ADDITIVE MANUFACTURING OF PARTS FOR HARSH ENVIRONMENTS

An Undergraduate Research Scholars Thesis

by

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We, Khan Hassan[1], Shahul Hameed Mohammed Irfan[2], Afzal Ahmed[3], and Ebrik Adnan[4], certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with our Faculty Research Advisor prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Additive Manufacturing of Parts for Harsh Environments

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Manufacturing parts by additive processes that can adequately function in harsh environments presents several challenges. This technical report presents initial results of a study investigating the merits of using additive manufacturing (AM) to produce steel parts and the process parameter optimization to make them suitable for use in corrosive environments. Specifically, a centrifugal pump casing and a cylindrical connector part were analyzed for production by AM with the intent to make them suitable for use in oil and gas industry in Qatar.

The initial stage of the study involved analyzing the amount of material wasted during subtractive manufacturing. For the subtractive manufacturing phase of the project, a mold for a semicircular part of a centrifugal pump's volute was machined using subtractive methods. Defects like corrosion in the semicircular bowl-like structure made it necessary to replace it. Based on the findings, it can be stated that about 40% of the total material utilized in the fabrication process was deemed as wastage while producing a component of 12 cm².

The cylindrical part given its benign complexity was measured by hand and modeled using SolidWorks and printed using ABS plastic.

The pump casing was also modeled but given its complex geometry and size, a 40% scaled down version was machined by the team. Whilst our primary objective was to scan the part, we encountered significant difficulties due to limitations caused by the reflection of metal, making it difficult to capture certain parts of the connector with the camera. However, despite these challenges, we were able to make some initial progress with 3D scanning and generate some results. While not meeting our complete scanning requirements, it represents a positive step towards our end goal. Consequently, we have adopted alternative methodologies to overcome these obstacles and continue our efforts towards achieving our ultimate goal.

An optimization study was then conducted to determine the best print parameters to achieve the required porosity level of less than 0.5% as per industry standards. A design of experiments (DoE) approach was used to vary the power and speed of the AM process and analyze the porosity level of the parts produced. The results indicated that a power of 200 W and a speed of 800 mm/s produced the lowest porosity level.

In conclusion, this study highlights the importance of optimizing AM parameters for industrial parts in harsh environments to reduce material waste and achieve required quality standards. The study results demonstrate that a DoE approach is effective in determining optimal parameters for specific parts and environments. Future work could focus on further optimization of the AM process parameters and mechanical property analysis of the parts produced.

ACKNOWLEDGEMENTS

Contributors

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The data analyzed for aiding with the experimentation process during additive manufacturing of our fabricated part, were provided by Engr. Anurag Srivastava and Dr. Vasanth Chakravarthy. The analyses depicted in the methodology section under Additive Manufacturing were conducted in part by EM2 lab and these data are unpublished. The student Authors also give thanks to Anurag Srivastava for his guidance, wisdom and help for the entire duration of the research project.

All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

AM	Additive Manufacturing
SM	Subtractive Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CNC	Computer Numerical Control
DOE	Design of Experiment
FDM	Fusion Deposition Modelling
SLM	Selective Laser Melting

1. INTRODUCTION

There are many countries that do not possess the capability or capacity to manufacture equipment or parts and therefore resort to importing them from other countries. Qatar being one of them is a home for a diverse range of large-scale companies that deal with Construction, Engineering and most importantly Oil and Gas. Due to the nature of their work, these sectors require the use of high-quality, precise machinery and equipment for the critical success of the operations. Usage of equipment and machinery however include disadvantages such as wear and tear, maintenance, repairs and upgrades, corrosion failure, and technological advancements. If such equipment fails, there is an urgent need for a replacement or a spare to replace the damaged equipment to prevent production and economic loss. However, acquiring new machinery and equipment can take a long period of time of up to but not limited to 8 months due to logistics and transportation, documentation, customs clearance and more [1]. Therefore, there is a need for countries like Qatar to be self-sustaining such that it can manufacture its' own machinery and equipment to avoid long waiting periods to acquire equipment. A solution to this problem is a slowly emerging technique used for manufacturing which is Additive Manufacturing.

Additive Manufacturing, also known as 3D printing, is a new technology that is being used to manufacture parts on a large scale. It involves creating three-dimensional objects with the help of computer-aided design (CAD) software. Slicing software is then utilized to convert the 3D object to a form suitable for 3D printers. There are various technologies used in additive manufacturing, including Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). One of the major advantages of additive manufacturing is its ability to produce complex geometries and shapes that would otherwise be difficult to produce using traditional manufacturing methods [2]. Additionally, additive manufacturing allows for rapid prototyping, which helps to reduce the time and cost involved in the product development process. This technology also offers the ability to produce customized products in small or large quantities, making it ideal for producing high-value products such as medical devices and aerospace components with reduced waste and improved design freedom.

Subtractive Manufacturing is a process by which material is removed using cutting, boring, drilling, and grinding from a stock material. The process can be performed manually or using computer numerical control also known as CNC Machining. A model can be designed virtually using a plethora of computer aided design (CAD) software's to be input into the machine for fabrication.

Metal 3D printing is one form of additive manufacturing that is increasingly becoming popular due to its material options, faster prototyping, and improved sustainability. The material options include steel, aluminum, stainless steel, copper, cobalt, tungsten, and some alloys [3]. Stainless steel was chosen as the material in interest to be 3D printed as it is widely used in a variety of applications due to its numerous desirable properties including corrosion resistance, durability, recyclability, low maintenance and other qualities. Currently there are few research papers that deal with testing AM steel parts to that of a subtractive manufactured part of the same material. This paper aims to explore and analyze how different properties of AM stainless steel such as hardness, porosity, differ from the conventionally manufactured stainless steel parts.

Corrosion is the degradation of material that is caused by a chemical reaction with the surrounding environment. It is vital to understand corrosion as the majority of equipment failures over the long term occur due to corrosion. Most of this equipment is manufactured by conventional manufacturing methods such as casting, and subtractive manufacturing as there already is enough data to create parts, determine the part quality, life, resistance to corrosion and other factors. Since additive manufacturing is still considered as a new field, there is still research being conducted on how corrosion affects the material that is additively manufactured.

To date, there has been only a few ranges of alloy compositions as powders examined and there is still room for development in this field [4]. Moreover, it has been stated that the defects and intrinsic issues from the process of additive manufacturing can influence the corrosion performance of the materials or part. Other part parameters include porosity, surface roughness, solute segregation, formation or presence of oxides, grain directionality and more.

Due to AM still being relatively new, there are certain gaps that need to be filled in to provide a better understanding of corrosion on metals. These gaps include conflicting findings of AM stainless steel, for example, the porosity and texture of the part plays a role in corrosion resistance. When different organizations or research teams perform the same test, the results are inconsistent. [4]. Considering these developments surrounding Stainless Steel in 3D Printing (Additive Manufacturing), the paper delves into an overview comprising the corrosion mechanisms, performance and improvements made in AM stainless steels.

The project is an important object of scholarly inquiry since the team is working on centrifugal pumps and connectors used for different pipe systems. A pump is a device that works to increase flow or pressure. One type of pump that is more suitable for controlling flow is a centrifugal pump; it is a mechanical device that converts mechanical energy produced by a shaft to hydrodynamic energy to move a fluid across a certain distance [5].

Qatar is the world’s largest LNG producer as of today [6]. LNG producing companies use the most common type of pumps, centrifugal pumps due to their low manufacturing cost and quieter operation, reliability, and high efficiency. The part studied upon is shown in figure 1, which involves a centrifugal pump in which the pump suffered from defects.

1.1 Goal and Objectives

The primary goal is to determine if additive manufacturing (AM) can be used as a replacement method for damaged components or parts in industries. The objective is to subject the AM part to the same environmental conditions as the damaged part to test its integrity and ensure that it performs equally or better than the subtractive manufactured part. The success of this project would have far-reaching implications, including reducing lead times and costs for part replacement, and creating more sustainable and eco-friendly manufacturing processes. Another objective could be to identify any challenges or limitations of the AM process in replicating components accurately, which could be useful in optimizing and improving the technology. Ultimately, the goal is to establish a reliable process for using AM in industrial part replacement applications.

The team's role is to 3D scan the pump and then look for any defects within it such as the lip of the curvature was damaged on the side of the pump that had the water inlet. Once the defects are found, the defected parts are then fixed virtually using solid works and then these parts are additively manufactured required to fit replace the defected parts of the centrifugal pump. The second part which is studied upon is figure 2 and it is a cylindrical connector. The action items mentioned for the pump casing need to be repeated for the cylindrical connector as well which are broken down into three phases in section 1.2.

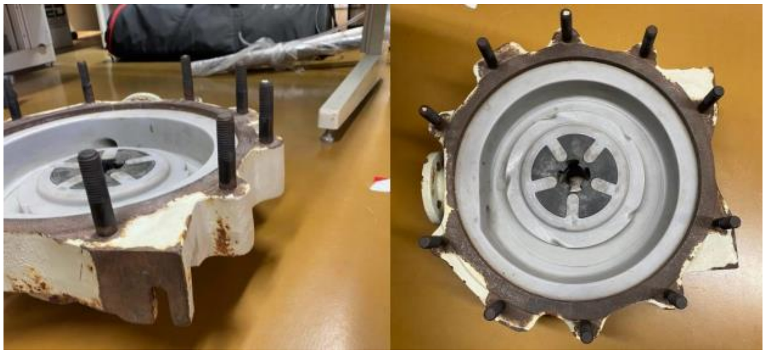

Figure 1: Defected Centrifugal pump provided for case study purposes.

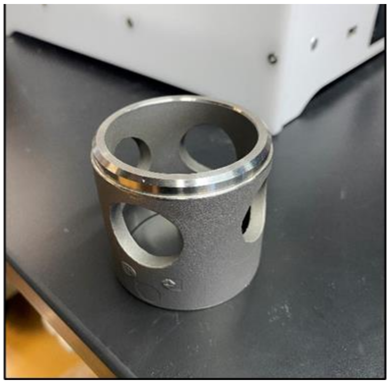

Figure 2: The cylindrical connector provided for case study purposes.

1.2 Project Phase Breakdown

The project is divided into three phases with the following objectives given for each phase:

1.2.1 Phase I: Manufacturing of a Metal/Polymer Pump Casing

- Compare the effects of additive and subtractive manufacturing on the strength, hardness, and ductility of a pump casing used in industry by conducting mechanical tests on parts produced using both processes.

