advantages	Limitations	Unique Features
	LAM	This process is based on melting the powder material over a substrate by using a source of laser beam. This technique is particularly useful for the replacement of parts or for the inclusion of materials in areas where there are design changes or specific requirements for materials.	Formation of melt pool when the laser energy source melts the metal powder	Metal jetting technology	1) Fabrication of all variety of materials	1) The process was slow and labour-intensive	1) can be used for coating as well as 3D parts printing applications
	LMD	This process is a generative method of adding materials over the substrate. The principle is same of DMD, but the difference is that laser beam and powder nozzle are held coaxially	Formation of melt pool when the laser energy source melts the metal powder	Metal jetting technology	1) High build rates 2) It provides rough as well as fine structures	1) Limited range of powder grain sizes can be used	It is flexible for even and uneven surfaces
	LENS	Uses the same principle as for LMD process, high intensity laser beam is focussed coaxially towards the powder jetting region, which creates a molten pool, melts over the substrate and add as a clad layer by layer	The powder material is melted by laser source will be formed to required shape with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) Ability to fabricate the high dense parts and high complex prototypes	1) Restricted to small lot part production	1) Ability to tailor deposition parameters to feature size for speed, accuracy, and property control
	LCT	This technology also closely resembles to LMD, LENS and DLD process, but in this process either powder or wire is used as a raw material, which is specific towards the coating process. The powder or wire will be melted by laser, creates a molten pool and finally gets coated over the surface	The powder material is melted by laser source will be formed to required shape with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) Low exposure time and depth of the laser 2) high surface quality and low warpage 3) No post-processing necessary	1) Cannot be used to fabricate the 3D components	1) specific towards the coating process
	LF3	Metal powder is coaxially adjusted towards the high-power laser beam focal point, gets melted and deposited over the substrate	The powder material is melted by laser source will be formed to required shape with the help of motion from the moving head which traces the path of CAD data.	Metal jetting technology	1) High quality surfaces can be obtained 2) High dimensional accuracies	1) High cost of machine 2) Complex geometry parts cannot be fabricated	1) manufacturing of thin wall components

2.4 OPERATIONAL CONSIDERATIONS IN ADDITIVE MANUFACTURING

Understanding the capabilities and potentials is an important factor to be considered for any manufacturing process before starting the production as various critical parameters are involved in the characteristics of product, such as material, shape, size, and geometry. This also applies to the Additive Manufacturing especially with the differences in each process in terms of buildup rate and characteristics of microstructure and quality. The most general considerations in all processes are quality, time and cost. Comparing characteristics of build between commercial systems of Additive Manufacturing is shown in Table 2, and mechanical properties of materials is in Table 3.

2.4.1 QUALITY

Quality is an essential factor for any manufacturing industry that must be achieved with maintaining low cost of production. The definition of quality can be explained differently, but as a general rule, meeting the customer's requirements and be satisfied. Usually, customers care about critical aspects including characteristics of both mechanical and material, accuracy of dimension, and quality of surface.

2.4.1.1 ACCURACY OF DIMENSION

The accuracy of dimensions differs from process to another. The process of SLA manufactures good accuracy of dimension of around ± 0.15 percent. The process of SLS is usually utilized in manufacturing geometries with complexity because of its accuracy of around ± 0.3 percent. Moreover, processes of SLS and DMLS along with SLM have minimum errors in dimensions of fewer than 0.1 mm for lengths of around 100 mm. In comparison of accuracy in SLA and SLS

depends on the volume of the part, the accuracy is high in SLA for volume less than 1000 cm³ although the accuracy is high in SLS for volume more than 1000 cm³. The process of Material Jetting has the highest accuracy of ± 0.1 percent. Additionally, the accuracy of dimension in EBM is half of the powder process in the applications of materials with high temperature, such as Titanium alloys; however, the accuracy of dimensions in the DED is lower for same applications [4].

2.4.1.2 QUALITY OF SURFACE

Parts that are manufactured by Additive Manufacturing normally have a rough structure because of the unbounded particles during molten on the external surface. When it comes to the technique of the powder bed, the roughness of the surface is below 15 mm, and manufactured parts by DMLS and SLS with applying post processing increase the quality of the surface finish in comparison of the parts without applying post processing. On the other hand, the process of EBM has a range of surface roughness between 25 to 35 mm while the process of DED creates a better smooth surface with range of roughness between 10 to 25 mm [4].

2.4.2 TIME

Time mainly depends on the rate of production and speed, which varies in each process. The rate of production differs remarkably based on several main factors, such as build rate, properties, and capabilities. Therefore, the lead time is affected by these factors.

For powders, processes of DMLS and SLS have quicker build rate than SLM. Both DMLS and SLS require post processing to attain closely fully dense components. LAM and DMD have the

capability of manufacturing non-porous parts with higher build speed. Processes of DED and EBM are relatively quicker to build parts without requiring finishing treatments [4].

2.4.3 COST

The total cost of production is subjected to numerous aspects that includes cost of machine operation, raw material, and hour rate. The production time is also counted in the cost of the product, which is different in each process because of the process nature and ability of the machine. As a general rule, the least expensive process of manufacturing is the powder with medium size chamber while DED and EBM processes are the most expensive ones [4].

Table 2: Comparison of build characteristics of Metal Additive Manufacturing processes [4]

Raw Material	Manufacturing Process	Machine	Build envelope	Build Capability	Beam Size	Layer Thickness	Build Rate	Surface Finish (μm)	Residual Stress	Heat Treatment	Post Processing
Liquid	LM3D	WOL 3D Printing	Large	Contours and Complex surface structures	90–100 μm	50–200 μm	$>320 \text{ mm}^3/\text{s}$	Ra 6–8	Medium	—	Sintering process
	SF3	Form 3L	Limited	Complex and intricate designs	70–85 μm	25–300 μm	$>280 \text{ mm}^3/\text{s}$	Ra 6–8	Medium	—	Bead blasting, surface machining processes
Solid	UAM	SonicLayer 4000	Limited	Complex work, including parts with embedded components and even parts made from dissimilar metals.	—	0.2	$>200 \text{ mm}^3/\text{s}$	Ra 14	High	—	Surface Grinding process
	LOM	LOM 1015 helisys	Limited	Not possible to print intricate and complex geometries, but it is a cheap process and freeform fabrication process are making it a good prototyping technique	—	0.1–0.19	$>200 \text{ mm}^3/\text{s}$	Ra 12–14	High	—	Surface Grinding process
Wire	WAAM	FIT technologies	Unlimited	Complex geometry, Cellular structure, Building hollow channels	1–2 mm	4.8 mm	600 cm^3/hr	Ra 20–26	High	High pressure heat treatment	Polishing and blasting
	WLAM	Sciaky	Limited	Complex geometry, Cellular structure, Building hollow channels	0.2 mm	0.5–2 mm	200–500 cm^3/hr	Ra 30–32	high	thermal forced treatment	machining process and Polishing
	SMD	Sculpteo	Limited	Complex and intricate designs	0.2–2 mm	0.5–2 mm	300–550 cm^3/hr	Ra 20–30	medium	thermal forced treatment	Bead blasting and lapping
	EBF3	Asiminternational	Limited	Complex and intricate designs	1–2 mm	0.5–2 mm	400–550 cm^3/hr	Ra 30–35	medium	thermal forced treatment	machining process and Polishing
Powder BJT	INKJET 3DP	HP jet fusion 3D printers	Limited	Complex geometry and Building hollow channels	—	Metal: 35–50 μm Full-color: 100 μm Sand: 200–400 μm	1.1 inch^3/hr	Ra 6–10	High	Stress Relief	Bead blasting, Infiltration and sintering
Powder Bed Fusion	SLS	Benchtop SLS 3D printers- Fuse 1	Limited	Production of complex geometries, such as monolithic designs, lightweight components, and mass-customized products	400 μm	100–120 μm	$>120 \text{ cm}^3/\text{hr}$	Ra 6/8 μm	High	Annealing, Normalising, tempering, Quenching	Tumbling, Dyeing, Painting, metal coating and flocking
	SLM	SLM solutions (SLM 125)	Limited	Complex geometry, Cellular structure, Building hollow channels	Diameter of 80 μm –115 μm	20 μm –90 μm	Up to 113 cm^3/hr	Ra 9/12 μm , Rz 35/40 μm	High	Annealing, Normalising, tempering	Stress relief and Hot isostatic press

Raw Material	Manufacturing Process	Machine	Build envelope	Build Capability	Beam Size	Layer Thickness	Build Rate	Surface Finish (μm)	Residual Stress	Heat Treatment	Post Processing
Powder	DMLS	EOSINT M 270	Limited	Complex geometry, Cellular structure, Building hollow channels	400 μm	20–50 μm	100 cm ³ /hr	Ra 6/10 μm	Medium	Annealing, Normalising, Quenching	Media blasting, metal plating, polishing, and micro-machining
	EBM	Spectra Arcam-S400	Limited	Complex geometry, Cellular structure, Building hollow channels	200 μm	100 μm	55–80 cm ³ /hr	Ra 25–35	Medium	Annealing, Normalising	Sintering process
	MPA	Herm's MPA 5 axis	Large and Flexible	Complex geometry, contours Cellular structure and Building hollow channels	200–400 μm	500–600 μm	90 cm ³ /hr	Ra 12–14	Very low	Annealing, Normalising, Quenching	Media blasting, metal plating, polishing, and micro-machining
Powder DED	DMD	DMG Mori Seiki AG	Large and Flexible	Complex geometry, Cellular structure, Building hollow channels	200–400 μm	500–600 μm	50–100 cm ³ /hr	Ra 16–18	Low	Annealing, Normalising, Quenching	Metal plating, and micro-machining
	DLD	DMD-505D	Large and Flexible	Complex geometry, Cellular structure, Building hollow channels	200–400 μm	650–700 μm	16–320 cm ³ /hr	Ra 20–22 Rz 150–155	Low	Annealing, Normalising, Quenching	Media blasting, metal plating, polishing, and micro-machining
	LDT	DMG Mori	Large and Flexible	Building layers for coating applications	200–400 μm	700–750 μm	20–200 cm ³ /hr	Ra 28–30 Rz 140–160	Low	Annealing, Normalising, Quenching	Media blasting, metal plating, polishing, and micro-machining
	LAM	Laserline	Large and Flexible	Building layers for coating applications	200–400 μm	700–750 μm	16–250 cm ³ /hr	Ra 30–34 Rz 150–155	Low	Annealing, Normalising, Quenching	Sintering process
	LMD	Trumpff	Large and Flexible	Complex geometry, Cellular structure, Building hollow channels	200–400 μm	800–1000 μm	100–300 cm ³ /hr	Ra 50–60 Rz 150–160	Very low	Annealing, Normalising, Quenching	Media blasting, and micro-machining
	LENS	Additive manufacturing (3D printing network)	Large and Flexible	Complex geometry, Cellular structure, Building hollow channels	200–400 μm	800–1000 μm	100–300 cm ³ /hr	Ra 40–60 Rz 160–165	Very low	Annealing, Normalising, Quenching	Media blasting, metal plating, and micro-machining
	LCT	Oerlikon Mitco	Large and Flexible	Building layers for coating applications	200–400 μm	500–700 μm	16–320 cm ³ /hr	Ra 30–35 Rz 165–170	Low	Annealing, Normalising, Quenching	Sintering process
	LF3	DMG Mori	Large and Flexible	Complex geometry, Cellular structure, Building hollow channels	200–400 μm	800–1000 μm	20–300 cm ³ /hr	Ra 55–65 Rz 170–175	Low	Annealing, Normalising, Quenching	Polishing, and micro-machining

Table 3: Comparison of mechanical characteristics of materials produced using MAM techniques [4]

Raw material	Manufacturing process	Material	Orientation	Young's modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
Liquid	LM3D	Aluminium alloys	Horizontal and vertical	60–80	300–370	150–230	8–9.95%
	SF3	ABS	Horizontal and vertical	384–418	47–53	36–42	8–16%
Solid	UAM	Aluminium foils	Horizontal and vertical	70–90	150–160	70–80	11.5–25%
	LOM	Aluminium foils	Horizontal and vertical	80–100	165–180	65–75	12–18%
Wire	WAAM	Titanium alloys	Horizontal and vertical	110–130	890–1050	820–850	10–12%
	WLAM	Titanium alloys	Horizontal and vertical	110–130	900–1000	850–870	20–25%
	SMD	Inconel alloy	Horizontal and vertical	110–140	680–695	470–495	19–20%
	EBF3	Aluminium alloy	Horizontal and vertical	60–80	200–420	75–280	10–20%
Powder BJT	INKJET 3DP	Stainless steel	Horizontal and vertical	130–180	40–70	215–470	14.5–40%
Powder Bed Fusion	SLS	Polyamide (p-12)	Horizontal	2080–2140	50–55	35–40	08–20%
	SLM	Titanium alloys	Horizontal and vertical	110–125	1115–1125	1020–1055	10.5–12%
	DMLS	Titanium alloys	Horizontal and vertical	60–70	310–350	165–230	3–12%
	EBM	Titanium alloys	Horizontal and vertical	100–110	900–930	840–850	8–9.5%
Powder	MPA	Titanium alloys	Horizontal and vertical	110–130	940–1000	1020–1055	12–16%
Powder DED	DMD	Titanium	Horizontal and vertical	110–120	900–1000	800–870	10–12%
	DLD	Titanium	Horizontal and vertical	110–140	820–940	845–855	14–16%
	LDT	Aluminium	Horizontal and vertical	60–80	310–370	75–280	8–10%
	LAM	Hastelloy (Hast-x)	Horizontal and vertical	140–150	755–770	455–480	8–9%
	LMD	Titanium	Horizontal and vertical	110–130	900–1020	820–850	12–16%
	LENS	Stainless steel SS 316L	Horizontal and vertical	195–220	680–695	470–495	10–12%
	LCT	Stainless steel 410L (Fe-Cr-B-Si-Mo)	Horizontal and vertical	190–200	565–1327	282–1154	7–9.5%
	LF3	Titanium	Horizontal and vertical	110–120	850–980	850–980	21–23%

2.5 METHODS IN DESIGN OPTIMIZATION

Additive Manufacturing is a revolution to the manufacturing industry shifting the way of designing and manufacturing in different applications [13]. Technologies of Additive Manufacturing have opened the door for new approaches in design due to its flexibility to manufacture complex geometries that is very hard or impossible to do in the traditional conventional manufacturing. Therefore, it has the advantage of creating designs and to manufacturing parts with reduced weight whereas part's rigidity stays within the expectation [14].

Design optimization in AM can be a good method for cost-effective solutions in the aerospace industry [13] and other industries as well. The capability of production in AM is unique in dealing with complex geometries, which changes the traditional way of topology optimization and weight reduction to a new era [15]. Systems of Computer Aided Design (CAD) have been developed and

enhanced lately to be more user-friendly in terms of interface in order to be easier to work in by users. CAD programs became more simplified which results in increasing the efficiency to generate models with complexity in a shorter time [16]. Some studies were conducted in design optimization for the framework of 2D designs [17] while the majority and capabilities of CAD programs are for 3D models.

One of the main factors to be considered and determined before manufacturing in AM is the build orientation as it has a major effect in terms of accuracy of dimension, strength of the part, finish of the surface, support structure and errors along with time and cost of production. Therefore, identifying the optimum build orientation results in minimizing the required support structure, which has a direct impact to the build time and cost of material and post-processing [18].

2.5.1 TOPOLOGY OPTIMIZATION

Additive Manufacturing allows to have the freedom in design to manufacture functional components. Utilizing topology optimization in design phase helps to reduce the weight of the structure to be manufactured by AM [19]. The definition of topology optimization (TO) is a method of computational design with the purpose of optimizing material's distribution in a specified space of design with respecting constrains and loads in parallel with maximizing the performance of design. Topology optimization is commonly utilized during the early design stage in order to discover and evaluate several possibilities of design based on the set requirements, such as [20]

- Minimize weight
- Reduce stress

- Maximize stiffness
- Reduce displacement

An approach to optimize a design of a part by Topology Optimization is shown in a flowchart in Figure 3.

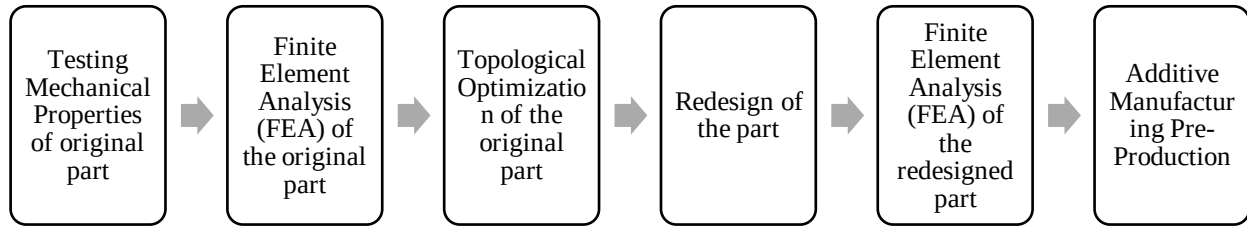


Figure 3: Flowchart of best strategy to optimize designed part [21]

2.5.2 LATTICE OPTIMIZATION

Lattice structure can be defined as a type of cellular architecture in 3D shape with integrated supports and nodes. For homogenous lattice structure, the mechanical properties can be customized by modifying the topology or the density. On the other hand, the properties of the heterogenous can be optimized by customizing the distribution of the material in the lattice. Thus, the lattice structure is utilized more and more in applications to reduce the weight. Manufacturing complex geometries used to be a major concern in traditional manufacturing; however, the technology of AM resolved this concern and increased the utilization of lattice structure. A case study was conducted by Guoying Dong et al. [19] to compare hybrid structure, pure lattice structure, and pure solid structure showed that results of simulation and experimental confirmed the hybrid has a higher yield strength, load of buckling, and stiffness than both pure solid and lattice structures.

2.5.3 GENERATIVE DESIGN

Generative Design is rapidly growing in CAD. It was developed due to the need of producing simultaneous complex parts in order to reduce the cost and time in model developments. Generative Design aims to reduce cost of production with optimizing created models dynamically [16]. Generative design can be defined as a method for creating large quantity of designs automatically through iterative algorithm while considering the defined limitations and criteria by the user. The use of generative design can be an assistant tool for designers to create products. Algorithms of generative design was mainly built based on the nature-mimicking. There are differences between generative design and shape optimization as generative design proposes numerous designs automatically with meeting the defined requirements from the designer while shape optimization concentrates in discovering one ideal design [22]. Therefore, the focus of generative design is to create new inspirational designs as it can generate unexpected solutions in terms of geometries [23]. The approach of generative design is evolutionary that is able to create alterations from the main design of a part with certain parameters, such as minimizing the mass or increasing the stiffness of the part. Each design generated by GD is processed at the same time with integrating Finite Element Analysis (FEA) with every iteration that is close to the set requirement until reaching the required safety factor. There are several advantages of utilizing the generative design during the process of development, which are: [24]

- The outcome optimizations from Generative design meet the requirements and set parameters.
- Reduction in weight
- Reduction in time of production

- Generations of various designs simultaneously with new and innovative designs
- Optimized designs that can be manufactured by Additive Manufacturing

Generative design can be utilized during the stage of conceptual design to explore different shapes of the product [25]. A study of redesigning a wind energy system by generative design showed that it is a practical method to optimize components for applications of electromechanical [24]. Additive Manufacturing and Generative Design are also used and applicable for fashion industry [26].

Generative design's overall procedure involves four phases, which is shown in Figure 4.

