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Bachelor thesis

Is the production of metal parts using fused filament fabrication technology a viable option for the navy?

by

Petter Bærvahr and Marte Teigen Gravem

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Preface

This thesis is a part of the requirements for the bachelor in military studies with specialization in leadership – Naval engineering at the Royal Norwegian Naval Academy. The work was started in September and the thesis was submitted in December.

The thesis was written during the Erasmus exchange program in Hamburg, Germany at the Helmut Schmidt Universität.

We would like to thank Univ.-Prof. Dr. -Ing. Christian Kreischer and Dipl.-Ing. Johannes Kemper at Helmut Schmidt Universität, for providing the 3D printing facilities we needed and all the support we could need regarding this.

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Also, we would like to thank our teacher Gisle Strand, who is always willing to help and guide us in the right direction.

Bergen, Royal Norwegian Naval Academy, 09-12-2021

Marte T. Gravem

Abstract

Additive manufacturing (AM) presents a possibility to enhance the endurance of the naval ships and their ability to conduct operations. This thesis aims to present the advantages and the challenges one faces with the production of metal parts through the 3D printing method fused filament fabrication (FFF).

Implementing AM techniques in various applications would make it necessary to establish standards to qualify and certify parts to ensure their reliability, especially under realistic cyclic loading conditions. A rotating bending fatigue test was therefore performed on test specimens printed in 316 stainless steel, with the intention of getting a rough S-N curve and identifying the printed material's endurance limit.

Fused filament fabrication is based on layer-by-layer manufacturing, and defects like poor adhesion, voids, porosity and shifted layers can occur. The defects can be difficult to notice and can lower the properties of the material drastically. Implementing FFF parts can therefore be difficult in industries where reliability and repeatability is crucial.

The printed specimens suffered from poor adhesion between layers and twisted during the sintering process which involves heat treatment. Due to limited time and resources, it was only possible to print five specimens. The results were very inconsistent, and some tests were deemed unusable. None of the specimens could withstand a lot of cycles. At most 58200 cycles at 23,7 MPa and 5700 cycles at 47,4 MPa, which is very little compared to for example stainless steel manufactured with selective laser melting, another AM method, which has an endurance limit of about 250 MPa.

The main impression of the technology is that there are many variables and parameters that can affect the quality of the metal prints, and the maturity of the technology is not at the level where it can offer reliability and repeatability. Nevertheless, it is a promising technology. An alternative would be to print parts in reinforced composites which is widely researched, and already a focus area in the Norwegian Navy. Selective laser melting is also a technology worth looking into for additive manufacturing of metal.

Keywords: Additive manufacturing, 3D printing, fused filament fabrication, rotating bending fatigue, 316L, microstructure

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Nomenclature

AM	Additive manufacturing
AISI	American Iron and Steel Institute
AMMA	Additive Manufacturing for Military Applications
ASTM	American Society for Testing and Materials
CNC	Computerized Numerical Control
CAD	Computer aided design
DLMS	Direct laser metal sintering
FDM	Fused deposition modeling
FFF	Fused filament fabrication
FFI	Forsvarets forskningsinstitutt (Norwegian Defense Research Establishment)
HSU	Helmut Schmidt Universität
MIM	Metal injection molding
PBF	Powder bed fusion
PDS	Printing debinding sintering
POM	Polyoxymethylene
SLM	Selective laser melting
SS	Stainless steel
STL	STereoLitography
WT	Weight, percentage
σ_b	Bending stress

1 Introduction

In a conflict, technological advantages have the potential to decide the outcome. To maintain a potent military capacity, it is therefore important to keep up with the technological evolution globally. To accomplish this, The Royal Norwegian Navy must investigate new forms for manufacturing and production that may enhance their ability to conduct operations.

The Norwegian naval ships are built in a small volume, with very specific demands regarding strength, weight, magnetic- and acoustic signature. Spare parts therefore often need to be specially made by the original manufacturer, which may come with a high cost and long downtime for the ship. In some cases, the original manufacturer has gone out of business, and parts must be specially produced by external producers. This challenge can be decisive in a critical situation. Because of globalization in recent years, the production of parts for ships has been spread over a vast number of countries, which result in its own set of challenges if an international conflict occurs. To solve this problem, one can either have spare parts in storage, or procure the necessary knowledge and tools to produce them independently.

1.1 Background

Today, additive manufacturing (AM) production of polymers is widely used by both hobbyists and professionals because of the ability to make parts fast and relatively cheap. This has made the technology very popular. A lesser used aspect is the production of AM metal parts, which requires more expensive machines and more difficult methods. Despite this, the production of AM parts is absolutely considered an interesting field of technology, because it widens the possibility for fast production of prototypes and spare parts.

