QATAR UNIVERSITY

COLLEGE OF ENGINEERING

EVALUATION OF 316L STAINLESS STEEL PART FABRICATION USING ADDITIVE AND SUBTRACTIVE MANUFACTURING: A GUIDELINE FOR PROCESS SELECTION

BY

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ABSTRACT

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Title: Evaluation of 316L Stainless Steel Part Fabrication Using Additive and Subtractive Manufacturing: A Guideline for Process Selection.

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Due to its favorable mechanical properties and high corrosion resistance and high carbon content, Stainless steel 316L is widely used in many applications including marine, biomedical and aerospace industries. With additive manufacturing technologies for metallic parts have now reached a critical acceptance level, and the interest for metal parts printing has grown significantly, the absence of a clear process versus performance/properties and cost correlations makes it necessary to have a guideline framework for process selection. Such guideline is needed in order to help investors in the industry understand the performance difference between conventional and additive means of manufacturing. Also it helps to realize the feasibility of additive manufacturing technologies for printing metal parts and when actually these technologies become worth investing in; giving the presence of better cheaper alternatives. This thesis studies the mechanical performance, cost and dimensional quality of 3D printed (using Direct Metal laser sintering) 316L stainless steel metal parts in comparison with conventional means, and accordingly develops a guideline framework for process selection by evaluating process effectiveness and investigating performance and cost. The results showed that tensile ultimate and yield strengths for CNC machined 316L Stainless steel samples are more superior to those additively manufactured samples. Furthermore, impact toughness energy resulted very poor performance for as built AM samples, and better higher energy absorption with CNC and heat treated AM samples. SEM images also showed unmelt particles and pores on as built AM samples. Dimensional quality of 9 model parts with various sizes and complexities fabricated has shown 50 µm in overall dimensional variation making the technology suitable for most applications (dimensional accuracy wise). Cost results showed more complex small parts are cheaper to fabricate with AM, while simple larger parts are cheaper to fabricate with CNC machining. Based on the available experimental data for mechanical and dimensional performance and cost, a process selection guideline framework was developed by process overall evaluation. The guideline can be used as tool to help in process selection for investors and industries and helps in understanding when and why metal part printing becomes more feasible and economical than conventional means.

DEDICATION

I would like to dedicate this work to my family and friends …

To my wife and parents who supported me throughout this journey,

To my friends and work colleagues who encouraged and motivated me to complete this project on the best possible manner,

To my supervisor, Dr. Faris Tarlochan, who supported me, and guided me throughout this project.

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CHAPTER 1: INTRODUCTION

1.1. Introduction:

Additive manufacturing or 3D printing has been defined as the process of joining materials – layer by layer – to make objects using 3D designs/models. This definition is applicable for all classes of materials including metals, ceramics and others. [1]

Additive manufacturing (AM) surfaced around 1980’s. AM technologies was adopted for rapid prototyping at first using polymer, wood and paper. AM has advanced since and it is now even possible to 3D print metal parts directly following design geometries, hence AM is now becoming rapid manufacturing. [2]

Additive manufacturing processes can be categorized according to the state of raw material (Figure 1) as liquid, discrete particle or solid sheet.

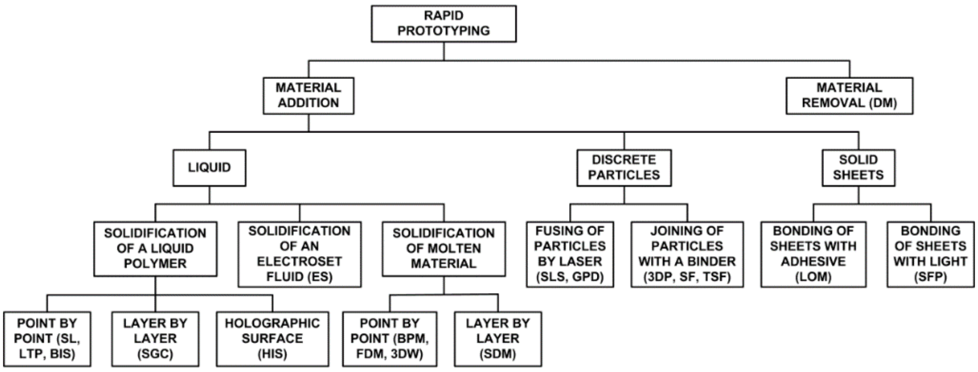


Figure 1: Categories of additive manufacturing processes according to the state of raw material [2]

1.2. Additive Manufacturing for Metal Parts

Metal AM is considered as direct metallic additive manufacturing which can be divided into layer-based and direct deposition. They include SLS, DMLS, SLM and EBM.

Layer based AM starts with a 3D design model of the metal part which is then sliced into multiple cross sections and these section are built layer by layer while a laser or a beam binds the material particles together.

Selective laser sintering or SLS (Figure 2) is a manufacturing technique used to manufacture complex 3D parts by the means of processing powder layers on top of each other by focusing a laser beam with a deflection system [3]. Direct metal laser sintering DLMS was developed in the 90’s, it is based on SLS but it is capable of building metal parts without binding the particles with polymer which eliminates the curing phase. [2]

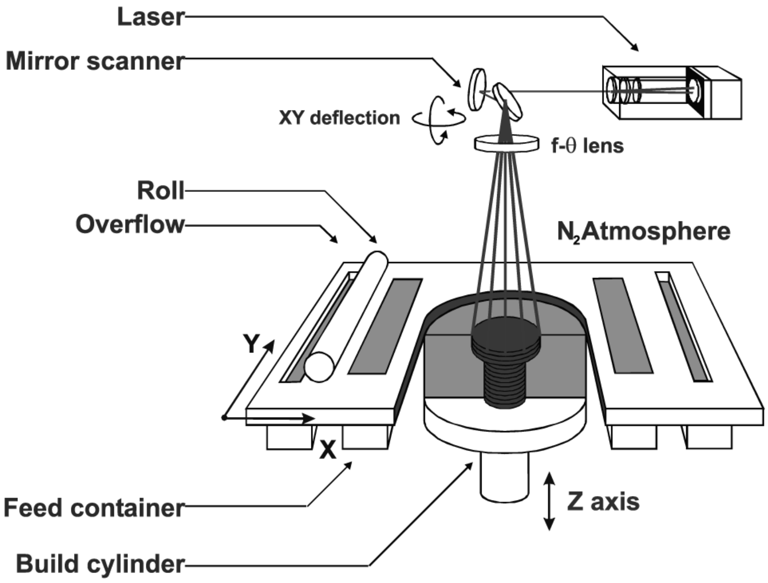


Figure 2: Schematic of SLS systems [3]

DMLS is perceived as one of the promising and flexible manufacturing processes. The process works well with a number of elemental alloys thereby producing an excellent surface finish, offers great feature resolution for the metals and is also industrially stage, however it suffers a major disadvantage which is the build-up of residual stresses between layers during the layer by layer manufacturing process. [4] .

Some applications, industrial or otherwise require certain material properties that cannot be achieved by DMLS as there is a high concern relating to internal stresses of parts producing additively by DLMS. There is also the concern of pores and lower density of parts produced using DLMS as they usually do not have a full density. Residual stresses problem also presents a major challenge (material dependent) and some parts require heat treatment to release the stresses [5].

One of the main consumers of mechanical spare parts is the factories or industries in general. Spare parts manufacturing and unpredicted demand over time presents a complex challenge. Various industries use complex logistics and partnerships with OEMs to supply such parts. Some industries use local suppliers to duplicate/machine mechanical parts that frequently need replacement such as gears, shafts and other mechanical components. [6]

1.3. Advantages of AM over conventional means of manufacturing

Additive manufacturing processes such as SLM, SLS, and DLMS offers great advantages over conventional means including high cooling rate resulting highly refined microstructure and less post production steps [7] [8]. Advantages also include lower material waste, high freedom in design and geometry complexity and better environmental impact. Furthermore, AM decreases the cost in using small quantity manufacturing compared to conventional means and the cost of manufacturing complex part is cheaper if compared to conventional means of manufacturing. [9], [10] Other advantages also includes less material scraping, freedom of design, fast prototyping, less weight if the part is redesigned specifically for AM, the ability to produce complex geometries that are impossible to manufacture by conventional means, the ability to produce spare parts on demand and production on location capabilities for spare parts in the industries which could have significate improvements in the logistics for spare parts industry, and lastly additive manufacturing processes has the advantage of producing models/parts without user intervention by feeding the machine with a three dimensional drawing file and the part will be produced directly from the said three dimensional drawing [11], [12], [13].

1.4. Disadvantages of AM technologies over conventional means of manufacturing

Disadvantages of AM include capacity limitations, poor surface finish, manufacturing accuracy, need of process validation, need of part post processing, long manufacturing time and it requires high level of skill in design aspects [14]. Furthermore, there is a concern that the dimensional accuracy and surface finish of the parts produced with AM might not be adequate for some applications including different industries, not to mention that in many cases those parts need finishing operations including surface machining and heat treatment operations [15] thus making the AM processes not desirable and not fully utilized regardless of its high potential.

1.5. Problem statement

As metal additive manufacturing techniques has now reached a critical acceptance level and has already started to get adopted by the industry with some applications reaching a readiness level for full production capabilities, thus making it very important to have a clear understanding and correlation of process, structure, properties and performance in order to have an acceptable, reliable and defect free metal parts produced through AM [16].

The mechanical behavior of metallic AM components are different from those of conventionally manufactured ones, thus a correlation between process and properties is essential in order to achieve widespread of AM technologies in the industry [7].

As the hype for the additive manufacturing technologies for metal parts printing has grown significantly, with unclear process versus performance/properties/cost correlations, a process selection decision making guideline is needed in order to understand how good the additive manufacturing technologies for metal parts have become and if it is actually worth investing in those technologies or switching over from conventional fabrication methods such as CNC machining or any other subtractive fabrication methods.

1.6. Research questions and research gap summery

Research work conducted on investigating mechanical, microstructure properties and dimensional quality of stainless steel 316L is very limited. 316L Stainless steel mechanical properties, high resistance to corrosion and high carbon content makes it the desired choice for many applications including marine, biomedical, automotive and aerospace industry, however, the available research work that shows direct metal laser sintering performance for 316L SS versus conventional manufacturing is rather very limited. Furthermore, there is lack of effectiveness evaluation for additive manufacturing processes. Also there is no clear framework on process selection based on part size and complexity. Detailed literature and research gap is included in Chapter 2 of this thesis.

Performance difference in mechanical performance and dimensional quality between additive manufacturing DMLS and conventional fabrication is under question. Moreover, the feasibility of the DMLS process for 316L SS is unclear and raises questions; is the technology really worth investing in? Is fabricating metal parts with DMLS cost effective and what is the energy consumption and environmental impacts? And why would users invest millions of dollars in these technologies given the existence of cheaper conventional technologies with a more solid ground?

This thesis aims to answer these questions by setting and developing fundamental guidelines to assist in decision making process for investing in metal additive manufacturing technology by studying and comparing the mechanical performance, dimensional quality and cost performance of 316L Stainless Steel fabrication using DMLS and CNC machining and conducting an overall evaluation on processes efficiency based on manufactured component size and complexity.

1.7. Objectives

The primary objective of this thesis is to develop a process selection guideline based on the mechanical performance, Cost and dimensional accuracy of 3D printed metal parts. This objective is achieved through the following:

1. Developing and fabricating a set of stainless steel 316L parts with various complexities and sizes in both conventional subtractive manufacturing (CNC) and through additive manufacturing.
2. Investigating and comparing the mechanical properties and microstructure for stainless steel 316L samples built using the two processes.
3. Investigating the dimensional accuracy and surface finish of 3D printed 316L stainless steel parts in comparison to conventionally built parts.

4. Investigating and comparing the cost and energy consumption for both manufacturing processes.
5. Conducting an overall evaluation on the effectiveness of using Metal Additive Manufacturing based on component size and complexity.

A visual graphic presentation summarizing the overall study aim and objective is shown in Figure 3 below:

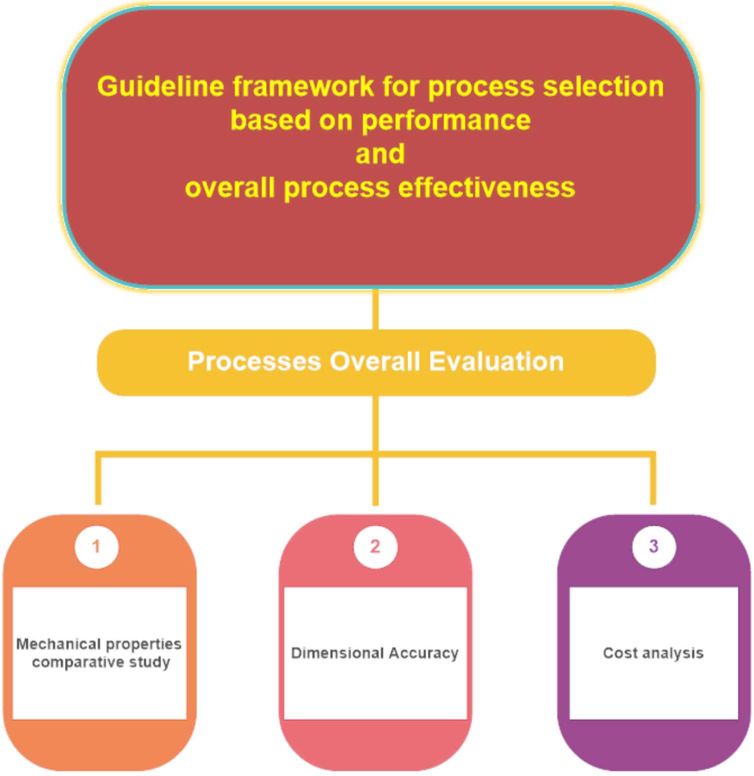


Figure 3: An infographic diagram highlighting overall study aims and objectives

1.8.Significance of the study

This study will contribute towards improving decision making criteria for metal part fabrication process selection by developing a process selection guideline. Such a guideline would be useful not only for investors, but for factories, distributers and machinery workshops as well as serving a large sector of automotive, marine, aviation and biomedical industries. It will also contribute towards improving and understanding the feasibility and effectiveness of metal additive manufacturing for stainless steel, grade 316L.

1.9.Thesis Layout

The thesis layout is as follows:

Chapter 1: Introduction

This chapter introduces the additive manufacturing technologies, advantages and disadvantages of those technologies against conventional means. It presents the problem statement and research question. It also includes detailed research objectives and thesis significance.

Chapter 2: Literature review

This chapter includes a literature survey of all previous research and contributions related to this thesis topic, published to date. The survey covers a review of different topics of interest related to the research project works for this thesis.

Chapter 3: Methodology

This chapter section describes the method used to carry out the study experiment and shows the steps followed to cover all the set objectives and answer the proposed research questions.

Chapter 4: Results and Discussion

This chapter presents the results and discussion for mechanical properties, microstructure, dimensional accuracy and cost for both conventional and additively manufactured samples.

Chapter 5: Process selection guideline

This chapter presents the development of process selection guideline framework and introduces selection matrix.

Chapter 6: Conclusions and Recommendations

This chapter presents the conclusion on the results discussed in this thesis. It also presents further recommendations and future works proposed for further improvements of this study.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter includes a literature survey of all previous research and contributions related to this thesis topic, published to date.

The survey covers a review of different topics of interest related to the research project works for this thesis. The main covered topics of interest are:

1) Additive manufacturing for metallic materials.
2) Mechanical properties & Microstructure of 3D printed Stainless Steel.
3) Dimensional quality.
4) Post-processing operations.
5) Cost, energy consumption and environmental impact.