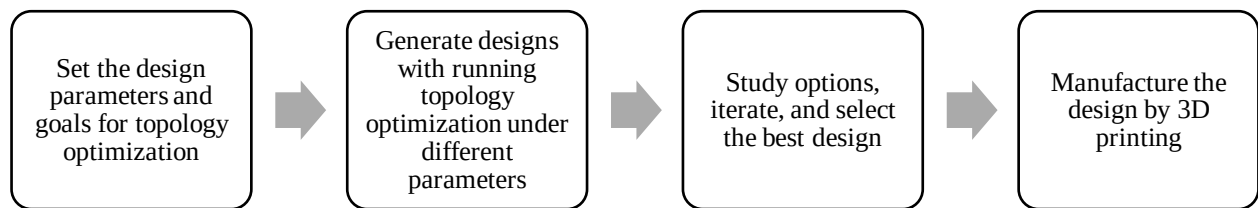


Figure 4: overall procedure of Generative Design [17]

AUTODESK FUSION 360

One of leading CAD systems in utilizing generative design is Autodesk Fusion 360, which has the function to work in a cloud-base with setting the required parameters to conduct the generative design, such as geometries, resolution, shape, materials, loads, and manufacturing types [27].

Initial design is always important in any industry as it works as the base of enhancing the design along with the manufacturing processes after it is finalized. Therefore, having an appropriate initial design can help the designer to accomplish better solutions in generative design. Generative design

is the future approach to be utilized by designers and engineers. Autodesk Fusion 360 has the feature of allowing all team members to access the design and can update and modify through cloud, which makes the work process easier during design. It also has a feature known as starting shape, which the designer can start the initial design in an easy way [27].

2.5.4 CASE STUDY OF GENERATIVE DESIGN AND TOPOLOGY OPTIMIZATION

Case study was conducted in a rocker by D. Vlah et al. [20] in 2020 with applying both generative design and topology optimization to compare their outcomes and results.

The initial model was captured from actual industrial design to be applied as the base of design for design optimization as shown in Figure 5.

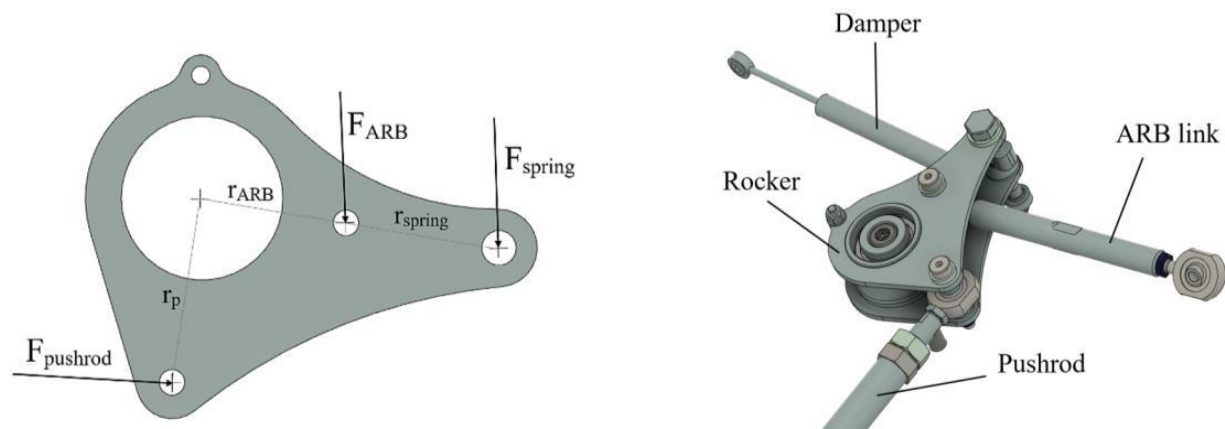


Figure 5: Acting forces on the rocker (left) and the suspension assembly model (right) [20]

Autodesk Fusion 360 was used for TO and GD. The workflow of TO and GD are shown in Figure 6 and Figure 7, respectively.

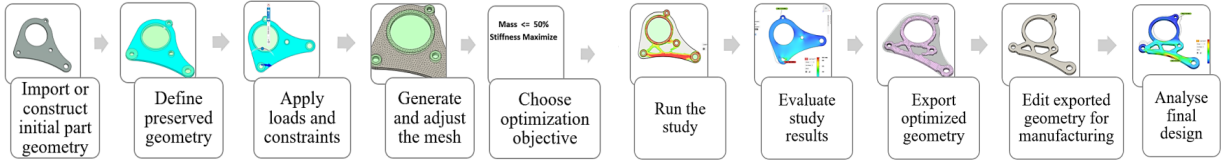


Figure 6: Process of Topology Optimization [20]

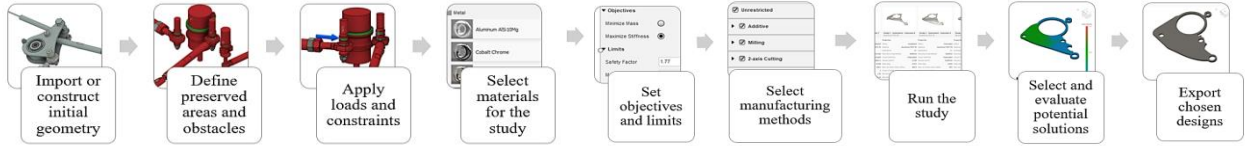


Figure 7: Process of Generative Design [20]

The result of TO is shown in Figure 8 and Figure 9 while the result of GD is shown in Figure 10.

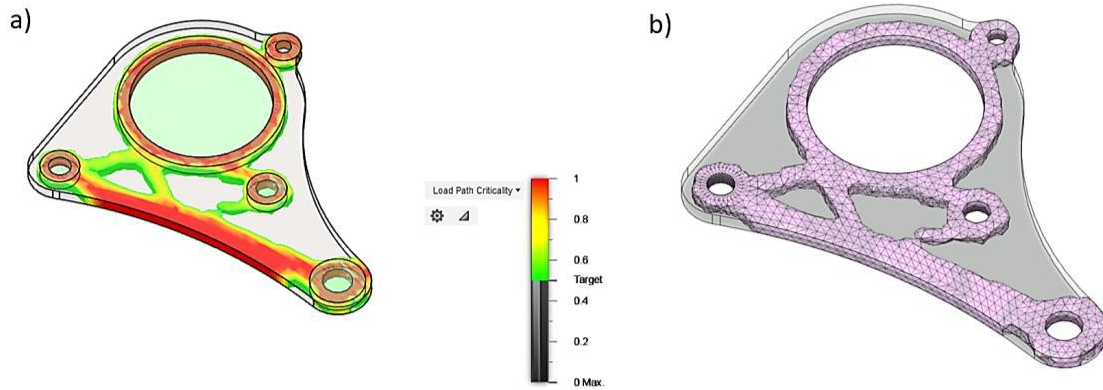


Figure 8: Optimization results as a) critical load path and b) mesh body [20]

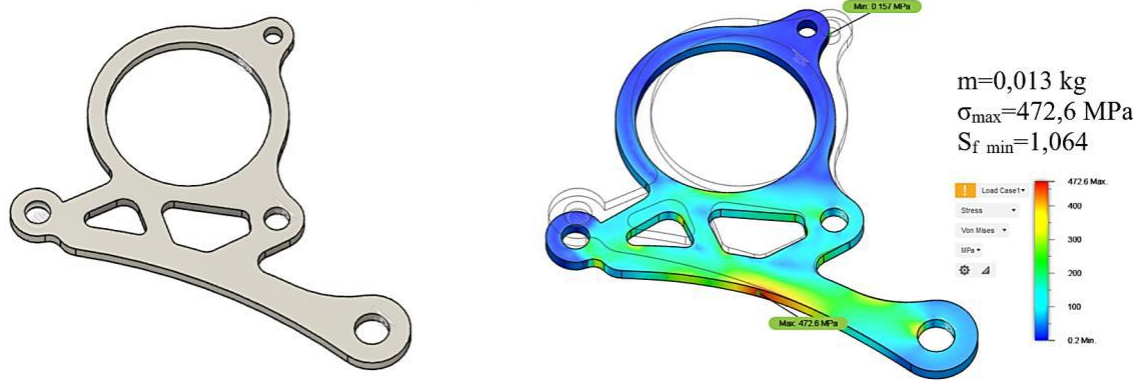


Figure 9: Geometry of final redesigned part (left) and stress analysis (right) [20]



Figure 10: Results of generative design [20]

It can be clearly seen that GD produced multiple options with different materials and safety factor of 1 while TO produced only one optimal design. Therefore, Autodesk Fusion 360 shows the performance of each design produced by GD in order to select the ideal one based on the set criteria as shown in Figure 11.

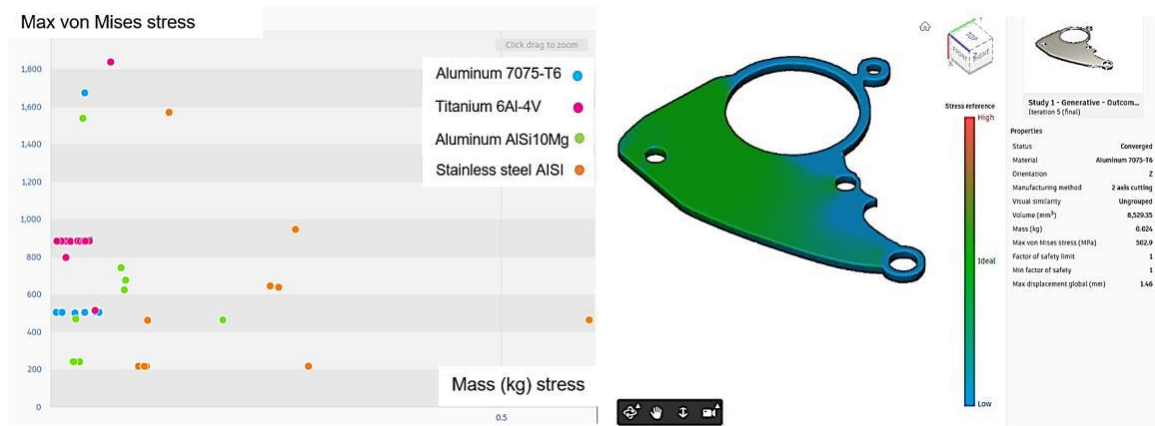


Figure 11: Generative design solution evaluation: design alternatives mapped in the design (left) space, stress analysis of selected design (right) [20]

Therefore, Table 4 summarized the general outcomes of the study.

Table 4: Requirements and parameters for topology optimization and generative design tools [20]

	Topology Optimization	Generative Design
Initial Geometry	Solid body of a maximum part volume	Surrounding bodies and/or surfaces (existing assembly or constructed parts)
Design Space Definition	Maximum volume and preserved geometry	Obstacles and preserved geometry
Number of Materials per Study	One	One or more
Design for Manufacturing	Not included	Numerous manufacturing methods
Study Result	Single as the most optimal design	Several optimal designs
Duration of a Study	Couple of minutes	Couple of hours
Parallel Design Comparison	N/A	Stress, mass, visual comparison
Additional Design Editing	Required	Not required for some cases

2.6 MATERIAL BEHAVIOR OF METAL ADDITIVE MANUFACTURING

The development in AM is massive due to its advantage of building up layer by layer that allows creating custom products with free-form design in parallel with reducing the usage of raw materials and lead time to produce the product [28]. AM technology gives a space for innovation in different aspects especially for Metal materials since the applications for metal is more sensitive with heavy duty use than other materials. Therefore, analyzing the material behavior of Metal AM is an important subject that contributes in the development of the technology as well as for the end product.

2.6.1 MECHANICAL PROPERTIES OF 17-4PH STAINLESS STEEL

A study about mechanical properties of additively manufactured 17-4PH Stainless Steel conducted by Andreacola et al. [28] in 2021 using Selective Laser Melting (SLM) process to evaluate the effect of changing the parameters in metal AM. The AM process and machine specification used are followings:

Additive Manufacturing Process	Selective Laser Melting (SLM)
Machine	SLM 280 from SLM Solutions GmbH
Effective Building Volume	280 mm x 280 mm x 320 mm
Laser Specification	Yb-fibre laser, 400 W
Gas Type	Argon Gas (Temperature up to 65°C)

The focus of the study is to conduct tensile tests with different sizes and orientations. The process parameters applied are the followings:

Laser Beam Diameter	75 μm
Laser Beam Power	200 W

Layer Thickness	800 mm/s
Laser Scanline Spacing	30 μm
Hatch Distance	120 μm

The nominal mechanical properties as a base of 17-4PH Stainless Steel is listed in the Table 5.

Table 5: Nominal Mechanical Properties of 17-4PH [29]

Mechanical Properties	Printing Direction	As-built	Heat Treated
Young's Modulus (MPa)	0°	171	154
	90°	154	182
Yield Strength (MPa)	0°	517	1024
	90°	506	1391
Tensile Strength (MPa)	0°	987	1359
	90°	931	1308
Elongation (%)	0°	26	16
	90°	28	14
Reduction of Area (%)	0°	56	27
	90°	56	26

Two sizes of tensile test specimen were printed and evaluated with total of 30 samples. The first size, 12 samples, is not up to the standard of tensile test specimen size shown in Figure 12.

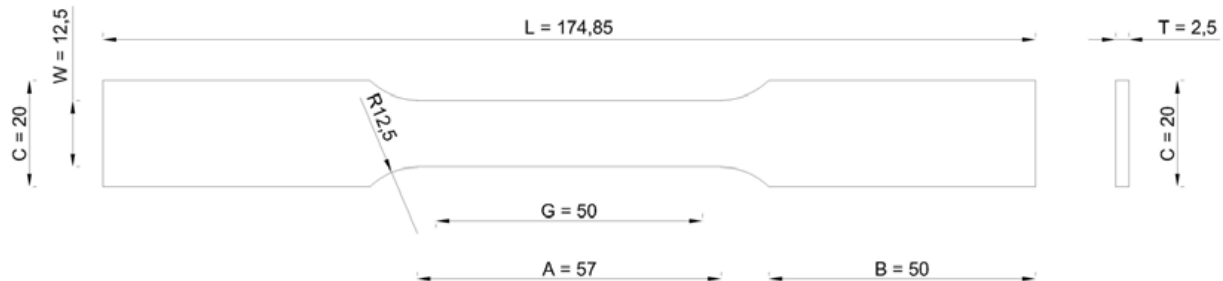


Figure 12: Dimensions of the first size of tensile test specimen [28]

Figure 13 shows how the tensile test specimen looked like on the building plate with the support structure.



Figure 13: Specimen on the top of the building plate with the support structure [28]

The intent from the first size is to assess the variances in the results of printed samples with different orientations and directions as well as with as-build and heat-treated samples. The directions for the first size were horizontal, 5 degree and 85 degree inclined, and vertical. For tensile test, it was performed at room temperature with maximum load of 600 kN and speed of 6 mm/min until the breakage of the specimen. Table 6 shows the result of the tensile test for the first size.

Table 6: Results of Tensile Test for the first size [28, 30, 31, 32]

Specimen	Printing Direction	Quantity	Heat Treatment	σ_y MPa	SD MPa	σ_u MPa	SD MPa	ϵ_u %	SD %
1	Horizontal, 5° inclined	3	No	818	±118	1314	±8	14.1	±0.68
2	Horizontal, 85° inclined	3	No	616	±131	1296	±13	14.2	±0.71
3	Vertical	3	No	636	±81	1282	±10	14.1	±0.78

4	Horizontal, 5° inclined	1	Yes	1163	/	1306	/	9.8	/
5	Horizontal, 85° inclined	1	Yes	1024	/	1266	/	10.6	/
6	Vertical	1	Yes	1037	/	1268	/	11.8	/

As per the results in Table 6, the yield strength shows a difference when it comes to printing directions while the ultimate tensile strength does not significantly vary. Also, the stain does not illustrate significant difference in terms of printing direction.

However, comparing the as-built with the heat-treated samples shows that the heat treatment changes the behavior of stress-strain in the material for all samples with the difference in the printing directions.

2.6.2 MECHANICAL PROPERTIES OF 316L STAINLESS STEEL

The use of Austenitic 316L stainless steel in critical applications such as structural materials in nuclear reactors is due to its ductility, fracture toughness, and strength that is considerably high [33]. Fedorenko et al. [34] experimentally studied in 2021 the mechanical properties of 316L stainless steel by printing cylindrical tensile test specimens with three different orientations. The test was conducted by utilizing Laser Powder Bed Fusion (LPBF) process with the three printing orientations that are listed below:

- Vertical
- Horizontal with 0 degree in X-axis
- Horizontal with 90 degree in X-axis

The dimension of the tensile test specimen is designed according to ISO 6892-1 [35] shown in Figure 14, and printing orientation on the build plate is clarified in Figure 15.

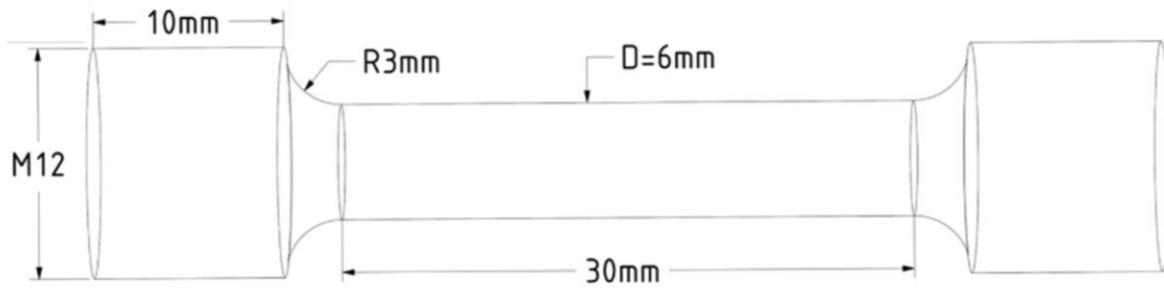


Figure 14: Geometry of Cylindrical Tensile Test Specimen [34, 35]

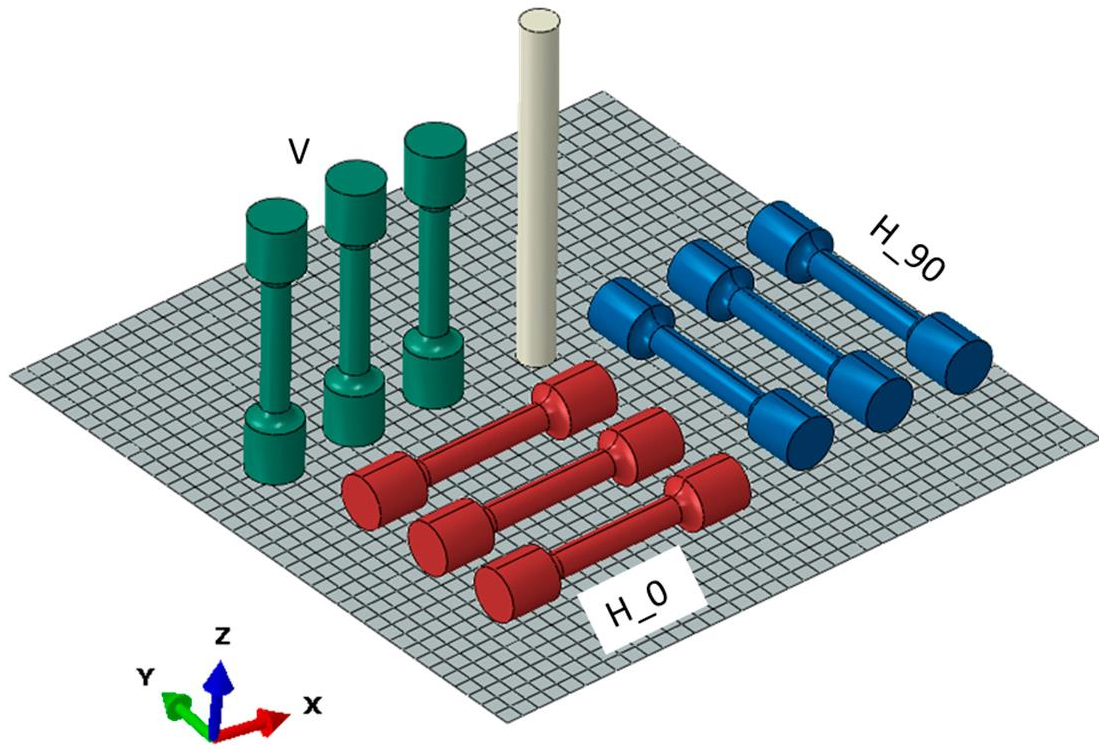


Figure 15: Building Orientation on Build Plate [34]

The used material for all parts is 316L stainless steel powder with utilizing 3D metal printer TruPrint 1000 machine (Trumpf). The process parameters applied as per the recommended parameters from the manufacturer that are followings:

Laser Spot Diameter	55 μm
Laser Power	113 W
Layer Thickness	20 μm
Laser Scan Speed	750 mm/s
Gas Speed (Argon)	2.5 m/s
Hatch Distance	80 μm

The tensile test was conducted based on ISO 6892-1 for all parts as-built using the machine of Instron 5969 and method of extensometer to measure the strain. The result of tensile test viewing stress vs. strain graph is in Figure 16.