- Identify the advantages and disadvantages of each process (subtractive vs. additive) in terms of achieving the desired mechanical properties and design features of the pump casing.
- Determine which manufacturing process is better suited to producing pump casings with the required mechanical properties and design features, based on the results of the mechanical tests and a cost-benefit analysis.

1.2.2 Phase II: Process Development for Selective Laser Melting

- Develop and optimize a process for selective laser melting of stainless steel 316 that minimizes porosity, maximizes strength, and maximizes corrosion resistance by characterizing and adjusting process parameters as necessary, utilizing a design of experiments approach.
- Conduct mechanical tests on the selective laser melted stainless steel 316 to evaluate its properties and compare it to conventionally manufactured stainless steel 316.
- Validate the process and evaluate its reproducibility by conducting multiple trials and analyzing the statistical variations in mechanical properties, microstructure, and corrosion resistance using design of experiments methodology.

1.2.3 Phase III: Manufacturing of a Metal Cylindrical Connector

- Develop an accurate model of the cylindrical metal connector using CAD software followed by fabrication of the part using a metal 3D printer.
- Optimize the design and printing parameters to ensure the properties of the 3D-printed part by printing using a polymer 3D printer. Analyze and correct defects if any.
- Optimize printing process parameters for the SLM printer and analyze the differences between the AM manufactured part and the subtractive manufactured part.

2. METHODOLOGY

2.1 3D CAD Modelling

3D modeling included measurement and CAD generation of selected parts i.e., the pump casing and the cylindrical connector. The selected components were 3D modeled accurately to start the creation of a virtual database that can be shared with the end-user. Exact CAD geometries with the actual dimensions were created since subtractive and additive manufacturing depends on accurate CAD models to achieve high dimensional tolerances.

As the cylindrical connector is significantly smaller in size compared to the pump casing, the steps describing how the part was 3D CAD modelled are discussed below.

To begin with the fabrication of the cylindrical part using the metal 3D printer, it should first be modeled on CAD software with dimensions approximately equal to those of the original part. Precision tools such as a vernier caliper and a micrometer were utilized for this purpose to provide accurate dimensions to that of the original part.

3D slicing software transforms the 3D model into series of instructions(layers) which can be understood by the operating system of the 3D printer. Following this, the layers are converted into strings of data that explain to the printer about the extrusion temperature, location, and rate of the extrusion. Moreover, the slicing software helps the user to adjust advanced settings such as layer height, infill, and density. The software also allows you to add support structures and optimize the surface finish of the part [7].

2.2 3D Scanning

To obtain a surface profile with high accuracy an optical 3D coordinate measuring machine was considered for component scans. TAMUQ measurement capabilities include a XX

CMM system shown in Figures 3 and XX given in Figure 4. For creating a CAD model using reverse engineering, the basis is the calculated high-resolution point cloud data describing free-form surfaces and regular geometries. For reverse engineering the scan data is reversed into mathematically described surfaces or solids, the data can be exported as a STL or as an ASCII point cloud. Obtained point cloud files can be imported to the appropriate modeling software for the actual conversion of the scan data into a CAD surface model. An example point cloud data can be seen in Figure 4. Solid CAD model development includes merging measurements of the part from different orientations using dedicated algorithms such as filtering, meshing, best fitting, and feature recognition (see Figure 3).

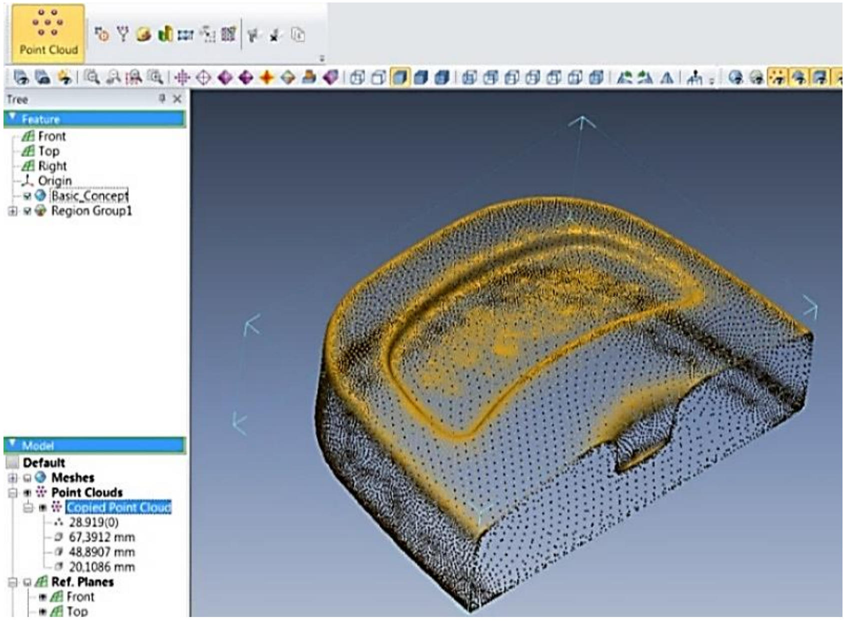

Figure 3: Sample point cloud geometry.

Solid CAD model development includes merging measurements of the part from different orientations using dedicated algorithms such as filtering, meshing, best fitting, and feature recognition (see figure 4). Our goal was to use the final CAD geometry for additive manufacturing process development.

Figure 4: 3D CAD model generation process steps

3D scanning is an essential step of reverse engineering which helps to capture and analyze the shape of a real-world object into a high precision 3D model. In this phase of the project, we used Polyga S1 compact to learn the art of 3D scanning. Polyga S1 compact is an entry level 3D scanner which can be used to make small scale mechanical parts by collecting up to 2 million points.

Figure 5 shows some necessary connections which should be made to initialize the scanner. The necessary connections include power, ethernet cable for internet access and a USB dongle for access of 3D scanning software(Flex Scan 3D).

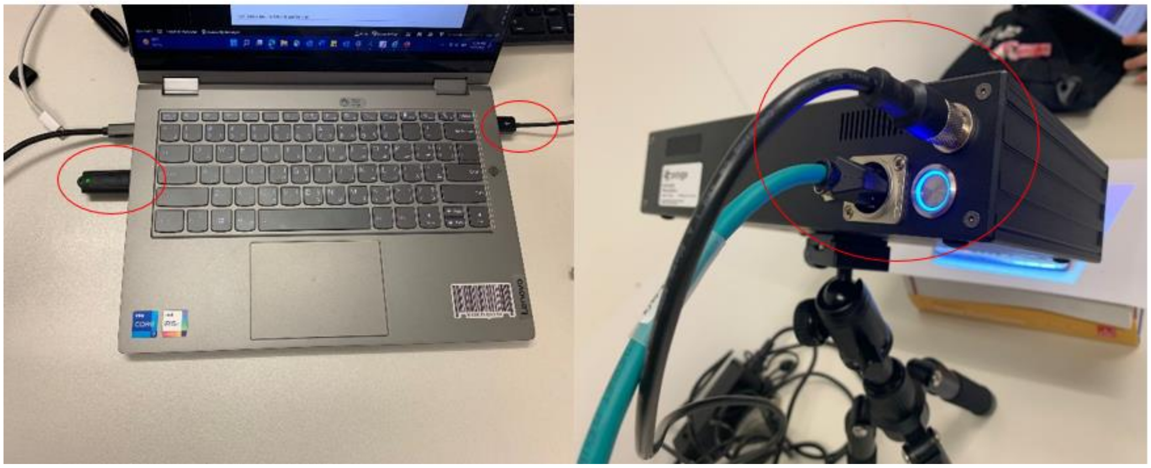

Figure 5: Necessary connections to connect Polyga S1 compact.

After some research on the product, we started scanning objects with flat surfaces as it is easier to scan flat surfaces over curved surfaces. It is easier for a scanner to detect edges of a flat surface compared to round surfaces which require more expertise and low number of scans can also result to a distorted scan. Figure 6 shows the setup to scan a flat surface cube. Each face was scanned one after the other and was imported to Flex Scan 3D to join the scans.

Figure 6: 3D scanner setup to scan a flat surfaced cube.

Followed by scanning the flat surface cube, our team focused on scanning the cylindrical connector part, with a round surface and more surface features. Figure 7 shows the setup for the scanning of the cylindrical part. Blue markers were placed on the base of the rotating stand to join the scanned faces of the cylinder, with the aid of Flex Scan 3D software.

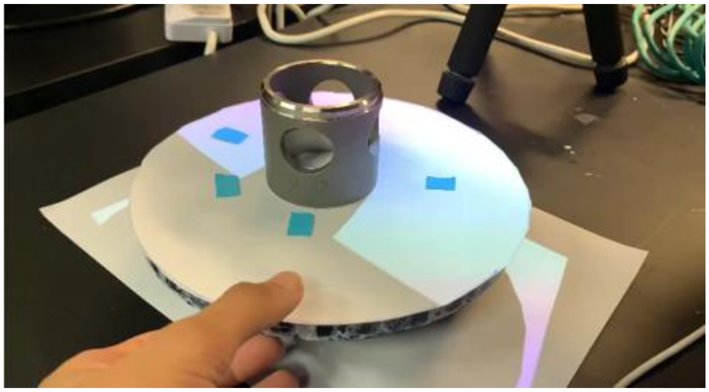

Figure 7: Setup for scanning the cylindrical part.

2.3 Manufacturing

2.3.1 Subtractive Manufacturing

In order to draw a meaningful comparison between subtractive and additive manufacturing techniques, it is necessary to first establish a clear understanding of subtractive manufacturing. To this end, we utilized Fusion 360 software to produce a G code, which was subsequently imported into the CNC machine to execute the machining of our component. In the preceding section, the CAD model of the part was imported into Fusion 360, a program that offers a variety of design tools and capabilities to make it easier to create 3D models [8]. One can create these models from scratch or import them from other software packages. The model can be altered by the user by adding or removing features, changing the object's dimensions, or changing its shape. After the 3D model is finished, Fusion 360's integrated CAM tools may produce toolpaths and G code for CNC machines. This makes it possible for the user to create the object using subtractive techniques like milling or turning.

2.3.2 Additive Manufacturing – Material Extrusion

Material extrusion or Fused Deposition Modeling was used as the additive manufacturing fabrication technique to prepare the CAD modelled parts. Whilst material extrusion utilizes a spool of material (often thermoplastic polymer) which is forced through a heated nozzle in a constant stream and then is selectively placed layer by layer to construct a three-dimensional (3D) object [9]. VAT Photopolymerization was considered an option as a fabrication technique but due to the size of the parts, it was decided to use material extrusion technique (Fused Deposition Modeling specifically) instead.