2.2. Additive Manufacturing for metallic materials

In the recent years, interest has been growing for digital printing of material instead of conventional means of fabrication. While the 3D printing technologies are advantageous and rapidly evolving, most of those technologies rely on polymeric materials, which are in turn lack most of the desired properties and characteristics for functional components/parts in the industry. The ability to print different metallic materials into functional usable parts is very important in making those technologies tangible and potentially work as a replacement for conventional processes or at least supplementing and improving those processes. [17]

As mentioned earlier in the introduction chapter metal additive can be classified into layer-based and direct deposition. Layer based AM processes are usually associated with powder bed fusion. Powder bed fusion technologies include Laser powder bed fusion and electron beam melting. EBM (Figure 4) technology was invented by a Swedish company named Arcam AB. This technology basically uses an electron-focused beam to melt particles of powder at the bed. This process is usually carried out in a vacuum environment with a small helium content. On The other hand, laser powder bed fusion (Figure 5) process uses a focused laser to fuse metal particles into desired layer on the fusion bed. The bed keeps lowering after each layer thickness is complete and the powder played out evenly for the next round of layer laser melting. This process is carried out in an inert, moisture free environment, such as argon or nitrogen gas. The reason behind using inert gas environment is to avoid oxidation of material built. [17]

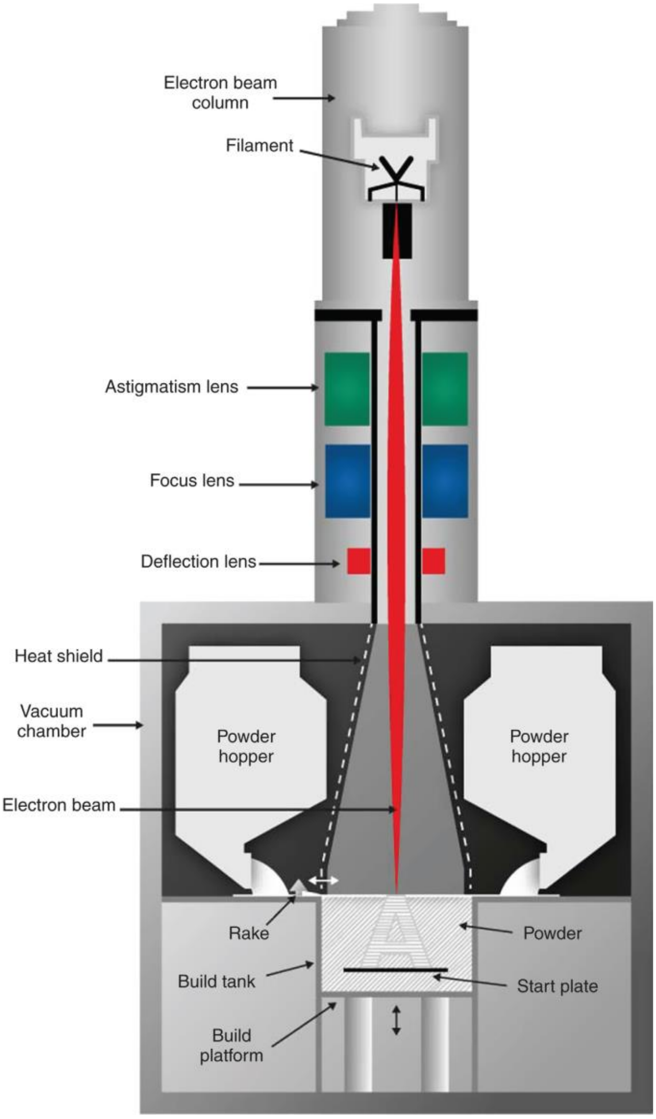


Figure 4: EBM 3D additive manufacturing technology schematic diagram [17]

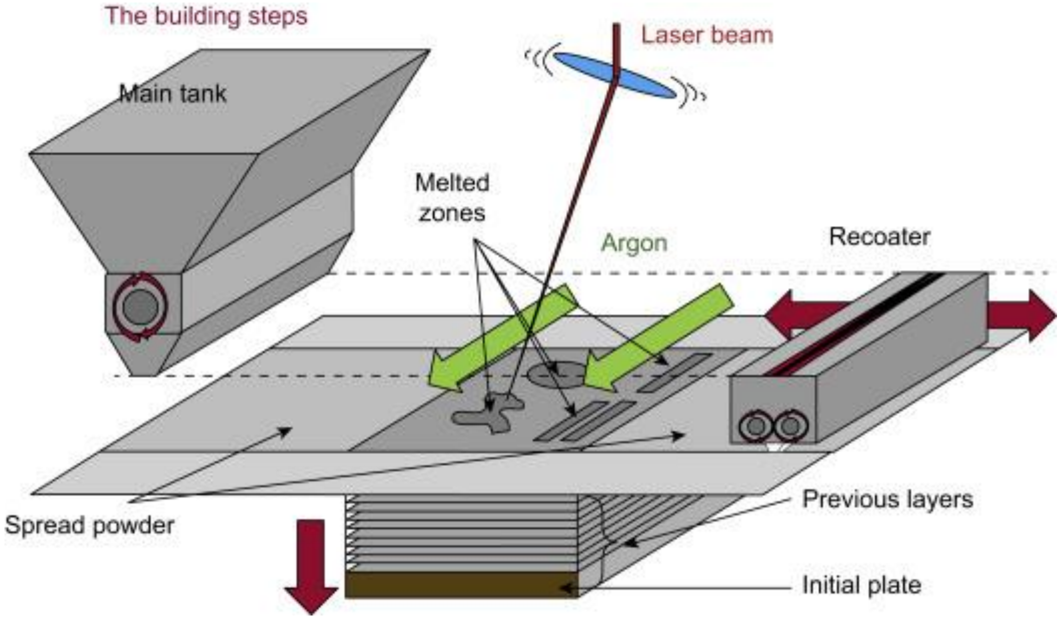


Figure 5: A schematic diagram of laser powder bed fusion technology [18]

Stainless steel 316L parts and components produced with L-PBF Additive Manufacturing has higher strength and low ductility in comparison with the conventionally casted components of the same material. It is used widely in many applications due to its high corrosion resistance and desired mechanical properties such as high strength and high wear resistance. Applications include medical industry such as orthopedic implants, prosthesis as well as other biomedical applications [9], [19].

In biomedical applications, being with attractive mechanical properties and biocompatible in the human body; 316L stainless steel is widely investigated for biomedical application due to its low carbon content, excellent mechanical properties and fair cost.

Other applications include automotive and aerospace industry; however, it is important to avoid failure of components during service life [7]. Additive manufacturing is being used widely in the automotive industry nowadays, metallic and non-metallic components of aircraft are being fabricated using AM technologies by manufacturers such as Boeing, airbus and Bell helicopters. In 2017 Boeing has used titanium alloy parts for its airplanes with future plans to fabricate 1000 parts saving 2-3 million dollars per airplane. NASA and SpaceX are also looking into using AM technologies for fabricating metallic components such as injectors and combustion champers for their rockets engines. [20] Figure 6 shows additive manufacturing use by market share in the industry. As seen from the chart aerospace, automotive industries as well as industrial machines control around 50% of the use of AM technologies, which indicates the increasing acceptance of additive manufacturing technologies in the advanced industries. [21]

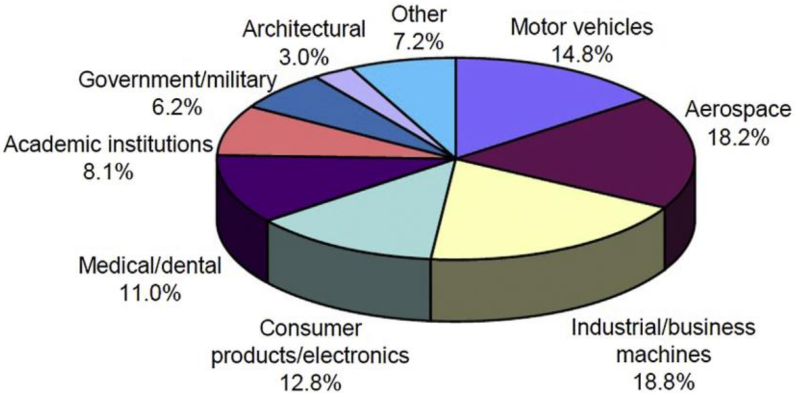


Figure 6: Use of Additive manufacturing in the industry

According to [22] Metal additive manufacturing technologies for metal production faces the problem of requirements such as mechanical properties and dimensional accuracy. The output of metal AM is not good enough for many applications and the produced parts usually require post processing operations such as heat treatment, coating and machining finish. For example, AM metal parts fabricated for aerospace application are usually very complex and require surface finishing, some surfaces can be easily machined using conventional methods while other post processing operations are required for some complex geometries such as etching and shot peening.

2.3. Mechanical properties & Microstructure

Mechanical properties and microstructure of metallic materials varies and is highly influenced by its fabrication process. Same Metallic material/alloy could be showing different microstructure, which in turn effects the mechanical properties and wear resistance behavior of that particular material.

Research by [9] shows the influence of three different manufacturing processes including additive manufacturing (SLM), Hot pressing and casting on the mechanical properties, microstructure and wear behavior of 316L stainless steel. The study shows that stainless steel produced with AM SLM process has shown higher yield strength 490MPa (+41%) and a higher tensile strength 640MPa (+144%) in comparison with conventionally cast specimens (200MPa yield strength and 450MPa tensile strength) of stainless steel of the same grade. While hot pressed and additively manufactured specimens (SLM) exhibited higher strength than casted specimens (Figure 7) they exhibit lower ductility as presented in Figure 8 as tensile strain percentage 25% and 34% for SLM and hot pressed specimens respectively. In addition, the Vickers hardness for the fabricated specimens were as follows: 165HV for casted samples, 176HV for hot pressed samples and 229HV for the AM fabricated samples and the highest hardness of them all.

In terms of microstructure the same study reports the difference in microstructure in each of the specimens for the different processes. As shown in Figure 9a casting sample of 316L stainless steel microstructure showed rectangular grains with size of 91±17 µ.m, where the hot pressed samples (Figure 9b) showed a grain size of 25±4 µ.m. finally the 3D printed sample showed the finesse microstructure of all samples (Figure 9c), with an average grain size of 13±4 µ.m. On the other hand, the wear performance of the fabricated samples was also influenced by the fabrication process. Wear rate was lowest on SLM samples, followed by hot pressed and highest wear rate appeared in the casted samples of 316L stainless steel. The reason behind such higher tensile strength for SLM is the grain size decrease, and those improved mechanical properties are due to finer microstructures.

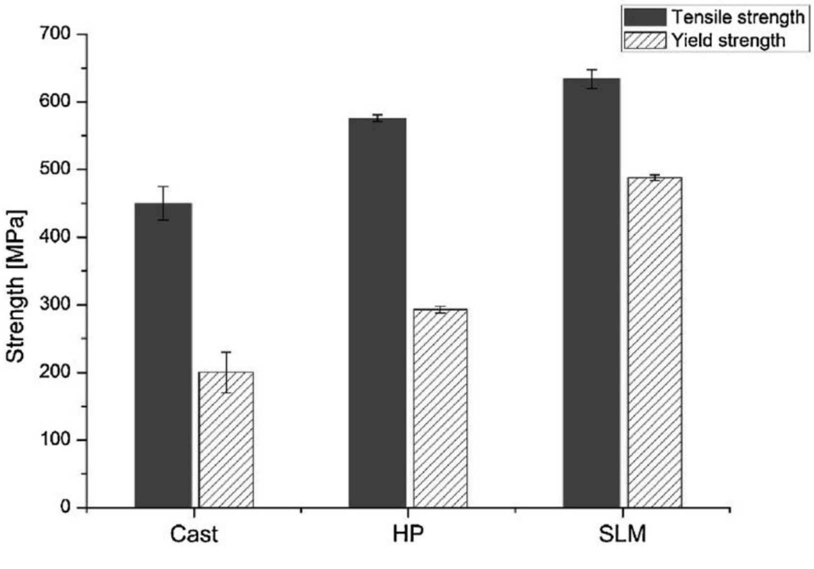


Figure 7: Tensile and yield strength for 316L stainless steel produced with casting, hot pressing and SLM [9]

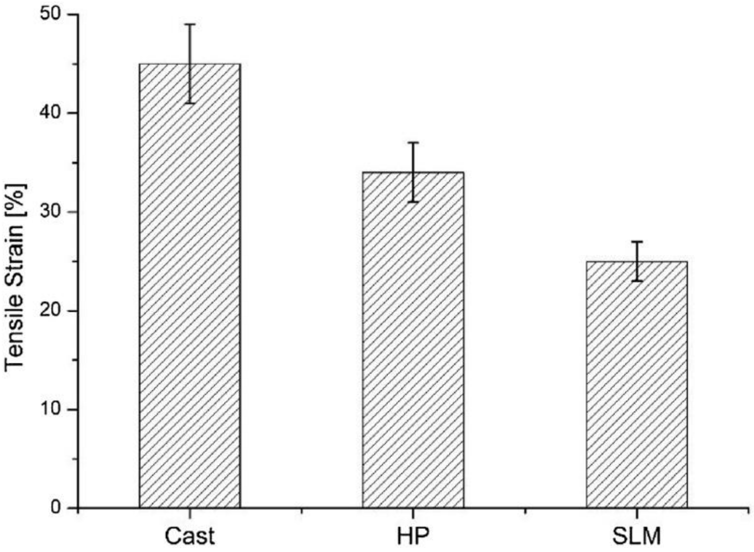
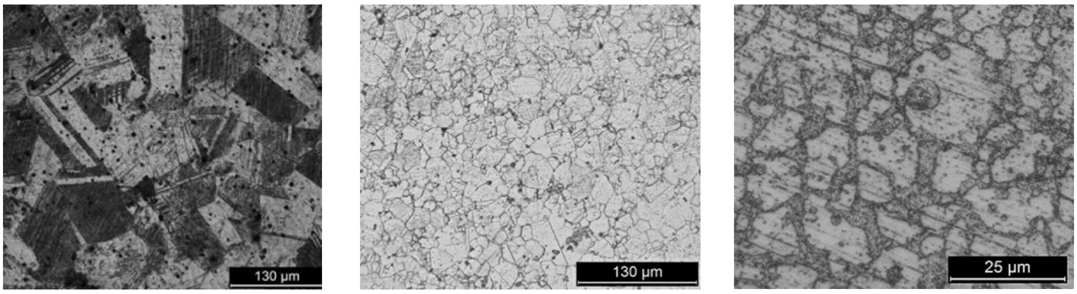


Figure 8: tensile strain for 316L stainless steel produced with casting, hot pressing and SLM [9]



a) **b)** **c)**

Figure 9: micrograph images of 316L stainless steel fabricated using a) casting, b) hot pressing and c) SLM [9]

Others like [23], [19], [24] and [23] have also reported similar range hardness values for as built and same lower range of hardness for heat treated 316L stainless steel built by different additive manufacturing machines.

[7] Reported a 60% improvement in yield strength and around 10% in ultimate tensile strength of additively manufactured (SLM) samples in comparison with conventionally fabricated ones for 316L Stainless steel. On the other hand, the ductility of samples produced with SLM reduced by 50-70% depending on the direction of the load axis (Table 1 and Figure 10). The study indicates that the mechanical properties enhancement for the SLM samples are due to the refined microstructure. The refined microstructure is caused by the high cooling rate in this type of process. This also affects the fracture toughness of the samples. The toughness of 316L Stainless steel produced with SLM was between 63-78 MPa $m^{0.5}$ in comparison with conventionally produced samples at 112-278 MPa $m^{0.5}$, which still has good potential for different applications.

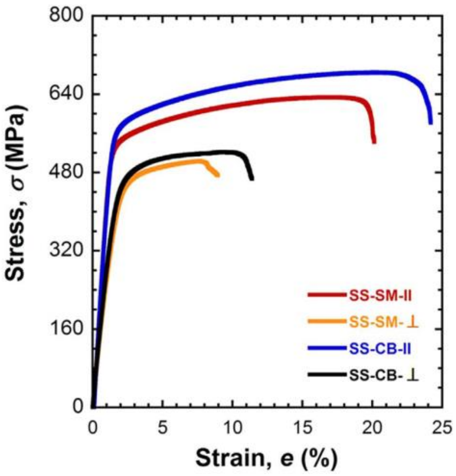


Figure 10: Stress strain curve for 316L manufactured samples for single melt and checker board strategies [9]

Others have also reported on the impact toughness of 316L stainless steel fabricated with additive manufacturing processes. [24], [25], [26] and [27] reported 100-140 J of impact energy for 316L stainless steel build in different directions.

Table 1: Yield Strength And Tensile Strength For Conventional And Additive Manufactured Samples For 316l [7]

Sample Type	**Yield Strength (YS)**	**Ultimate Tensile strength (UTS)**
316L SS Conventionally fabricated	220-270 MPa	520-680 MPa
316L SS SLM parallel direction	511.6±14 MPa	621.7±12 MPa
316L SS SLM perpendicular direction	430.4±11 MPa	509.0±3 MPa

[28] Have reported 700±8 MPa ultimate tensile strength and 456±17 yield strength for parallel build direction using DLMS technology (EOSNT M 270) with reported elongation of 48%. The study also has reported the effect of heat treatment on the samples and results are shown in figure 11 with 674 ± 30 MPa ultimate tensile strength and 419 ± 17 MPa yield strength.