One of the more accessible methods for hobbyists is the PDS method, meaning printing, debinding and sintering. Here the part is printed on a relatively standard polymer 3D printer, using the fused filament fabrication method (FFF). After printing, the part must go through a complex process called debinding and sintering. This process is usually carried out by a professional company.

Recently, additive manufacturing (AM) has started being considered a viable option for production of parts and spare parts in the Norwegian armed forces (Andås, 2020). AM has been tested for use in special forces operations, and aboard Norwegian frigates with success. Although, mainly with polymer printing. Additive manufacturing methods for metal parts is therefore a field that requires further investigations.

1.2 Task definition

This thesis experimentally investigates the production of metal parts using the fused filament fabrication (FFF) method, and its mechanical properties. It also includes a literature study on the state of the art of the metal FFF technology and alternative AM technologies, to discuss its viability for use in the navy. The fatigue behavior of the printed metal in correlation with the manufacturing technology, and the characteristics of defects in the microstructure was studied. The results will provide a basis/contribution for further assessments in relation to the procurement of AM technology for use on naval ships.

Is the production of metal parts using fused filament fabrication technology a viable option for the navy?

1.3 Method

To build an understanding of the state of the art in additive manufacturing, a study of literature took place in the early phase of the project. Informal interviews and consultations with scientists at Helmut Schmidt Universität, the Norwegian Defense Research Establishment, Royal Norwegian Naval Academy, and technicians at the company Fieldmade, working with AM, were conducted. Furthermore, the conference AMMA2021 was attended, where the state of AM technology was presented by multiple companies, giving good insight to what one can do with 3D printing as of today, and what might be possible in the future.

The process of printing the test specimens was commenced during the literature study. After printing, the specimens were measured, and preparations for the microscopic examinations were made. Then, the samples were sent to the company IGO3D for debinding and sintering. After debinding and sintering the specimens were sent to the Norwegian Defense Research Establishment (FFI), where they were tested for fatigue strength with a rotating bend fatigue test. The microanalysis of the green part, and the sintered metal was also conducted at FFI. When all tests were completed, results were compared to similar studies to validate the results.

1.4 Delimitations

Due to limited time and materials available, the experiments performed were limited to dynamic fatigue tests and microscope testing. In addition, the material's tensile strength and reaction to chemicals etc. would be of interest to study. It is also possible to print in several other metals, such as aluminum, copper, bronze and brass, but this thesis concentrates on 316 stainless steel.

The test specimens were limited in size and quantity, because of the sintering chamber size, the time and material needed. The debinding and sintering was done at an external firm and because of company policies, it was not possible to participate in this part of the process. This limits the insight to the process and the methods used.

The thesis will not focus on the costs of the materials and the machines. Material properties in relation to sample size and thickness will not be discussed either.

1.5 Structure

The thesis will be initiated with an introduction to different AM types to give the reader an understanding of the available technologies. Followed by the literature study which presents the theory that is relevant, and results from similar studies that have been performed on the matter. After the literature study, the method used for making, testing and analyzing the test specimens will be described. Then, results from the test will be presented, and discussed. Finally, our experiences with the technology will be used to discuss the feasibility of the FFF method to produce metal parts in the navy.

2 Theory

In this chapter the advantages and disadvantages of additive manufacturing in general will be described. Then, the technologies selective laser melting and fused filament fabrication will be presented. Lastly, the fatigue test is described.

2.1 Additive manufacturing

The development of additive manufacturing, commonly known as 3D-printing, started in the 1980s. It is based on building parts layer by layer by depositing discrete amounts of material at a time, from a three-dimensional virtual drawing. There is a wide array of different additive manufacturing (AM) technologies commercially available on the market, and ASTM (American Society for Testing Materials) International has catalogued them into seven groups; the binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (Shahrubudin, Lee, & Ramlan, 2019). Each of them has their own targeted applications, and it is therefore seldom debated which one functions better. The materials that are commonly printed include polymers, ceramics, metals, and composites.