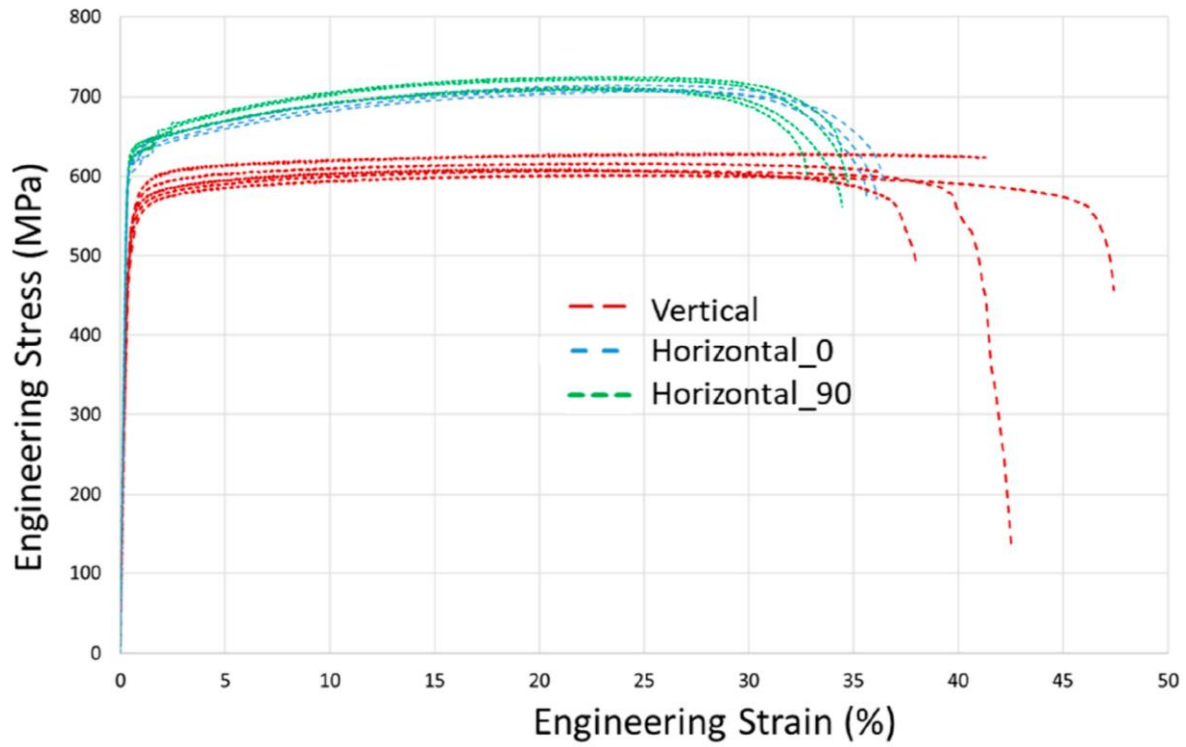


Figure 16: Tensile test results of as-build samples [34]

The mechanical properties result for Vertical, Horizontal with 0 degree in X-axis, and Horizontal with 90 degree in X-axis are shown in Tables 7, 8 and 9, respectively.

Table 7: Mechanical Properties of Vertical Tensile Test Specimens [34]

Specimen	Young's Modulus (GPa)	Yield Tensile Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at Fracture (%)	Reduction of Cross-Sectional Area at Fracture (%)
1	160	535	630	41	48
2	163	535	615	37	46
3	157	530	610	38	43
4	161	535	615	46	42
5	159	525	605	36	40

6	152	510	600	36	41
Average	158.7	528.3	612.5	39.0	43.3
SD	3.8	9.8	10.4	3.6	3.1

Table 8: Mechanical Properties of Horizontal with 0 degree in X-axis Tensile Test Specimens [34]

Specimen	Young's Modulus (GPa)	Yield Tensile Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at Fracture (%)	Reduction of Cross-Sectional Area at Fracture (%)
1	200	630	725	32	58
2	198	615	710	31	55
3	201	610	705	30	56
4	185	610	705	30	54
Average	196	616.2	711.2	30.8	55.8
SD	7.4	9.5	9.5	0.8	1.7

Table 9: Mechanical Properties of Horizontal with 90 degree in X-axis Tensile Test Specimens [34]

Specimen	Young's Modulus (GPa)	Yield Tensile Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at Fracture (%)	Reduction of Cross-Sectional Area at Fracture (%)
1	199	615	705	29	52
2	211	620	705	30	58
3	188	605	695	28	56
4	198	610	700	28	49
Average	199.0	612.5	701.3	28.8	53.7
SD	9.4	6.5	4.8	0.8	4.3

Based on the results from Table 7, 8 and 9, there is an observed difference in terms of response in comparison between vertical and horizontal parts. Instead, the difference is minimal when it comes to comparing the result of horizontal with 0 degree in X-axis and horizontal with 90 degree in X-axis. Furthermore, it was noticed that the variation in mechanical results between vertical parts is high. The average result of the Young's Modulus in vertical parts is lower than both of horizontal parts where horizontal average is close to the results of conventional manufacturing parts. Also, the result of ultimate tensile strength along with the yield tensile strength in vertical parts are lower than the horizontal ones. However, the ductility of the vertical parts is higher around 5%.

2.6.2.1 CONVENTIONAL MANUFACTURING (CM) VS. AM

There are variety of fabrication processes in Conventional Manufacturing (CM), such as forging and casting [36]. Each process differs than the other and results in changing the mechanical property. Table 10 shows some results from previous studies about the effect in mechanical properties from process to another for 316L Stainless Steel material.

Table 10: Mechanical Properties of 316L Stainless Steel with different manufacturing processes

Type of Manufacturing	Process Condition	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (HV)	References
Wrought	-	483	172	30	220	[37]
Wrought	Heat Treated	505	222	76	155	[37]
Casting	Gas-Atomized	518	255	35	220	[38]

Metal Injection Molding	Water-Atomized Powder	548	203	57	286	[39]
Spark Plasma Sintering	-	315	275	-	345	[40]
Sintering	-	431	207	23	127	[41]
Sintering	With MoSi ₂	486	-	22	146	[42]
Sintering	With Nitrogen Addition	600	420	14	137	[43]
Electron Beam Melting (AM)	-	509	253	59	165	[44, 45]
Hot Isostatic Pressing	-	450	160	42-54	-	[46]
DMLS	-	518	288	47.4	235	[47]
Gas Metal Arc (AM)	-	533	236	64	200	[48]

Moreover, considering the differences between the processes in CM, Table 11 shows the difference in mechanical properties between a CM process along with Laser Powder Bed Fusion (LPBF), which as an additively manufacturing process, with as-built and after heat treatment cases.

Table 11: Difference in Mechanical Properties of 316L Stainless Steel from previous studies between CM, as-built LPBF, and heat treated LPBF

	Wrought	LPBF As-Built	LPBF After Heat Treatment	References
Yield Strength (MPa)	150 - 230	350 - 640	350 - 500	[49, 50, 51]
Ultimate Tensile Strength (MPa)	450 - 818	480 - 760	550 - 600	[50, 51, 52, 53]
Elongation (%)	50 - 62	10 - 30	30 - 40	[50, 51, 52, 53]

Hardness (Hv)	133 - 155	220 - 280	210 - 275	[50, 51, 54, 55, 56, 57]
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Based on Table 11, yield strength, ultimate tensile strength, and hardness are greater in LPBF than CM.

2.6.2.2 EFFECT OF GEOMETRY ON MECHANICAL PROPERTIES

316L Stainless Steel is one of the main materials in engineering that can be utilized in numerous applications. Laser Powder Bed Fusion (LPBF) is commonly used to fabricate metal components in AM [58]. Processed material from LPBF has a microstructure containing large elongated grains which extent over boundaries of multiple melt pool. Fine cellular structures are forming inside crystallographic grains [59, 60, 61]. It is associated with alloying element segregation, for instance Mo, at the dislocation network and boundaries of cell. This microstructure is considered unique resulting in enhancing the mechanical properties in comparison with the conventional manufacturing [60]. Therefore, the present state of the art is being able to produce full dense components with outstanding mechanical properties; however, the effect of geometries on mechanical properties of metal AM is in need for further studies [62].

Leicht et al. [62] studied the effect of changing the thicknesses on mechanical properties of additively manufactured 316L stainless steel in 2021. The machine specification is listed below:

Additive Manufacturing Process	Laser Powder Bed Fusion (LPBF)
Machine	EOS M290 (EOS GmbH)
Laser Specification	Yb-fibre laser, 400 W
Gas Type	Argon Gas
Focus Diameter	100 µm

Laser Power	400 W
Layer Thickness	20 μm

Tensile test specimens were printed with same geometries but changing the thicknesses. Two different thicknesses were considered, which are 1mm and 3mm, shown in Figure 17a. Also, other tensile test specimens were produced with the standard geometry according to ASTM E8/E8M-15a [63] as presented in Figure 17b. All parts were printed with three samples from each design in a vertical orientation as shown in Figure 17c.

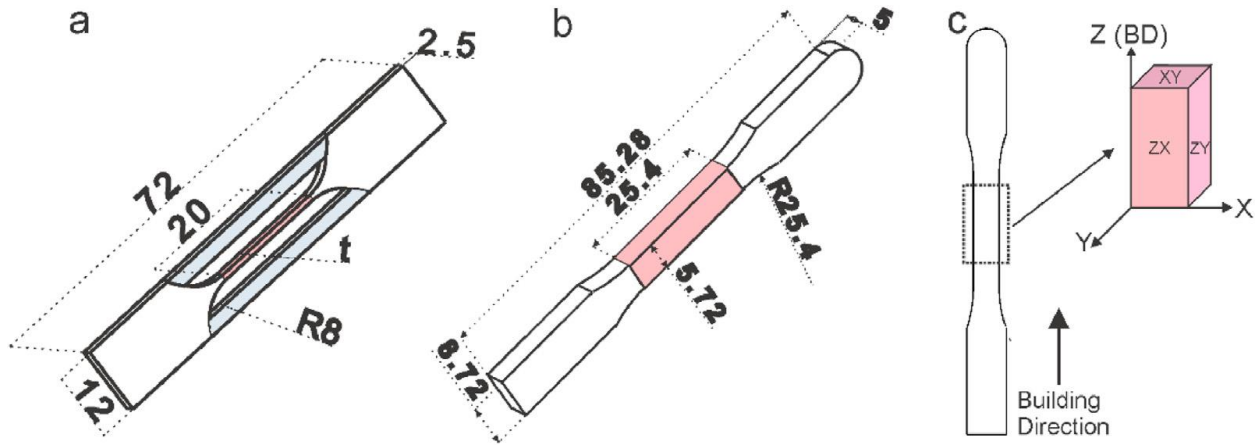


Figure 17: Drawing of (a) the tensile test specimen with thickness t representing the changing thickness (1mm and 3mm) and (b) the standard specimen according to ASTM E8/E8M-15a (c) Building orientation [62]

Tensile test was performed at room temperature with utilizing Instron 5500R. All samples were tested with as-built condition. Extensometer was used to obtain the strain with a maximum gauge length of 10mm with approximate elongation of 35%. Extensometer's maximum distance was reached since the elongation of the samples went beyond the limit, which is 35%. Therefore, the test was stopped at 35%, and continued then until reaching fracture with control of load. The reported results from the ultimate tensile strength (UTS), yield strength (YS), and elongation are

averaged from the three samples for each design. The measurement of the gauge length before and after the test determined the elongation to fracture as per the procedure of ASTM E8/E8M-15a.

Figures 18a and 18b represent the results of the tensile test along with the mechanical properties of the printed samples. Moreover, Figures 18c and 18d represent the results of same design in Figure 17a produced by cutting a sheet with water jet in order to be compared with the results of the printed parts.

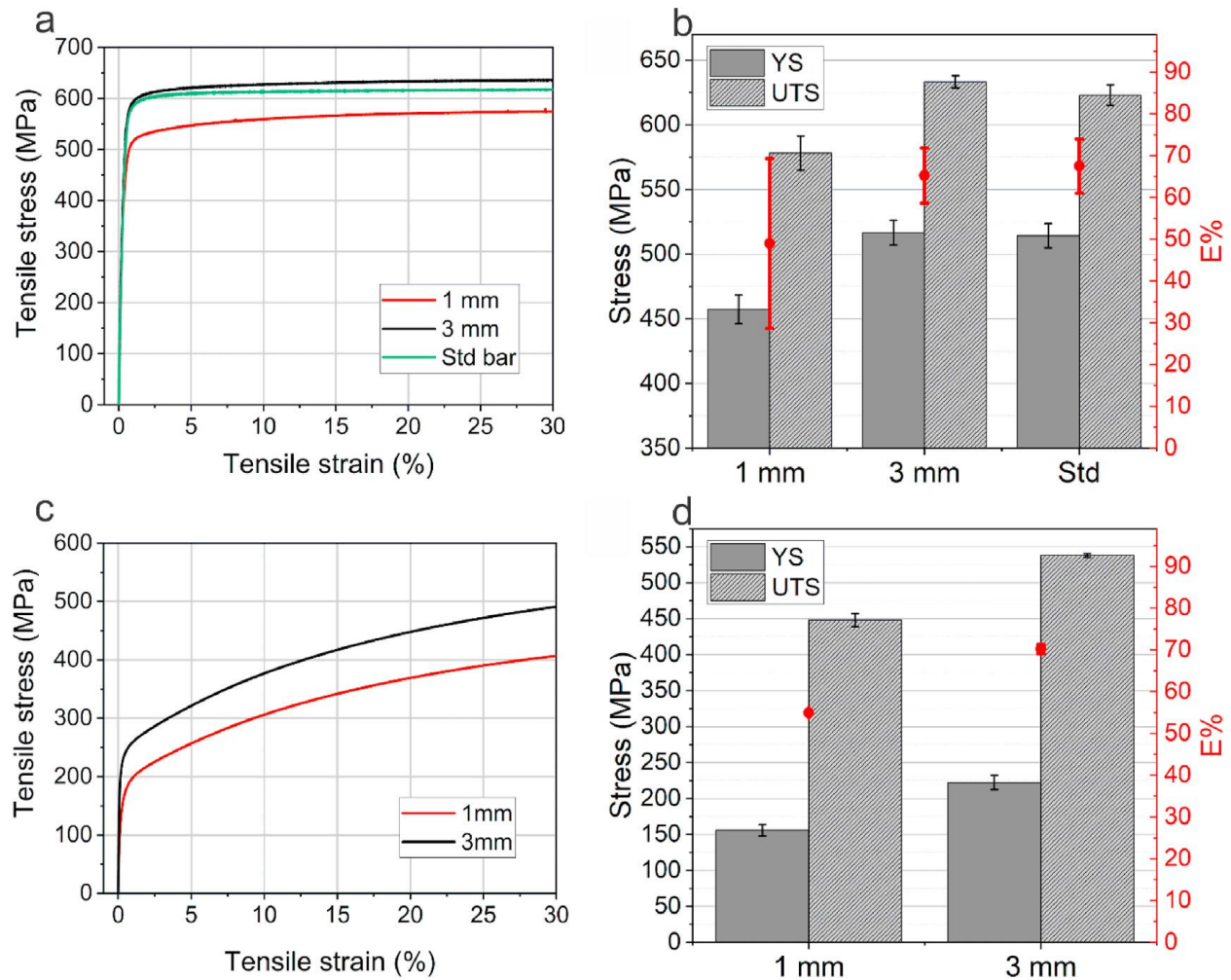


Figure 18: (a) Stress vs. Strain curves of printed samples and (b) Mechanical Properties of averaged three printed samples. (c) Stress vs. Strain curves of metal sheet cut by water jet samples (d) Mechanical Properties of averaged three samples from metal sheet cut by water jet. [62]

As per Figure 18, the sample with 1mm thickness is the lowest in terms of yield strength which means it is the weakest compared to the other samples. Looking at the result of the 3mm thickness, it is noticeable that increasing the thickness results in increasing the yield strength along with the ultimate tensile strength. It is also clear that the mechanical properties of the 3mm thickness samples are comparable with the mechanical properties of the standard geometry samples. Therefore, increasing the thickness results in increasing the elongation to fracture. Even though the 1mm thickness sample is the lowest, it is still in compliance with the minimum yield strength and ultimate tensile strength for 316L stainless steel according to A240/A240M-18 [64]. All other samples are exceeding the requirement in terms of the yield strength with good ductility.

For the samples manufactured by metal sheet cut by water jet, the 1mm thickness samples have lower values of mechanical properties than the 3mm thickness samples. Therefore, it can be realized that the thickness has an effect even with the conventional manufacturing. Furthermore, the tensile strength should not be influenced significantly by the surface roughness even by the reduction of the thickness [65]; however, the surface roughness should affect the ductility [66].

2.6.3 ANALYSIS OF X-RAY DIFFRACTION (XRD)

X-ray diffraction (XRD) was conducted in previous studies to analyze phase distribution within manufactured 316L Stainless Steel samples by PBF. Figure 19 displays the pattern of XRD for same sample printed and analyzed as-built with taken two parts from the steel, which one is from the horizontal section and the other from the vertical section. Both parts have similar patterns with shown FCC austenite pattern [67].

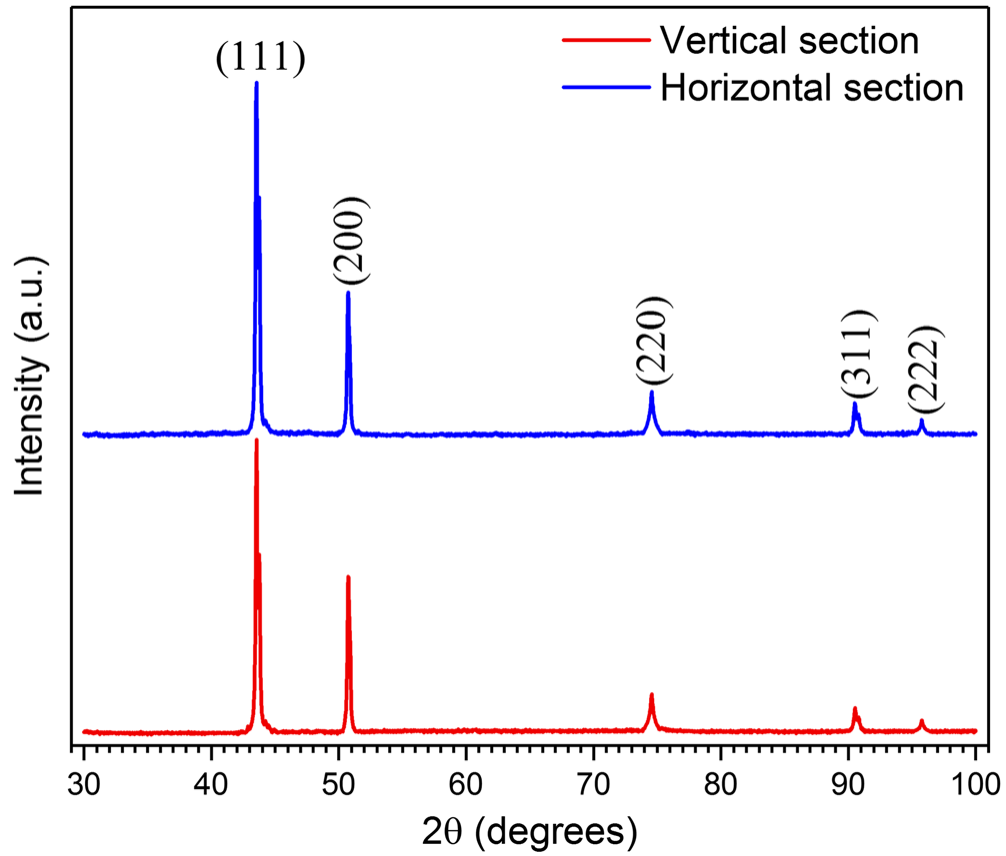


Figure 19: XRD pattern of 316L Stainless Steel samples analyzed as-built [67]

Another study conducted XRD analysis for tensile test specimens with different thicknesses as shown in Figure 20 [62]. The XRD patterns for all thicknesses are austenitic with insignificant difference in terms of width and intensity.