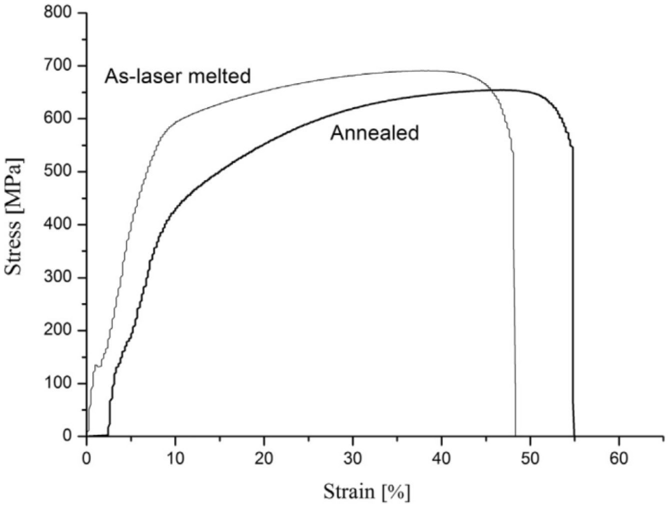


Figure 11: stress strain curves for 316L samples before and after heat treatment [28]

Others like have reported similar findings but with less elongation indicating less ductile behavior. [29] work has shown that the ultimate tensile stress decreases when increasing the building angle.

Research by [30] shows an enhanced tensile strength properties for 316L Stainless steel samples produced with SLM with lower ductility by a factor of 1.5. Furthermore, the research shows a lower impact toughness by a factor of 2 compared to steel manufactured with conventional technologies.

Many more research have reported similar results for mechanical properties of 316L stainless steel fabricated with different additive manufacturing process. Although the results vary depending on build direction, machine manufacturer, process parameters and testing standards. According to [19], metal parts fabricated using additive manufacturing could have similar or even superior mechanical properties to those of bulk materials, however process parameters selection highly influences the final properties of those parts. The study shows that it is possible to additively manufacture 316L stainless steel samples with great density and higher tensile strength than those fabricated using conventional means. Furthermore, the study shows that the density is highly effected by the laser power level, and the highest density obtained during the experiment was using the highest laser power level.

A research done on 316L stainless steel samples built with AM technologies have shown tensile fracture behavior. SEM images (Figure 12) have shown this behavior with dimples formed on the tensile fracture surface indicating ductile behavior. Samples produced a higher yield and ultimate strength for perpendicular build direction than parallel built ones. Furthermore, the study indicates that higher dense samples had an improved impact toughness over lower dense samples. [31]

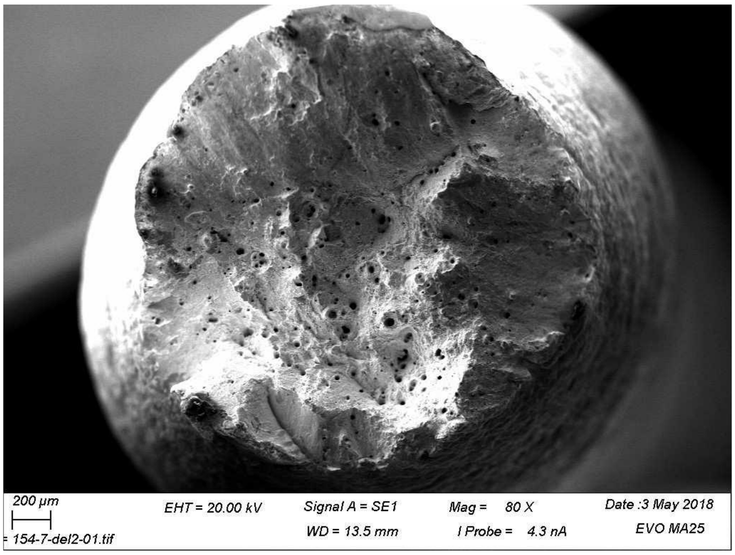


Figure 12: SEM image of tensile sample fracture surface indicating ductile behavior [31]

2.4. Dimensional quality

Dimension accuracy or in case of additive manufacturing print tolerance is a very important aspect of the additive manufacturing industry. Dimensional accuracy indicates the difference in actual dimension between the 3D design and actual printed product. Most additive manufacturing machines have a very tight tolerance to the fraction of millimeter, however with the current grow and expectations of additive manufacturing technologies and in order for it to be used to finished parts fabrication rather than prototypes, dimensional accuracy standards need to be established. [32].

SLM and DLMS technologies have become more dominant in the industry due to its desired high accuracy and performance compared to other metallic additive manufacturing technologies. They are used widely in different industrial applications such as defense and aerospace industries especially in product development stages of parts. [33]

According to [34], additive manufacturing technologies such as FDM and SLS are improved over the years and they could achieve an accuracy of 0.1 to 0.2 mm.

According to [35] Dimensional accuracy is calculated by deducting nominal part size from the measured part size:

$$Dimensional\ Accuracy = \text{Measured size } - \text{Nominal Part size}$$

Ti-6Al-4V parts were built using EOS DLMS M 280 & M290 machines to assess the error in accuracy in terms of different influencing factors including machine model, build number, virgin vs reused powder and manufacturing steps. The results presented did not show any correlation between parts build number and dimensional accuracy, however a maximum variation of 0.088 mm in dimensional accuracy between the two machine types was indicated. The reason behind variability is that machines undergo calibration procedures and different material shrinkage calculations.

Manufacturing steps and powder state have shown no significant in dimensional accuracy. Furthermore, the research explains the difference in accuracy requirement by each individual application. Applications where dimensional control is not necessary, the accuracy presented is sufficient, however if tighter dimensional control is required the current dimensional accuracy presented in the work requires more improvements, and further investigations of dimensional accuracy from more AM builds is needed to improve accuracy of statistical analysis in order to understand the root causes of dimensional accuracy variations.

According to EOS 316L stainless steel material data sheet [36], achievable part accuracy of small parts is ±20-50 µm, and ±0.2% of large parts, however CNC machining can vary and parameters could be optimized more with precision machining techniques up to 0.5 µm [37], [38], [39] and [40] giving the conventional manufacturing the advantage in the context of dimensional quality over additive manufacturing in case of precision oriented applications. It is worth noting however that both processes can satisfy application with required dimensional quality above 50 µm.

[41] Has reported that the surface texture of additively manufactured parts is affected by many factors that include:

- Distribution of particles size
- Heat
- Layer thickness
- Surface angle
- Finishing and post processing effects.

During fabrication / printing of components, some layers become deformed which effects the layer edge resulting in a rough surface on the underside of the fabricated part. Furthermore, surrounding particles also melt to the part contributing to the variation in surface texture and roughness.

According to [42] surface roughness of additively fabricated metal parts is very high, which prevents these technologies from being directly used in their intended applications. Also it is more challenging to reduce the roughness of internal surfaces of metal additive manufactured parts, which can be performed using electro and chempolishing processes. High surface roughness of metallic components is not desired as the irregular surface will be open to failure, which in turn will affect the different mechanical properties of the parts fabricated using additive manufacturing.

2.5. Post-processing operations

In [43] work, the effect of post process heat treatment effect has been studied for 316L stainless steel. Samples produced through additive manufacturing process SLM with 316L stainless steel were post processed in a heat treatment furnace in argon gas atmosphere as shown in Table 2:

Table 2: Post Process Heat Treatment Applied To The 316L Stainless Steel Samples [43]

Heat treatment	Heat treatment Cycle
1	600℃ 2 hours, air cool
2	950℃ 2 hours, air cool
3	1095℃ 2 hours, water cool

The study showed that there was no grain size difference between the heat treated samples and the original additively built samples. Furthermore, the first post process heat treatment condition increased the Vickers hardness to 271±25 as compared to 245±21 in the original built samples. Also a slight decrease of hardness for the second and third heat treated samples was observed as shown in Table 3:

Table 3: Vickers Hardness Measurements For 316L Stainless Steel Samples Pre, And Post Process [43]

Condition	As built	1st heat treated sample	2nd Heat treated sample	3rd heat treated sample
Vickers Hardness	245±21	271±25	215±14	212±20

Furthermore, the same study has shown a higher yield and tensile strength for the pre and 1st condition heat treated samples. In the same time the elongation varied with values from 40% in XY direction and 48% in XZ direction for as built, to 50% in XY direction and 35% in XZ direction in the 3rd heat treatment condition. Finally, Charpy impact test showed the highest absorbed energy at 154±6 J for XY direction and 152±8 J for XZ for the 2nd heat treatment condition, while the 1st and 3rd heat treated samples showed similar absorption compared to the originally build samples. [28] and [43] have reported similar behavior for tensile samples for additively built stainless steel 316L samples. Both reported an increase in ultimate tensile and yield strength values while the elongation was reportedly increased upon heat treatment operation.

On the other hand [24] and [44] research reported slightly different findings with heat treatment decreasing the elongation which indicates decreasing in ductile behavior.

[45] Work shows that mechanical properties can be influenced by building a single build part or multiple build parts of the same additive manufacturing process. This effect is due to different thermal history from different layer build time intervals. The study also shows the effect of post process heat treatment on mechanical properties. Vickers Hardness of single build 316L stainless steel samples was shown to be lower than the multiple built 316L stainless steel samples and higher than heat treated single built samples. As for the compressive strength, single built samples showed lower compressive yield values than multiple build samples and higher compressive values than heat treated single build samples. Furthermore, the yield and ultimate tensile strength of additively build 316L stainless steel was higher than of those conventionally manufactured samples of the same material, however increasing layer build time interval increased samples yield and tensile strengths. On the other hand, heat treated single built samples had decreased the yield and tensile strength. In terms of microstructure, single built samples had 60 µm at the lower built region and increasing to 140µm at the higher region of the build. Also due to the increased layer build interval, multiple sample builds showed finer grain size at 45µm. Heat treatment effected the microstructure as well. The heat treated samples had shown an increased grain size averaged at 80 µm and a recrystallized more isotropic configuration.

2.6. Cost, Energy and environmental impacts.

Additive manufacturing technologies after being used primarily for prototype fabrication has improved a lot and is able to produce final parts of different materials including metals while skipping production development step by producing usable parts from a CAD design and reducing material waste during manufacturing. On demand parts fabrication and reducing stock of parts for different industrial application could have a significant effect on the cost for the final metal part production. Also cost parts is reduced when used additive manufacturing due to no material cost involved in the process as well as no tooling costs.

The cost of 3D printed parts is the sum of the following: Material cost, processing cost, pre and post processing cost. [46]

$$P = MP + AP + CP + BP$$

Where:

$P = Total\ cost\ per\ assembly$

$MP = Material\ cost\ per\ part$

$AP = Preprocessing\ cost\ per\ part$

$CP = Processing\ cost\ per\ part$

$BP = Post\ processing\ cost\ per\ part$

The cost can also be estimated as a sum of direct costs and indirect costs. The total cost for each AM build is calculated by [47]:

$$C_{Build} = (C_{Indirect} \times T_{Build}) + (w \times P_{Raw\ material}) + (E_{Build} \times P_{Energy})$$

Where

$C_{Indirect} = Indirect\ cost\ per\ machine\ per\ hour$

$T_{Build} = Total\ build\ time.$

$w = Total\ weight\ of\ the\ part\ including\ support$

$P_{Raw\ material} = Price\ of\ raw\ material\ per\ kg$

$E_{Build} = Total\ energy\ consumption\ per\ build$

$P_{Energy} = Mean\ price\ of\ electricity$

According to [48] additive manufacturing technology is only suitable for low production volumes due to high cost of material and machines, however in some cases additive manufacturing can substitute conventional (subtractive means) manufacturing. It is also noted that the current models do not consider the fact that AM allows for user end part fabrication, which could affect the actual cost of parts by reducing redesign, material removal costs and other costs that include logistics and other operational needs.

The cost for parts manufactured using CNC machining [49] consists mainly of:

- Material Cost
- Machining Cost
- Tool replacement cost and
- Nonproductive costs
- Direct Energy cost [50]

A more detailed model for cost estimation/calculation by [51] as follows:

$$\begin{aligned} CNCCost = {} & Tool\ Path\ generation\ cost\ (CTP) + Machining\ Cost(CM) \\ & + Tool\ Cost(CT) + Setup\ cost(CS) + Material\ Cost\ (CMa) \\ & + Overhead\ Cost(CO) \end{aligned}$$

$$CNCCost = CTP + CM + CT + CS + CMa + CO$$

Where:

$CTP = (Time \times Programmer\ rate)$

$CM = Machining\ time \times (Machine \frac{cost}{hour} + Labour \frac{cost}{hour})$

$Machine \frac{cost}{hour} = \frac{Purchase\ cost}{Years\ of\ return\ \times Average\ work\ hours\ per\ year}$

$CT = Cutting\ tool\ costs$

$CS = Setup\ Cost$

$CMa = Material\ cost\ per\ piece$

$CO = All\ other\ cost\ including\ management, rent \dots etc.$

2.7. Summary of literature review

This chapter included a comprehensive literature review on the most relevant topics to this thesis. This chapter discussed the mechanical and microstructure properties of similar additive manufacturing processes for 316L stainless steel. It also discussed dimensional accuracy and surface finish of metal parts built using similar processes as well as post process operations. Furthermore, it discussed the energy and cost estimation models available in the literature.

2.8. Literature survey main findings and summary

The literature survey has shown that there is plenty of research done in the area of additive manufacturing in general, however the research published on metal additive manufacturing is still lacking. Studies investigating mechanical properties and microstructure for 3D printed stainless steel 316L is very limited and process versus performance correlations are not investigated thoroughly. Cost estimation models were available for additive manufacturing processes, while actual case studies that investigates mechanical performance and part dimensional quality while considering the cost at the same time for stainless steel 316L material and direct metal laser sintering process are not available. Lastly comparative studies between metal additive manufacturing and subtractive fabrication are very limited and the main focus of those studies is mechanical properties and microstructure. There is a lack of comparative studies for process performance, cost, part quality and mechanical properties for metal parts fabricated using additive manufacturing and DMLS.

2.9. Research Gaps

To the extent of the author’s knowledge, available research work that shows direct metal laser sintering performance for 316L SS versus conventional manufacturing is very limited. More importantly, there is lack of effectiveness evaluation for additive manufacturing processes. Furthermore, there is no comprehensive framework guideline on process selection based on part size and complexity that investigates mechanical performance and part dimensional quality while considering the actual manufacturing cost at the same time for stainless steel 316L.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter section describes the method used to carry out the study experiment. Testing samples were fabricated using additive manufacturing using direct metal laser sintering as well as conventional manufacturing (CNC). Mechanical and microstructure testing has been performed for the samples built using additive manufacturing (DLMS) using EOSNT M280 machine, heat treated additively manufactured samples and machined samples. The material used throughout this study was stainless steel 316L. Nine part models with different complexities and sizes were designed and fabricated using both processes as well in order to assess dimensional quality and cost, and use the collected data to formulate a guideline framework to assist in process selection decision making criteria for interested parties.

3.2 Mechanical Testing

In order to test the mechanical properties and behaviors of the additively manufactured material and check mechanical performance against conventionally manufactured material 3 different sets of testing specimens have been produced and different mechanical standardized testing was performed, in order to have a comparative view of the mechanical properties as follows:

Conventionally produced (machined), additively manufactured specimens and heat treated additively manufactured specimens. The properties examined was tensile, impact and HRB hardness testing. These tests satisfy requirements for understanding material properties when assessing metallic materials. Micrograph SEM was performed on the failed surfaces in order to understand the failure difference between the different sample setups.

3.2.1 Sample fabrication

Samples were fabricated according to each test standards. A total of 3 samples was machined using CNC lathe for tensile testing, and 3 samples were machined with CNC for notched Charpy impact test. The remaining additive manufactured samples was produced in the same build using perpendicular direction (Figure 13). A total of 6 samples for tensile testing and 6 for Charpy notched test was built. Half of the printed samples were then heat treated at 950 ℃ for two hours under argon gas environment using Carbolite ESF1275 electrical furnace (Figure 14&15).