In FDM, molten thermoplastic material is carefully extruded through a nozzle or head to build up an item layer by layer. The FDM machine uses the information from a CAD model that is often separated into thin layers to deposit the material on each layer in a preset manner. As more layers are added, they combine to form a final solid structure [10].

With respect to the pump casing, the intricate geometry and considerable dimensions necessitated a 40% scaled-down model to be fabricated via machining, following the design procedure conducted using CAD software.

To understand if the cylindrical connector will be accurate as the subtractive part when printed using metal fabrication technique, two parts were fabricated using Fusion Deposition Modeling. The material chosen was ABS plastic and the infill percentages were varied. The printing parameters include changing the infill percentage from 20% - 40%, resolution was varied from “extra fine” to “extra fast”, presence of support structures and adhesion.

2.3.3 Additive Manufacturing – Selective Laser Melting (SLM)

SLM is a bottom to top additive manufacturing process which uses a laser beam to solidify layers of powder [11]. A sliced STL part is imported into the SLM machine to start the SLM process. First, a thin layer of powder is spread over a built platform, the platform is lowered. Followed by this, a laser beam of a specific pattern solidifies the powder. The process is repeated until the part is complete.

Laser power, scan speed, powder bed temperature and layer thickness are some process parameters of SLM process. These parameters can be varied and optimized accordingly to get the desired quality of the part. Process parameter optimization of SLM process encompasses design of experiments (DOE) in order to design a series of experiments with different input parameters to get optimum output parameters such as surface porosity, and micro hardness [12]. The different DOEs that were considered were keeping the power of the printer consistent whilst varying the print speeds and then second DOE was to vary the powers whilst keeping the speed consistent.

For the optimization study, a 1x1 squared centimeter cube was fabricated using Sharebot MetalOne printer which were placed in molds made from epoxy resin. The samples were provided by EM2 lab's graduate student Engr. Anurag Srivastava. Epoxy coating provides the samples stability and keeps any contaminants away from the sample, hence acting as a protective barrier to prevent any surface damage and provides a smooth surface for grinding and polishing. Following that, grinding of the samples helps to remove any irregularities and provide a flat and uniform surface. Polishing is the final step for the preparation of samples, and it needs very fine abrasive materials to polish the surface of the sample to produce a smooth and reflective surface.

Following this, the samples were kept under an optical microscope to get high quality 5x images and calculate the area porosity of each sample. The microhardness of the samples was tested under FM310 micro hardness tester, and 10 readings were taken on each sample to get the hardness values of the samples.

The epoxy molds were cut, and the same process was repeated for the second aimed surface of the printed samples.

2.4 Optical Microscopy

In order to obtain microscopic images of the structure of the additively manufactured parts for the different printing parameters, microscopy was performed with the Axiovert 40 MAT microscope as shown in figure 8. The reason this microscope is a great option is because it allows the adjustment of polarization contrast which aids with materials that have low birefringence [13].

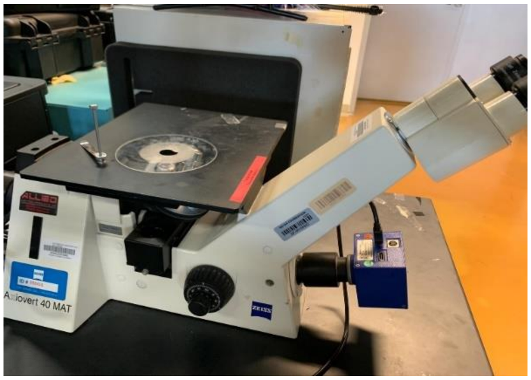

Figure 8: Axiovert 40 MAT microscope.

2.5 Porosity Measurement

The mechanical characteristics and functionality of items made using additive manufacturing (AM) can be greatly impacted by porosity. The volume percentage of voids or pores within a substance is known as porosity. As a result, precise porosity assessment is crucial for quality control and guaranteeing the functionality of AM parts. Analyzing microscopic pictures of the part is a popular way to determine porosity in AM parts [14].

To calculate the porosity, the first step involves capturing microscopic images of the AM part. The images are then imported into a software program, such as ImageJ, for analysis. In ImageJ, the pores are identified by assigning a dark color to empty spaces and a light color to the space occupied by the metal part. The software can then calculate the amount of dark space present, which represents the pore area [15].

Next, the pore area is divided by the total area of the image to obtain the porosity of the object, expressed as a percentage (Area%). This method of calculating porosity based on the analysis of the size and distribution of voids within a material is commonly used in materials science and engineering to evaluate the quality and performance of manufactured components.

For AM parts to function accurately, a reliable assessment of porosity is necessary. By analyzing microscopic images of the part and utilizing software tools like ImageJ, we can calculate the porosity of AM parts, which helps in quality control and further optimization of the manufacturing process [16].

2.6 Mechanical Properties

Initially, some microhardness tests and surface roughness measurements were carried out on the original cylindrical part shown in Figure 2. In short, microhardness testing is used to quantify a material's hardness on a microscopic scale.

The microhardness test included various steps. The bottom surface of the part was taken to be examined since the top surface contained chamfers and design features. The specimen is prepared by polishing its outermost layer to a high level of purity and roughness in order to reduce any surface contamination or roughness that might impact the experiment's outcomes. Therefore, the bottom surface was first grinded and polished with a 1200 grit sandpaper to remove any scratches or surface defects that might hinder the hardness test.

To ensure precise measurement of the load and displacement throughout the indentation process, the microhardness instrument has been calibrated. The load cell, displacement sensor, and/or indenter tip may need to be calibrated for this.

The part was then placed on a micro-hardness testing machine FM-310 and an optical microscope AXIOVERT 4-IV was used to examine the surface of the object. An area between grain boundaries, devoid of any imperfections was chosen to be the site of indentation.

The indenter tip is brought into contact with the sample's surface, and a light load is then imparted to it. Depending on the experimental design, the load may be increased gradually over time or in discrete stages. The sample's surface is penetrated by the tip as the load is applied, and the displacement of the surface is measured. A total of 10 measurements were recorded at 4 points over the region of the surface spread equally.

To extract the appropriate mechanical characteristics of the part, such as hardness, elastic modulus, and plasticity, the data collected during the indentation process, including the load-displacement curve, is studied.

The information acquired from microhardness tests can be used to describe the characteristics of the materials, compare how different materials behave mechanically, or assess how different processing methods or environmental factors affect the mechanical properties.

3. RESULTS

The pump casing was used as a means to understand the amount of material wasted during its machining process as it had a lot of intricate shapes that needed special tools to create.

The scope of this paper was then narrowed down to examining the cylindrical metal connector that is frequently utilized in the industrial sector. The decision to focus on this particular component was primarily motivated by its physical dimensions, which are small enough to facilitate usage for our project within a reasonable timeframe. The compact size of the connector renders it highly manageable, and therefore a practical choice for the study at hand.

3.1 Pump Casing

3.1.1 CAD Model

The model represents a pump casing that was built in SOLIDWORKS and had dimensions of 453 mm in diameter and 100 mm in thickness. The features used to create this model include Boss-Extrude, Cut-Extrude, Chamfers, Fillets and Cut-Sweep. This was accomplished by generating the physical steps mentioned previously in Fusion 360 software. Figure 9 portrays the CAD models that were generated but were not manufacturable with the CNC machines available at the university. Therefore, a size reduction of 40% was required. Certain features such as sharp edges, chamfers and fillets were not able to me CNC machined.

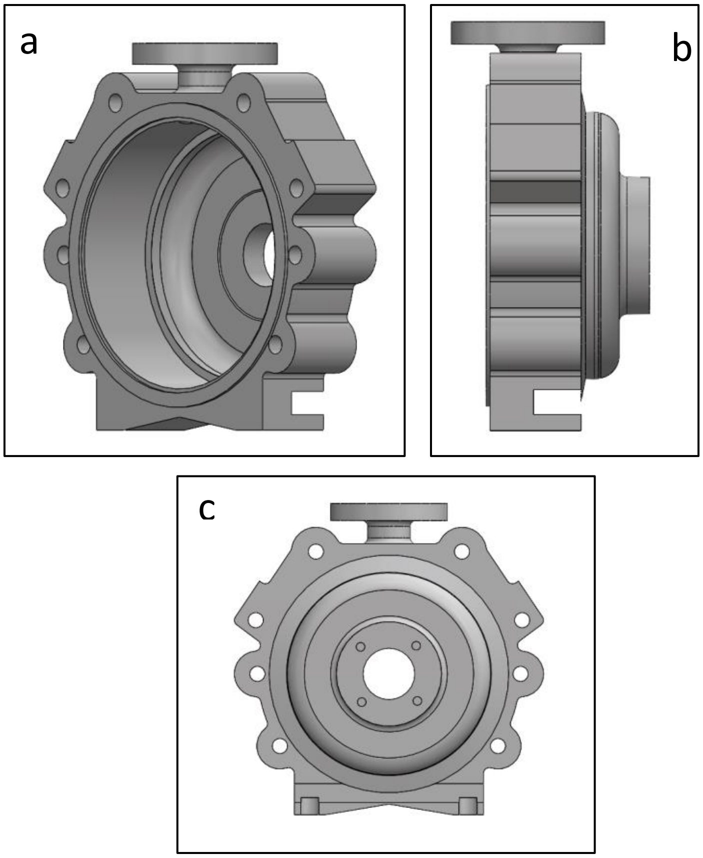

Figure 9: CAD Models of Centrifugal Pump (a.,b.,c.,)

The modified CAD model of figure 9 is portrayed in figure 10:

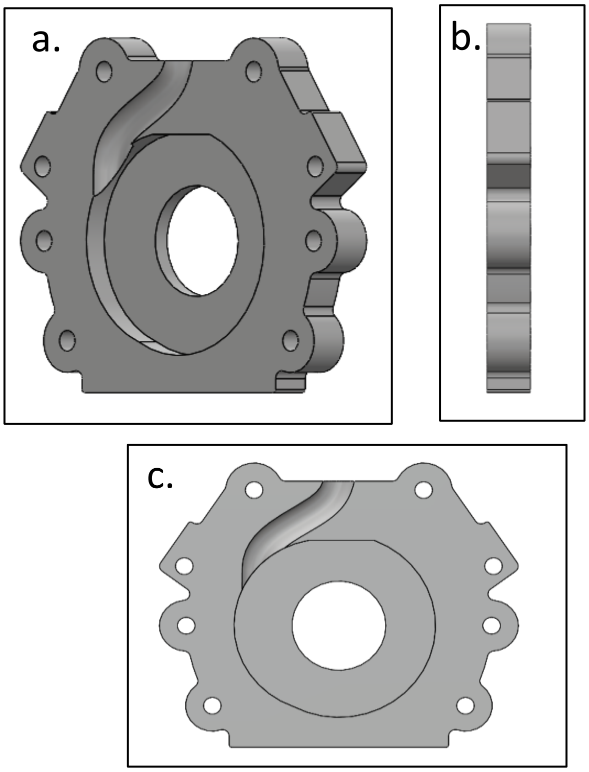

Figure 10: Modified Versions of CAD model with 40 % size and feature reduction (a.,b.,c.,)