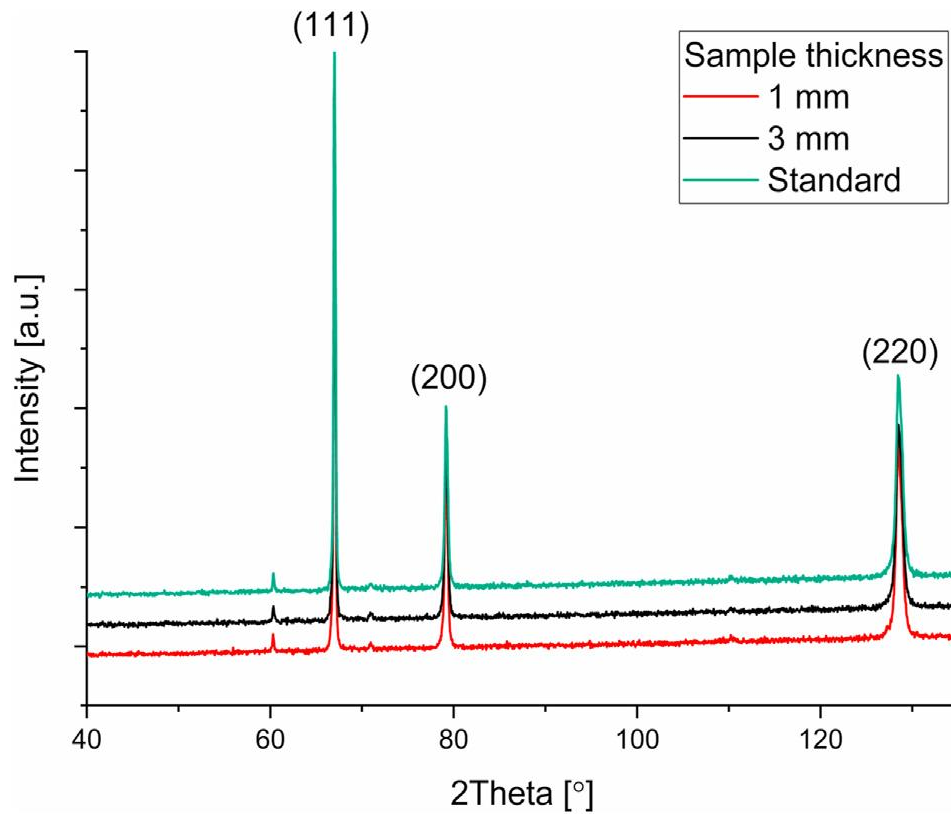


Figure 20: XRD Pattern of 316L Stainless Steel with different thicknesses samples (1mm, 3mm, and standard) [62]

However, other studies have conducted XRD for as-built 316L stainless steel parts manufactured by direct energy deposition (DED) and observed BCC ferrite [68, 69].

2.6.4 THE EFFECT OF SURFACE ROUGHNESS

Surface roughness is an important physical property of any element and can be described as the deviations' measure of the real surface from the ideal one. Grooves and peaks are found in real surfaces that results in weaken the strength [70]. Manufactured parts by DMLS in almost all applications are not used as-built as further post-processing treatments are needed to overcome deficiencies, such as dimensional discrepancy, poor ductility and high surface roughness [71]. The most noticeable drawback in DMLS is the poor surface roughness, in which high surface roughness

is correlated with poor mechanical properties [70]. Therefore, DMLS parts require additional post-processing treatments that includes mechanical or thermal processes to improve the overall microstructure and mechanical properties [72]. Table 12 lists some of the effects on the surface roughness.

Table 12: Effects of DMLS parameters on Surface Roughness

Parameters	Effect	References
Laser Power (W)	Extreme low or high laser power results in high roughness	[73]
Scan Speed (mm/s)	Extreme low or high scan speed results in high roughness	[74, 75]
Layer Thickness (μm)	Small layer thickness creates balling while large layer thickness creates layer delamination	[76]
Scanning Pattern	Track of small scan decreases surface roughness	[77, 78]
Building Direction	Parallel plane to the scan direction has lower surface roughness than the perpendicular plane because of the partial attachment of powder particles	[79]
Type of Surface	Vertical, round or inclined planes has higher surface roughness than flat and horizontal one	[80]

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 ADDITIVE MANUFACTURING MACHINE AND MATERIALS

The selected machine is GE Concept Laser M1, which is under the process of Directed Metal Laser Sintering (DMLS) with the following specifications:

Effective Building Volume	245 mm x 245 mm x 300 mm
Laser Specification	Yb-fibre laser, 400 W
Layer Thickness	Depends on the material, 0.03 – 0.06

Available materials are listed in the Table 13.

Table 13: Available Materials for GE Concept Laser M1

Material Group	Material Type
Stainless Steel	17-4PH
	316L
Maraging Steel	M300
Tool Steel	H13
Aluminum	AlSi10Mg
	A205
	AlSi7Mg
Nickel Alloy	718
	625
	X
Titanium	Ti6Al4V ELI Grade 23

	cp-Ti Ti6242
Cobalt	CoCrMo CoCrW

Therefore, the selected powder material for this study is GE Additive 316L (316L Stainless Steel).

The known applications of 316L Stainless Steel (GE Additive 316L) are the followings [81]:

- Acid and corrosion resistant prototypes
- Plant engineering
- Automotive
- Medical
- Jewelry
- Mold components

The chemical compositions are in Table 14:

Table 14: Chemical Composition of GE Additive 316L [81]

Component	Indicative Value (%)
C	0 – 0.03
Si	0 – 1.0
Mn	0 – 2.0
P	0 – 0.045
S	0 – 0.030
Cr	16.5 – 18.5
Mo	2.0 – 2.5
Ni	10.0 – 13.0
Fe	Balance

This study will not consider heat treatment post-processing; however, the material datasheet provides a technical data for the expected mechanical properties after applying the recommended heat treatment shown in the Table 15.

Table 15: Mechanical Properties of GE Additive 316L [81]

	90° (Upright)	45° (Polar Angle)	0° (Horizontal)
Yield Strength (N/mm ²)	374 ± 5	385 ± 6	330 ± 8
Tensile Strength (N/mm ²)	650 ± 5	640 ± 7	529 ± 8
Elongation (%)	65 ± 4	63 ± 5	63 ± 5
Young's Modulus (N/mm ²)	Approximately 200x10 ³		
Thermal Conductivity (W/mK)	Approximately 15		
Hardness (HRC)	20		

3.2 SAMPLE DESIGNS

The selected samples to be designed are Tensile Test Specimen. All parts have been designed with different sizes and orientations while keeping in consideration the available resources in terms of printing volume as well as laboratory equipment. The tensile test specimens are designed with same height and width, but with different thicknesses, which are 0.5, 2, and 5mm. The reason is to study the material behavior with different thicknesses along with different printing directions. The CAD program is used for designing is Solidworks followed by converting the design file to STL file in order to be ready for printing. The list of designed parts is in Table 16.

Table 16: List of Designed Parts

#	Material	Specimen Type	Dimension	Printing Direction	Quantity
1	Stainless Steel (316L)	Tensile Test	0.5mm Thickness	Vertical	3
2		Tensile Test	2mm Thickness	Horizontal	3
3		Tensile Test	2mm Thickness	45 Degree	3
4		Tensile Test	2mm Thickness	Vertical	3
5		Tensile Test	5mm Thickness	Vertical	3
Total Printed Parts					15

3.2.1 TENSILE TEST SPECIMEN

The designs of tensile test specimen are presented in Figure 21. All tensile test specimens are designed to be standardized for this test in terms of height and width as shown in Figure 21, but with different thicknesses, which are 0.5, 2, and 5mm. Each design of specimen is printed with multiple samples in order to ensure accurate data. For 0.5mm thickness, the design is printed at vertical orientation (90 degree) with 3 samples, and the side view of the specimen is shown in Figure 22. For 2mm thickness, the design is printed at horizontal (0 degree), 45 degree and vertical (90 degree) orientations with multiple samples of each orientation. The side view of the specimen is shown in Figure 23. For 5mm thickness, the design is printed at vertical orientation (90 degree) with 3 samples. The side view of the specimen is shown in Figure 24.

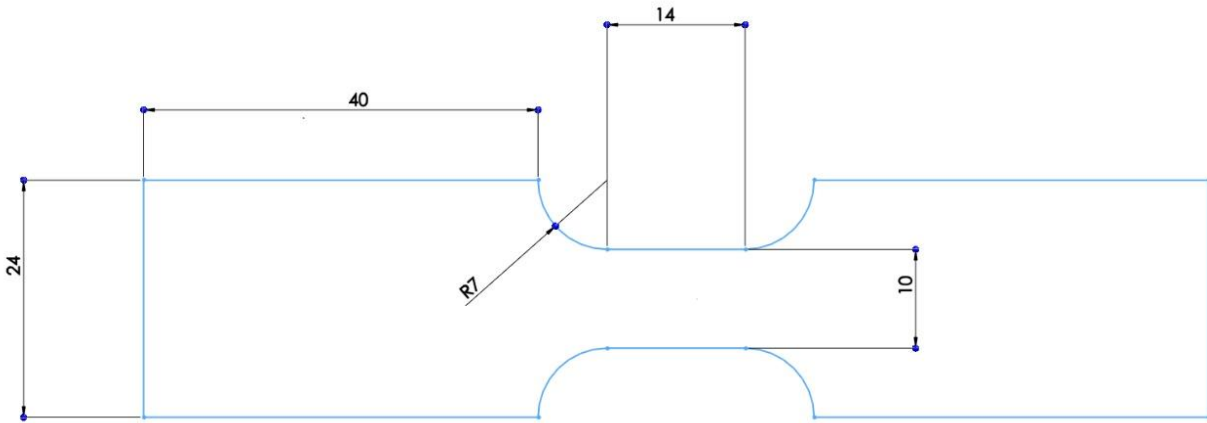


Figure 21: Design of Tensile Test Specimen (Front View) (Dimension in mm)

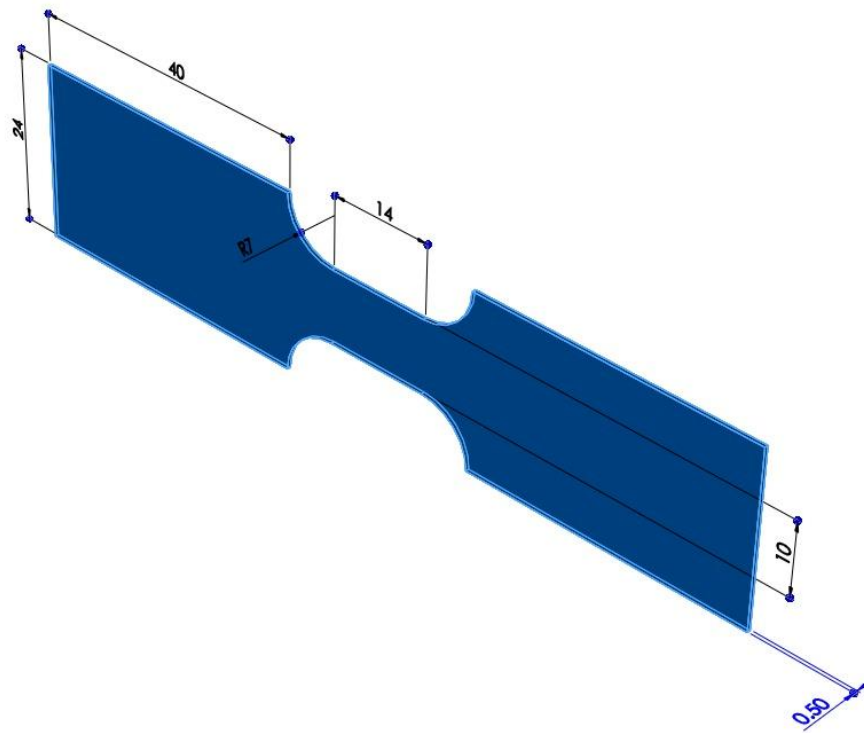


Figure 22: Design of Tensile Test Specimen (0.5mm Thickness)

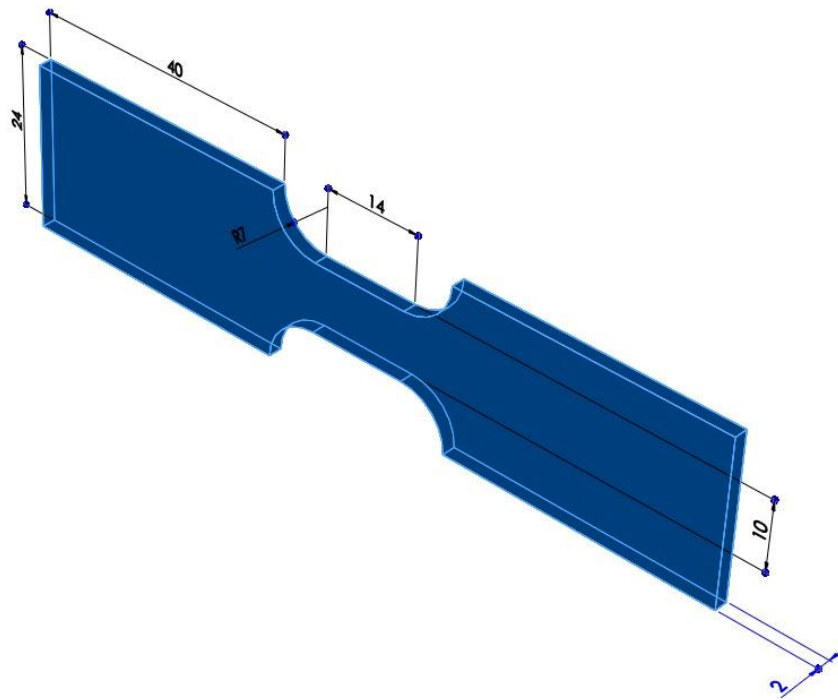


Figure 23: Design of Tensile Test Specimen (2mm Thickness)

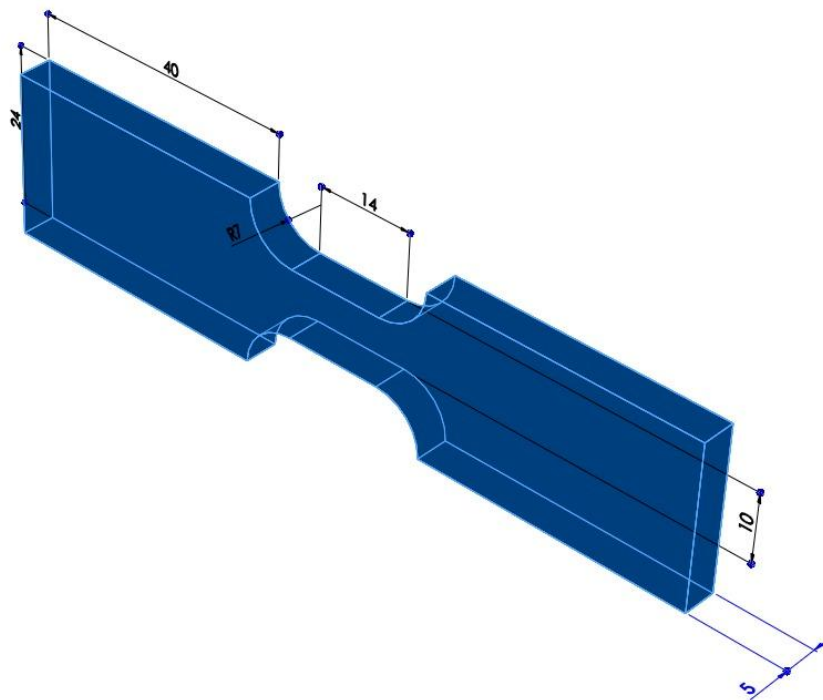


Figure 24: Design of Tensile Test Specimen (5mm Thickness)

3.2.2 BUILD PLATE ARRANGEMENT

All parts for this study along with others are to be printed at the same time in one build plate. The layout of the build plate is shown in Figures 25 and 26. The support structure of every part is shown in Blue, and the main part is shown in Grey.