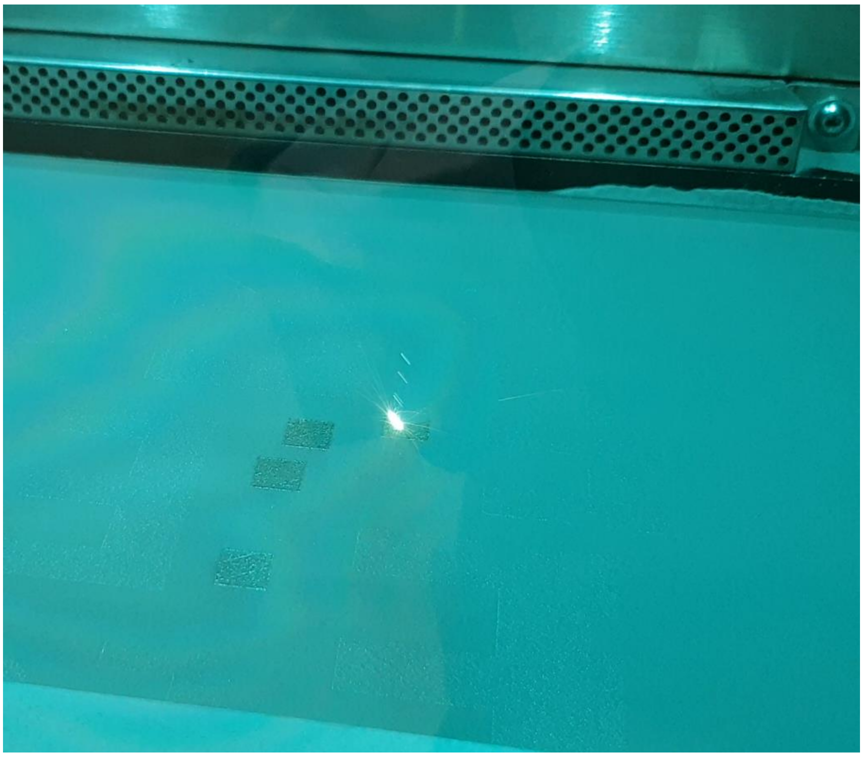


Figure 13: Testing Samples As they are being built with DLM

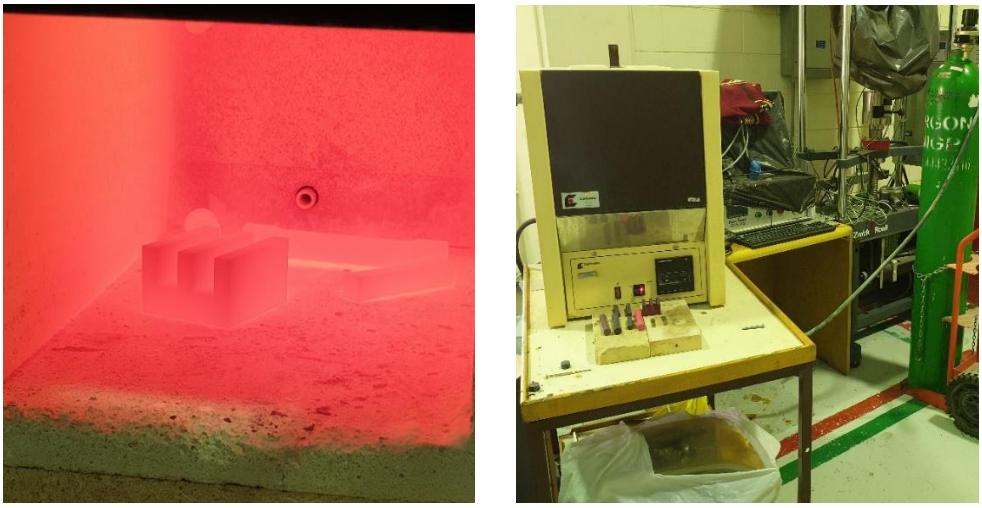


Figure 14: Samples during heat treatment process

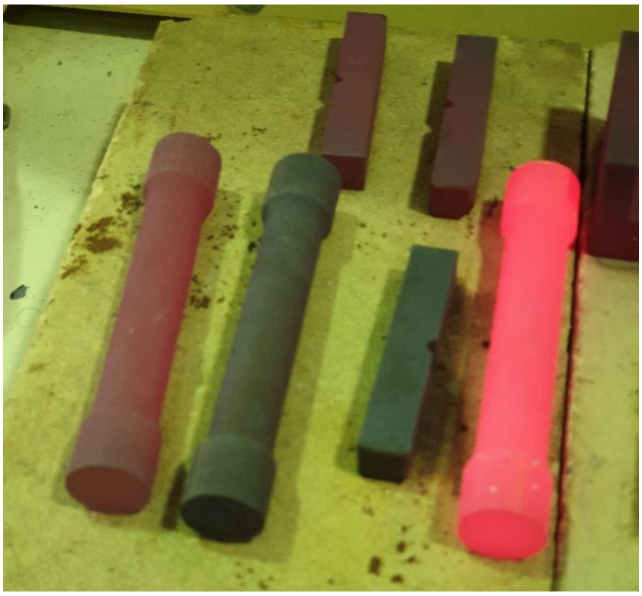


Figure 15: Heat treated samples

3.2.2 Tensile Test

In order to provide information on material ductility and strength under tension force. The testing specimens were prepared according to ASTM E8/E8M-16a standard [52]. A total of 9 specimens seen in figure 16 were fabricated as shown in table 4.

Table 4: Tensile Samples Fabricated

Specimen description	**Number of samples**
CNC machined from cast 316L SS	3
As built 3D printed with 316L SS powder	3
Heat treated (950 ℃@2 hours) printed with 316L SS powder	3

Figure 16: Fabricated tensile samples ready for testing right to left: As built 3D printed, Heat treated 3D printed & CNC machined

The samples were tested under tensile load and the results are presented in the next chapter of this thesis.

3.2.3 Charpy impact test

In order to provide information on material behavior following multiaxial stresses as a result of impact force. The testing specimens were prepared according to ASTM E23-18 testing standard [53]. A total of 9 specimens seen in figure 17 were fabricated as shown in table 4 in the previous section.

Figure 17: Fabricated impact samples ready for testing right to left: CNC machined, As built 3D printed & Heat treated 3D printed

3.2.4 Hardness test

Hardness test (Rockwell hardness B scale, 100 kgF, and 1/16-inch steel ball) was performed in accordance with ASTM E18-19 standard. The test was performed on polished surfaces for the same categories of specimens mentioned in table 4 earlier.

3.3 Dimensional Quality

For testing the dimensional accuracy of the additively fabricated parts, a variety of parts were designed in a combination of size and complexity in order to test the variation in accuracy of DLMS fabricated parts in comparison with reference measurements. The parts were designed and fabricated using conventional (subtractive) means as well as additive manufacturing with direct metal laser sintering using EOSNT 280 3D printer, same material was used for both cases (Stainless steel 316L) in order to achieve a suitable and comparable set part for testing the dimensional accuracy.

The following parameters were used for part fabrication using CNC and additive manufacturing EOSNT 280M (Table 5):

Table 5: Part Fabrication Parameters

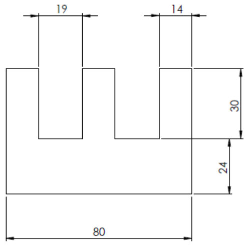
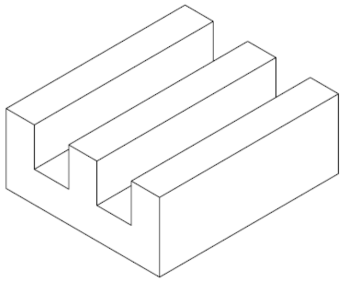
AM parameters	**CNC Machining parameters**
Programming Software: Magics, Decoder: Stainless steel Printing parameters: Layer Thickness: 0.03mm Platform temp: 80℃ Support: 3mm thickness Laser power: 330 watts Gas flow: 2.7 Inert Gas: Argon Oxygen Level: 0.02%	Machine Model: DMG MORI DMU 50 Programming software: Master CAM **Simple and Medium Models:** 1. Rough cutting: (Spindle speed: 800, Depth of cut: 0.2mm, Feed Rate: 500mm/min, Cutters used: 63mm and 12 mm end mill). 2. Finishing Cutting: (Spindle speed: 2500, Depth of cut: 0.08, Feed Rate: 1000mm/min, Cutters used: 12mm and 6mm end mill). **Complex Models:** 1. Rough cutting: (Spindle speed: 800, Depth of cut: 0.2mm, Feed Rate: 500mm/min, Cutters used: 63mm and 12 mm end mill). 2. Finishing Cutting: (Spindle speed: 3500, Depth of cut: 0.05, Feed Rate: 800mm/min, Cutters used: 8mm ball nose, 6mm end mill).

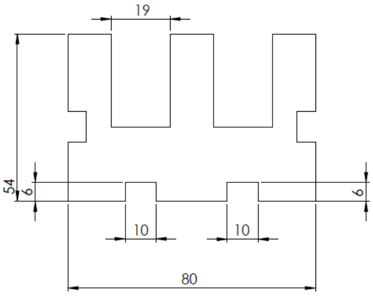
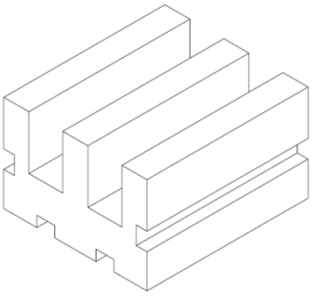
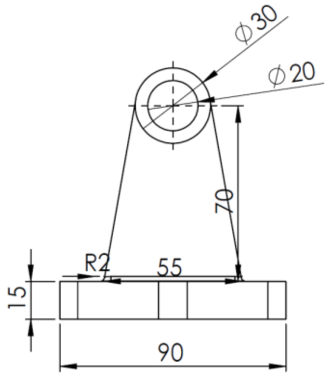
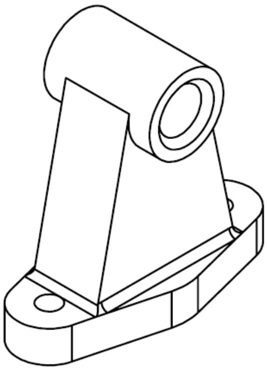
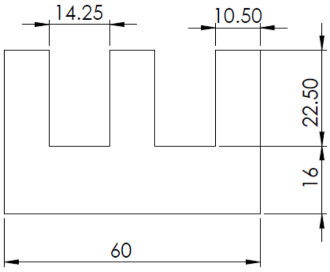
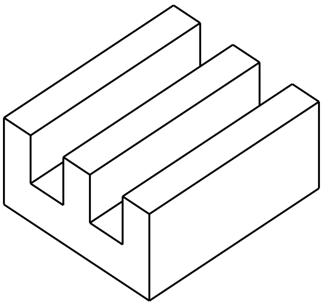
Three sets of parts (small, medium and large scale) were fabricated (table 6) as follows:

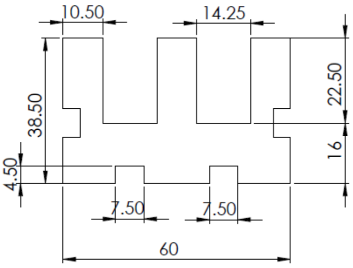
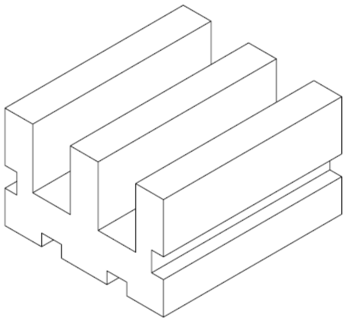
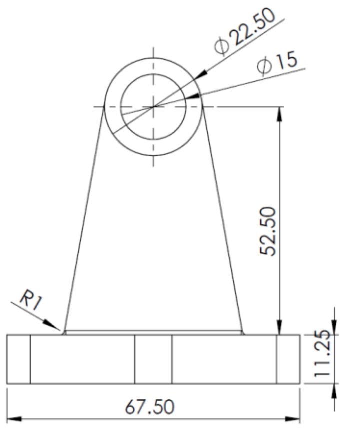
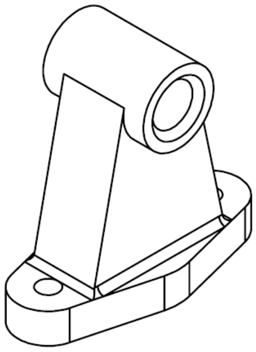
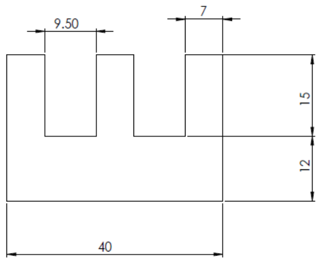
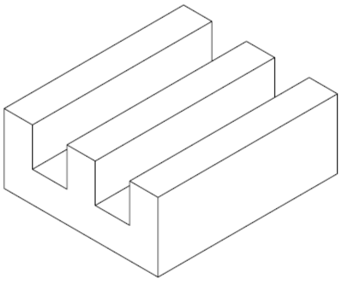
- Simple Geometry – Cubic thin walled structure.
- Medium complex geometry – Grooved thin walled structure.
- Complex geometry – complexly shaped shaft holder that includes fillets, holes, complex surfaces and edges.

The fabricated parts dimensions were taken using a digital Vernier caliper with 0.01mm resolution. All the measurement was repeated 3 times and average for best results. Table 7 shows pictures of the actual fabricated models, and the difference in visual appearance between the machined and additively manufactured models.

Table 6: Fabricated Model Parts

Model ID	Geometry	Scale Factor (mm)	CAD drawing
L11	Simple	Large size 	

Model ID	Geometry	Scale Factor (mm)	CAD drawing
L12	Medium	Large size 	
L13	Complex	Large size 	
M11	Simple	Medium size 	

Model ID	Geometry	Scale Factor (mm)	CAD drawing
M12	Medium	Medium size 	
M13	Complex	Medium size 	
S11	Simple	Small size 	

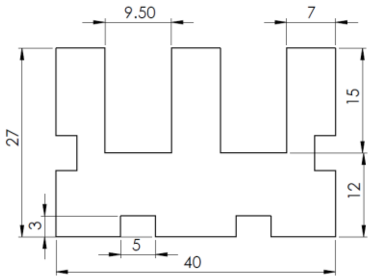
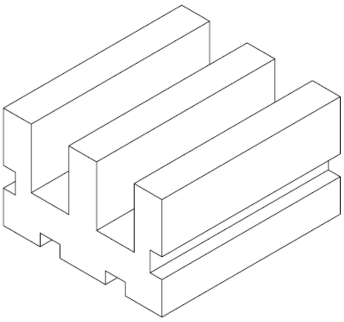
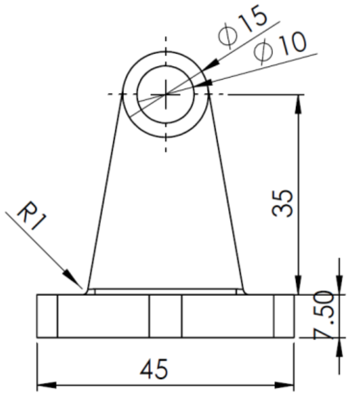
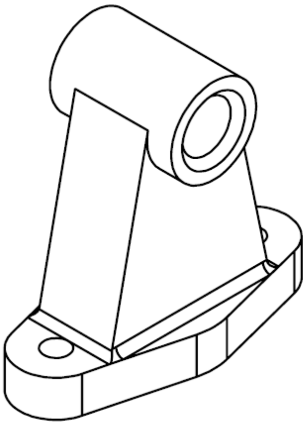
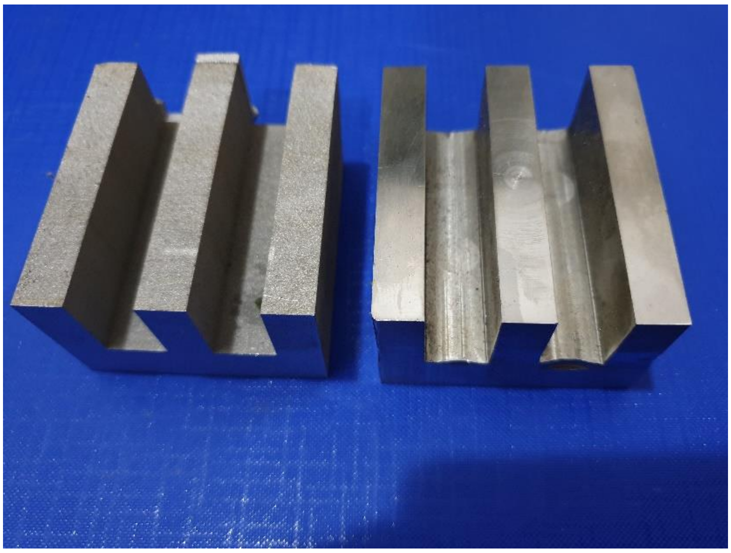
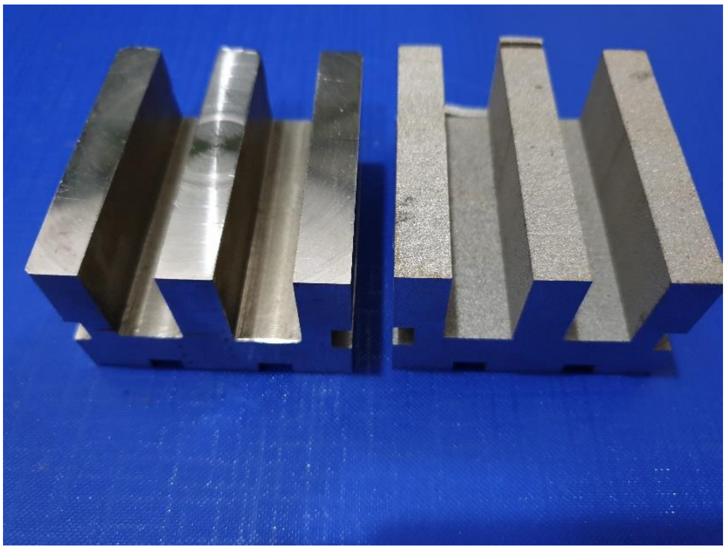
Model ID	Geometry	Scale Factor (mm)	CAD drawing
S12	Medium	Small size 	
S13	Complex	Small size 	

Table 7: Fabricated Models

<table>
<tr><th>Geometry</th><th>Image</th></tr>
<tr><td>Simple</td><td>
AM left, CNC right</td></tr>
<tr><td>Medium</td><td>
CNC left, AM right</td></tr>
</table>

Geometry	Image
Complex	 CNC left, AM right

3.4 Cost Estimation

Cost phrase in this context refers to the amount of money or equivalent spent to deliver an output produced parts/models. While cost is a general term, cost estimation refers to the approximation process of cost for the whole project parts fabrication based on the available data/information acquired during fabrication processes. The estimation does also include any other costs encountered during the delivery of the final products including design costs, management, material, machine costs, tooling, overhead and any other hidden costs. Cost estimation models uses more variables and considers more aspects for the actual costs that is reflected in the final cost value for each product/service which is very important in order to reflect a more precise value as close as possible to the actual fabrication cost.