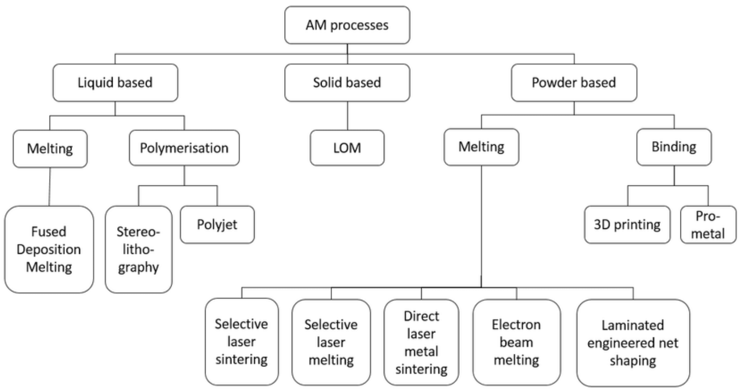

Figure 2.1-1 *Classification of additive manufacturing technologies based on Wong and Hernandez (2012)* **(Deradjat & Minshall, 2016)**

"Due to the prevalence of digital design tools in the past two decades, manufacturing technologies that significantly shorten the time from design to finished part have attracted much interest" (Thompson, 2019). Recent advancements in AM have lowered the prices, increased the level of quality, and allowed most people to start 3D-printing at home. This explosive development of the additive production technology in later years is due to some of the critical patents that expired in 2009, making the technology available to others than

the patent holders (Flathagen, Norberg, Nilssen, Nonsvik, & Nordmoen, 2016). AM is increasingly used in the production of open-source designs in the field of agriculture, architecture, aviation, transport, medicine, healthcare, clothing, firearms, construction, education and even in the food industry (Shahrubudin, Lee, & Ramlan, 2019).

3D printing provides the user with freedom of design and the ability to manufacture complex structure that machining, and metal injection molding may struggle with or may simply not be able to make. Additionally, it gives the user the opportunity to customize parts, print on demand, as well as reduce waste and be cost efficient. 3D printing is widely used to make prototypes, which is a considerable benefit, as it allows a fast iteration process and can shorten the time from idea to finished product (Flathagen, Norberg, Nilssen, Nonsvik, & Nordmoen, 2016). Furthermore, 3D printing enables the production of parts to be close to the consumer, allowing a more flexible and responsive process, as opposed to production techniques that rely on centralized manufacturing (Shahrubudin, Lee, & Ramlan, 2019) (Flathagen, Norberg, Nilssen, Nonsvik, & Nordmoen, 2016).

On the other hand, 3D printing is a new field of technology, especially additive manufacturing of metal parts. Therefore, the knowledge about the materials properties and limitations is limited. Also, since the technology is not widely used, machine costs and production costs are usually higher than for more conventional subtractive manufacturing techniques, like CNC machining. Some other disadvantages include restricted build size and warping due to thermal history, and that the process calls for a strict quality assurance system.

2.2 Selective Laser Melting

One of the more established technologies for metal additive manufacturing is Selective laser melting (SLM). This technology generally achieves better results than the fused filament fabrication printers, but the machinery is a lot more expensive.

In this process, fine metal powder is deposited on a build plate. Then, a laser beam melts the powder selectively until all the powder in that layer is melted together. After this, a new layer of metal powder is introduced on top, and the process is repeated until the desired part is finished. The printing process is done in an inert environment, usually by filling the building chamber with argon or nitrogen to prevent oxidation during the melting process. Variables like laser power, speed, layer thickness are optimized to make the layers fuse completely together.

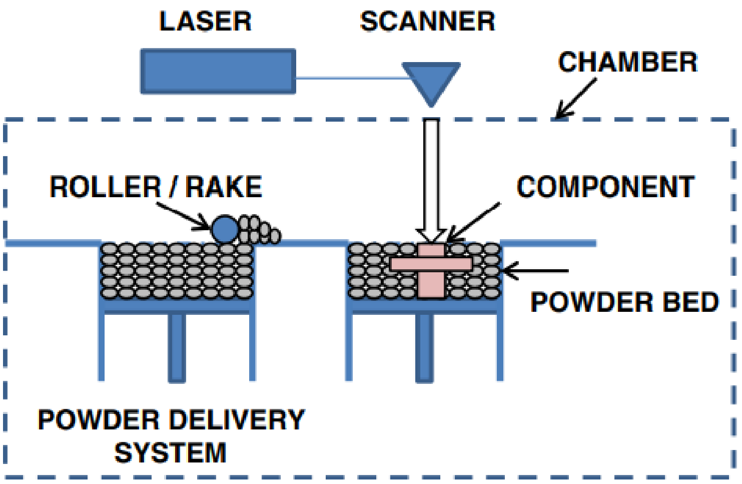

Figure 2.2-1 *The SLM process* **(Frazier, 2014)**

The quality of the print is dependent on the size of the metal particles. The resolution of the print becomes higher with smaller particles, but so does the chances of powder lumping together due to Van Der Waals forces. (Yap, et al., 2015) by optimizing machine parameters with particle size, it is possible to make parts with a very smooth surface. SLM can print many different materials, for example, titanium, 316L steel or aluminum. Although, changing the material can be a quite time-consuming process, because the old powder must be completely removed before one can print with another material.