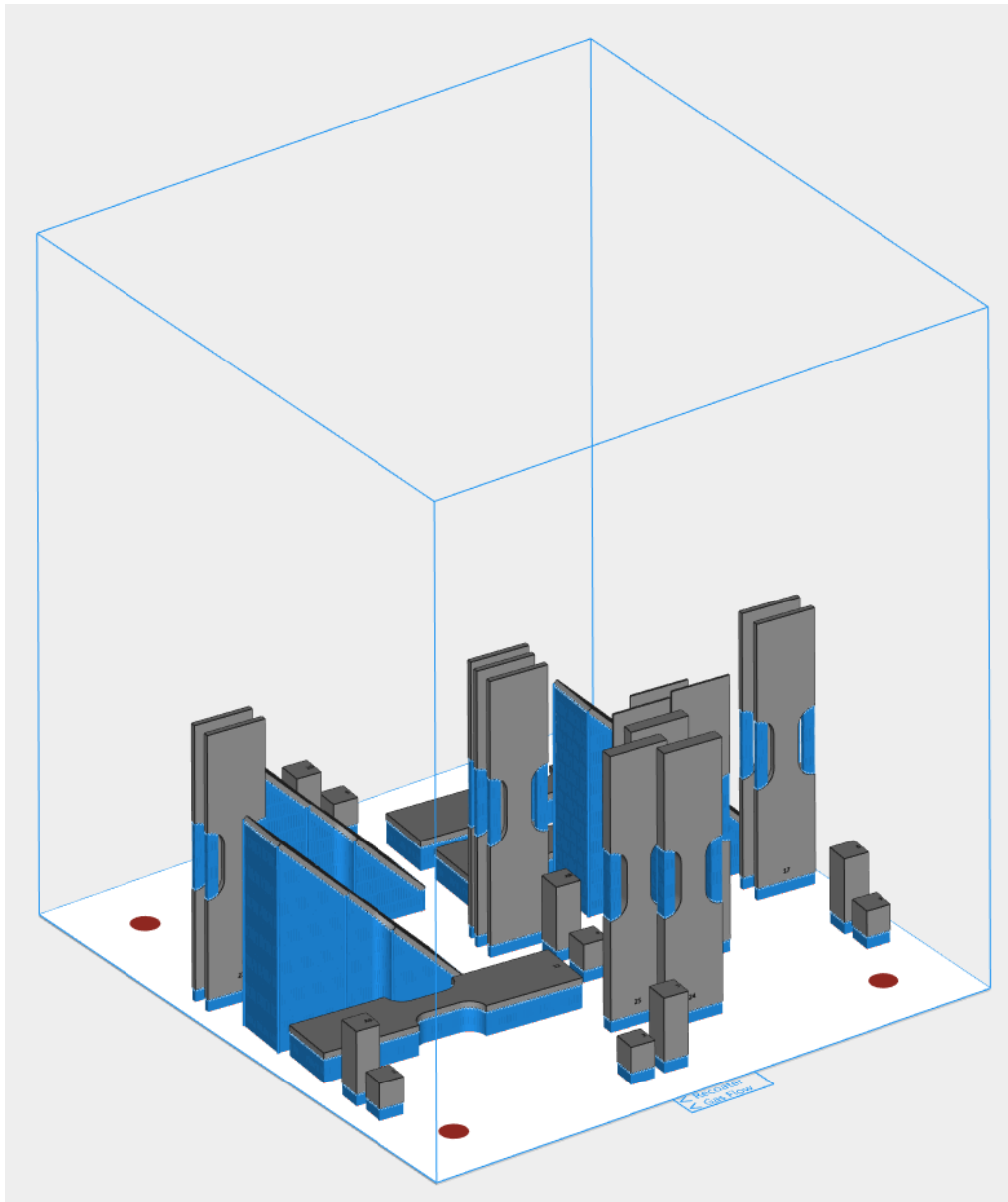


Figure 25: Arrangement of Build Plate

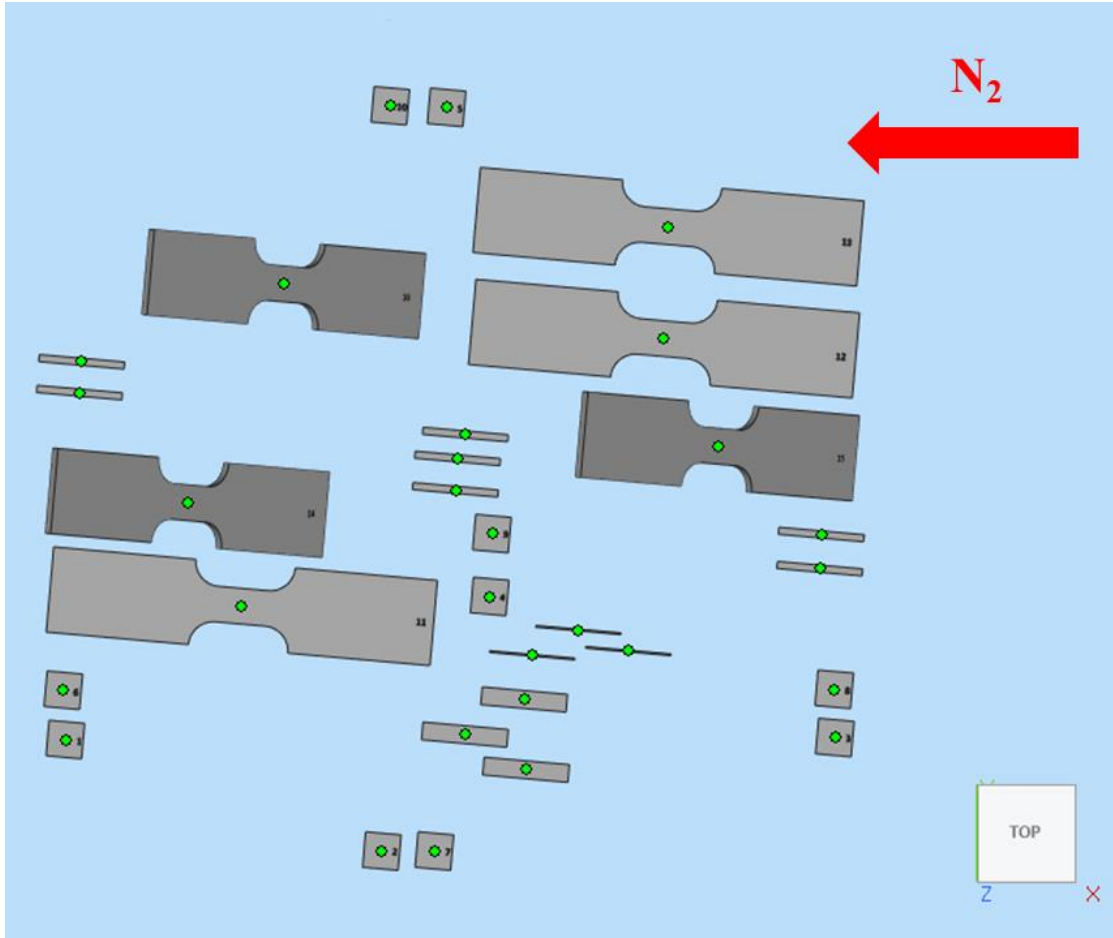


Figure 26: Arrangement of Build Plate (Top View)

3.3 PRINTED PARTS

All samples have been printed as per the design in Section 3.2, which are Tensile Test Specimen with GE Additive 316L (316L Stainless Steel) powder. Parts are printed and kept as-built without post-processing and heat treatment. Table 17 specifies the parameter settings of the produced parts.

Table 17: Parameter settings of produced parts

Material	Laser Power (W)	Scan Speed (mm/s)	Layer Thickness (mm)	Trace width (mm)	Energy Density (J/mm ³)
SS316L	180	800	0.045	0.15	33.33

3.3.1 BUILD PLATE ARRANGEMENT

All parts have been printed in the same build plate as shown in Figures 27 and 28. The build plate states the airflow direction of inert gas during the printing. The used inert gas is Nitrogen (N_2).

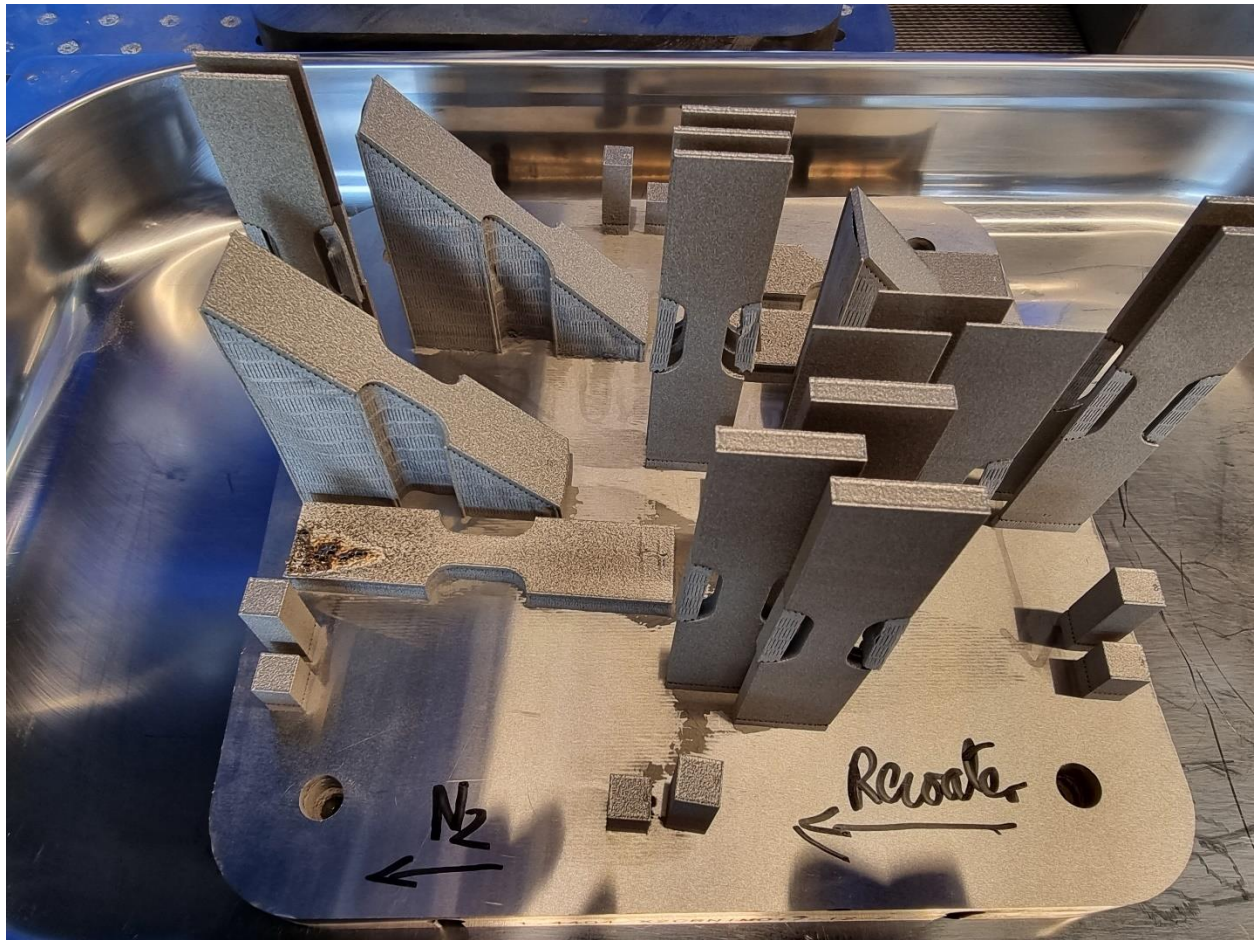


Figure 27: Printed Samples on the Build Plate

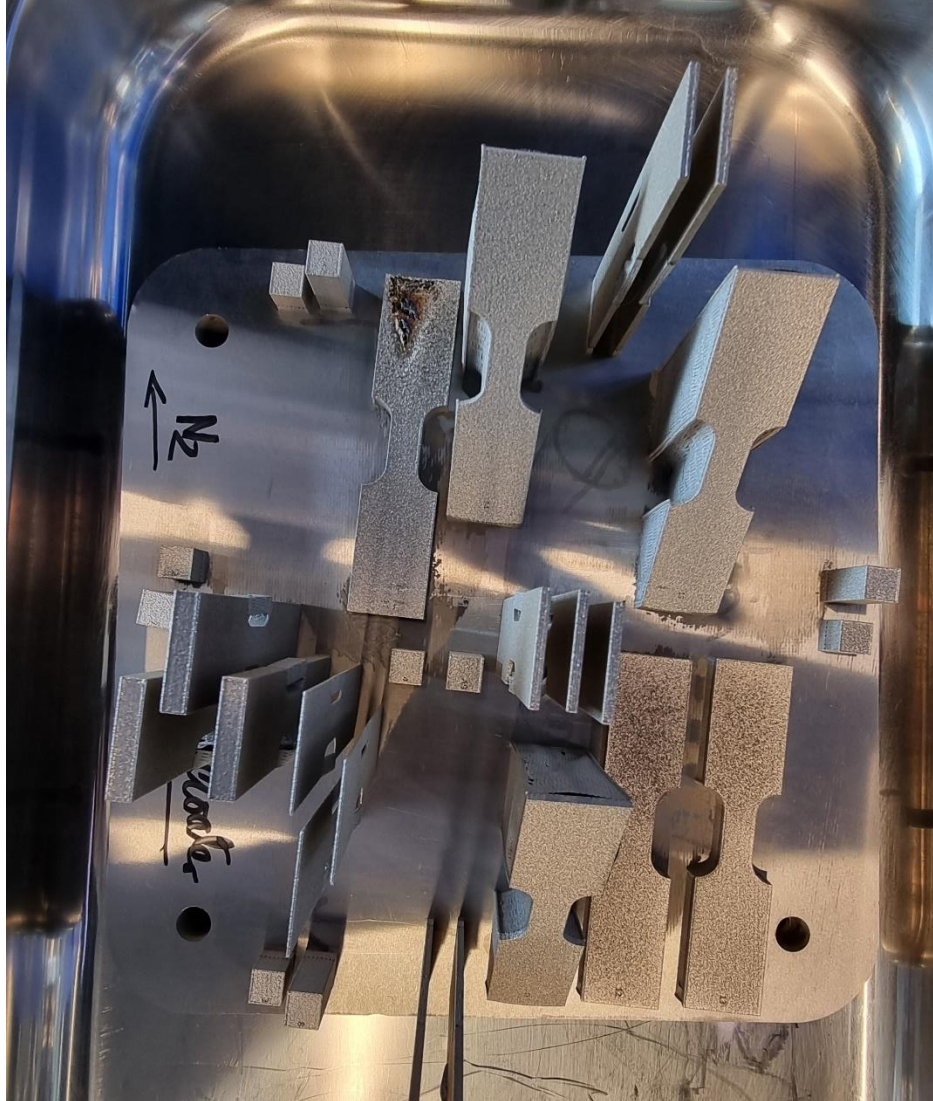


Figure 28: Printed Samples on the Build Plate (Top View)

3.3.2 TENSILE TEST SPECIMEN

The tensile test specimens have been printed with different thicknesses and directions. The layer direction during printing is shown in Figure 29. Figures 30 and 31 show tensile test specimens printed with different building orientations.



Figure 29: Layer Direction during printing

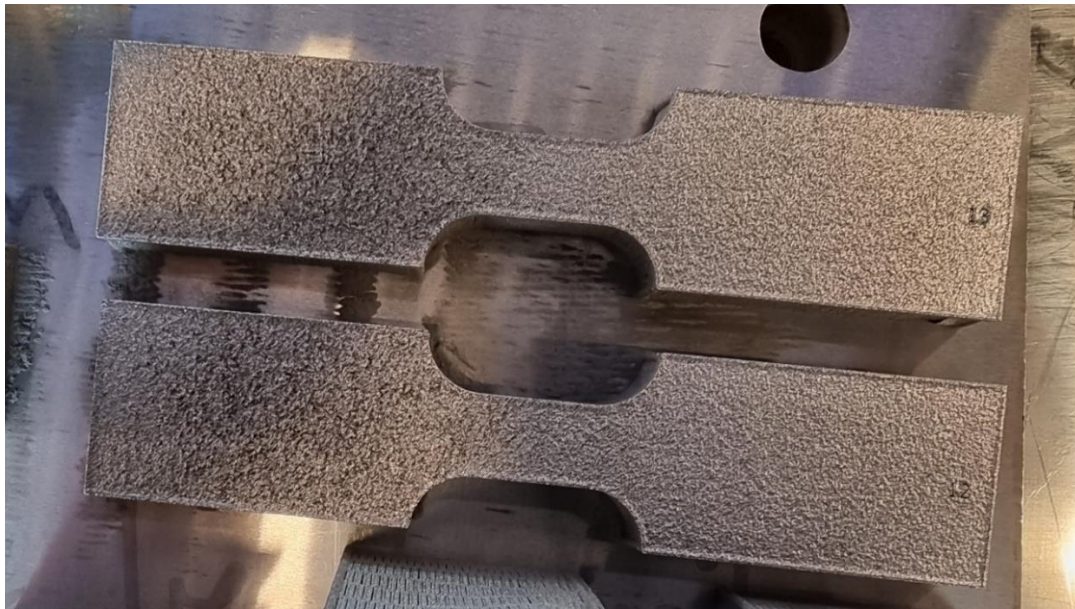


Figure 30: Printed Tensile Test Specimens on the Build Plate

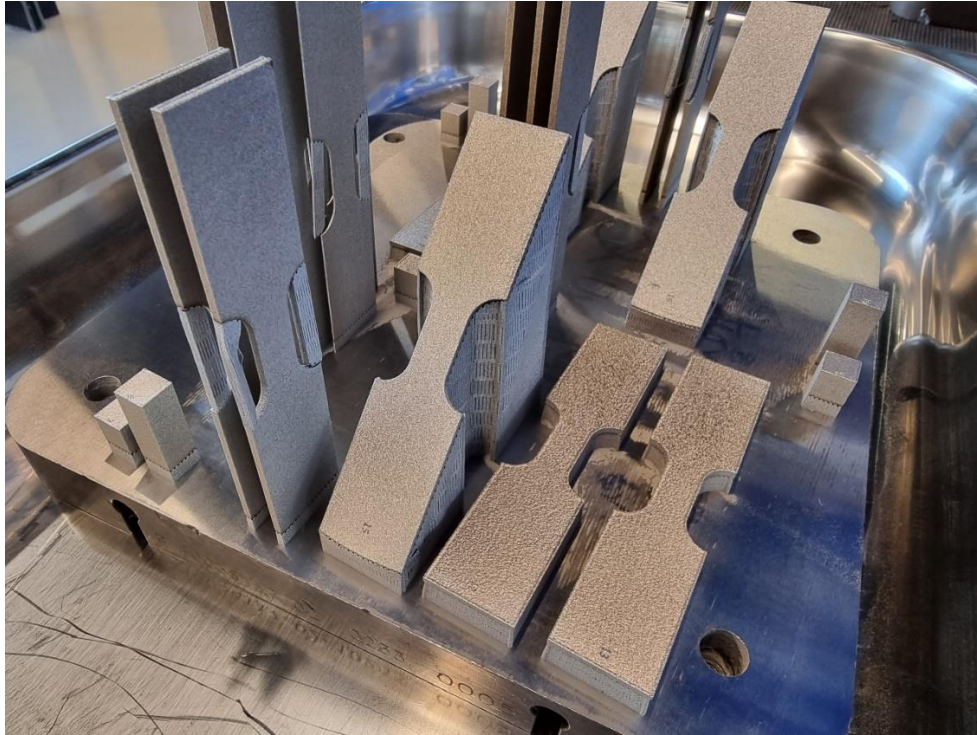


Figure 31: Printed Tensile Test Specimens on the Build Plate with different Orientations

Figure 32 presents the breakdown of all parts after printing and removed from the build plate.



Figure 32: Printed parts

3.4 TENSILE TESTING

The available machines for tensile test are Instron 3367 and Instron 5569 shown in Figure 33 and 34, respectively. The maximum load for tensile test to be conducted by Instron 3367 machine and Instron 5569 machine are 30kN and 50kN, respectively.



Figure 33: Instron 3367 for load up to 30kN



Figure 34: Instron 5569 for Load up to 50kN

Therefore, Instron 5569 is selected to conduct the tensile tests for this study. Also, other equipment is required for the tensile test to be conducted is the extensometer. The selected extensometer to be used shown in Figure 35 is Instron, CATALOGUE 2620-601 with the range of $\pm 5\text{mm}$. Therefore, this dimension shall be considered during designing the size and dimension of the samples. The extensometer shall be removed after 4.8mm displacement. The setup of the tensile test is represented in Figure 36, and Figure 37 presents the tensile specimen before and after fracture.