Cost of CNC model parts fabrication was estimated using the following equation, the cost is calculated separately for each fabricated part:

$$CNC\ Cost = Tool\ Path\ generation\ cost\ (CTP) + Machining\ Cost(CM) + Tool\ Cost(CT) + Setup\ cost(CS) + Material\ Cost\ (CMa) + Energy\ Cost\ (CE) Overhead\ Cost(CO)$$

$CNCCost = CTP + CM + CT + CS + CMa + CE + CO$ (Equation 1)

The equation is based on [51] CNC machining cost estimation model with revision. All the data was collected based on actual cost of manufacturing process and any other costs encountered during this project. The data in hand was then used to estimate the cost for each model part using the Equation 1 above. Detailed Cost breakdown is attached in appendix A.

Cost of built AM model parts was estimated using the following equation:

$P = MP + AP + CP + OP$ (*Equation 2*)

Where:

$P = Total\ cost\ per\ assembly$

$MP = Material\ cost\ per\ part$

$AP = Preprocessing\ cost\ per\ part$

$CP = Processing\ cost\ per\ part$

$OP = Overhead\ costs\ including: Energy\ , Inert\ Gas\ and\ Post\ processing\ costs$

The equation is based on [46] cost estimation model with minor revisions to the model based on the actual cost data encountered during the fabrication process. The revision included other costs such as overhead and energy costs. All the data collected based on actual cost of manufacturing process. Equation 2 was then used to estimate the additive manufacturing build cost (includes all model parts).

Cost of each fabricated part was then calculated respectively by weight percentage of each part model. Detailed cost breakdown is attached in appendix B.

3.5 Process selection guideline framework

In order to assess both manufacturing processes compared in this thesis and present a framework guideline for process selection, both additive and conventional (subtractive) manufacturing technologies – more specifically Direct metal laser sintering and CNC machining processes- were studied based on an actual manufacturing scenario with various part complexity and size fabricated using both processes.

Furthermore, mechanical properties were studied and compared. Using various testing standards mentioned in the previous sections of this chapter, for better evaluation of mechanical properties. Finally, the dimensional quality and cost estimation output data was analyzed and overall process evaluation was performed. Furthermore, determining parameters such as required mechanical properties, required dimensional quality and most important of all, cost was studied and implemented into developing a process selection guideline that uses all available parameters to guide the use to the best direction for process selection of manufacturing stainless steel 316L parts based on the needs and requirements (mechanical properties, dimensional precision, expected manufacturing complexity and size ... etc.) from investor/user point of view. The guideline framework development process is summarized in figure 18 below:

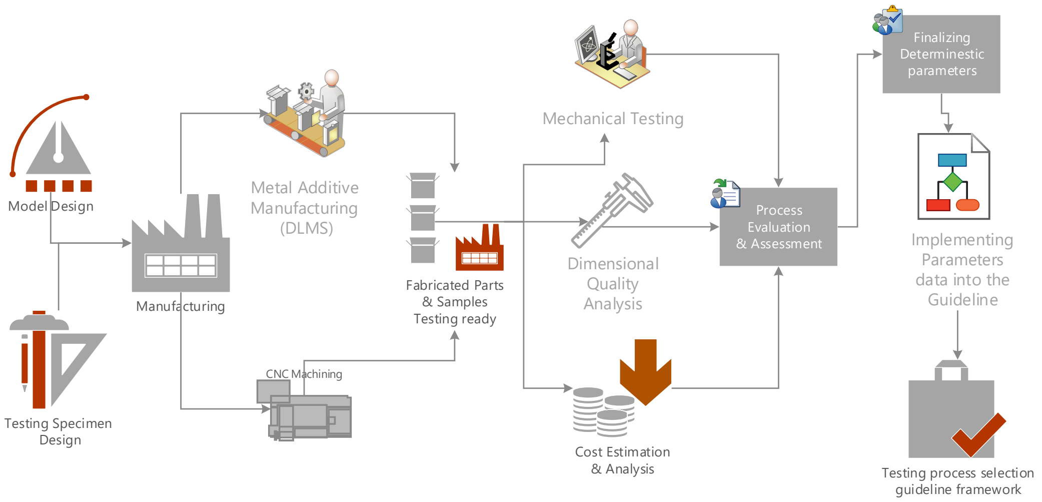


Figure 18: Guideline development process summery

For example, a user would have to identify the requirements for part fabrication, including mechanical properties, dimensional precision needed, complexity and size. Entering those parameters into the matrix would lead to the best possible option for fabrication. The matrix was designed based on actual cost data from real life manufacturing scenario used in this thesis to fabricate stainless steel 316L parts in both CNC and Additive manufacturing DLMS.

3.6 Summary

Mechanical testing samples has been fabricated and used to perform Tensile, Charpy impact, and hardness Tests. 316L stainless steel part models of various sizes and complexities was designed and fabricated using two different approaches; CNC machining and Direct metal laser sintering 3D printing process. Mechanical Properties and Dimensional Quality Evaluation and cost estimation data of the fabricated parts were used to introduce a guideline matrix framework for process selection to assist investors in realizing the current potential of additive manufacturing technologies and helping answering questions about worthiness of investing in the current metal additive manufacturing technology for stainless steel part fabrication.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents the results and discussion for mechanical properties, microstructure, dimensional accuracy and cost for both conventional and additively manufactured samples. It also presents the developed process selection framework. The process selection framework is machine specific for EOSNT M280, due to the available fabrication and testing data output in hand which includes experimental data outputs from the mentioned machine as well as CNC conventional machining.

4.1 Mechanical Testing

Mechanical testing for AM, Heat treated AM and CNC samples were conducted in order to investigate key mechanical performance differences as well as investigating the effect of the manufacturing technique on the overall performance and checking for any major discrepancies between the manufactured parts.

4.1.1 Tensile Test

Tensile test results help identify the properties/behavior of material to help in knowing the material potential in engineering applications. The test helps to characterize material behavior and properties under tensile load. A high Ultimate and yield strength results indicates the amount of strength needed to cause plastic deformation under tensile load, while elongation helps identifying material ductile behavior. These characteristics are important in engineering design applications mainly for identify safe load limits.

The tensile test has shown a significant difference in tensile properties between the 3 different designed scenarios. Table 8 shows tensile properties for 3d printed as built samples, 3d printed heat treated samples and CNC machined samples. Figure 19 shows stress strain curve difference between the samples.

Table 8: Tensile Properties for AM As Built, AM HT and CNC Samples

Sample type	**UTS (MPA)**	**Yield Strength**	**Elongation %**
As Built 3D Printed	538±20	397±20	54±2
Heat treated 3D printed	512±20	388±20	65±2
CNC machined	647±30	494±20	70±2

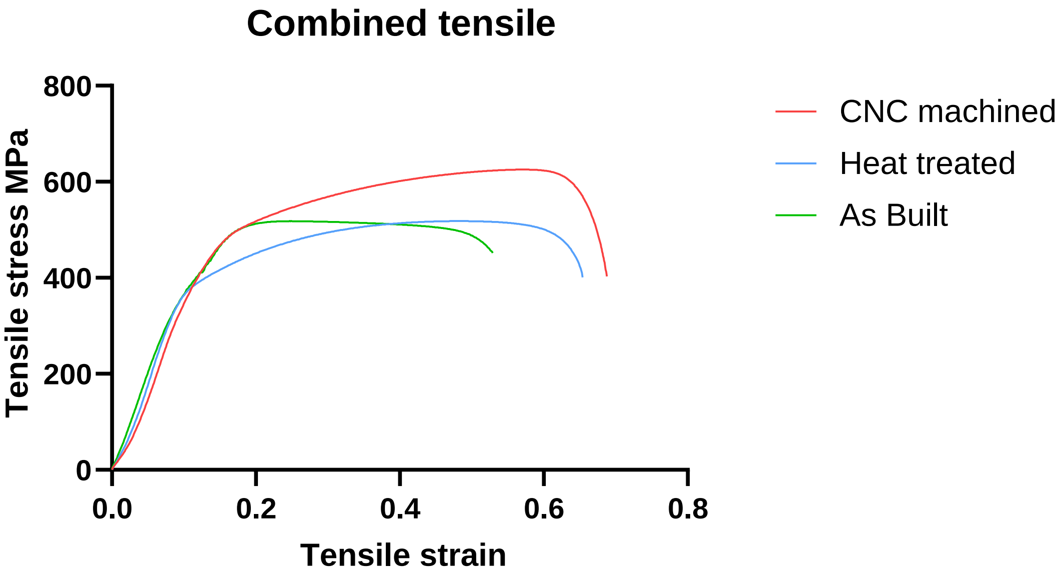


Figure 19: Stress strain curve difference between fabricated samples

The CNC machined samples has shown the highest ultimate tensile strength (647±30 MPa) and yield strength (494±20) over all samples. Furthermore, the 3D printed as built samples has shown a higher ultimate strength and yield strength than heat treated samples, however the elongation of the heat treated samples were higher at 65%± compared to as built 3D printed samples at 54%±2.

As seen from the previous table, the CNC fabricated samples have shown a 18% higher ultimate tensile strength and 26% higher yield strength and 25% more elongation than as built samples and 23% higher ultimate tensile strength, 24% yield strength and 7% more elongation than additively built heat treated samples, which is similar to what have been reported by [43],[29] and [7]. Also the ultimate tensile and yield strength values and elongation is almost the same as what reported in the manufacturer's datasheet for 316L stainless steel; 540 ± 50 MPa UTS and 470 ±90 YS with 50%±20 elongation [54].

Furthermore, the as built samples have shown 5% higher ultimate tensile strength, 2% higher yield strength and 18% less elongation than the heat treated samples. As seen in Fig. 15, the plastic region for the heat treated samples is higher, which is reflected in the results by showing a clear ductile behavior and wider plastic region over as built samples. The main reason behind this decrease in ultimate tensile and yield strength is due to grain size increment by heat treatment. The values reported are close to what have been reported in the literature in previous research. [28] and [43] Reported similar behavior for stainless steel 316L fabricated with a similar process with heat treatment decreasing ultimate tensile strength as well as yield strength while increasing the elongation indicating improvement in ductile behavior. On the other hand, others like [24] and [44] have reported the same decrease in tensile and yield strength but with a decrease in elongation as well, indicating that for those specific processes and heat treatment conditions the heat treatment had a negative effect and no improvement at all for the material ductility, which could be due to impurities or machine parameters not optimized. It is worth noting and taking into account that the mechanical properties vary according to machine manufacturer, fabrication parameters tensile geometry and test conditions. The fractured samples have been analyzed using

SEM and the fracture surface is shown in Figure 20.

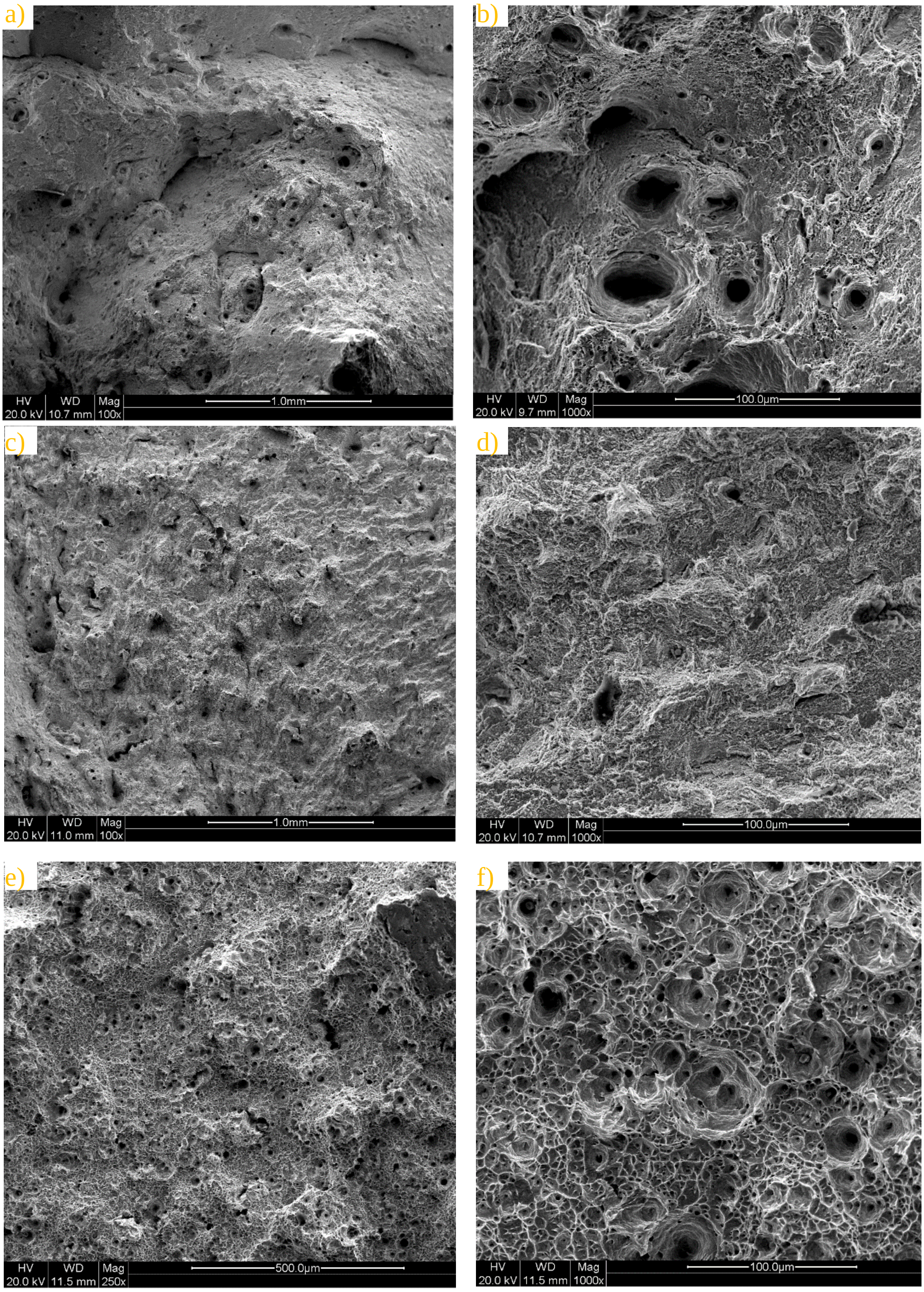


Figure 20: SEM images of the tensile fracture surface for: a&b as built 3d printed samples, c & d heat treated 3D printed samples, e&f CNC machined samples

Although the tensile properties are different for each sample, their fractured surfaces has similar properties. As built and CNC (Figures 20a, 20b, 20e, 20f) machined samples fractured surface looks more ductile than the heat treated samples. Furthermore, pores and dimples are seen on the micron scale with various sizes and shapes for all samples with the exception of less pores on the heat treated fractured surface. The bigger pores seen on the SEM are due to elongation and plastic deformation behavior during the test.

From the results above, it is found that the differences in tensile properties are very significant, and CNC machining have shown highest of them all. While there is a difference, parts mechanical performance lies within a range that allows them to be used in most engineering applications. Furthermore, mechanical properties could also be altered/enhanced using coating or any other post processes to reach the required mechanical performance specified for any engineering applications.

4.1.2 Impact Test

Impact test results help identify the impact toughness properties/behavior of material to help in knowing the material potential in engineering applications. The Charpy notched impact test is a high strain test that helps identifying the energy required to fracture specimens and helps identifying the material impact resistance, thus it is rather helpful for engineering design applications mainly for identify safe load limits.

The impact toughness for 3d printed, heat treated and CNC machined samples are shown in table 9 and fig 21.