The detailed dimensions of the modified CAD model are shown in figure 11:

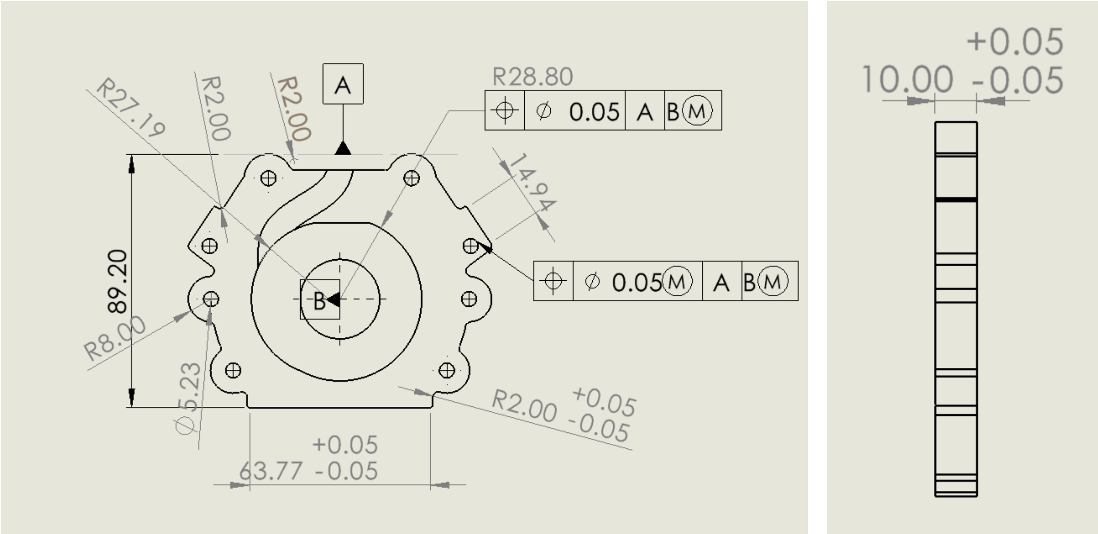

Figure 11: Dimensions of Modified CAD model.

3.1.2 Subtractive Manufacturing

Starting off with the base, the theoretical Solid works value had a value of 63.77mm with a tolerance of +- 0.05mm. The actual machined part came out with a value of 63.58mm exceeding the tolerance by 0.14mm. The extruded circles around the part were designed to have a diametral value of 5.23mm with a tolerance of 0.05mm. The actual part turned out to be 5.31mm exceeding the tolerance value by 0.03mm. The thickness was designed to have a value of 10mm with a tolerance of +- 0.05mm. The actual machined part had a thickness value of 10mm which met the criteria. One of the possible reasons which would explain the reason for the part exceeding the tolerance is due to human error when using the Vernier caliper for the measurements. Another possible reason for the part exceeding the tolerance is that there could have been an incorrect calibration in the Vernier caliper as well. A third possible reason why the size was not achieved within the tolerance value could possibly be due to the machine type not being able to produce the parts within these tolerance limits. Possible ways to reduce this error is that the measurements were supposed to be taken multiple times and average for a more reliable result.

The channel for the machined part was much better than the CAM model we generated due to the use of an alternative tool which increased the surface finish of the part but also reduced the machining time as the operation did not have to make as many passes now to have a high surface finish.

The overall surface finish of the machined part which is portrayed in figure 12: G-code model for the pump casing is excellent due to the expertise and operation optimization of the CAM model. As mentioned in the latter half of the report, there is a standard for each machine, each material, each level of tolerance that needed to be followed to avoid damage to the machine but also to reduce the possibility of part failure.

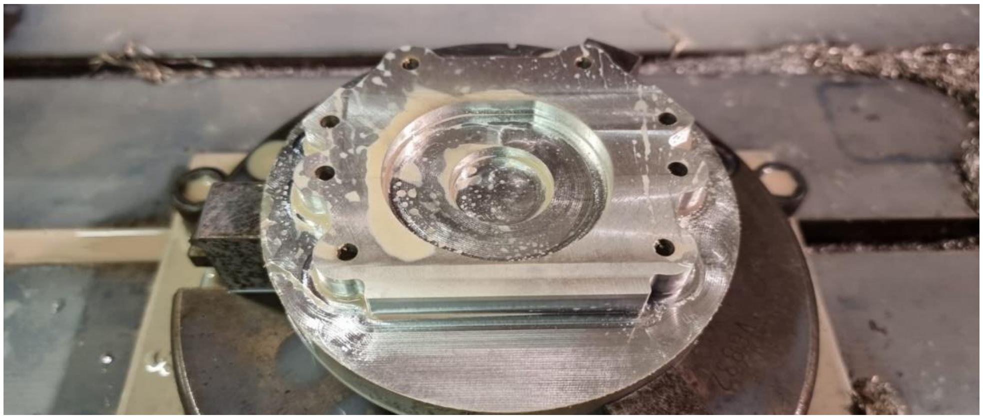

Figure 12: Results of the fabricated part obtained after computer aided manufacturing and machining.

The project's material, aluminum, has a friction coefficient factor that lowers the quality of the surface finish and lengthens the machining process; instead, brass, or alloyed Aluminum 6061 T6, which has a lower friction coefficient factor, might be employed. Because a lower friction coefficient would provide less post processing and hence less time spent fabricating the part.

Moreover, it is also observed that at the end of the channel that integrates into the cavity at the lower surface of the part, there is a sharp edge which may have been due to the sudden shift in the tool angle that came about due to the tool change but also limited space to work in.

The part's curves made it impossible to machine it to the highest feasible standard. This is because the tool wouldn't fit due to the severe rotations that would occur. Future studies should consider a standard for performing such high profiled curvatures.

Due to constraints in the stock material dimensions (150 mm x 150 mm x 12.7 mm) and the availability of tools in the machine shop (flat endmills ranging from 2mm – 12 mm diameter, with 3 flutes for 2,3,4,6 and 4 flutes for 6,8,10, and 12, drills of 1mm to 13 mm). Other constraints include that no sharp corners can be manufactured, and that the corner diameters of the part should be greater than the tool diameter. Therefore, the part/model had to be further modified and scaled down by a factor of 0.2 to give the following CAD model. The red arrows in figure 13 portray the areas where the fillets were required. In the CAM model, the channel was constructed with a 3 mm flat end mill, which bore the fruit of the blue continuous line on the channel that portrays that the stock material was not effectively eliminated.

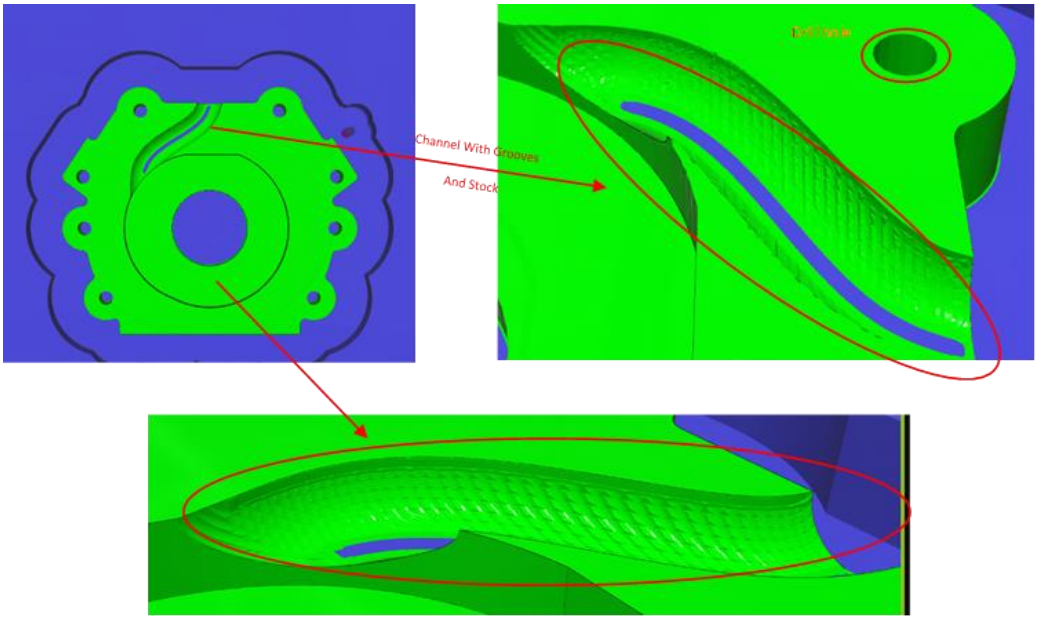

Figure 13: G-code model for the pump casing.

3.1.2.1 Determination of Parameters and Machine

The cutter's principal cutting edges run along its flutes, while its secondary cutting edges are located at the bottom. By allowing a cutting edge to enter the workpiece progressively, the flutes' helix angle contributes to balancing out the force fluctuation that the cutter experiences. The secondary cutting edge's secondary concavity angle can significantly affect the roughness hence these factors have to be taken account when machining the part.

Furthermore, the type of material used is a vital factor as soft materials are not so desirable by machinists due to the low yield strength and hence leading to deformations much easily.

3.1.2.2 Machine Time

According to the theoretical calculations provided by the simulation software, the total time of production was 21 minutes. However, in practice a greater time was taken. The tool changes along with any pauses within the CNC process taken to adjust the tool and maintain safety within the CNC procedure, may have resulted in the added time. Facing was the operation that theoretically took the longest amount of time, which may be due to the slow nature of facing and its need to produce a smooth and equally flat surface.

3.1.2.3 Microscopy

High speed milling operations of complex parts requires hand finishing operations such as grinding of the surface to obtain a smooth and consistent surface. The machined surfaces are smooth when visualized by naked eyes and touched by bare hands. However, there could be surface defects which can only be seen under a microscope.