After printing, the remaining powder is removed with vacuuming, shaking, or brushing the part. In some systems, this powder can be reused later after a process where the powder is shaken through a fine mesh in a vacuum. When the powder is removed, support structures and build plate can be detached from the part. After this, the part is ready for use, or eventually post processing for parts that require higher tolerances.

2.3 Fused Filament Fabrication

FFF uses a continuous filament, which is fed from a large coil, through a moving, heated extruder. The molten material is forced out of the nozzle, which is computer controlled to define the printed shape. The nozzle moves in two dimensions depositing one horizontal plane at the time (Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021). When 3D printing with metal-polymer composites, an appropriate build plate with heating is required. One also need a specialized hardened extruder nozzle in for example steel or ruby, and a cooling fan due to the higher temperature conductivity of the metal filament (Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021) (Roberson, 2021).

The advantages of fused filament fabrication are the low machine costs, the ease of operation and the uncomplicated change of filament material. However, the low geometrical precision and poor surface quality compared to selective laser melting or photo polymerization, for example, limit the field of application (Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021).

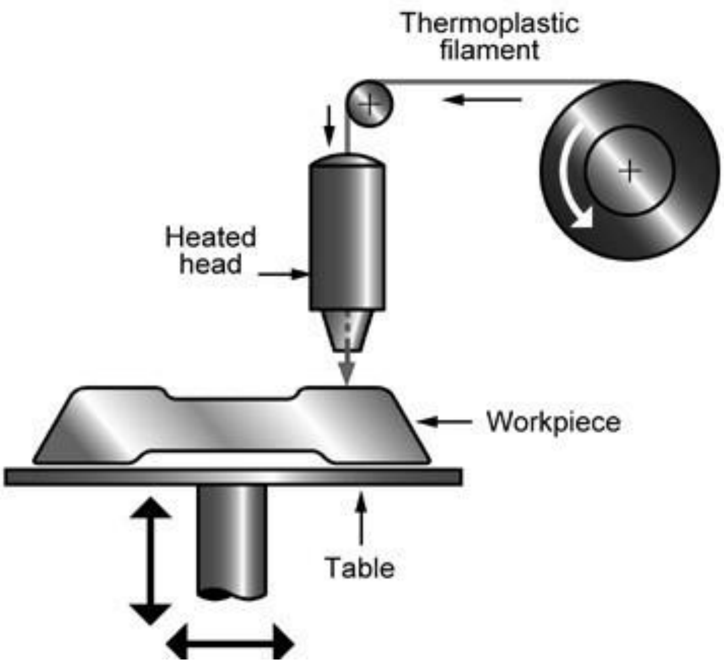

Figure 2.3-1 *The FFF process* **(Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021)**

Filament

The process of creating 3D printing filaments is called “compounding”. The raw material is first produced in the form of pellets, then mixed with additives to alter the properties and melted. When the mixture is dried, it is extruded with the desired width and wound on a spool. For the FFF method we print with thermoplastics, which are polymers that melt rather than burn when heated, can be shaped and molded, and solidify when cooled.

The Ultrafuse 316L filament used in this experiment, is made up of about 88%wt 316L metal powder. It is bound together by a polyformaldehyde POM-based binder system and an additive mixture consisting of polypropylene, dioctyl phthalate, dibutyl phthalate and zink oxide (Jiang & Ning, 2021).

State of the art

Investigations in recent years have been conducted on the processability, material and mechanical properties of FFF manufactured 316L stainless steel (Thompson, Gonzalez-Gutierrez, Kukla, & Felfer, 2019). Both macrostructures and microstructures of the sintered parts have been categorized relative to processing parameters, and shrinkage and density for fused filament fabricated 316L has been identified (Jiang & Ning, 2021). Gonzalez-Gutierrez et al. found that the decreased tensile strength in their 17-4 PH stainless steel was due to insufficient layer bonding. The study concluded that the debinding and sintering process (described in section 2.4 and 2.5) with its heating rates, operating temperature and the time in each stage were crucial for optimizing the mechanical properties.

Gong et al. has done a comparative research on microhardness and tensile strength with 316L made with fused filament fabrication and selective laser melting, and the results showed both less hardness and lower tensile strength in the FFF steel, due to coarser grains and porosity. They printed their FFF specimens in the same filament as used in this thesis, the Ultrafuse 316L, and below is the comparison with the SLM built specimens.