Table 9: Impact Toughness for 3d Printed, HT and CNC Samples

3D printed	3D printed, heat treated	CNC Machined
100±8 (J)	182±18 (J)	199±5 (J)

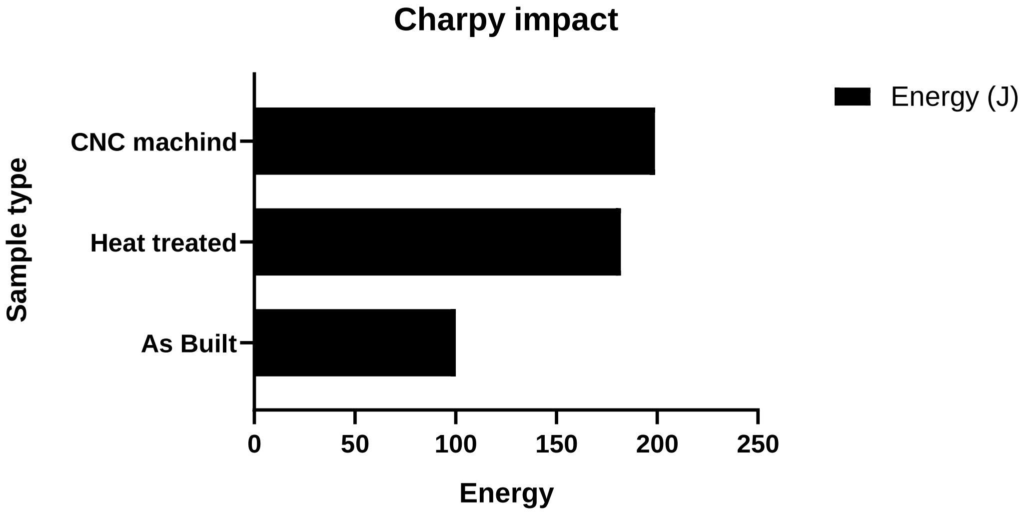


Figure 21: Charpy Impact toughness difference of the 3 categories

The results have shown that the impact toughness was the highest for CNC machined samples at 199±5 (J), while the heat treated samples has shown improved impact toughness over the as built samples. The improvement is significant at 182±18 (J) for heat treated samples versus only 100±8 (J) for the as built samples. These results indicate that the 3D printed as built samples had shown a more brittle behavior than the heat treated samples with almost 57% more energy absorbed in the impact test for the heat treated samples. Furthermore, the CNC machined and heat treated samples have shown a close impact energy results with 10% advantage for the CNC machined samples which is to be expected and matches what have been reported in the literature by [25], [26], [27] and [24].

Figure 19 shows SEM images for impact samples fractured surfaces. Unmelt particles are seen in the 3D printed as built samples (Figure 220a&22b) with a more brittle fracture with narrow shear lips. Same pores as the tensile samples is present, all together with unmelt and partially melt particles could be the reason behind the low impact energy resulted by this process as the porosity decreases density which in turn negatively influences the impact toughness.

As for the heat treated samples (Figure 22c, 22d), it is clear from the SEM photos that the treatment improved the binding and decreased the pores thus increasing the impact toughness from the original as built samples by approximately 60%. Lastly the ductile behavior can be seen for the CNC machined samples (Figure 22e, 22f), there is fewer pores and wider shear lips indicating partial ductile fracture behavior.

From the results above, it was found that there is a significant difference in impact toughness properties for as built AM samples and others due to unmelt particles during the printing processes. It was also found that the poor impact toughness performance could be improved by heat treatment under inert gas environment.

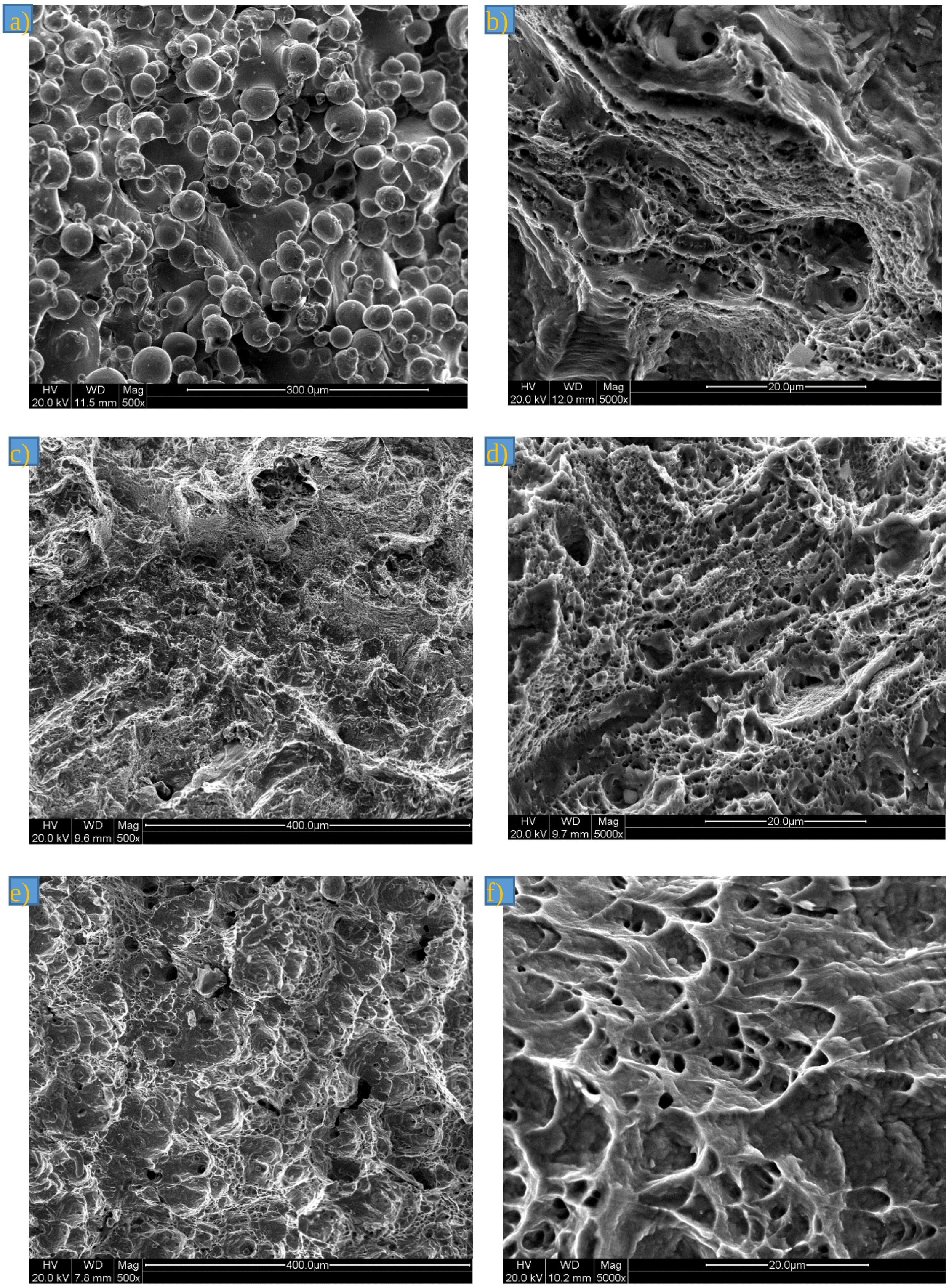


Figure 22: SEM images of the Impact fracture surface for: a&b as built 3d printed samples, c & d heat treated 3D printed samples, e&f CNC machined samples

4.1.3 Hardness test

Hardness testing identifies the material indentation by applying a force to material surface. The hardness test results are important in engineering design applications because it helps to characterize material resistance to indentation.

Rockwell hardness B scale, 100 kgF, 1/16-inch steel ball round results are shown in table 10 and figure 23. All the 3D printed as built and CNC machined samples have shown a similar hardness at 77 and 81 (5% higher in CNC machined samples), and a lower hardness at 74, 4% less than as built samples.

While the CNC machined samples have shown higher overall hardness, the difference is not significant as the hardness values is very close to each other. The lower hardness in case of heat treated samples is a normal behavior due to the softer ductile material properties. The reason behind these results that the CNC machined sample material is harder and more resistance to indentation than the additively manufactured material. The results confirms what have been reported in the literature ([24], [55], [23] and [19]) as well as manufacturers' materials data sheets for EOS and other manufacturers ([54], [56], [57] and [58]).

Table 10: Rockwell Hardness for 3D Printed, HT and CNC Samples

Type	**3D printed**	**3D printed, heat treated**	**CNC Machined**
Hardness	77±3	74±3	81±3

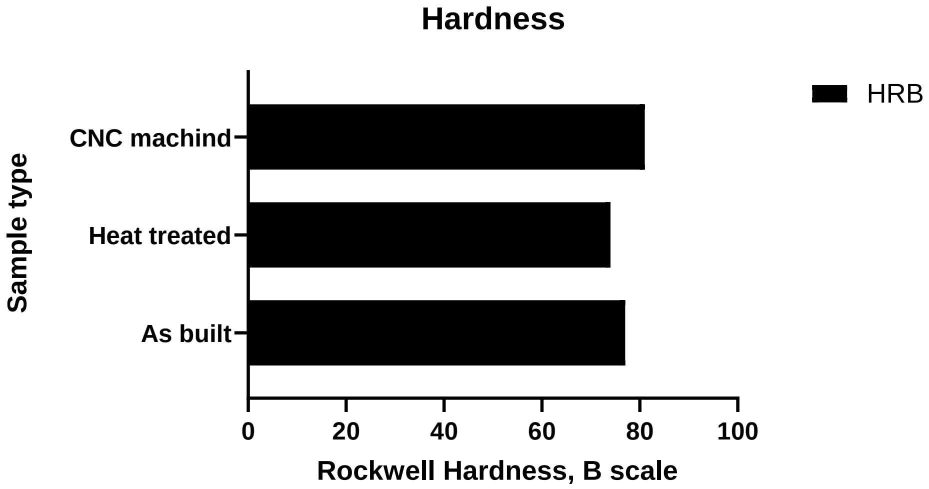


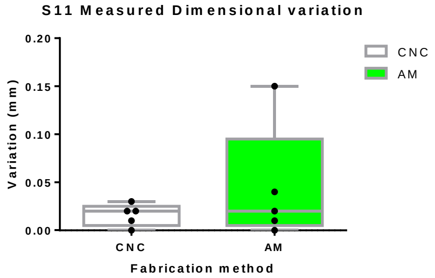
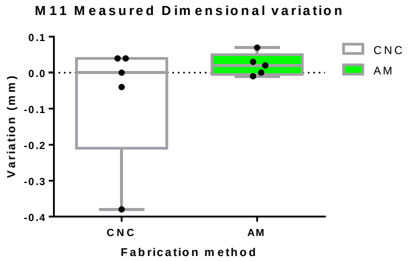
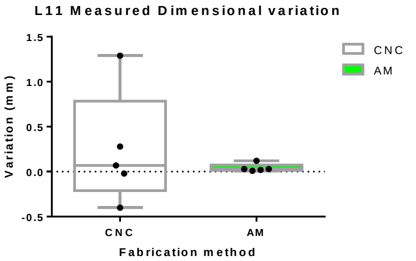
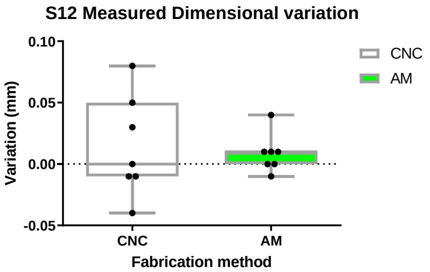
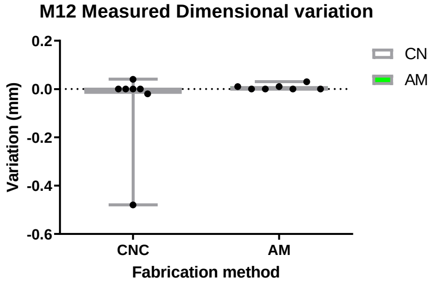
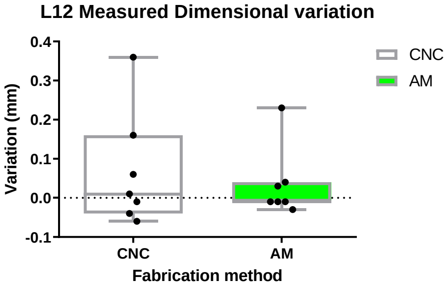
Figure 23: Rockwell hardness for 3D printed, HT and CNC samples

4.2 Dimensional Quality

The achievable dimensional accuracy for additively manufactured parts using EOSNT 316L stainless steel powder achievable is ±20-50 µm (0.001), CNC machining on the other hand has the ability to achieve up to 0.5 µm with precision machining. Table 11 and 12 lists the dimensional variation for AM and CNC fabricated models of different complexities. It can be seen that additive manufacturing using EOSNT 280 machine resulted an impressive dimensional quality for all fabricated part models, in part of what reported in their material specification sheet mentioned in Chapter 2 of this thesis, however it was noted that all complex geometry models had a high deviation in dimension for the outer-hole diameter (±0.23mm). The reason behind this deviation is a deformed outer diameter of the shaft hole. This type of deformation can be avoided by better optimization of parameters and part build support placement for complex geometries. An overview of the dimensional accuracy variation for all parts fabricated using both processes can be seen in table 11. Even though the achieved dimensional accuracy of CNC machined parts are less than AM in this case, it is a known fact that CNC can be optimized and the accuracy achieved could be improved more than what actually resulted in this experiment. The reason behind this lower dimensional quality in case of CNC fabricated parts is less skilled CNC operator, human error in offset adjustment and not optimized machine parameters. ([37] to [40])

To summarize, the dimensional quality achievable with both processes is acceptable for most applications for both direct metal laser sintering and CNC machining, however, for processes with precision accuracy less than 0.5 µm, using Additive Manufacturing is not an option, and the only option in such applications is to use precision machining applications or any other manufacturing method that could achieve such a high precision.

Table 11: Dimensional Variation for the Fabricated Models

Small Sized	Medium Sized	Large Sized
		
		

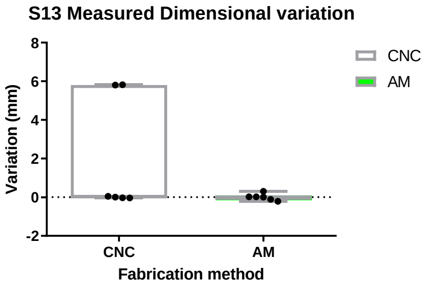
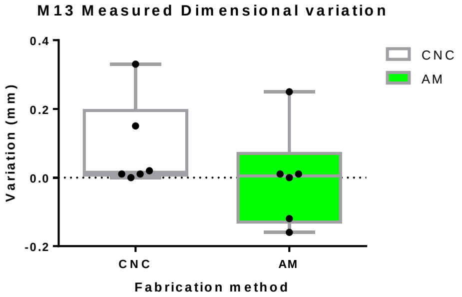
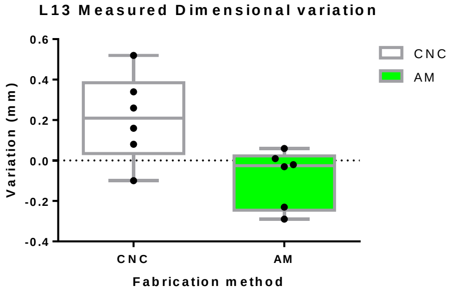
Small Sized	Medium Sized	Large Sized
 S13 Measured Dimensional variation 	 M13 Measured Dimensional variation 	 L13 Measured Dimensional variation

Table 12: Dimensions Measurements for Fabricated Models

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
L11												
	R	M1	M2	M3	Average	**Variation**	R	M1	M2	M3	Average	Variation
	80	80.31	80.28	80.27	80.28	+0.28	80	80.06	79.99	80.05	80.03	+0.03
	54	55.23	55.33	55.32	55.29	+1.29	54	54.01	53.97	54.06	54.01	+0.01
	19	18.98	18.97	19.00	18.98	-0.02	19	19.04	19.07	18.94	19.02	+0.02
	14	14.01	14.14	14.08	14.07	+0.07	14	14.07	14.02	14.00	14.03	+0.03
	90	89.69	89.5	89.62	89.60	-0.40	90	89.93	90.17	90.26	90.12	+0.12

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
L12												
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	80	80.36	80.35	80.38	80.36	+0.36	80	80.09	79.92	79.91	79.97	-0.03
	54	54.05	53.95	54.05	54.01	+0.01	54	54.06	54.08	54.00	54.04	+0.04
	19	18.9	18.93	19.01	18.94	-0.06	19	18.99	18.96	19.02	18.99	-0.01
	14	14.28	14.04	14.16	14.16	+0.16	14	14.01	13.99	13.97	13.99	-0.01
	90	90.07	90.05	90.07	90.06	+0.06	90	90.33	90.09	90.28	90.23	+0.23
	10	9.97	10.01	10.00	9.99	-0.01	10	9.97	9.99	10.01	9.99	-0.01
	6	5.97	5.98	5.94	5.96	-0.04	6	6.06	6.01	6.03	6.03	+0.03