An advanced microscope is used to visualize the surface of the machined part. The boundary in red, in figure 14, shows the separation between the surface finish done by two different tools. It is evident that the tools used in the machining process had different levels of microns. The machinist used a 3mm tool with 20 microns to machine the corner of the lower surface. A 3mm tool had to be used because the inner vertical face has fillets of 3mm. The middle part of the lower surface was machined by 12 mm tool with a different level of microns, which is why there is a surface finish difference in the two surfaces.

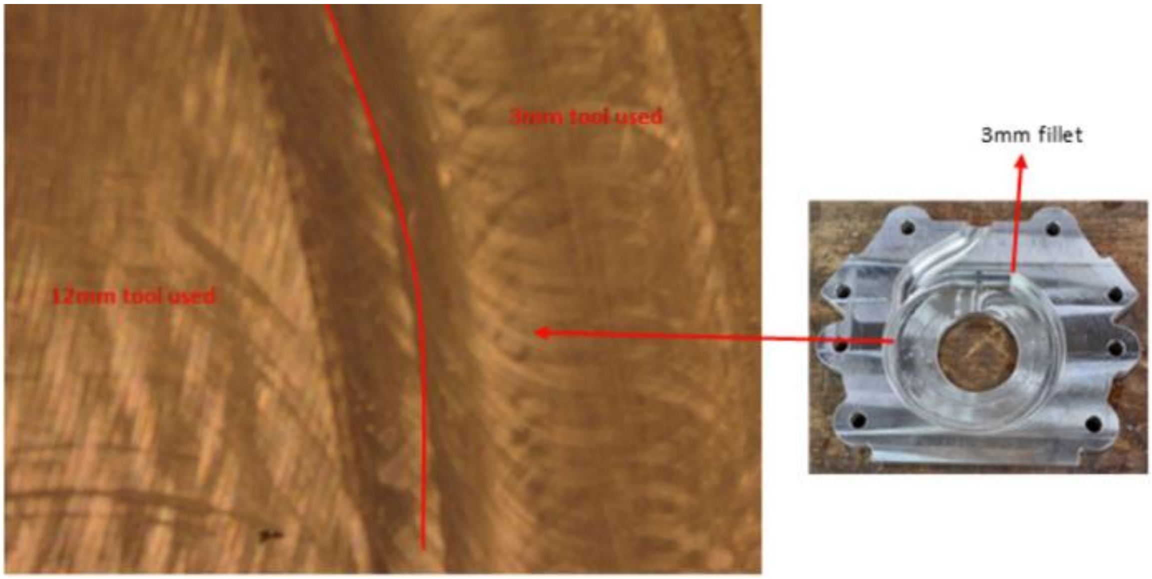

Figure 14: Comparison of the corner and middle part machining using different tools.

The top picture in figure 15 shows the difference in the surface finish of the flat surface of the machine and the semi-circle of the channel. The nose ball mill has a multiple edge cutting action part which results in a surface patina on the semi-circular face.

The bottom picture in figure 15 shows circular patterns on the lower surface of the part which could be due to the excessive stress of the 3mm flat end mill on the point of the surface. The circular marks on the part are also seen because the tool might have spin on the part with an excessive speed and it left circular marks on the part.

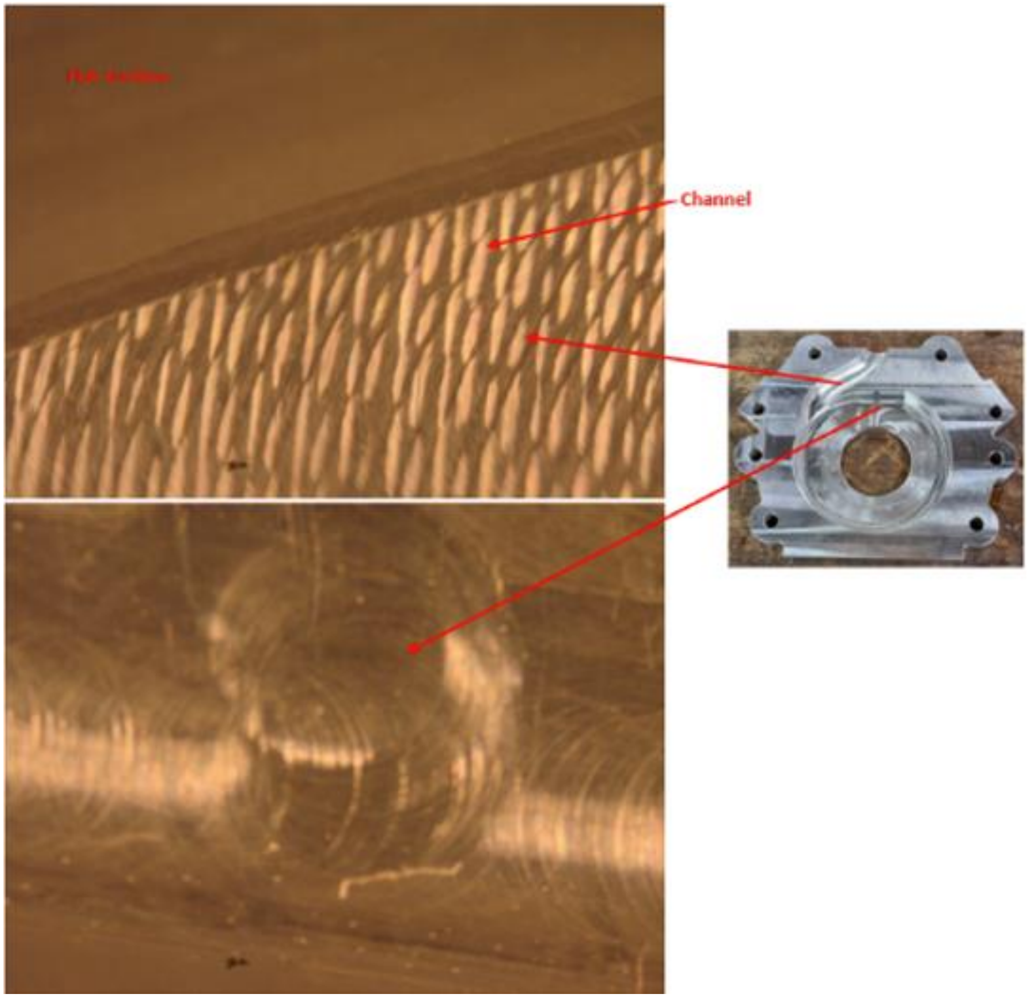

Figure 15: Comparison of channel with flat surface (TOP), effect of pressure of tool on the lower surface (BOTTOM).

3.1.2.4 Amount of Material Utilized

Irrespective of the manufacturer's expertise, current CNC machine techniques are very advanced and exceedingly accurate, but they also produce a lot of waste. This avalanche of debris must be recycled, frequently at a cost to the business and the environment, increasing the cost of the end user's parts. The machined part had a total length of 10 mm (about 0.39 in), but the amount of stock used to create fabricate the part was 30 mm (about 1.18 in). Figure 16 portrays that a significant amount of material was wasted. The removal of surplus material in the form of chips during the milling operation makes it potentially wasteful in terms of both material and energy utilization. Productivity and revenue in every production process depend on limiting wastage of materials. A lot of abrasive particles like chips and debris can be produced during the milling operation particularly. Specifically, if the milling process isn't well-optimized.

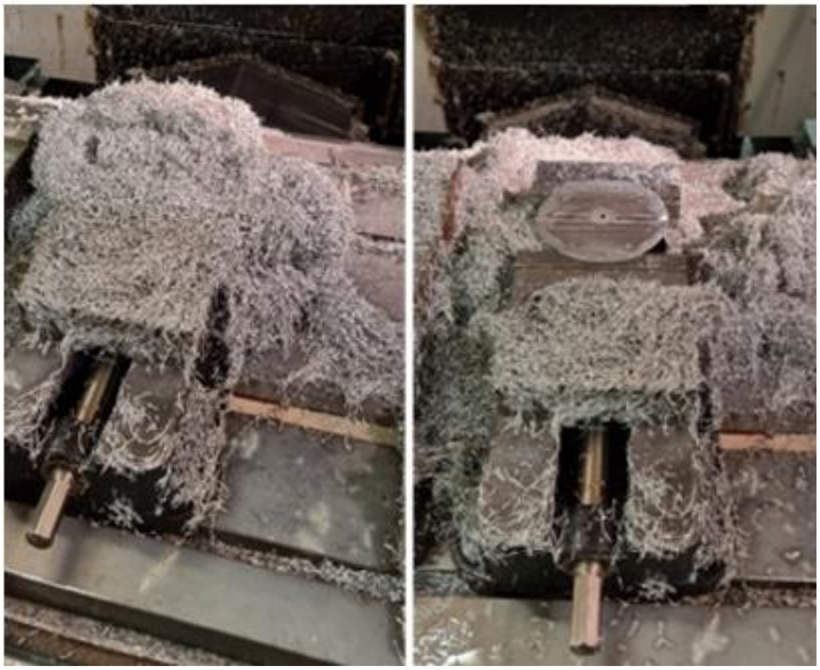

Figure 16: Amount of material wasted in the machining process.

3.1.3 Additive Manufacturing – Material Extrusion

The material extrusion process used to fabricate the pump casing enabled us to gain a comprehensive understanding of additive manufacturing and analyze the crucial characteristics of 3D printing with the printed component.

With respect to the pump casing, the intricate geometry and considerable dimensions necessitated a 40% scaled-down model to be fabricated via machining, following the design procedure conducted using CAD software, SOLIDWORKS which was then imported into

CURA for slicing to be able to print. Figure 17 portrays the 3D fabricated part (along with the supports).