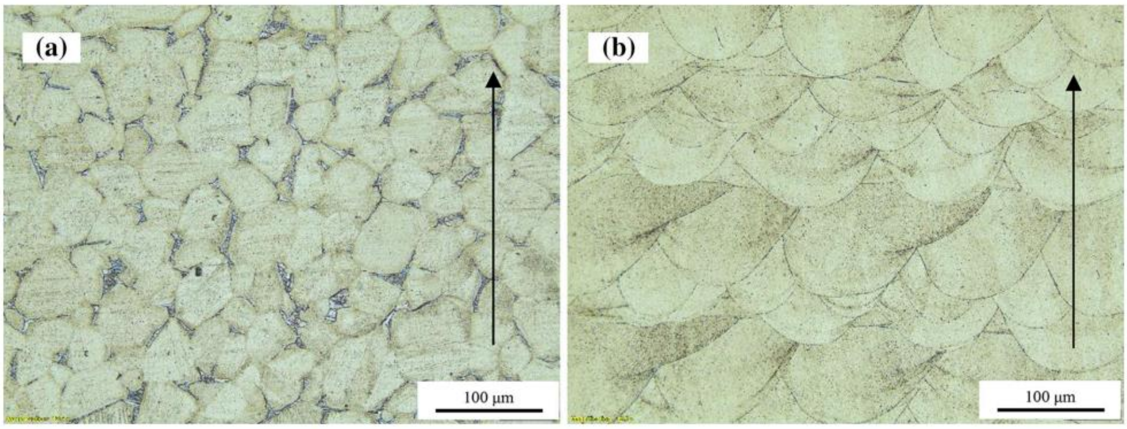

Figure 2.3-2 *Microscopy of Ultrafuse SS 316L (after sintering) and SLM SS 316 (arrows indicate build direction)* **(Gong, Snelling, Kardel, & Carrano, 2018)**

The inherent porosity of the Ultrafuse 316L, seen in figure 2.3-2, may deteriorate the ductility of the material (Gong, Snelling, Kardel, & Carrano, 2018). This is also concerning regarding the result of the fatigue test, as it could cause local stress concentrations in the material, ultimately ending in cracks and fracture. The results of the tensile tests, seen in table 1, indicates that the FFF SS (Stainless steel) 316L (referred to as FDM in the table) has lower yield strength, ultimate tensile strength (UTS) and elastic modulus than the annealed AISI type SS 316L and the SLM built SS 316. This can be attributed to its equiaxed grains and austenitic microstructure, which gives the material less plasticity. The SLM built specimens on the other hand, show high tensile properties due to grain boundaries with high dislocation density which blocks internal motion (Gong, Snelling, Kardel, & Carrano, 2018).

Table 1 *Tensile properties of SS 316 alloy* **(Gong, Snelling, Kardel, & Carrano, 2018)**

	FDM SS 316L	SLM SS 316L	AISI type SS 316L[a]
Yield strength (MPa)	167	541	205
UTS (MPa)	465	648	515
Elongation at break (%)	31	30	60
Young's modulus (GPa)	152	320	193

2.4 Debinding

Debinding is one of the three essential steps in producing metal parts with the FFF method. This is a thermochemical process where the polymer that binds the metal particles together gets extracted from the part. With the filament used in this experiment, the Ultrafuse 316L from BASF, debinding is done by exposing the part to gaseous nitric acid (HNO3) in an oven at 120 ˚C. The process time depends on how thick the object is. BASF states that the process time is 1-2 mm/hr. After debinding, the part is considered a "brown part", and is relatively porous. In this state, the metal particles are still held together by a small amount of polymer that will burn off during the first part of the sintering process (BASF 3D printing solutions GmbH, u.d.). The debinding process produces some formaldehyde which can react with oxygen. When the content of oxygen is over 4.5% this may cause an explosion. There is also a health hazard related to formaldehyde, as it may increase cancer risk (Kierulf & Langård, 2021).