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
L13	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	90	90.10	90.17	89.98	90.08	+0.08	90	89.72	89.71	89.72	89.71	-0.29
	15	15.32	15.17	15.31	15.26	+0.26	15	15.11	15.04	15.03	15.06	+0.06
	23	23.45	23.58	23.54	23.52	+0.52	23	23.04	22.99	23.00	23.01	0.01
	30	30.14	30.2	30.15	30.16	+0.16	30	30.01	29.97	29.93	29.97	-0.03
	20	19.85	19.93	19.93	19.90	-0.10	20	19.72	19.80	19.78	19.76	-0.23
	43	43.34	43.35	43.35	43.34	+0.34	43	42.95	42.97	43.04	42.98	-0.02

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
M11	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	60	60.08	59.99	60.07	60.04	+0.04	60	60.07	60.05	60.09	60.07	+0.07
	38.5	38.51	38.55	38.57	38.54	+0.04	38.5	38.51	38.48	38.52	38.50	0
	14.25	14.28	14.24	14.23	14.25	0	14.25	14.24	14.26	14.24	14.24	-0.01
	10.5	10.47	10.47	10.46	10.46	-0.04	10.5	10.52	10.51	10.53	10.52	+0.02
	68	67.56	67.66	67.65	67.62	-0.38	68	68.12	67.99	67.98	68.03	+0.03

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
M12	60	60.02	59.98	60.01	60	0	60	60.02	60.04	59.99	60.01	+0.01
	38.5	38.08	37.99	38.05	38.04	+0.04	38.5	38.52	38.50	38.49	38.50	0
	14.25	14.23	14.27	14.26	14.25	0	14.25	14.25	14.27	14.25	14.26	+0.01
	10.5	10.49	10.51	10.46	10.48	-0.02	10.5	10.51	10.49	10.50	10.5	0
	68	67.53	67.49	67.52	67.51	-0.48	68	68.03	68.01	68.05	68.03	+0.03
	7.5	7.51	7.50	7.49	7.5	0	7.5	7.51	7.49	7.50	7.5	0
	4.5	4.51	4.50	4.49	4.5	0	4.5	4.50	4.52	4.49	4.5	0

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
M13												
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	67.5	67.48	67.49	67.55	67.50	0	67.5	67.35	67.33	67.33	67.33	-0.16
	11.25	11.40	11.38	11.42	11.40	+0.15	11.25	11.51	11.52	11.49	11.50	+0.25
	17.25	17.28	17.29	17.26	17.27	+0.02	17.25	17.26	17.27	17.25	17.26	+0.01
	22.5	22.65	22.45	22.43	22.51	0.01	22.5	22.48	22.51	22.49	22.49	+0.01
	15	15.01	15.02	15.01	15.01	+0.01	15	14.89	14.90	14.86	14.88	-0.12
	27.25	27.56	27.58	27.62	27.58	+0.33	27.25	27.25	27.26	27.25	27.25	0

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
S11												
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	40	40.06	40.02	40.01	40.03	+0.03	40	40.03	40.05	40.04	40.04	+0.04
	27	27.02	27.05	27.00	27.02	+0.02	27	27.01	27.03	27.02	27.02	+0.02
	9.5	9.51	9.50	9.52	9.51	+0.01	9.5	9.51	9.51	9.49	9.50	0
	7	7.03	7.02	7.02	7.02	+0.02	7	7.03	7.00	7.01	7.01	+0.01
	45	45.00	45.01	45.00	45	0	45	45.07	45.13	45.25	45.15	+0.15

Model ID	Dimensions (Measured) - CNC						Dimensions (Measured) - AM					
S12												
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	40	39.98	39.99	40.01	39.99	-0.01	40	40.01	40.00	40.02	40.01	+0.01
	27	27.06	27.06	27.05	27.05	+0.05	27	27.02	27.01	27.00	27.01	+0.01
	9.5	9.52	9.53	9.56	9.53	+0.03	9.5	9.49	9.51	9.51	9.50	0
	7	6.98	6.95	6.96	6.96	-0.04	7	7.02	7.03	7.00	7.01	+0.01
	45	45.05	45.11	45.09	45.08	+0.08	45	45.05	45.04	45.03	45.04	+0.04
	5	5.00	5.02	4.99	5	0	5	4.98	4.99	5.01	4.99	-0.01
	3	2.99	3.00	2.98	2.99	-0.01	3	2.99	3.00	3.01	3	0

Model ID		Dimensions (Measured) - CNC						Dimensions (Measured) - AM				
S13												
	R	M1	M2	M3	Average	Variation	R	M1	M2	M3	Average	Variation
	45	45.03	45.05	45.06	45.05	+0.05	45	44.92	44.88	44.87	44.89	-0.11
	7.5	7.49	7.50	7.51	7.50	0	7.5	7.81	7.79	7.80	7.8	+0.3
	11.5	17.31	17.35	17.31	17.32	+5.82	11.5	11.50	11.49	11.51	11.5	0
	15	14.97	14.96	14.99	14.97	-0.03	15	15.00	15.02	15.06	15.02	+0.02
	10	9.95	9.97	9.96	9.96	-0.04	10	9.72	9.83	9.84	9.79	-0.21
	21.5	27.30	27.31	27.30	27.30	+5.80	21.5	21.52	21.53	21.52	21.52	+0.02

4.3 Cost

Total of 18 models were fabricated using both Direct Metal Laser sintering and CNC machining. The models fabricated are of 3 scales and mixed geometrical complicity (simple to complex): Large, medium and small. The fabricated model parts were shown in table 6 in chapter 3.

Each fabricated model/component cost was estimated based on equation 1 and 2 detailed in chapter 3 of this thesis. A detailed cost breakdown for each fabricated model is attached in appendix A and B. The final individual cost was estimated using equation 1 for CNC parts and equation 2 for DMLS parts. Table 13 below shows cost components for CNC manufactured models:

Table 13: Individual cost components for CNC fabricated models

$CNC\ Cost = Tool\ Path\ generation\ cost\ (CTP) + Machining\ Cost(CM) + Tool\ Cost(CT) + Setup\ cost(CS) + Material\ Cost\ (CMa) + Energy\ Cost\ (CE) + Overhead\ Cost(CO)$ (Eq. 3)

S11Cost = 30+269.6667+15+13+48+3.7+20 = 425$

M11Cost = 30+494.44+20+13+64+6.1+20 = 650$

L11Cost: = 30+791.1+30+13+120+9.8+20 = 1010$

S12Cost = 30+395.5+20+13+48+4.9+20 = 530$

M12Cost = 30+593.3+30+13+64+7.4+20 = 760$

L12Cost = 30 +1186.6+40+13+120+14.8+20 = 1425

S13Cost = 60+741.7+40+32+9.25+30 = 940$

M13Cost = 60+1186.67+50+26++48+14.8+35 = 1420$

L13Cost = 60+1483.33+60+26+120+18.5+4 = 1800

For AM built parts, the cost was estimated for each model based the following equation which estimates the total build cost for additive manufacturing. The cost of each additively fabricated model was then estimated using weight percentage (table 14).

$$P = MP + AP + CP + OP$$

Total AM cost (P) = 1303+1275+9194+1002.5 = 12775$

The Cost for each model fabricated using the two different process is summarized in table 14 below. Figure 24 shows the individual cost of each model fabricated using Additive Manufacturing DLMS and CNC Machining.

Table 14: Individual Cost for Each Model Fabricated Using Different Processes

	3D printing (USD)	**CNC Machining (USD)**
L11	3060	1010
L12	2840	1425
L13	1300	1800
M11	1215	650
M12	1120	760
M13	520	1420
S11	380	425
S12	355	530
S13	160	940

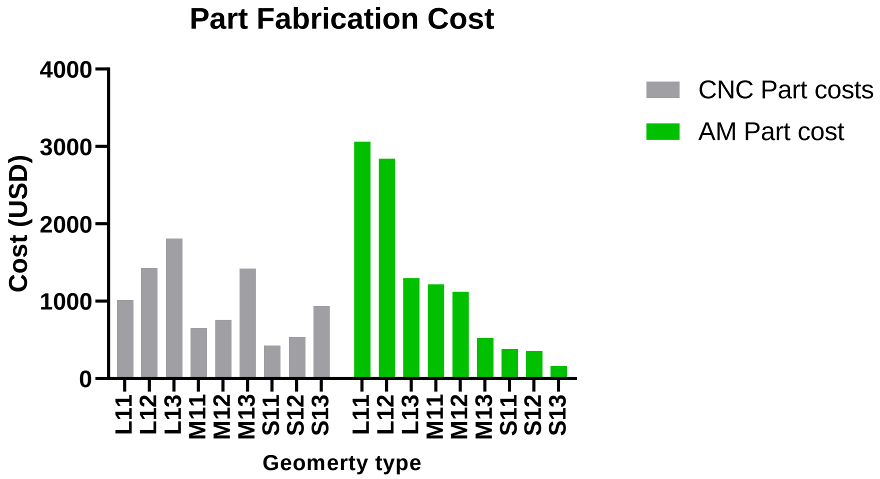


Figure 24: Individual model costs for AM and CNC

The cost results have shown a significant difference in cost of the same parts fabricated using different processes, AM and CNC machining. The highest cost was estimated for the simple and medium complex parts. This result was expected due to the material and machine cost for AM. Furthermore, the complex geometries fabrication cost was less in AM than conventional CNC machining, especially in the small scale. The results clearly show the expected advantage of Additive manufacturing over conventional means for complex geometry fabrication.

A sensitivity analysis has been performed in order to identify the most critical cost components. As seen from appendix A, the most critical cost components for CNC parts were machining and material costs, however when the sensitivity analysis was performed the most critical component appeared to be machining cost, as increasing this component by 10% led to an overall increase of 7-8%. Furthermore, decreasing 10% from machining cost component as seen in table 15 below. Material cost component when analyzed using sensitivity analysis had a minimal effect on overall cost, by ±1% overall increase/decrease when increasing/decreasing the material cost value ±10% (Table 16).

Finally, for AM build, the sensitivity analysis as shown in table 17 shows a 7-8% increase/decrease in the overall build cost when changing the value of processing cost. Similarly, a 1% overall increase/decrease of the final build cost was observer when changing the material cost value by 10% as seen in table 17 below. The sensitivity analysis has shown that a reduction in machining and processing costs would significantly impact the overall cost estimations for both processes.

Table 15: Sensitivity Analysis for Machining Cost Component on Overall Cost Estimation

Model	Machining cost($)	+10%	Overall cost	New cost	-10%	New cost($)
L11	790	869	1010	1089 (+8%)	711	931 (-8%)
L12	1187	1305.7	1425	1543.7 (+8%)	1068.3	1306.3 (-9%)
L13	1483	1631.3	1800	1948.3(+8%)	1334.7	1651.7 (-9%)
M11	495	544.5	650	699.5 (+8%)	445.5	600.5 (-8%)
M12	594	653.4	760	819.4 (+8%)	534.6	700.6 (-8%)
M13	1187	1305.7	1420	1538 (+8%)	1068.3	1301.3 (-9%)
S11	297	326.7	425	454.7 (+7%)	267.3	395.3 (-8%)
S12	396	435.6	530	569.6 (+7%)	356.4	490.4 (-8%)
S13	742	816.2	940	1014 (+8%)	667.8	865.8 (-9%)

Table 16: Sensitivity Analysis for Material Cost Component on Overall Cost Estimation

Model	Material cost ($)	+10% Material	Overall cost	New cost	-10% Material	New cost ($)
L11	120	132	1010	1022 (+1%)	108	998 (-1%)
L12	120	132	1425	1437 (+1%)	108	1413 (-1%)
L13	120	132	1800	1812 (+1%)	108	1788 (-1%)
M11	64	70.4	650	656.4 (+1%)	57.6	643.6 (-1%)
M12	64	70.4	760	766.4 (+1%)	57.6	753.6 (-1%)
M13	48	52.8	1420	1424.8(+1%)	43.2	1415.2 (-1%)
S11	48	52.8	425	429.8 (+1%)	43.2	420.2 (-1%)
S12	48	52.8	530	534.8 (+1%)	43.2	525.2 (-1%)
S13	32	35.2	940	943.2	28.8	936.8 (0%)

Table 17: Sensitivity Analysis for Processing and Material Costs for AM

Cost component	Original value ($)	+10% Material	Overall cost	New overall cost	-10% Material	New cost($)
Processing cost	9195	10114.5	12775	13694.5 (7%)	8275.5	11855.5 (-8%)
Material cost	1303	1433.3	12775	12905.3 (1%)	1172.7	12644.7 (-1%)

As cost plays a major role in decision making for process selection and investment in the technology, these results help in understanding the relation between process, manufactured parts complexity and cost. Based on a real life case study, it appears that smaller complex models or parts are more economical to fabricate using additive manufacturing technology, while simpler larger parts should be fabricated using conventional means. The reason behind this is the higher cost of technology and metal powder. Table 18 below shows a summary of the cost difference between material and machine costs for CNC and additive manufacturing for 316L stainless steel.

Table 18: Cost Break Down for Material and Machine Costs

	CNC Machining	Additive Manufacturing
Material Cost	20 USD/kg	138 USD/kg
Machine purchase cost	410000 USD	1.37 Million USD
Machine Cost/hour	36 USD/hour	47 USD/hour

It was observed that raw material cost has the highest impact on the total build cost for each part with steel powder costing around 150% more than the normal cast material (138 USD/kg for 316L SS powder vs 20 USD/kg for raw cast 316L SS). Furthermore, the machine cost and time plays a major role as well in this consideration. The time used in manufacturing complex parts using CNC is considerably higher that AM technology considering that multiple parts are built together in AM, this increases the individual machine cost for each built in case of complex parts fabrication. These results are in part of what have been reported in literature by [48] that additive manufacturing technology is only suitable for low production volumes due to high cost of material and machines, and in some cases AM could potentially replace conventional means.

On the other hand, energy has a very low impact on part in comparison to other costs encountered in this project. The energy cost is based on energy prices in Qatar, however this could be different in countries where electricity prices is higher and should be considered as such in process cost evaluation.

CHAPTER 5: PROCESS SELECTION GUIDELINE

A process selection guideline introduces a tool that assists users for selecting between conventional and additive means of manufacturing. The guideline is basically a tool that will make the decision on the best manufacturing process to fabricate metal parts without the need of conducting an actual product plan and cost estimates. This could be very useful for interested investors in factories, distributers and machinery workshops as well as automotive, marine, aviation and biomedical industries.

5.1: Mechanical properties

As seen from the results presented in this research, both manufacturing techniques have adequate output for mechanical properties, while conventionally machined is more advantageous, additive manufacturing using direct metal laser sintering (EOSNT M280) has also produced good results in terms of mechanical properties. The mechanical properties can satisfy most of engineering applications, however, in case the user would like some specific better properties the choice would always be for conventional CNC machining as there is a significant difference in tested properties making mechanical properties a deciding factor when it comes to process selection. A user would need to identify the required mechanical properties and whether the additive manufacturing mechanical properties set is satisfactory in order to proceed with the rest of the process selection matrix.

5.2: Dimensional Quality

Dimensional quality is excellent for additive manufactured models/parts and it can satisfy most of the applications, even with tight tolerance. Conventional machining process also can be easily modified and dimensional quality output can be manipulated using machine parameters, tools and optimized CNC codes and the conventional processes has advanced to a level where precision levels can be less than 0.5µm [37] and much less in precision machining operations. As for the mechanical properties, the dimensional quality is a prerequisite factor and the user should first identify the required dimensional accuracy for the desired applications. The requirements are also a deciding factors for process selection, if the required dimensional accuracy is below the set limit, additive manufacturing cannot satisfy those requirements and the user would have to go for conventional means of fabrication in order to achieve the desired dimensional quality.

5.3: Cost

While the current metal printing technology is nowhere near the capabilities in terms of dimensional quality of conventional precision machining, other advantages presented earlier in this research makes the technology compelling for fabrication of complex geometries where replacing the conventional machine is convenient as well as more profitable and acceptable in terms of parts dimensional quality and mechanical properties. This leaves the cost and economical factor as the deciding factor for process selection and/or acceptance, given mechanical properties and dimensional quality is acceptable for the required applications. This guideline cost approach did not take into account the cost implications for storage, on-demand manufacturing and logistics costs.

The cost was implemented in the guideline based on cost estimation data for fabricated models. Model complexity and size were the major deciding cost factor, and hence, a size and complexity selection would guide the user to select the appropriate process for the desired applications.