Figure 35: INSTRON CATALOGUE 2620-601 Extensometer

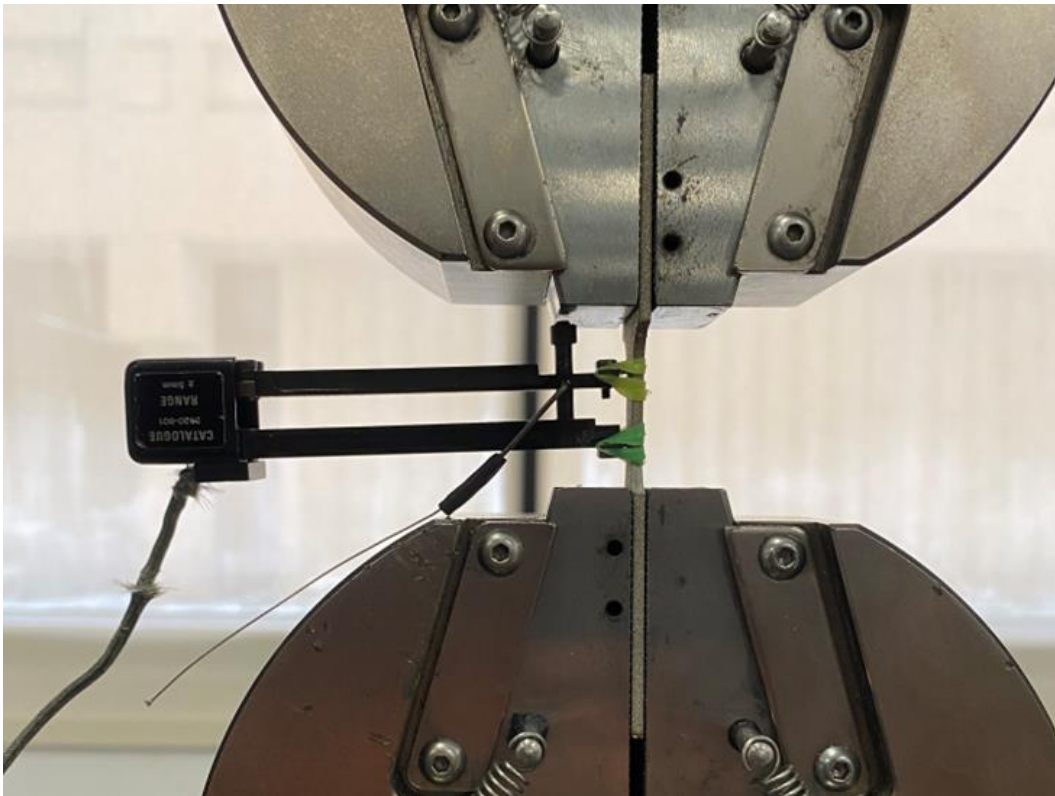


Figure 36: Setup of Tensile Test

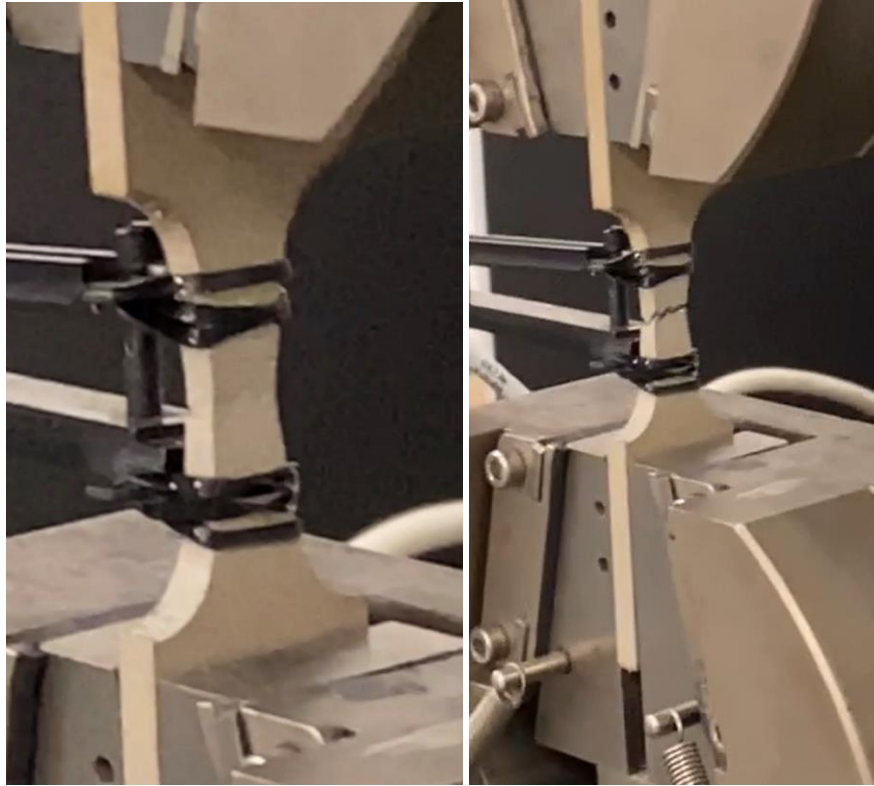


Figure 37: Tensile Specimen before and after Fracture

3.5 HARDNESS TESTING

LECO R-600 Hardness Tester Machine shown in Figure 38 is to be used for Rockwell B or C hardness test with specifications listed in Table 18.



Figure 38: LECO R-600 Hardness Tester Machine (Rockwell B or C)

Table 18: LECO R-600 Hardness Setting

LECO R-600 Hardness Tester Machine (Rockwell)			
B	Load	100	Kgf
	Setting	Ball	
	Time	10	Sec
C	Load	150	Kgf
	Setting	Dia (Diamond)	
	Time	10	Sec

Rockwell B hardness test has been selected for this test to be conducted for each 316L Stainless Steel sample category to measure the hardness in printed parts with different thicknesses and printing orientation.

3.6 SURFACE ROUGHNESS TESTING

The surface roughness test is to be conducted by using BRUKER ContourGT machine shown in Figure 39. Change of geometry and building orientation is considered for the surface roughness test. Therefore, the specimens to be tested are listed in Table 19.

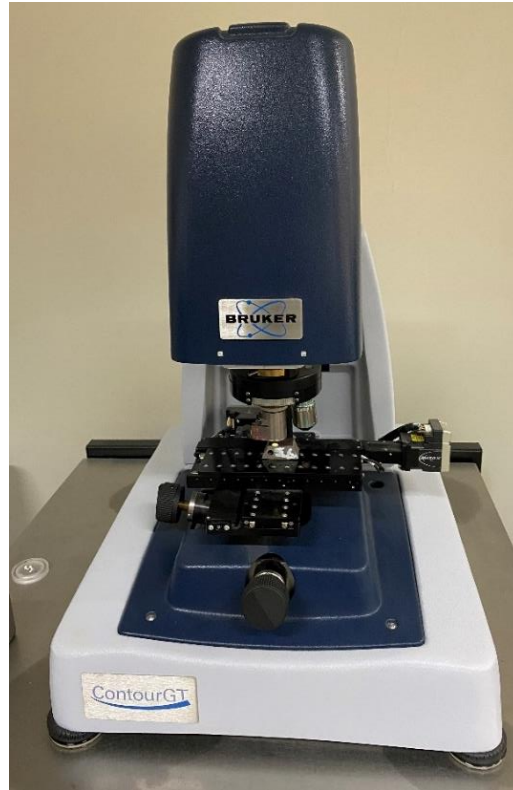


Figure 39: BRUKER ContourGT (Roughness)

Table 19: Tested Specimen for Surface Roughness

Type of Sample	
1	5mm-Vertical
2	2mm-Vertical
3	2mm-Horizontal
4	2mm-45deg
5	0.5mm-Vertical

3.7 X-RAY DIFFRACTION (XRD)

All samples, 0.5mm-Vertical, 2mm-horizontal, 2mm-45degree, 2mm-vertical and 5mm-vertical, were cross-sectioned and grinded to conduct XRD analysis to measure the patterns by changing the thickness and building orientations. The used machine for XRD is Bruker AXS D8 Advance as shown in Figure 40.



Figure 40: Bruker AXS D8 Advance Machine for XRD

3.8 POROSITY ANALYSIS

OLYMPUS DSX510 digital microscope illustrated in Figure 41 was used for five samples to measure the porosity in each type of sample as per Table 20:

Table 20: Tested Specimen for Porosity Analysis

Type of Sample	
1	5mm-Vertical
2	2mm-Vertical
3	2mm-Horizontal
4	2mm-45deg
5	0.5mm-Vertical

Each sample was cross-sectioned from the top part for the 45 degree and vertical parts and from one side for the horizontal part. Then, parts were mounted, grinded and polished before placing them in the digital microscope.



Figure 41: OLYMPUS DSX510 Digital Microscope

3.9 COMPOSITION ANALYSIS

Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray (EDX) by JEOL SEM JSM-6610LV shown in Figure 42 was used for four samples to further analyze the microstructure with focusing on identifying the composition in each type of sample after printing as listed in Table 21. Same mounted, grinded and polished samples used in the digital microscope was then used in SEM.

Table 21: Tested Specimen for Composition Analysis

Type of Sample	
1	5mm-Vertical
2	2mm-Horizontal
3	2mm-45deg
4	0.5mm-Vertical



Figure 42: JEOL SEM JSM-6610LV Machine

CHAPTER 4

RESULTS & DISCUSSION

4.1 TENSILE TESTING

The tensile test results and the mechanical properties of as-built printed samples by DMLS are presented in Figures 43 and 44, and Table 19, respectively. Figure 43 represents tensile test results with the effect of thickness change, and Figure 44 shows the tensile test results of different building orientation. Table 22 summarizes the results of the mechanical properties for each sample. The overall range of the ultimate tensile test varies from 538 to 784 MPa depending on the thickness and building direction. Also, the overall range of elongation to failure is from 33 to 65%.

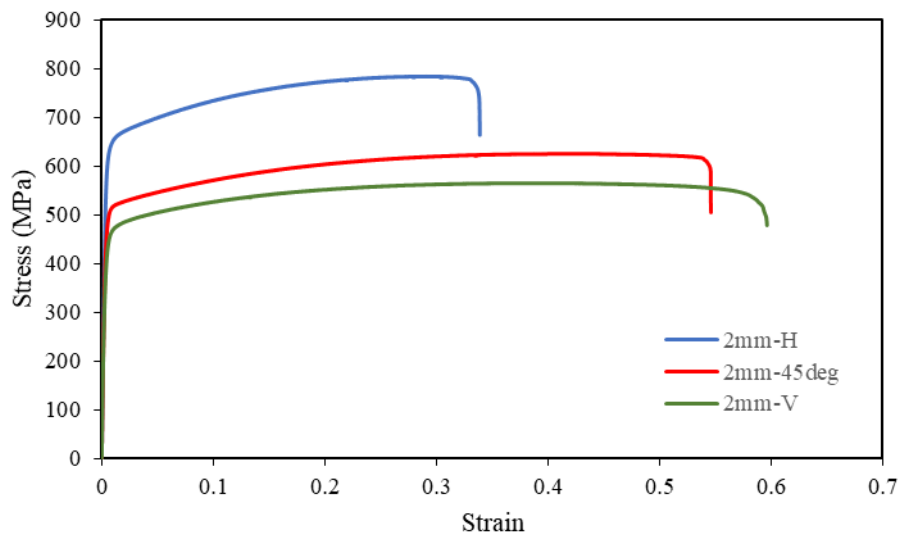


Figure 43: Tensile Test Results of as-built 2mm thickness samples with different building orientations (horizontal, 45 degree, vertical)

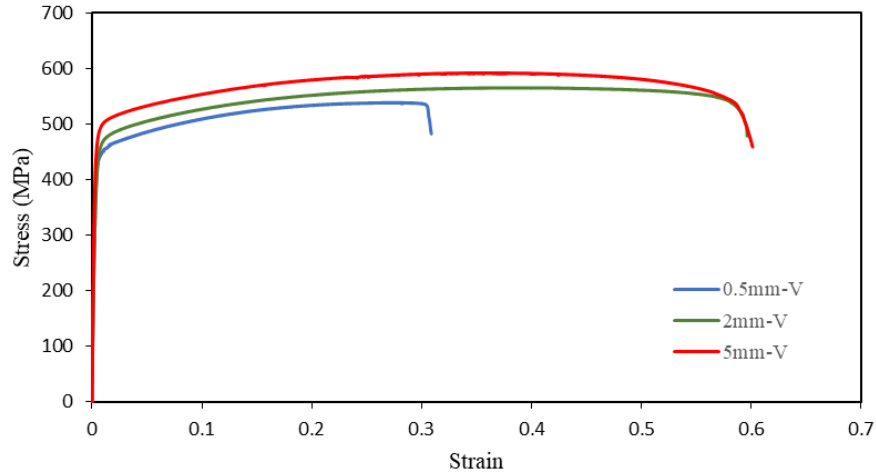


Figure 44: Tensile Test Results of as-built Vertical samples with different thicknesses (0.5mm, 2mm, 5mm)

Table 22: Mechanical Properties of 316L Stainless Steel

Specimen	Ultimate Tensile Strength (MPa)	Elongation to failure (%)
2mm-Horizontal	784 ± 1.04	0.38 ± 0.023
2mm-45degree	628 ± 2.5	0.55 ± 0.015
2mm-Vertical	566 ± 1.46	0.57 ± 0.012
0.5mm-Vertical	538 ± 2.08	0.33 ± 0.037
5mm-Vertical	585 ± 1.51	0.65 ± 0.024

For building direction effect, the range of ultimate tensile strength and elongation is from 566 to 784 MPa and 38 to 57%, respectively. The ultimate tensile strength in the horizontal direction has a significant increase with lower elongation in comparison with 45degree and vertical specimens. The 2mm-45degree specimen has the second highest ultimate tensile strength after the horizontal with higher elongation than the horizontal. The vertical sample with same thickness, 2mm, has the lowest ultimate tensile strength with the highest elongation.

For thickness effect, specimen samples with different thicknesses, 0.5mm, 2mm, and 5mm, were tested with vertical orientation. The range of ultimate tensile strength and elongation is from 538 to 585 MPa and 33 to 65%, respectively. The ultimate tensile strength of 5mm specimen, which is the highest thickness in this study, has the highest value among the lower thicknesses, 0.5mm and 2mm. Also, the specimen with the highest thickness, 5mm, has the highest elongation as well. The second highest thickness, 2mm, comes as the second highest values of both ultimate tensile strength and elongation with lower value than 5mm of approximately 3.25% and 12.3%, respectively. The lowest thickness, 0.5mm, is a very thin specimen with resulting to have ultimate tensile strength of 538 MPa and elongation of 33% with reduction from the highest thickness of approximately 8% and 49%, respectively. Therefore, both ultimate tensile strength and elongation decrease by decreasing the thickness; however, the elongation reduction in 0.5mm specimen is significant.

Therefore, the building orientation can significantly affect the ultimate tensile strength and elongation where vertical has the lowest value and horizontal has the highest value of ultimate tensile strength, and elongation is the opposite. The value of 45degree specimen falls in between. Also, it can be seen that the thickness significantly affects the mechanical properties up to a certain range, then the affect is insignificant when reaching to a certain thickness. Moreover, the overall results of mechanical properties produced by DMLS with all thicknesses and orientations are higher than the conventional manufacturing properties.

4.2 HARDNESS TESTING

Hardness is a key indicator of the mechanical properties in additive manufacturing. The results of the rockwell B hardness test are presented in Table 23.

Table 23: Results of Hardness Test (Rockwell B)

#	Specimen	Test Location	Rockwell B
1	0.5mm-Vertical	Top	39.92 ± 0.79
		Bottom	40.12 ± 0.35
2	2mm-Horizontal	side1	91.40 ± 0.95
		side2	
3	2mm-45deg	Top	90.50 ± 0.51
		Bottom	90.80 ± 0.84
4	2mm-Vertical	Top	89.45 ± 0.72
		Bottom	91.03 ± 0.28
5	5mm-Vertical	Top	88.20 ± 0.44
		Bottom	89.2 ± 0.57

According to GE Additive 316L material datasheet [21], the Rockwell C hardness for heat treated parts is 20, which is equivalent to 95 in Rockwell B. Therefore, it can be seen that the results of 2mm with horizontal, 45degree, and vertical orientations along with 5mm vertical have insignificant values with considering the fact that the tested parts are as-built and no post-processing and heat treatment were involved. The result of 2mm horizontal is slightly higher than the 45degree and vertical. However, the 0.5mm vertical is significantly lower than the rest with more than 50%. It is noticeable that the hardness values remain consistent within the samples with considering the orientation as the top and bottom parts for 45degree and vertical have similar values. Therefore, based on the above, the thickness does affect the hardness significantly up to a

certain point, then the affect is minimal. Moreover, the effect of the building orientation in the hardness is insignificant.

4.3 SURFACE ROUGHNESS TESTING

All samples are tested as-built without any post-processing. The results of the surface roughness for all samples with different thickness and building orientations have been attained from top and bottom sides of the specimen. Figure 45 illustrates the surface roughness of 0.5mm-vertical specimen. Figure 46 shows the surface roughness of 2mm-horizontal specimen. Figure 47 illustrates the surface roughness of 2mm-45degree specimen. Figure 48 presents the surface roughness of 2mm-vertical specimen. Lastly, Figure 49 shows the surface roughness of 5mm-vertical specimen.

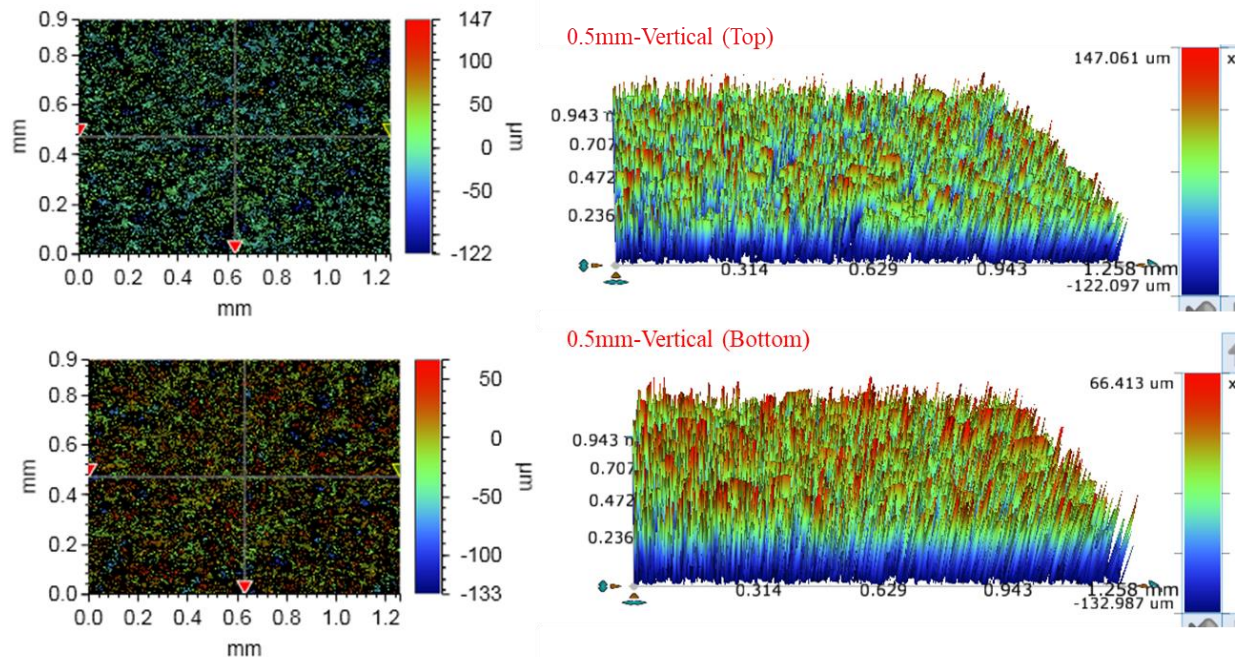


Figure 45: Surface Roughness of 0.5mm-Vertical Specimen from the top and bottom sides