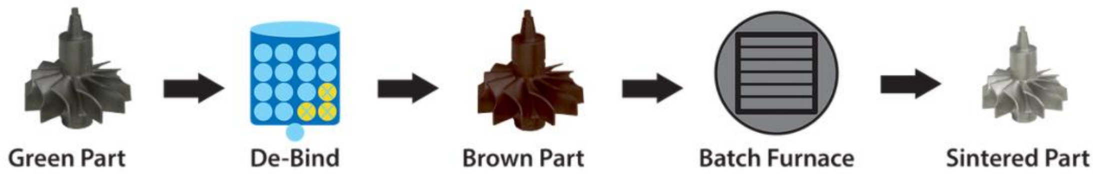

Figure 2.4-1 *Debinding and sintering process* **(Fine technology, u.d.)**

2.5 Sintering

Sintering is a process where the brown part becomes a denser solid metal part, by binding the metal particles to each other. This is achieved by introducing heat within 70 to 90% of the metals melting point and pressure in a pure hydrogen or argon atmosphere (Ziółkowski & Dyl, 2020). Hydrogen or argon is used to stop the metal from oxidizing. The sintering cycle described by BASF is going from room temperature to 600˚C with 5˚K/min, then hold it there for one hour. In this stage the remaining polymers and additives are burned off, according to other studies (Thompson, Gonzalez-Gutierrez, Kukla, & Felfer, 2021) (Jiang & Ning, 2021). After that stage, the temperature is increased from 600˚C to 1380˚C, then held for three hours, to densify the material into a solid metal part. Then, a cooling cycle takes place, this is not specified by BASF nor the other studies.

There are also other ways to sinter parts. In a study on metal FFF from 2019 (Thompson, Gonzalez-Gutierrez, Kukla, & Felfer, 2021) it was found that one can get similar results with sintering in a vacuum chamber. But with considerably lower heating rates of about 0.3˚ K/min. By doing the sintering in a vacuum, the dangers of operating with pressurized gas are avoided.

2.6 Fatigue testing

Fatigue is a type of failure that occurs when a material is subjected to a fluctuating dynamic stress situation, normally over a longer period. Stress can be applied as axial, flexural, and torsional stress, or a combination of them. There are three different stress-time modes that are possible. The stress can be applied with a reversed stress cycle, which is when the stress cycles between σ_{max} and σ_{min} in a sinus-wave pattern. The stress can also be applied in a repeated manner, where the maximum and minimum stress are unequally far from the zero-point. Finally, the stress can be applied randomly in frequency and magnitude (Callister & Rethwisch, 2011, s. 255).

Some materials have a fatigue limit when exposed to cyclic stress. The fatigue limit is the minimal stress level that can cause fatigue failure. Under this limit, fatigue failure should not occur. To determine the fatigue limit of a material, a series of fatigue tests are conducted at different stress levels until the test specimen runs to failure. The fatigue limit is usually set to the stress that the material can withstand for more than 10^6 to 10^7 cycles (British Stainless Steel Association, 2021).

For fatigue characterization of metallic materials, the most common loading is axial and rotating bending (Shrestha, Simsiriwong, & Shamsaei, 2019). In this thesis, a rotating bend fatigue test was used to test the material's properties. The rotating bending test machine exposes the test specimen to a fully reversed stress cycle with a sinus-wave pattern. As voids are coherently included in the printed part, because the FFF process cannot build fully dense samples, the expectations of the fatigue strength of the specimens were initially that they would not withstand a lot of cycles.

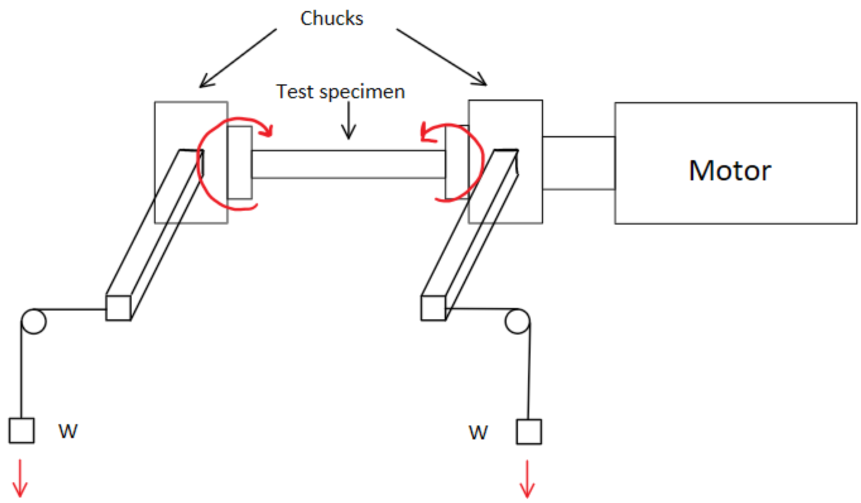

Figure 2.6-1 *Illustration of rotating bending test*

Testing the fatigue properties of the FFF built specimens is still important, as it is estimated that about 90% of all metallic failure is caused by fatigue (Callister & Rethwisch, 2011, s. 255). Despite this, few studies have been conducted on the fatigue properties of 3D printed metal.