5.4: Process selection guideline matrix

From investor’s point of view, first the required mechanical properties and dimensional quality levels needs to be realized. Once those parameters are set, the part complexity and size which needs to be manufactured helps in giving an estimation of cost difference between AM and conventional fabrication which assists overall process selection. Figure 25 presents a flowchart diagram for process selection to assist in evaluating process and aid the selection of technology based on need, mechanical and dimensional quality, geometry complexity and economic factors. This approach was designed based on stainless steel 316L case study and it could be different for other materials, parameters and machine manufacturers.

For example, L12 model part as fabricated with costs of 1425$ for CNC and 2840$ for Additive manufacturing, with the following parameters to be entered in the matrix: 90×80×45mm with medium complexity. Following the matrix, and assuming the mechanical properties of the AM machine are acceptable and no precision dimensions required (less than 50µm variation in dimensions); this leads to conventional manufacturing choice, which is what makes since for a large scale less complex pieces. All models pass in using this matrix for the process selection except L13 (high complex large sized part), probably due to the extreme complexity and contours in the part design made the CNC fabrication costlier than AM, all other parts matched with the matrix criteria with 88.9 success rate for process selection using the matrix. More importantly the general idea remains that the more complex and smaller the part to be fabricated, one should look into fabrication using Additive means of manufacturing, and the larger and less complex the part geometry is one should look into investing in conventional means of fabrication. These results are in parts of what reported in the literature by [9] and [19] of the current use of metal additive manufacturing technologies with small individual complex geometries mainly for medical industry and biomedical applications such as orthopedic implants and prosthesis, and some specific automotive and aerospace industries.

The process selection guideline framework gives the investor/user a decision on which process to use based on part complexity and size without the need of performing any actual cost estimations and process planning. It guides the user to the best possible option for part fabrication manufacturing process. By incorporating cost data from the experiment, it was apparent that the cost is the deciding factor and it was influenced mainly by part complexity and size as seen from section 4.3 of this thesis. A user will be able to select between the processes by following the process selection matrix shown in figure 25. The matrix basically sets some requirements which can be set by the user depending on the additive manufacturing machine user. If those requirements (mechanical properties and dimensional quality) are acceptable for the application required by the user, the matrix will guide the user for the appropriate process selection based on part cost by requesting the user to input the expected complexity and geometry, which by the end will give the user the best choice for fabrication process.

This framework guideline helps in realizing the current potential of additive manufacturing technologies against conventional means by assisting in decision making process in metal part fabrication. Furthermore, it helps identifying current limitations and advantages of metal additive manufacturing against conventional means. Finally, it helps investors identify which factors influence the process selection which could assist in future process improvements.

5.5: Summary

This chapter has investigated the mechanical properties and behavior for two types of stainless steel grade 316L, machined from cast 316L SS, and additively manufactured 316L SS from steel powder using various mechanical testing standards. Also it studied the impact of heat treatment on the additively built samples. Furthermore, the variation in cost, dimensional quality was also investigated. Finally, a guideline for process selection was discussed and developed based on 18 model parts fabrication data from both processes to help investors and other interested users in process selection for stainless steel 316L part fabrication.

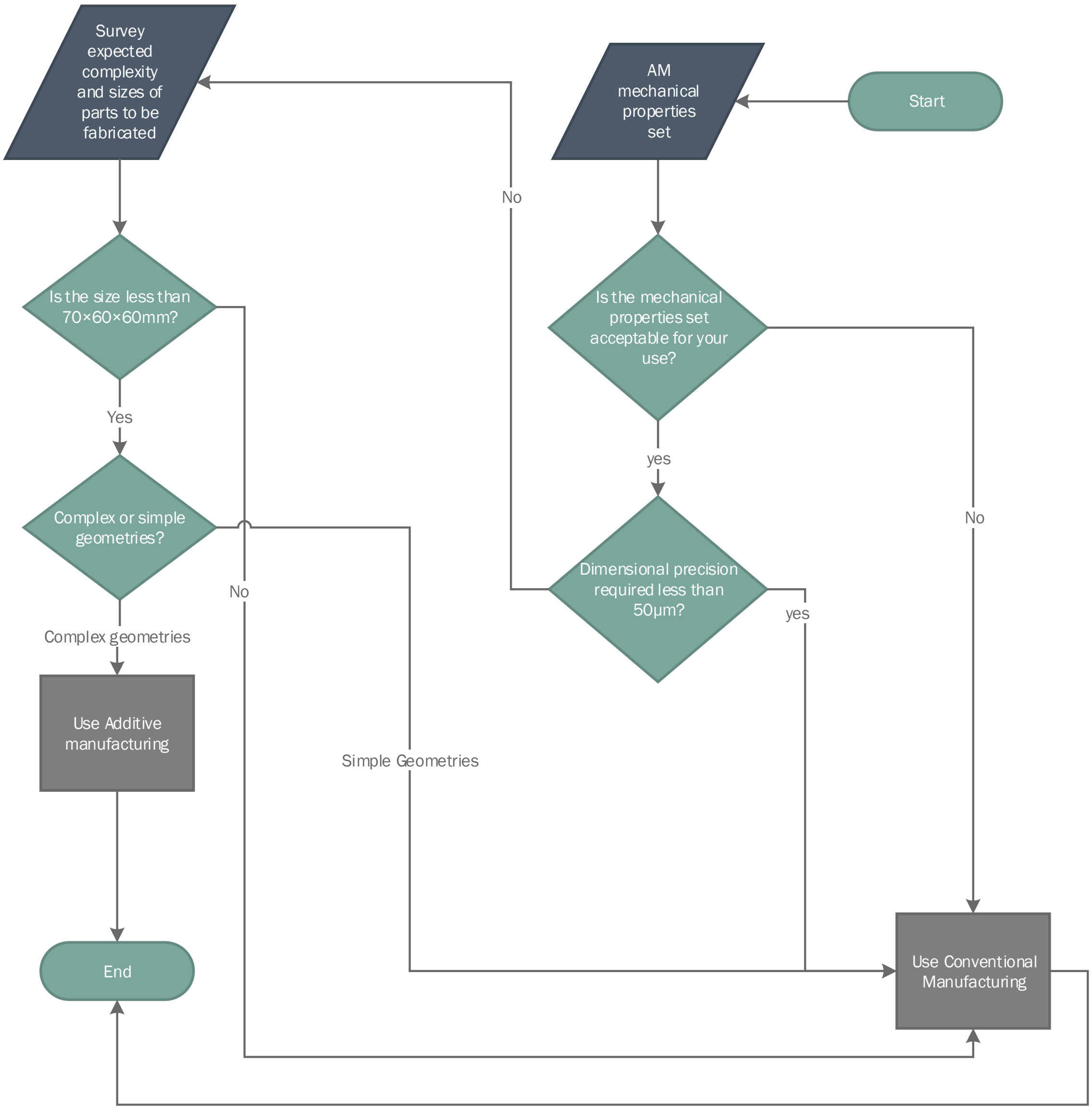


Figure 25: Process evaluation flowchart diagram

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Metal Additive Manufacturing technologies acceptance is increasing and has reached a critical acceptance level. There is a tremendous increasing of research on additive manufacturing technologies for metallic part fabrication, which shows an increasing interest in the recent years to fabricate metal parts using additive means instead of conventional ones especially for harder and more difficult to cut materials such as stainless steel. Additive manufacturing has shown many advantages over conventional fabrication for metal parts which include less post production steps, high geometrical freedom for complex parts, cost saving for complex geometries as well as less material scraping. While additive manufacturing offer those amazing advantages, there are limitations as well that makes the technology unfeasible if compared to conventional means. Those limitations include capacity limitations, poor surface finish, long fabrication time, dimensional quality limits and finally huge initial investment cost and high machine maintenance. This study experiment has been conducted through investigating mechanical performance, dimensional quality and cost of 316L stainless steel parts fabricated using direct metal laser sintering as well as CNC machining. The outcome of this project was used to conduct and overall process evaluation and develop a framework guideline for process selection. The following is the conclusions made from this project experiments:

- Tensile properties for CNC machined samples was more superior of those additively manufactured ones. CNC samples have shown the highest ultimate tensile and yield strength and highest elongation, while as build 3d printed samples ultimate tensile and yield strength was not effected a lot by heat treatment, however it was noted that heat treatment increased elongation by

11%.

- SEM images of the fractured tensile samples surfaces have shown pores and dimples due to elongation and plastic deformation with various pores and shapes on both CNC and as built additively manufactured samples, however heat treated as built AM samples have shown less pores and dimples indicating more ductility.

- Impact toughness energy for v-notched samples of the same categories as tensile samples have shown a poor impact toughness for AM as built samples (100J), and better for heat treated AM samples with an average of 182J, and a 199J for CNC machined samples, thus making the machined samples with the highest advantage.

- SEM images of the fractured v-notched impact samples have shown unmelt particles (steel powder) in as built AM samples with some pores, unlike heat treated samples that have shown a better binding and less pores with fully melt structure. CNC samples have shown the highest impact toughness behavior, and it is reflected in the SEM imagery as well with fewer pores and wider shear lips indicating partial ductile behavior.

- Rockwell hardness resulted from testing all samples have shown very close results with a noticeable decrease in hardness for heat treated AM samples.

- Direct metal laser sintering with EOSNT 280M and using 316L stainless steel powder (9 parts of various sizes and complexities) has resulted an impressive dimensional quality of parts (less than 50 µm dimensional variation) with a small deviation in complex geometries outer hole diameter which can fixed by optimizing building parameters and support design. While the achieved dimensional accuracy was less than AM in this case due to human error, poor machining parameter and limitation of recourses, however it is a well-known fact that CNC can achieve up to 0.5 µm with precision and ultra-precision machining applications.

- Simple and medium complex geometries with large sizes had the highest build cost using additive manufacturing. The reason behind it is the high cost of machine and material powder. On the other hand, CNC machining for those same part geometries was less due to the huge difference in material cost/kilogram for cast 316L stainless steel compared 316L stainless steel powder as well as cheaper machine hourly cost. Furthermore, it was observed that complex small sized parts are cheaper to manufacture with additive manufacturing due to the long machining time which will make complex parts costlier to machine and requires many setups and tool changes.

- A process selection guideline was developed based available data, a base decision to be made by the user/investor is the minimum required mechanical and dimensional qualities, with additive manufacturing required properties data set as the datum; the developed guideline takes into account cost as the main deciding factor for process selection by looking into size and complexities. Geometries above certain dimensions (70*60*60mm) should be fabricated with CNC, while only complex geometries less than the above dimensions should be fabricated using additive manufacturing. 8 out of 9 parts fabricated during this project passed using this criteria, and more data could enhance accuracy of process selection.

Recommendations for future work:

- Due to limited resources, only nine parts were fabricated with 3 complex variations, thus giving a limited set of data for cost analysis and process selection guideline framework development. It is recommended for more parts to be fabricated with different designed scenarios, which would improve the overall framework accuracy.

- It is highly recommended to repeat this experiment with more metallic materials such as aluminum, titanium and any other materials that could be fabricated nowadays with additive manufacturing. Having results for more materials could prove beneficial because it will help prove the concept of this guideline, and possibly combine different materials into one guideline that can help in process selection for multiple processes and/or materials.

- It would also be beneficial to seek out different additive manufacturing machine providers to see if the same results could be applied to different additive manufacturing technologies for metal parts.

- It will also be highly beneficial to perform extra mechanical testing for bending, torsion, shear as well as corrosion resistance and performance at normal elevated temperatures if the application requires.

- In regards to cost, a deeper cost analysis that considers storage, transport cost and on demand fabrication ability could also improve the effect on the overall cost estimation results.

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APPENDIX A: CNC COST BREAKDOWN

CNC machined parts cost breakdown:

S11:

Part weight (kg)	2.4
Material Cost/kg	20
Material cost per piece (Cma)	48
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444
Labor hourly rate (usd)	13
Machining time (hours)	6
Machining Cost (CM)	296.6667
Cutting tool costs (usd)	15
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	90
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	3.699
Other costs including finishing operations	20
Overhead costs (CO)	23.699
CNC Cost	**426.3657**

M11:

Part weight (kg)	3.2
Material Cost/kg	20
Material cost per piece (Cma)	64
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	10
Machining Cost (CM)	494.4444444
Cutting tool costs (usd)	20
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	150
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	6.165
Other costs including finishing operations	20
Overhead costs (CO)	26.165
CNC Cost	**647.6094444**

L11:

Part weight (kg)	6
Material Cost/kg	20
Material cost per piece (Cma)	120
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	16
Machining Cost (CM)	791.1111111
Cutting tool costs (usd)	30
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	240
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	9.864
Other costs including finishing operations	20
Overhead costs (CO)	29.864
CNC Cost	**1013.975111**

S12:

Part weight (kg)	2.4
Material Cost/kg	20
Material cost per piece (Cma)	48
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	8
Machining Cost (CM)	395.5555556
Cutting tool costs (usd)	20
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	120
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	4.932
Other costs including finishing operations	20
Overhead costs (CO)	24.932
CNC Cost	**531.4875556**

M12:

Part weight (kg)	3.2
Material Cost/kg	20
Material cost per piece (Cma)	64
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	12
Machining Cost (CM)	593.3333333
Cutting tool costs (usd)	30
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	180
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	7.398
Other costs including finishing operations	20
Overhead costs (CO)	27.398
CNC Cost	**757.7313333**

L12:

Part weight (kg)	6
Material Cost/kg	20
Material cost per piece (Cma)	120
NC programmer hourly rate (usd)	30
Time spent program preparation	1
TCP (Path generation cost)	30
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444
Labor hourly rate (usd)	13
Machining time (hours)	24
Machining Cost (CM)	1186.667
Cutting tool costs (usd)	40
Setup time (hours)	1
Setup cost	13
Machine power kWh	15
Electrical energy consumption (kWh)	360
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	14.796
Other costs including finishing operations	20
Overhead costs (CO)	34.796
CNC Cost	**1424.463**

S13:

Part weight (kg)	1.6
Material Cost/kg	20
Material cost per piece (Cma)	32
NC programmer hourly rate (usd)	30
Time spent program preparation	2
TCP (Path generation cost)	60
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	15
Machining Cost (CM)	741.6666667
Cutting tool costs (usd)	40
Setup time (hours)	2
Setup cost	26
Machine power kWh	15
Electrical energy consumption (kWh)	225
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	9.2475
Other costs including finishing operations	30
Overhead costs (CO)	39.2475
CNC Cost	**938.9141667**

M13:

Part weight (kg)	2.4
Material Cost/kg	20
Material cost per piece (Cma)	48
NC programmer hourly rate (usd)	30
Time spent program preparation	2
TCP (Path generation cost)	60
Machine cost (usd)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444444
Labor hourly rate (usd)	13
Machining time (hours)	24
Machining Cost (CM)	1186.666667
Cutting tool costs (usd)	50
Setup time (hours)	2
Setup cost	26
Machine power kWh	15
Electrical energy consumption (kWh)	360
Cost of Electricity per kWh	0.0411
Total energy cost (usd)	14.796
Other costs including finishing operations	35
Overhead costs (CO)	49.796
CNC Cost	**1420.462667**

L13:

Part weight (kg)	6
Material Cost/kg	20
Material cost per piece (Cma)	120
NC programmer hourly rate (USD)	30
Time spent program preparation	2
TCP (Path generation cost)	60
Machine cost (USD)	410000
Years of return	15
Hours used per year	750
Machine cost/hour	36.44444
Labor hourly rate (USD)	13
Machining time (hours)	30
Machining Cost (CM)	1483.333
Cutting tool costs (USD)	60
Setup time (hours)	2
Setup cost	26
Machine power kWh	15
Electrical energy consumption (kWh)	450
Cost of Electricity per kWh	0.0411
Total energy cost (USD)	18.495
Other costs including finishing operations	40
Overhead costs (CO)	58.495
CNC Cost	**1807.828**

APPENDIX B: ADDITIVE MANUFACTURING COST BREAKDOWN

Additive manufacturing cost breakdown (USD):

Setup time (hours)	5
Labor cost per hour	25
Labor cost	125
Filters and parts costs	1150
Total preprocessing cost	**1275**
Machine cost	1369863.014
Years of return	8
Hours used per year	3650
Machine cost / hour	46.91311691
Processing cost	**9194.970914**
Total Build time	196
W	9.445
Praw/Kg (USD)	138
Total material cost	**1303.41**
Machine power kWh	10
Ebuild	1960
Energy Price	0.0411
Total Energy cost	80.556
Inert gas cost	821.9178082
Post processing and cutting	100
Total overhead including post processing	**1002.473808**
Total build cost	12775.85472

Individual part costs for Additive manufacturing (USD):

L11	3061.065033
L12	2843.287096
L13	1299.904329
M11	1217.392192
M12	1121.353474
M13	523.4786424
S11	382.8022114
S12	353.0437356
S13	159.6136429