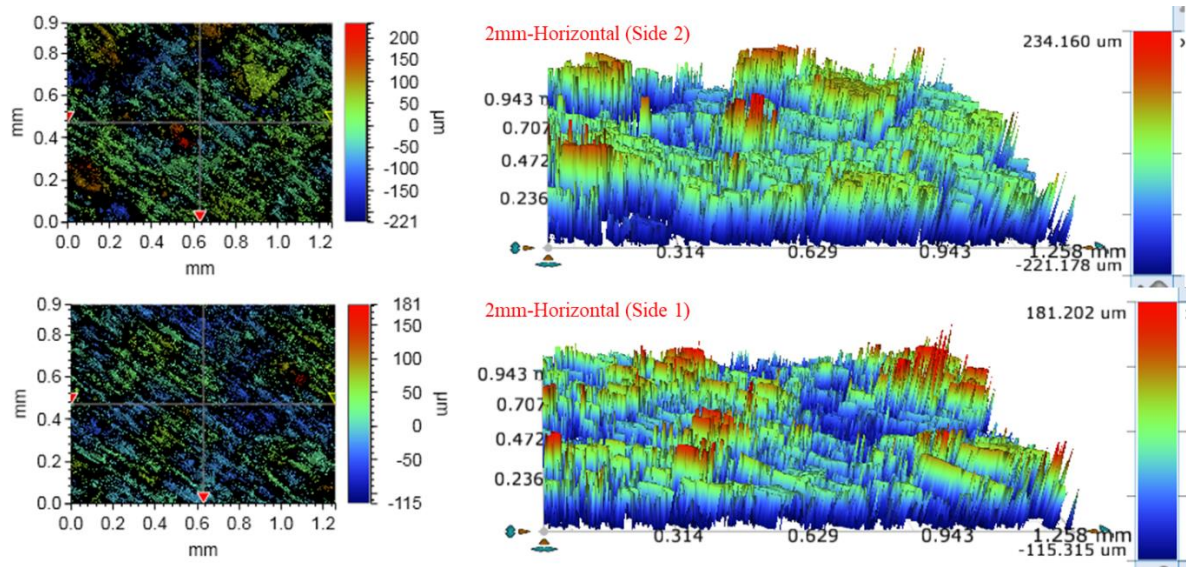


Figure 46: Surface Roughness of 2mm-Horizontal Specimen from both sides

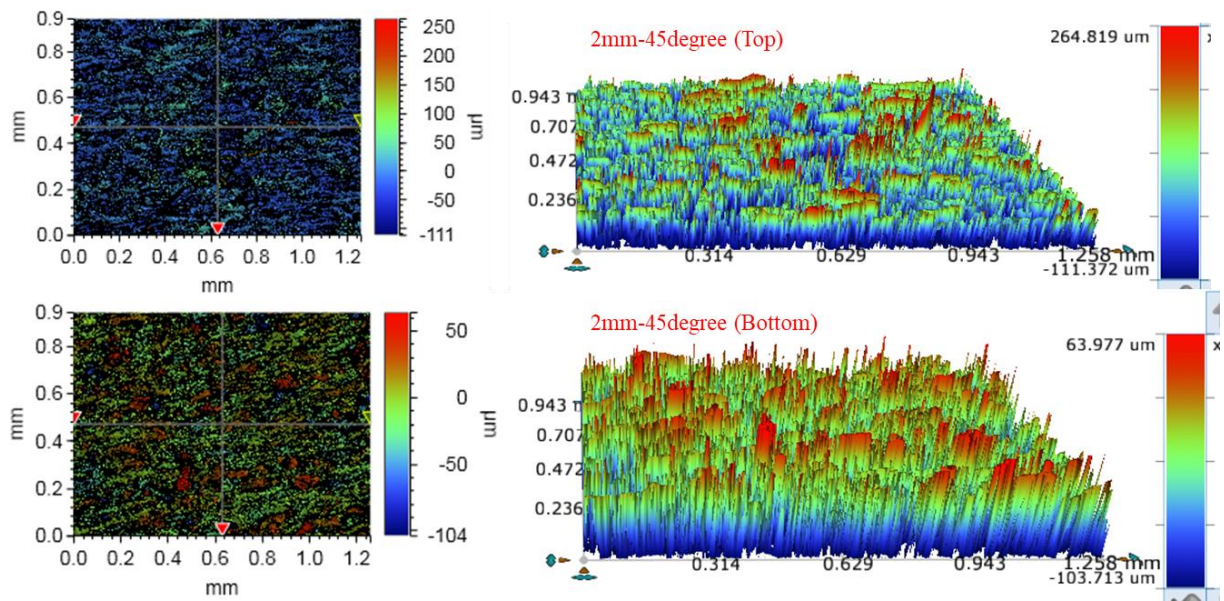


Figure 47: Surface Roughness of 2mm-45degree Specimen from the top and bottom sides

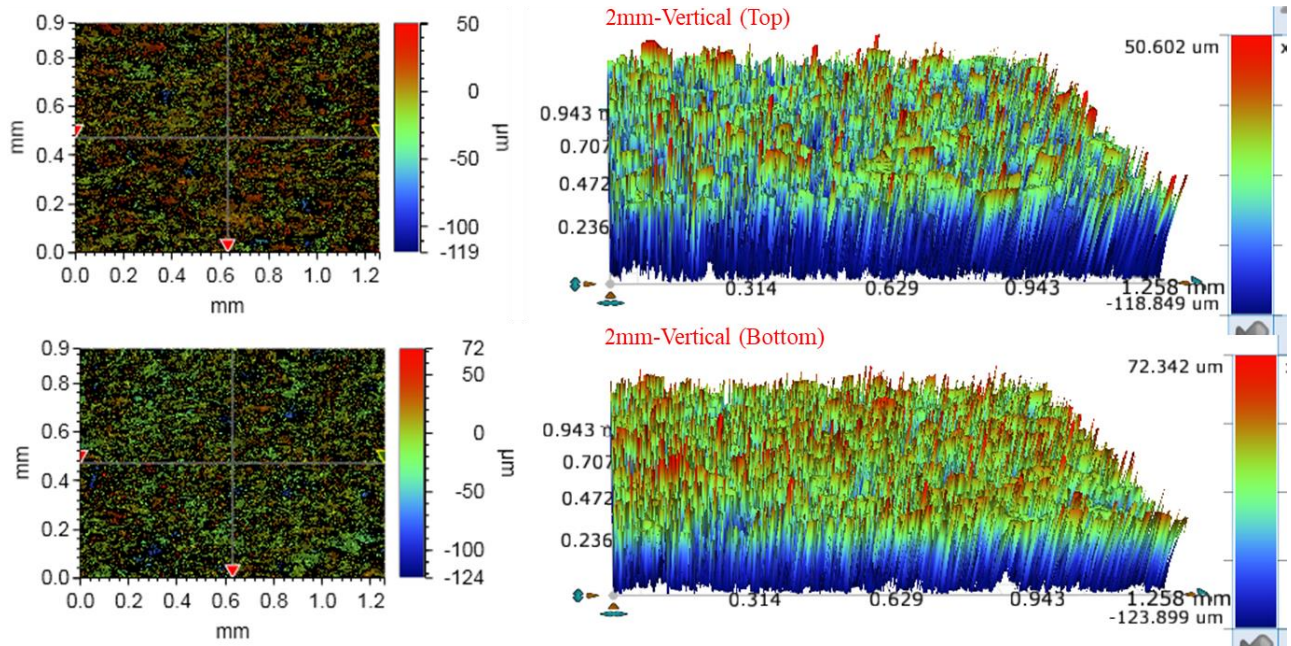


Figure 48: Surface Roughness of 2mm-Vertical Specimen from the top and bottom sides

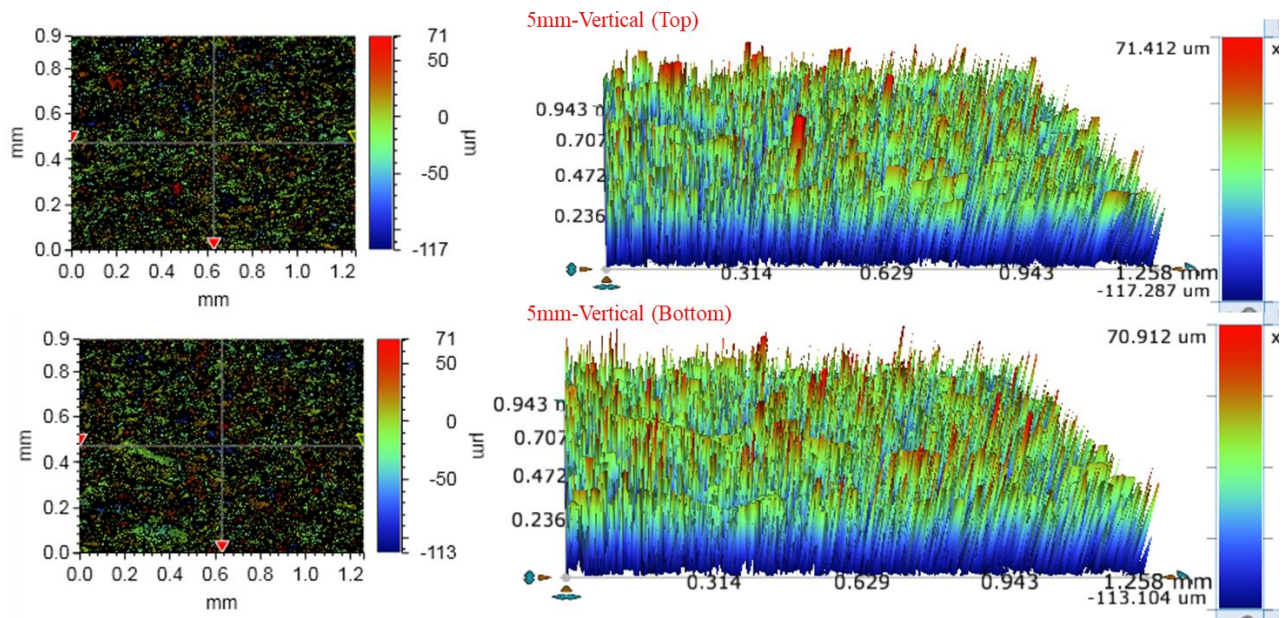


Figure 49: Surface Roughness of 5mm-Vertical Specimen from the top and bottom sides

It can be seen that there is a difference in surface roughness level within the specimen; however, it varies from one sample to another. The 2mm-45degree specimen has the highest surface

roughness in the top side while the bottom side is the second lowest roughness among all specimens. The increase in the top side might be due to the high volume of support structure. Also, similar behavior with significant increase in the surface roughness from the top side is obvious in 0.5mm-vertical specimen and the second side of 2mm-horizontal specimen. However, the 2mm-vertical specimen has an opposite result in which the top side has lower surface roughness than the bottom. Moreover, the 5mm-vertical has almost similar surface roughness result in the top and bottom sides.

The results have proven that all parts have high surface roughness, and there is a need of post-processing for DMLS parts to improve the surface roughness as mentioned in Section 2.6.4 in the literature. Therefore, it can be stated that printing parameters, such as laser power, scan speed and printing direction, have the significant effect on the surface roughness. Also, change in geometry and orientation have a secondary effect as the length increases in direction, the surface roughness changes especially with lower thickness.

4.4 X-RAY DIFFRACTION (XRD)

The results of XRD analysis are shown in Figure 50. 0.5-vertical, 2mm-horizontal, 2m-45degree, 2mm-vertical and 5mm-vertical specimens illustrate similar patterns in XRD. The peaks in all specimens are austenite located at the same location with similar width and intensity. Therefore, changing the orientation and thicknesses does not affect the XRD pattern.

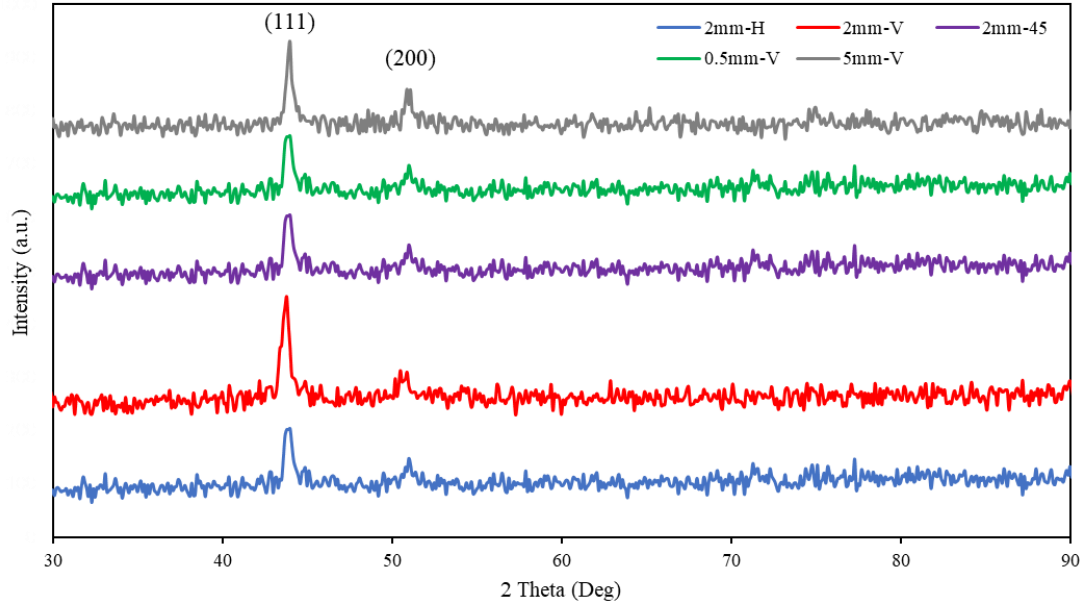


Figure 50: XRD patterns for all specimens

4.5 POROSITY ANALYSIS

Optical Microscope was conducted to analyze the porosity in every specimen to identify the pore sizes. The result of optical microscope for 0.5mm-vertical specimen is shown in Figure 51. Figure 53 illustrates the result of 2mm-horizontal specimen. Moreover, for 2mm-45degree specimen, the result is presented in Figure 53. Figures 54 and 55 present the result of optical microscope for 2mm-vertical specimen and 5mm-vertical specimen, respectively.