3 Method

The way the literature study and experiment were conducted is described.

3.1 Literature study

To acquire the necessary knowledge on 3D printing and the FFF technology the thesis work started out studying relevant books, articles and completed experiments. This was essential to understand the FFF technology in an AM perspective. The professors at Helmut Schmidt Universität and the researchers at FFI could also refer to several academic sites and projects.

The 9th of November 2021 FFI (Norwegian Defense Research Establishment) hosted their fifth AMMA conference (Additive Manufacturing for Military Application). Among the speakers were representatives from the Royal Norwegian Navy, Stratasys UK, GE additive, the British Army, WiWEB from the German Armed Forces and the CEO of Fieldmade AS. Attending the conference helped to understand alternatives and possibilities for different technologies and presented good cases of what already has been done. It also presented a network of people who are already studying this field in depth and could answer a lot of questions.

Being at the conference and FFI also enabled a visit to the Norwegian company Fieldmades container-based units for 3D printing. Fieldmade is a company that delivers portable 3D printing solutions for operating in harsh environment conditions. They provide cutting-edge industrial additive manufacturing in high-demanding environments. Their unit NOMAD03 features a LASERTEC 30 SLM metal printer and can print in 316 steel and Inconel. The personnel at Fieldmade AS could also provide information about their experiences in exercises and operations.

3.2 Printing

The printing of the test specimens was done with the 3D-printer Ultimaker S5, fused filament fabrication machine. This is one of the latest versions of their desktop printers, and as the name implies it can be placed on any even surface. The metal filament was placed on a roller on the back of the machine, and the filament was fed through a tube leading it to the nozzle. A plastic sheet was glued to the printing bed to help the metal filament stick to the surface. The extruder was equipped with a ruby nozzle with 1,75mm input and 0,4mm output, and the Ultrafuse 316L filament had a diameter of 1,75 mm. The dimensions of the furnace that was used for the sintering process limited the part size to 100x100, even though the Ultimaker S5 can print up to 330x240x300 mm.

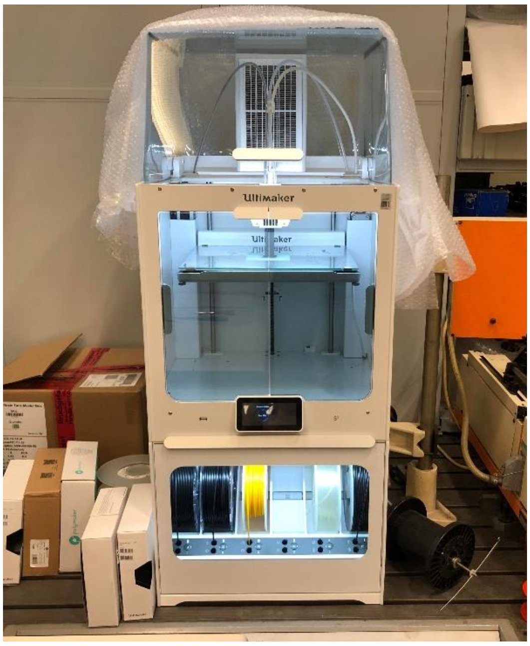

Figure 3.2-1 *Printer setup*

Figure 3.2-2 *Backside of printer with tubes for filament*

Solidworks was used to make the CAD (Computer aided design) 3D-drawings for the parts. Next, a STL-file was generated from the 3D-drawing, containing a code for the surface of the model approximated with triangles. Before printing, the STL-file was "sliced" using Ultimaker's own program Cura (version 4.6). This divides the file into hundreds of horizontal layers with printer instructions, including the necessary amount of material and the time required to print (Chakravorty, 2021). The information was then transferred to a GCode file and downloaded to a SD-card, in the native language of the 3D-printer, which can then be put directly into the printer.