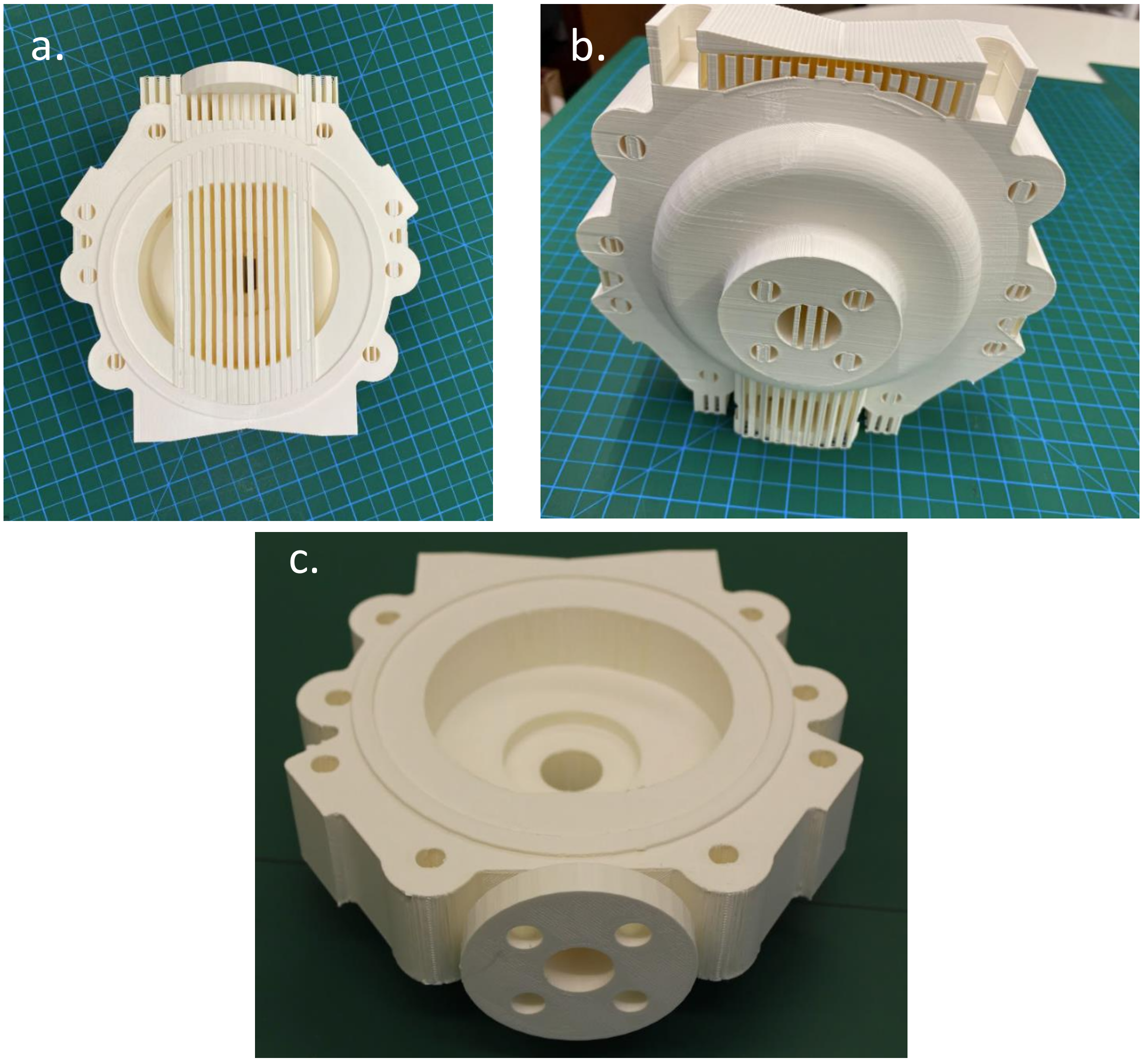

Figure 17: Top left and right pictures portray the Material Extruded Pump Casing before supports were removed, and bottom prototype with supports removed ((a., b., c.)

3.2 Cylindrical Part

3.2.1 Computer Aided Design (CAD Modelling)

To ensure that the cylindrical part could be fabricated using the metal 3D printer, we took steps to develop a precise and approximate model of the part. This was important as factors like design could impact the hardness measurements and mechanical properties of the part. We used precision tools such as a vernier caliper and micrometer to create a CAD model that closely matched the dimensions of the original part. Figure 18 includes images of the cylindrical part along with its dimensions.

Although the cylindrical part had features like chamfers, we couldn't measure them using our current tools. Therefore, we had to approximate them. Minor features such as slight bulges and extruded designs were present on the body of the cylindrical part. However, we considered these features insignificant and assumed they wouldn't affect the overall mechanical properties of the object.

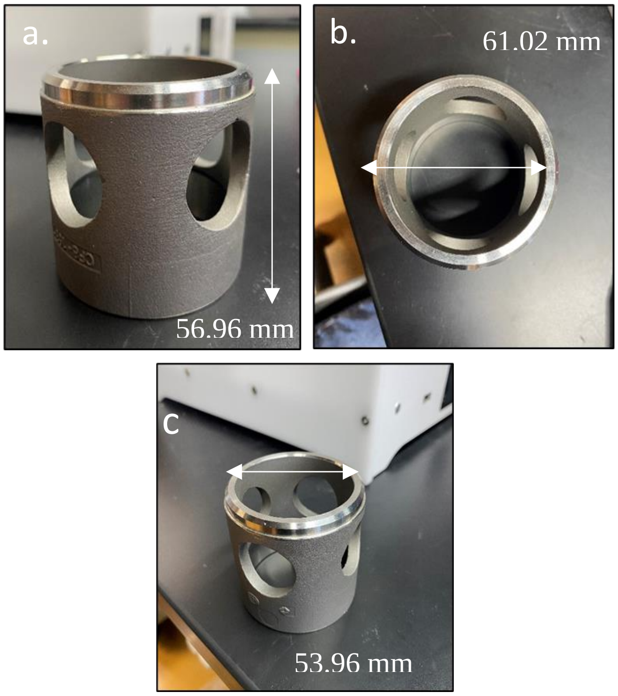

Figure 18: Cylindrical Part Views and Dimensions (a.,

In summary, our focus was to develop an accurate model of the cylindrical part using CAD software to enable fabrication using a metal 3D printer. We used precision tools to provide precise dimensions of the original part and approximated some features like chamfers. Minor features on the body of the part were considered insignificant and excluded from the CAD model. We utilized the dimensions obtained from the actual part to create a CAD model of the cylindrical part using SOLIDWORKS. The resulting model is depicted in Figure 19.

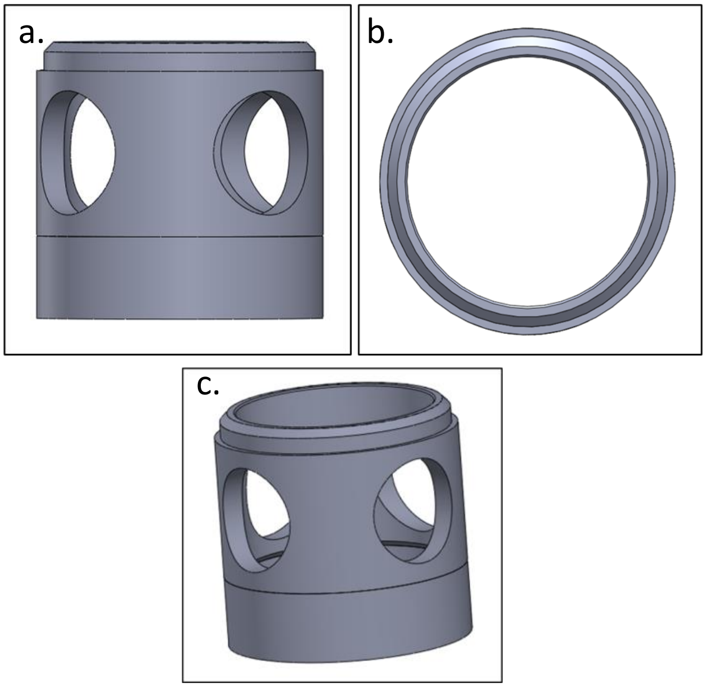

Figure 19: Different views of CAD model (a.,b.,c.,)

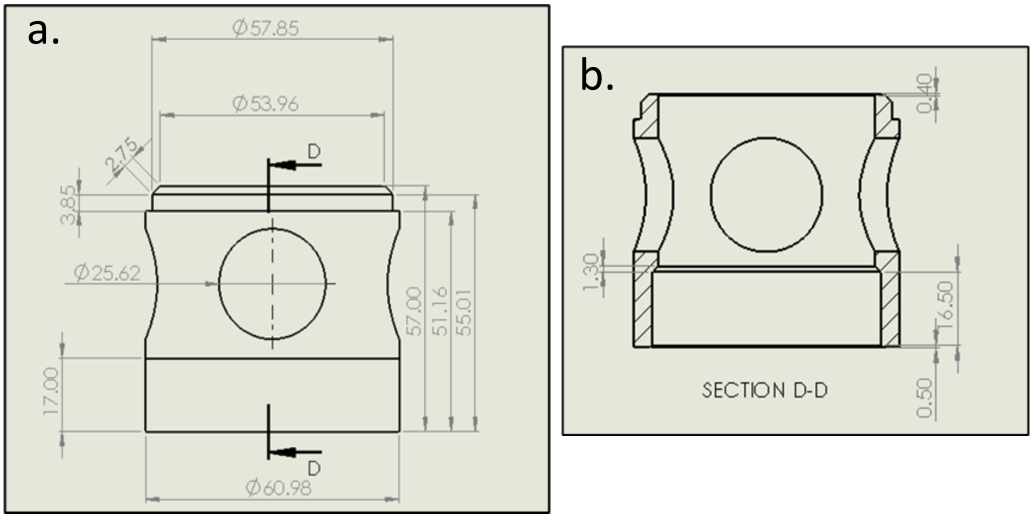

Figure 20: Cylindrical part drawing and section view of cylindrical part (a., b.)

Finally, Figure 20 provides the dimensions that were used in creating the model shown in figure 19. It should be noted that all dimensions are in mm.

3.2.2 3D Scanning

Figure 21 shows some of the scans of cube which were used to generate a 3D model of the cube, represented by figure 22.

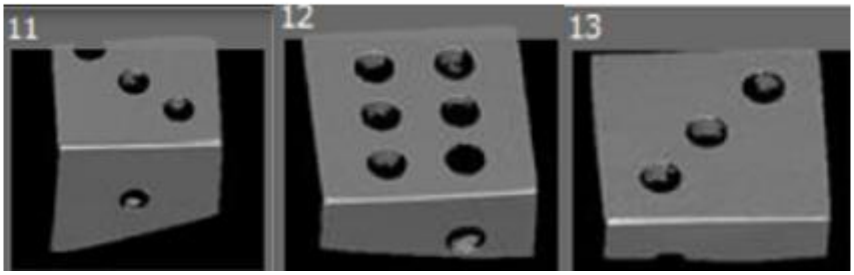

Figure 21: Scanned faces of the cube.

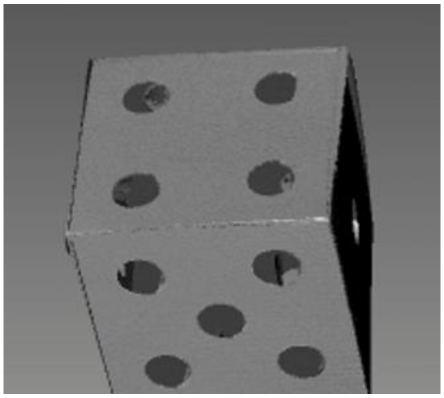

Figure 22: Scanned 3D cube after merging the scan results.