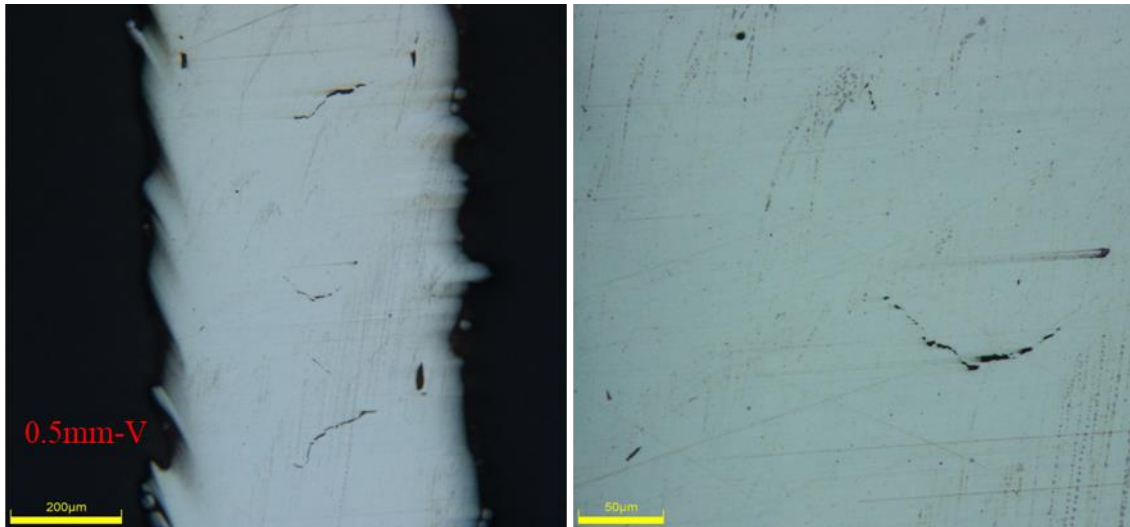


Figure 51: Optical Microscope on 0.5mm-Vertical Specimen

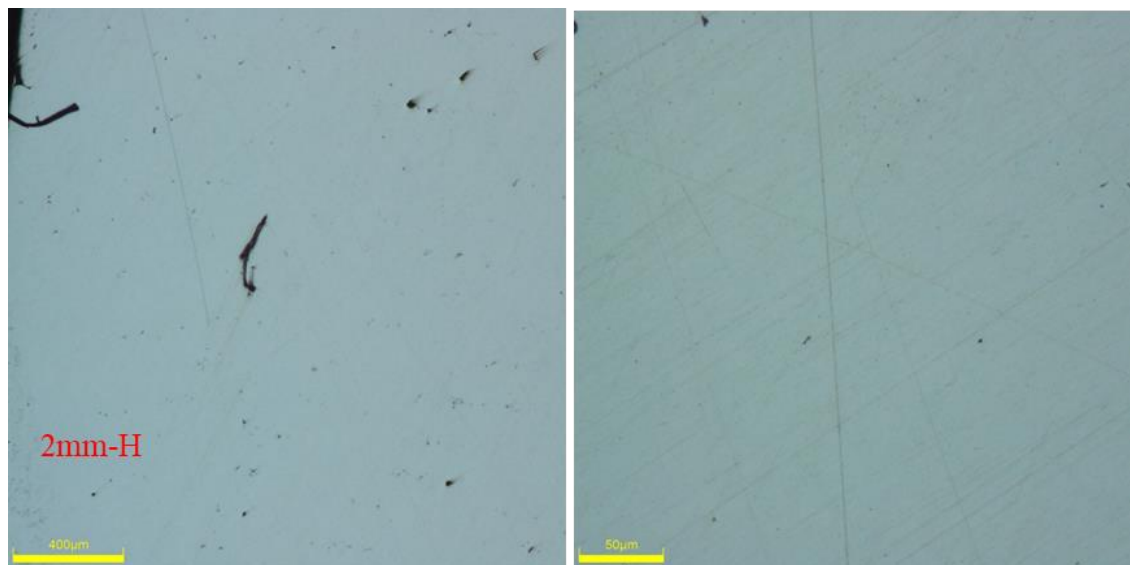


Figure 52: Optical Microscope on 2mm-Horizontal Specimen

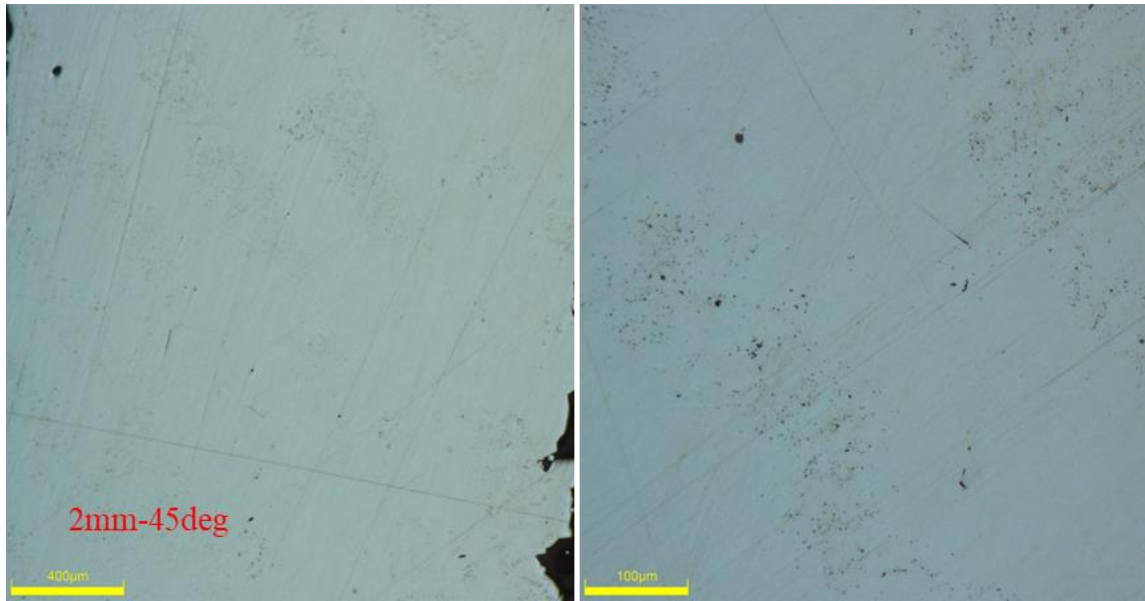


Figure 53: Optical Microscope on 2mm-45degree Specimen

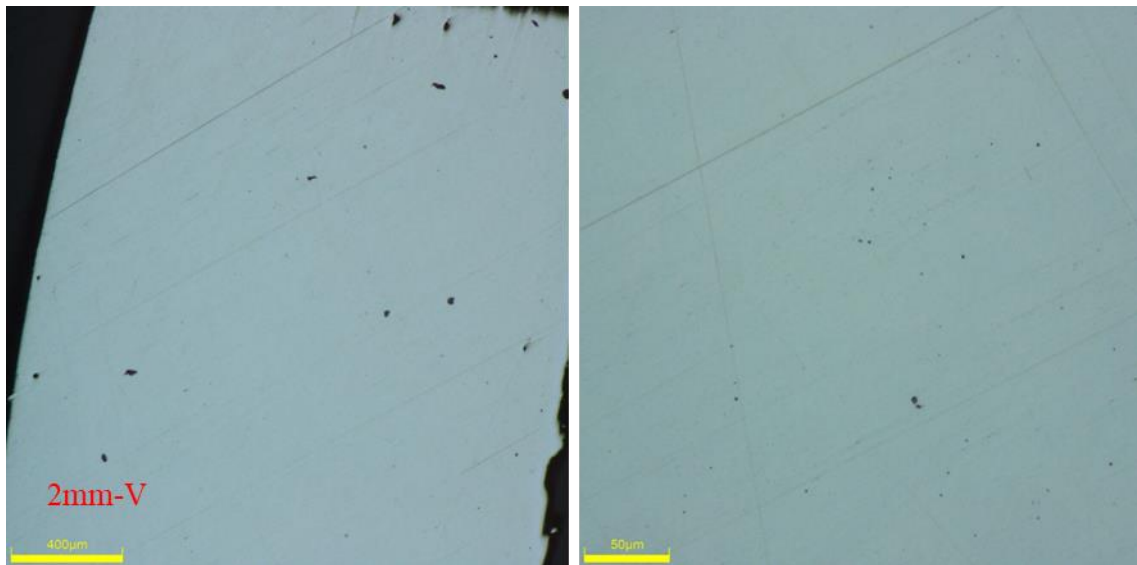


Figure 54: Optical Microscope on 2mm-Vertical Specimen

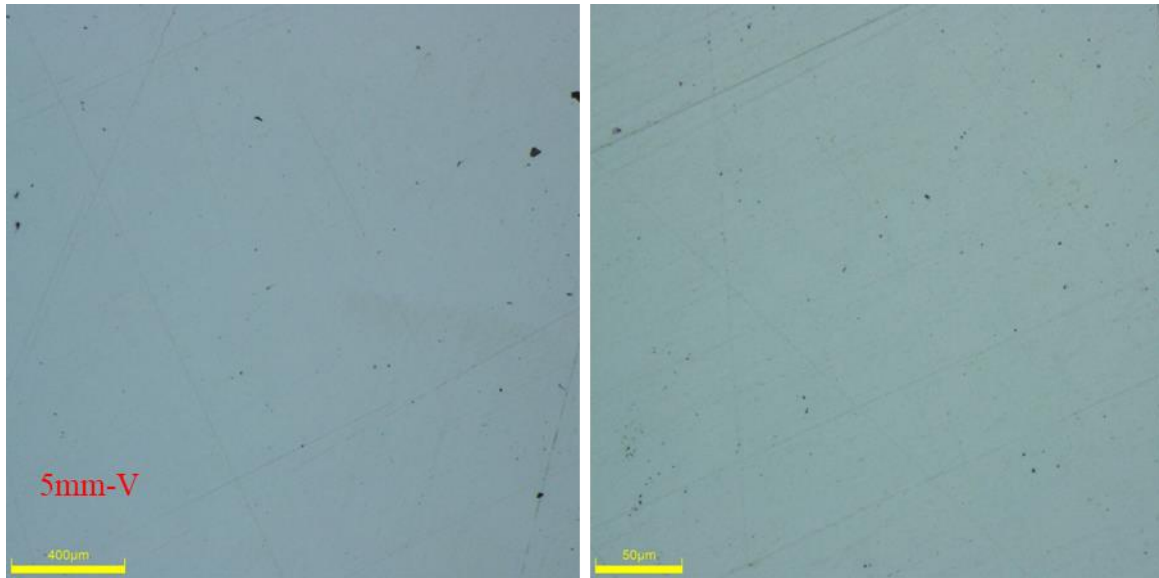


Figure 55: Optical Microscope on 5mm-Vertical Specimen

The optical microscope results indicate that porosity exists in all samples. However, there is higher porosity in the thin sample (0.5mm-V) more than the others. The horizontal specimen has large pores size than the 45degree and vertical with same thickness as illustrated in Figure 52. Also, porosity in the edges is higher as can be seen in Figure 54. Figure 55 demonstrated that the higher the thickness, the lower in porosity. Therefore, porosity can be affected by changing the thickness of samples and changing the geometry.

4.6 COMPOSITION ANALYSIS

Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray (EDX) was conducted to further analyze the microstructure to identify the chemical composition in each sample after printing with as built condition. Figures 56, 57, 58, and 59 illustrate the EDX graphs for 0.5mm-vertical specimen, 2mm-horizontal specimen, 2mm-45degree specimen, and 5mm-vertical specimen, respectively. Also, Table 24 shows the chemical compositions in each sample from

EDX with comparing the results with the chemical composition of GE Additive 316L from Table 14.

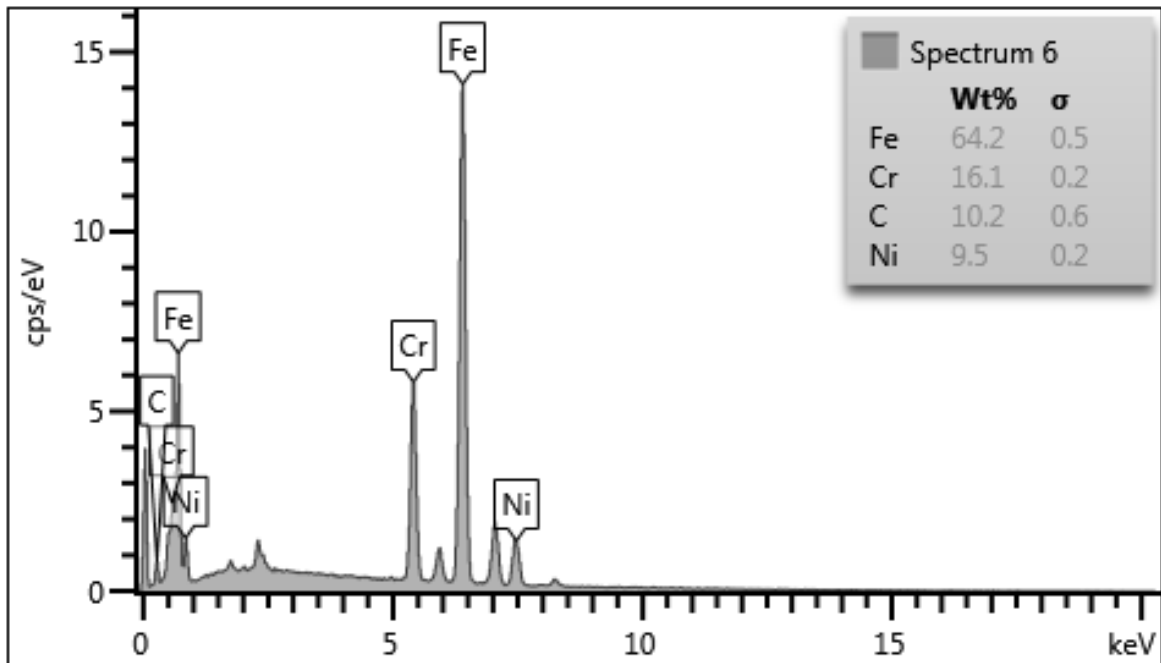


Figure 56: SEM and EDX on 0.5mm-Vertical Specimen

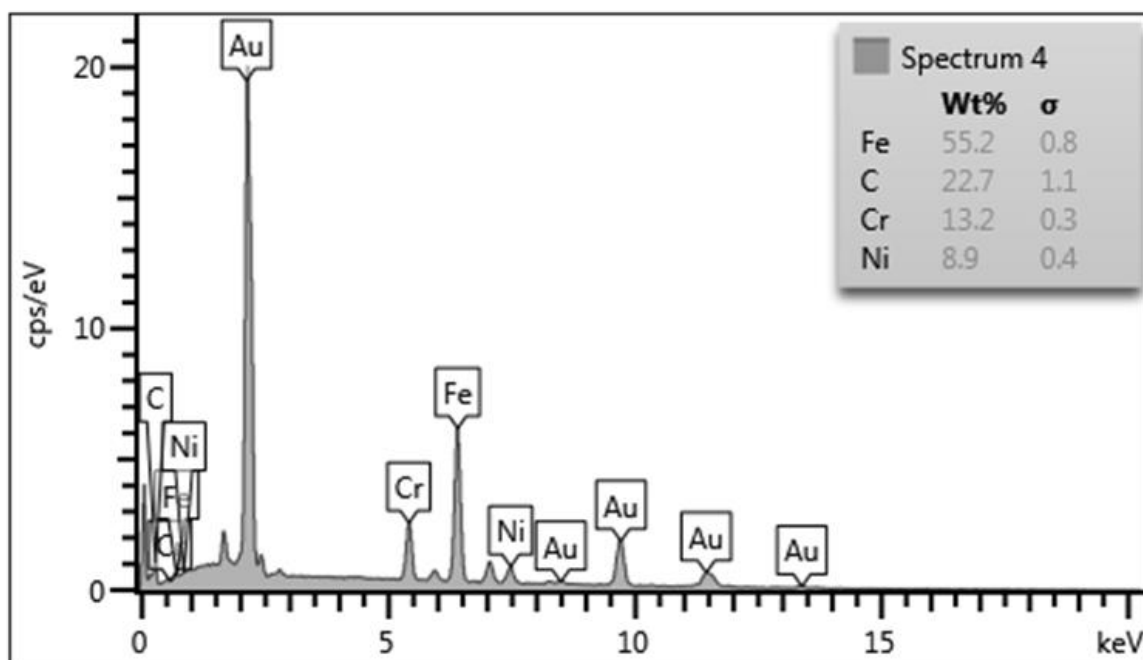


Figure 57: SEM and EDX on 2mm-Horizontal Specimen

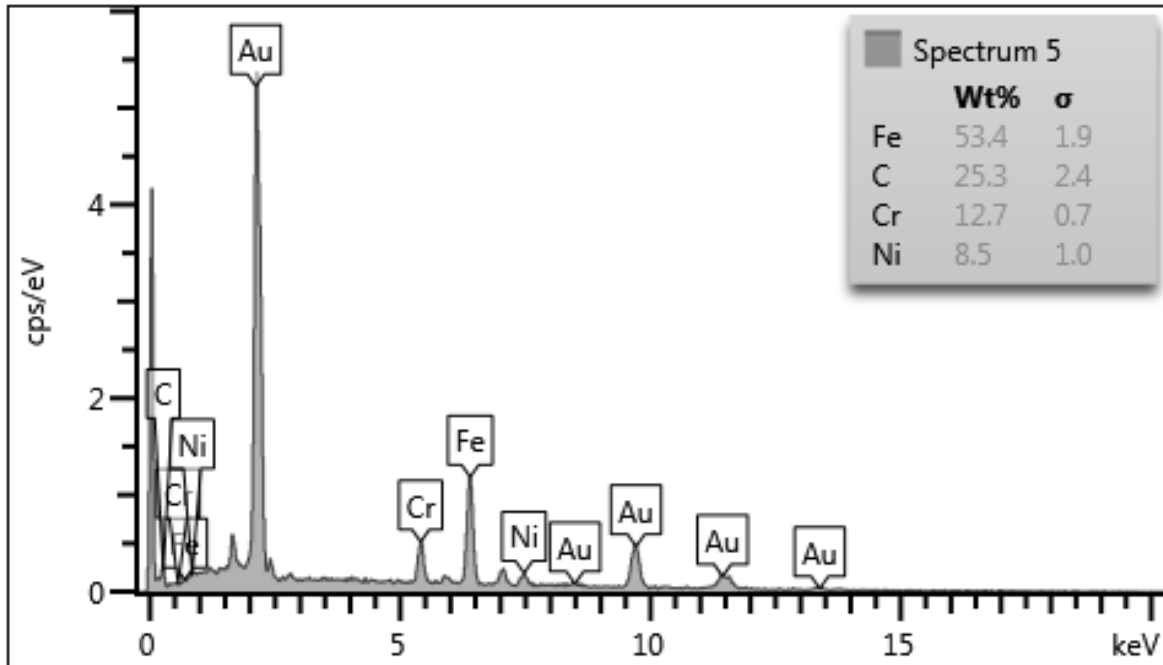


Figure 58: SEM and EDX on 2mm-45Degree Specimen

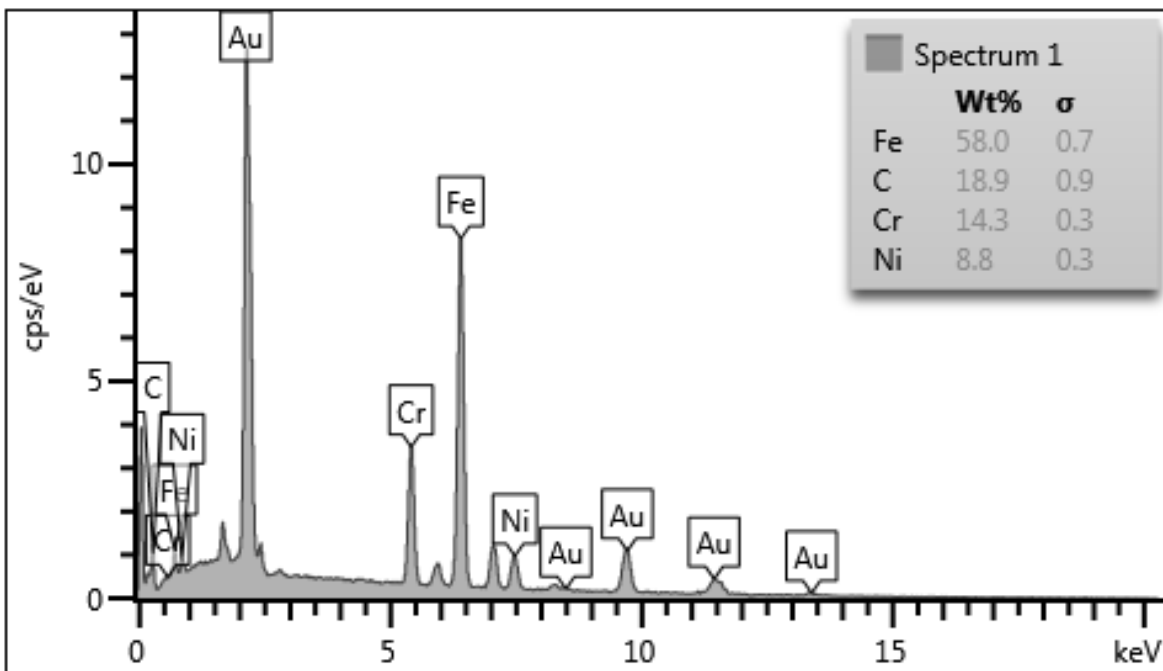


Figure 59: SEM and EDX on 5mm-Vertical Specimen

Table 24: Chemical Composition from EDX and Table 14

Component	Indicative Value (%)				
	Table 14	0.5mm-V	2mm-H	2mm-45Deg	5mm-V
C	0 – 0.03	10.2	22.7	25.3	18.9
Cr	16.5 – 18.5	16.1	13.2	12.7	14.3
Ni	10.0 – 13.0	9.5	8.9	8.5	8.8
Fe	Balance	64.2	55.2	53.4	58.0

2mm-Horizontal, 2mm-45Degree, and 5mm-Vertical samples were cross-sectioned and mounted together with gold coating, first mount, while 0.5mm-Vertical sample was cross-sectioned and mounted separately without gold coating, second mount, before applying SEM. It can be seen from Figures 57, 58 and 59 that EDX results of the first mount have Gold (Au) spike due to the gold coating while Figure 56 does not have Au spike since coating was not applied to the second mount. Moreover, it is noticeable that the chemical composition from EDX in Table 24 has a higher Carbon than in Table 14, and this is definitely because of the acrylic mount. The range of Fe content in Table 14 is between 62.9 to 71.5 while the average from EDX in Table 21 is 57.7, which results in having a difference of 8%. Furthermore, the range of Ni in Table 14 is 10.0 to 13.0 while EDX shows an approximate average of 9, which therefore has a lower of 1% from the total content. For Cr, the average from the manufacturer is between 16.5 to 18.5 though EDX of 0.5mm-Vertical is 16.1, which has a very slight difference of approximately 2%.

Therefore, based on the discussed results, it can be stated that directions and thickness do not have a major effect in EDX composition.

4.7 DISCUSSION

The overall results from the tensile test, hardness, surface roughness, XRD, and optical microscope have shown the impact of the thickness and building orientation. All tested specimens have the same printing parameters that includes the printing direction. Lower thicknesses have a significant impact on mechanical properties and mainly affects hardness and ductility; however, by increasing the thickness, the impact is insignificant. Also, the lower thicknesses result to have higher porosity as can be seen in 0.5mm-vertical specimen, which consequently lowering the hardness. Furthermore, thickness and change of geometry affect the surface roughness especially with lower thickness. Increasing the thickness can reduce the surface roughness.

Building orientation can significantly impact the tensile strength and elongation as can be realized that horizontal orientation has the highest value of tensile strength while the vertical orientation has the lowest, and elongation has the opposite values. Moreover, the effect of the building orientation in the hardness is insignificant. It is obvious that hardness in the horizontal specimen is higher than the other since it has the highest tensile strength and lower ductility. Also, the 2mm specimen with 45degree orientation has a good hardness and good ductility as well. It is visible that pore sizes in horizontal orientation is larger than other orientations. Furthermore, building orientation can impact surface roughness, but it is not considered as the main cause of effect.

Printing direction is one of the process parameter settings. Printing parameters that include laser power, scan speed and printing direction have the significant impact on the surface roughness. Therefore, the surface roughness can be improved by post-processing. Changing of thickness and building orientation do not have an influence in XRD patterns since all specimen have similar austinite peaks. Additionally, composition from EDX has not shown any significant difference in

any of the samples in regards to thickness, printing direction, and building orientation. Lastly, the overall results of mechanical properties produced by DMLS with all thicknesses and orientations are higher than the conventional manufacturing properties since the overall range of the ultimate tensile test in this study varies from 538 to 784 MPa while wrought, wrought with heat treatment process, casting with gas-atomized process, and metal injection molding with water-atomized powder process have values of 483 MPa, 505 MPa, 518 MPa, and 548 MPa, respectively.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 CONCLUSION

An overview of Additive Manufacturing (AM) with the focus on metal materials and design optimization techniques has been covered to identify the gap in the market by obtaining the positioning and importance of AM in the industry and be aware about how and when this technique can be utilized. Complex shapes and customized products with innovative designs can be maximized with the use of AM because of the layer-by-layer manufacturing method. However, complex shapes with reduction of weight in AM requires strength in the material to be compatible with the traditional manufacturing especially for metal. Therefore, this study focuses on experimentally analyzing material behavior of 316L Stainless Steel additively manufactured by Direct Metal Laser Sintering (DMLS). The study covers the mechanical properties along with microstructure analysis.

The investigation starts by material selection and 316L Stainless Steel has been selected as it is one of the main materials that can be used in various applications. Then, the selected design for parts is the tensile test specimen with considering different thicknesses and orientations in order to perform tensile test to obtain the mechanical properties followed by microstructure analysis. The aim is to analyze the effect on changing the geometry and printing orientation in printed parts. Five designs are selected that includes three thicknesses and three building orientations with three samples from each design to confirm the experimental data. The parts are printed by GE Concept

Laser M1 machine and experimentally investigated by performing tensile tests, hardness tests, surface roughness, X-ray diffraction, and optical microscope.

The outcomes from the experimental results have shown the impact of changing the thickness and building orientation. Mechanical properties can be affected by having lower thicknesses especially hardness and ductility. It also can have a significant impacted by building orientation in tensile strength and elongation since horizontal orientation is the highest value of tensile strength and vertical orientation is the lowest, and elongation is lowest in horizontal and highest in vertical. Surface roughness is mainly affected by the printing parameters that includes laser power, scan speed and printing direction. Change in thickness and orientation have a secondary effect as the length increases in direction, the surface roughness changes especially with lower thickness. Moreover, porosity can be affected by changing the thickness of samples and changing the geometry, which lower thicknesses has more porosity than larger thicknesses and horizontal orientation has larger pore sizes than other directions. All specimens have similar austinite peaks in XRD patterns with insignificant different. Moreover, EDX composition in all samples are considered similar with no major difference, in which thickness and printing direction do not have an influence in changing the composition. Most importantly, the overall results of mechanical properties produced by DMLS with all thicknesses and orientations are higher than the traditional manufacturing properties.

5.2 RECOMMENDATIONS

The overall results from the conducted tests on the 316L Stainless Steel manufactured by Direct Metal Laser Sintering (DMLS) have shown promising outcomes for the AM technology that can

be further studied to be utilized with confidence in the industry. This study was focusing on studying the material behavior of additively manufactured metal with as-built condition. Therefore, it is recommended to take the next step on new researches to further study the material behavior for practical applications. Recommended concentrations are the followings:

- Studying the effect of changing of printing process parameters, such as change of scan speed, laser power and printing direction.
- Studying the effect of post-processing from both mechanical and thermal point of view.
- Studying the effect of cyclic loading for as-built and post-processed.

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