Figure 23 shows some of the scans of cylindrical part which were used to generate an aligned 3D model of the cylindrical part, represented by figure 24. Followed by figure 25 which shows the combined part after the alignment was done.

Figure 23: Scanned faces of the cylindrical part.

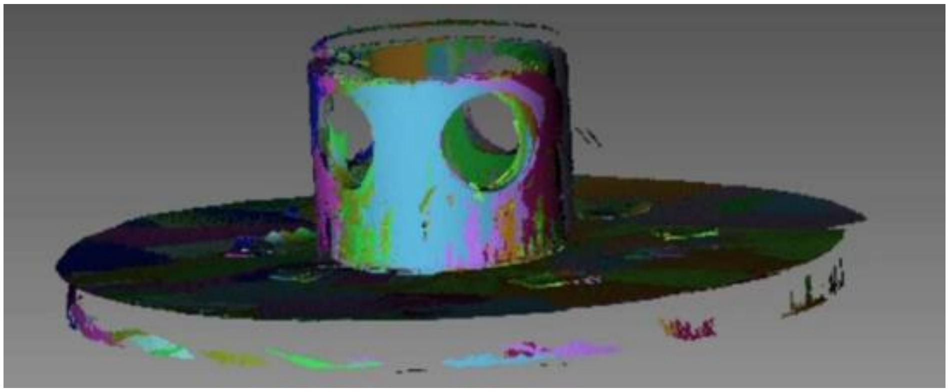

Figure 24: Number of scans aligned with alignment tool.

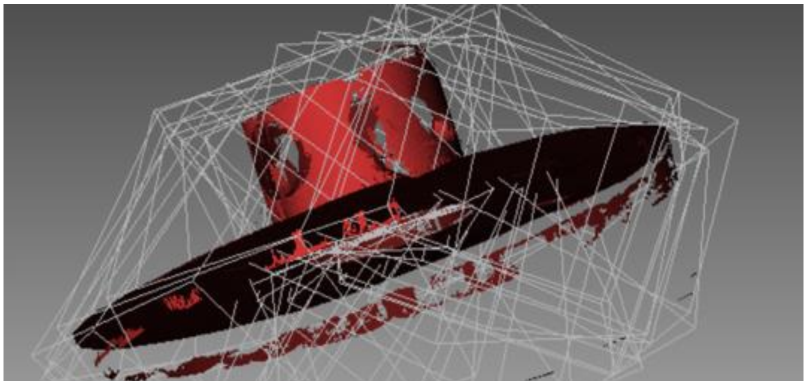

Figure 25: Scans combined to make one part.

3.2.3 Additive Manufacturing – Material Extrusion

The cylindrical component was a crucial part of our project, and we wanted to create an accurate 3D replica to understand the additive manufacturing process details and workflow. As the structure of the component was relatively simple, we decided to undertake manual measurements to gather the necessary data. After acquiring the measurements, we utilized SolidWorks to create a three-dimensional CAD model. The SolidWorks software enabled us to design the component with precision and accuracy, considering all the necessary details and dimensions and we were able to convert the CAD file into the required .stl file for 3D Printing.

The 3D slicing software, CURA 5.0 transformed the 3D model into a series of instructions (layers) that could be understood by the operating system of the 3D printer. After this, the layers were converted into strings of data that explained to the printer about the extrusion temperature, location, and rate of the extrusion. The slicing software also helped us adjust advanced settings such as layer height, infill, and density. We were able to add support structures and optimize the surface finish of the part with the help of the software. Finally, the software converted the CAD model into a file format suitable for the 3D printer to use.

Next, we chose to use material extrusion, an additive manufacturing technique, and ABS plastic material to create the final product. The cylindrical part was 3D printed with the aid of Ultimaker S5 printer. The bed temperature where the material is extruded onto has a temperature of 39-40 degree Celsius and the print speed was kept at 35 mm/s to ensure the print is obtained fast but also of high resolution.

After the CAD design of the cylindrical part was finalized, the 3D printer was prepared to run. The filament spool is loaded into the printer, the build plate is levelled, and the 3D CAD model is imported into the slicing software. After we obtained the optimal combination of parameters from the CURA software and after a few pilot experiments, we were able to print the prototype of the cylindrical component.

To understand if our cylindrical part will be accurate as the subtractive part, two parts were printed using ABS plastic and different infill percentages. The printing parameters include changing the infill percentage from 20% - 40%, resolution was varied from “extra fine” to “extra fast”, presence of support structures and adhesion. Different printing parameters were used and tested to help us optimize the density and strength of the prototype. After several attempts, we were able to obtain the optimal combination of parameters, and the prototype was printed successfully as seen in figure 26 below. It is evident that with the 40% infill, the sequence of layering is denser and more compacted whereas in the 20% infill the different layers can be seen meaning there is not enough coalescence to hold it together if extra force was applied.

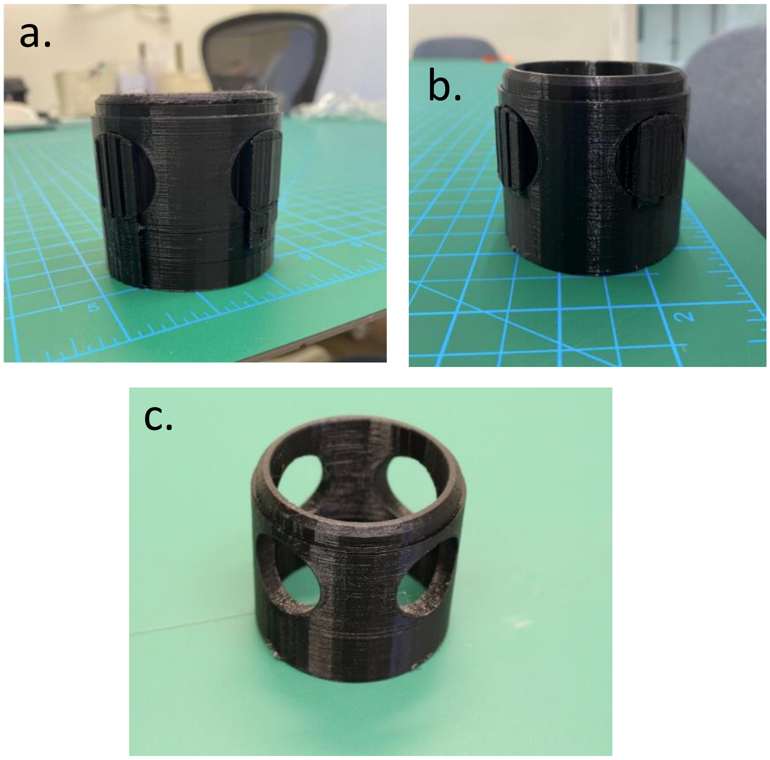

Figure 26: Left 20% Infill, right 40% infill prototype, and bottom 20% infill prototype without supports ((a., b., c.)

To summarize, creating a three-dimensional replica of the cylindrical steel component from ABS was a crucial part of our project. We utilized manual measurements and CAD software to create an accurate model, and 3D printing via material extrusion to visualize our design as a product. We tested different infill percentages and printing parameters to ensure the accuracy of the model and optimized the density and strength of the prototype. The final product was a successful and accurate replica of the original cylindrical component, and it gave us confidence that we can now print this part by selective laser melting.

3.2.4 Additive Manufacturing – Selective Laser Melting

Figure 27 shows the 3D printed parts in which different printing parameters were used and tested to optimize the density and strength of the prototype. After following the method to optimize the parameters to print 12 samples. Figure 27 shows 12 printed samples, with series of power and speed, for optimization of the parameters. The ultimate goal was to print the original metal cylindrical connector using SLM fabrication technique but before that, an optimization study had to be carried out to understand the process parameters of the fabrication technique.

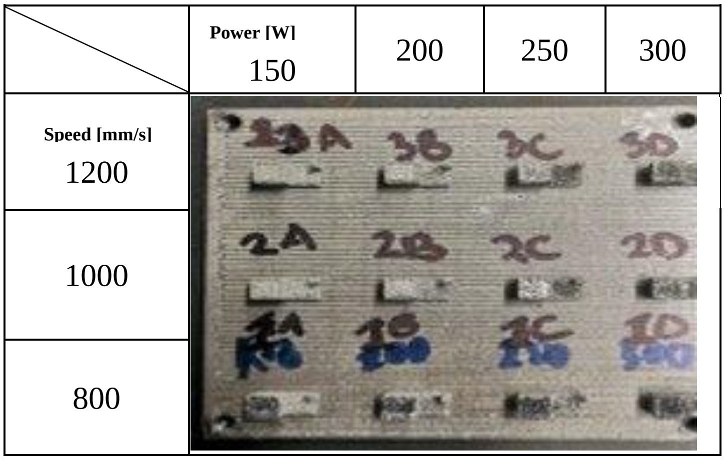

Figure 27: Power and speed parameters chosen to print the testing samples.

Figure 28 displays the results that are the results obtained from the samples after performing microscopy as well as the micro hardness test.

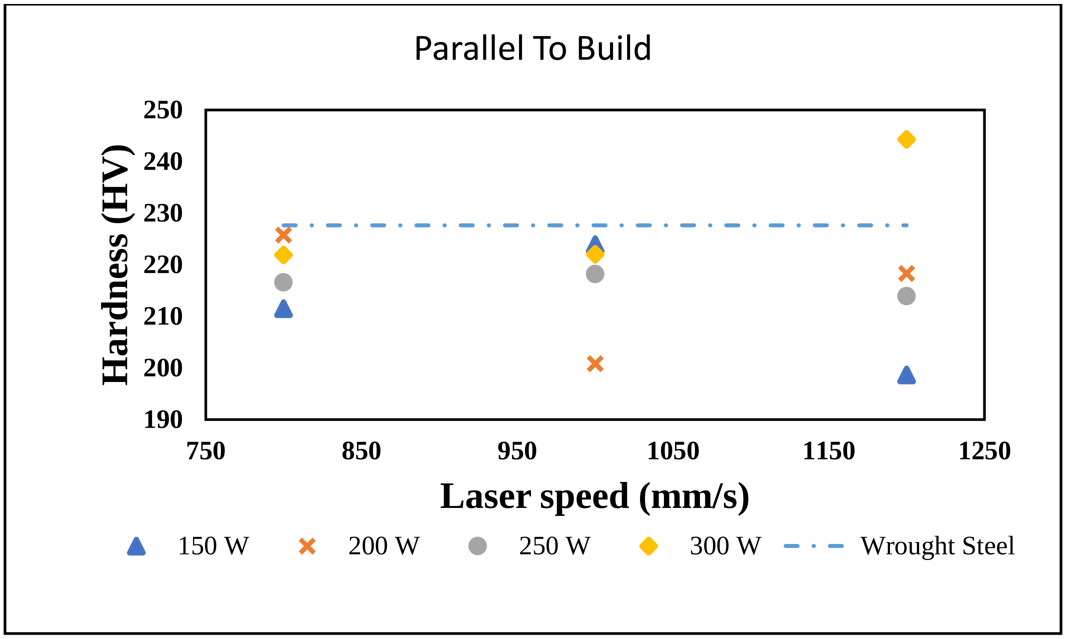

Figure 28 Microhardness Results

Figure 28 displays the HV values for the samples that are manufactured by the AM process parallel to the build. For a maximum laser speed value of 1200 mm/s as well as at a power of 300, a hardness of 250 HV can be achieved which is preferred. However, it is necessary to consider that a lot of energy is being used to create a miniscule sample. Utilizing the information that is obtained, the energy required to build the cylindrical part of interest would be immense. Figure 29 below shows the HV values for the samples perpendicular to the build.

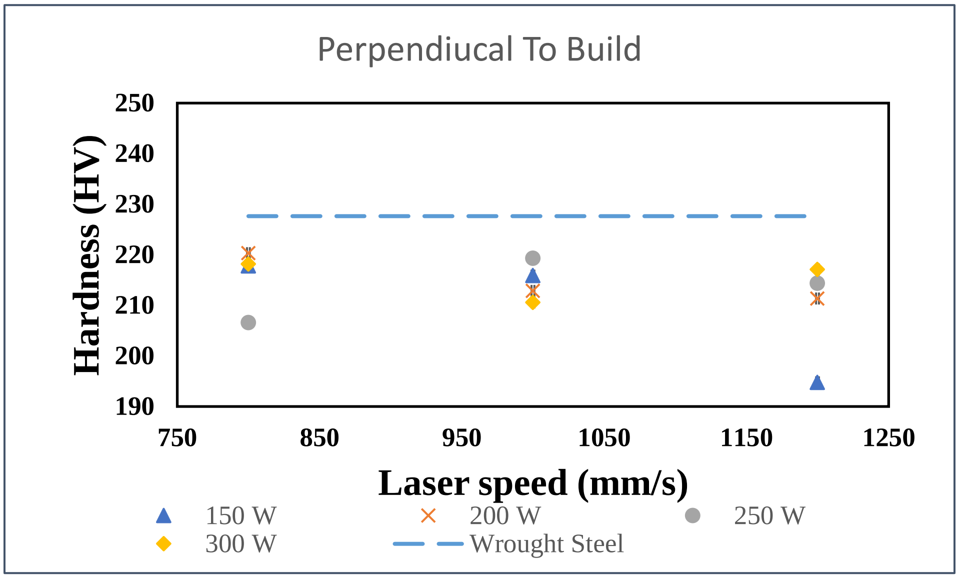

Figure 29: Microhardness Results

The analogy similar to Microhardness Results in figure 28, can also be used for figure 29. In figure 29, it can be seen that the hardness values across the different parameters (laser speed, power) are relatively similar with no major difference. Finally, to conclude with the best possible combination of parameters, Figure 30 is utilized.

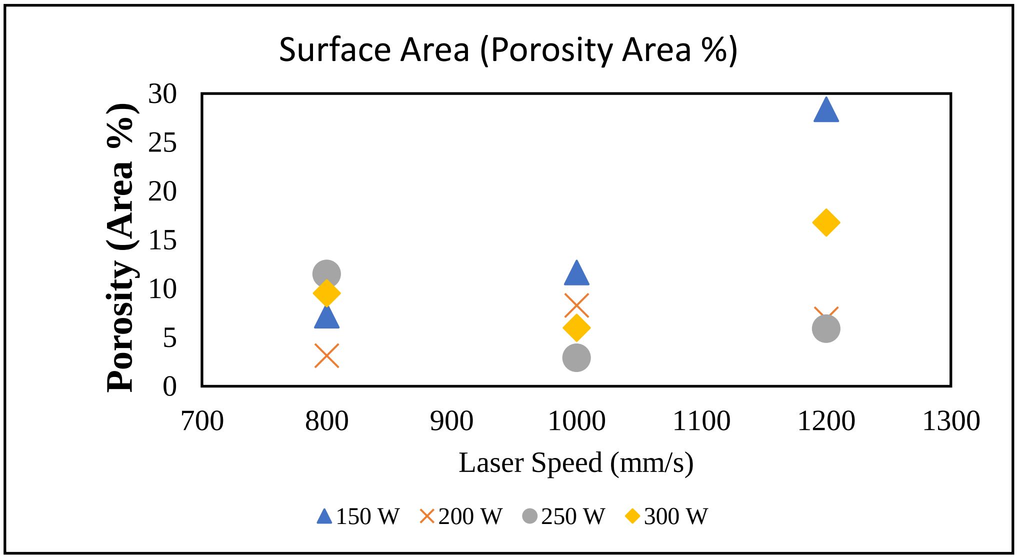

Figure 30: Porosity Results.

In Figure 31, since the scanning/laser speed was extremely high, large porosities could be observed when under the microscope. Moreover, the greater the porosity percentage, the less the hardness or strength of the sample. Here, it can be seen that for a laser speed of 1000 and 800 mm/s, the porosity percentage for a certain area remains relatively the same. It can be concluded from figures 28, 29 and 30 that the best possible combination of parameters to utilize for printing the cylindrical part would be to employ a laser speed of 800 mm/s and power of 250W. Figure 31 portrays the porosity pictures relative to the laser speed and power.

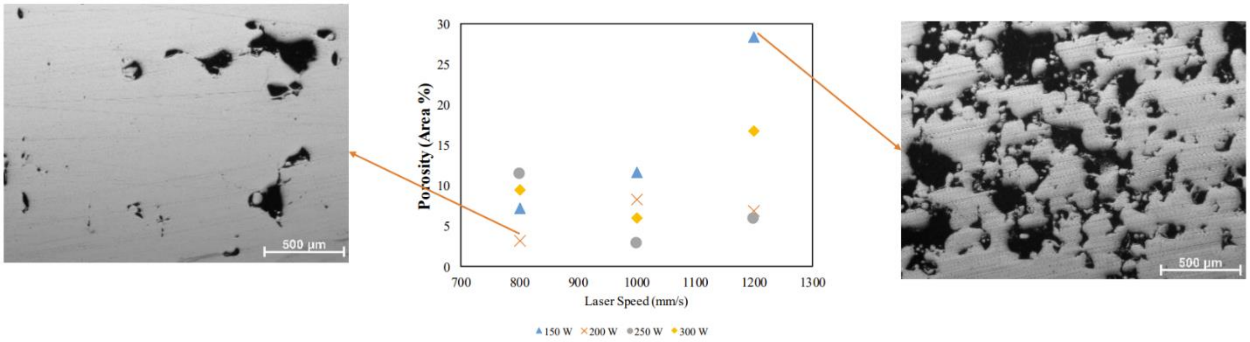

Figure 31: : Porosity images relative to print speed and power.

3.2.5 Mechanical Characteristics

The microhardness tests conducted on both subtractive and additive manufactured parts revealed important information about their mechanical properties. The results indicated that the subtractive manufactured part had an average Vickers hardness (HV) value of 385, while the additively manufactured part exhibited a maximum HV value of 250.

Although the part made by additive manufacturing had a lower hardness rating, this does not necessarily mean that the production technique was flawed. Instead, it implies that, like the SM fabricated part, the component may need heat treatment to increase its hardness. Overall, our findings offer insightful information about the mechanical characteristics of both manufacturing processes and offer new directions for enhancing the functionality of additively built parts.

4. CONCLUSION AND FUTUREWORK

The ability to produce materials with the appropriate material properties, such as Vickers hardness and corrosion resistance, is one of the difficulties faced by additive manufacturing. When parts are exposed to corrosive materials in hostile environments, corrosion resistance is very crucial. Vickers hardness, on the other hand, measures how resistant a material is to being indented and deformed, making it a crucial characteristic in parts that are subjected to significant stress and wear.

Porosity, which can influence the material's characteristics and the part's functionality, is another aspect to take into account in additive manufacturing. In our research, we discovered that the lowest porosity level was achieved at a speed of 800 mm/s and a power of 200 W. This emphasizes how crucial it is to optimize the printing parameters in order to obtain the desired material qualities.

During the experimentation phase, it was found that the additive manufactured part had a Vickers hardness of 245 HV, while the desired hardness was 380 HV. This indicates that further testing is required to optimize the additive manufacturing process and achieve the desired material properties.

Further testing is necessary to evaluate the corrosion resistance of parts made with additive manufacturing. While the method has the potential to produce components with good corrosion resistance, further study is still required to fully comprehend how these components would behave over time in challenging situations.

Heat treatment is one method that may be utilized to increase the Vickers hardness of items made with additive manufacturing. To change a part's microstructure and properties, it must be heated and cooled under controlled conditions. Metals can be strengthened, made harder, and more resistant to corrosion with this method.

There are various measures that need to be followed in order to further this investigation. We must first finish the 3D scanning procedure, which was hindered by reflection and marker placement concerns. To ensure that the part can be scanned completely, we will look at alternative techniques.

The selectively laser-melted components will next undergo a heat treatment to increase their hardness, and after that, microhardness testing will be done to make sure they satisfy the industry standard of 380 HV. Additionally, we will evaluate the part's porosity levels to make sure they are within acceptable bounds (<0.5%).

Following the completion of these procedures, the part will be fully selectively laser melted. As a result, we will be able to compare the mechanical characteristics of subtractive and additive manufacturing processes and assess how well each technique works when producing functioning components.

We also intend to investigate how various design parameters affect the effectiveness and efficiency of the items produced by additive manufacturing. This can involve looking at how the final product's mechanical qualities are affected by layer thickness, build orientation, and infill level.

To summarize, additive manufacturing has the potential to transform industrial manufacturing, but more research is needed to perfect the procedure and produce the requisite material qualities. This entails examining how heat treatment might increase the Vickers hardness of the parts, adjusting the printing settings to minimize porosity, and evaluating the long-term corrosion resistance of additively made components. We can fully utilize additive manufacturing and produce parts with higher material characteristics and performance by addressing these issues.

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