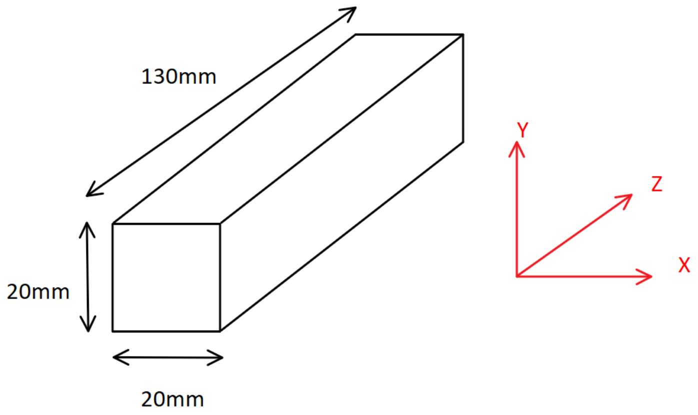

Figure 3.2-3 *Dimensions and direction of printed prisms*

The test specimens for the fatigue test were printed as 20x20x130 mm prisms in an upright position. As this was the first time printing metal with this machine there was simply not enough time to test different setups to be able to print the specimens laying down. This was done because of complications with warping during printing tests, but also because it is common to experience issues when making parts with gaps, support structures and angles. The parts were therefore later lathed to fit the test machine. The chosen measurements take the shrinkage during sintering into consideration, which was said to be 16% along the X/Z direction and 20% in the Y direction respectively. After some test prints the parameters used was the ones recommended for the Ultrafuse 316 L by BASF, shown in table 2.

Table 2 *Printing parameters*

Printing parameters	Values
Nozzle temperature	240 °C
Nozzle size	0,4 mm
Infill density	100 %
Printing speed	30 mm/s
Layer thickness	0,2 mm
Bed temperature	100 °C

3.3 Debinding and sintering

The debinding- and sintering process was done at an external firm called IGO3D because neither Helmut Schmidt Universität nor FFI had these facilities available. This left us out of an important part of the manufacturing, because the final properties and results are dependent on the thermal history which can cause macroscopic defects and undesirable microstructure (Thompson, Gonzalez-Gutierrez, Kukla, & Felfer, 2021). There are a lot of studies on how the debinding and sintering parameters can be optimized to achieve the best possible mechanical properties. The specimens, however, went through a standard process at IGO3D. The technicians there recommended to sinter the parts in the same direction as they were printed but did not recommend sintering the specimen standing upright because of the height to width ratio.

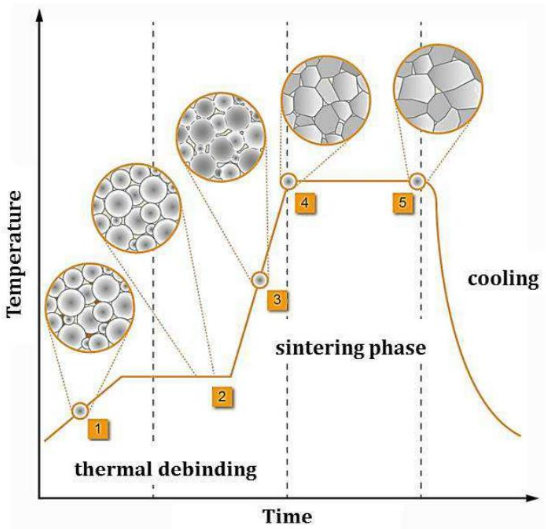

Figure 3.3-1 *Thermal debinding and sintering* **(Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021)**

3.4 Fatigue strength tests

The fatigue strength tests were conducted using a Amsler Rotary Bending Machine type ARBM 120, testing on rotating rods after ISO 1143-210 standard (See figure 3.4-1). The printed prisms were lathed into cylinders to fit the clamp standard, and for the rotating bending tests they were exposed to a range from 23,7MPa to 118,5MPa load at a speed of 5000 rpm.

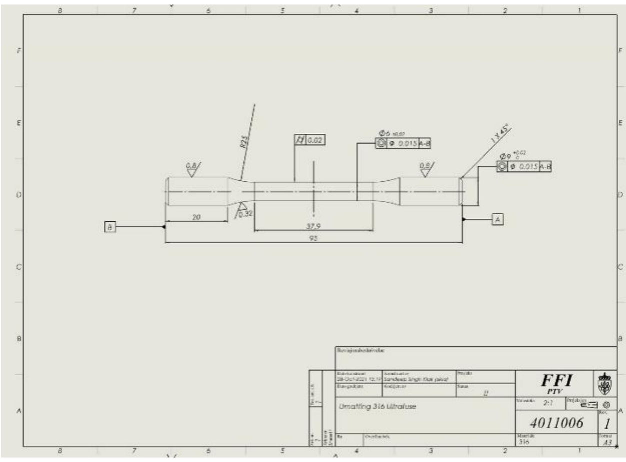

Figure 3.4-1 *Drawing for specimen ISO 1143-210 standard*

The bending stress was calculated with this formula:

$$\sigma_b = \frac{32 * F * L}{\pi * d^3} \; MPa$$

Formula 1 *Bending stress*

Where d is diameter of the specimen at the slimmest, F is the load on the arms in newtons, and L is the length of the arm applying the load.

Figure 3.4-2 *Amsler rotary bend machine*

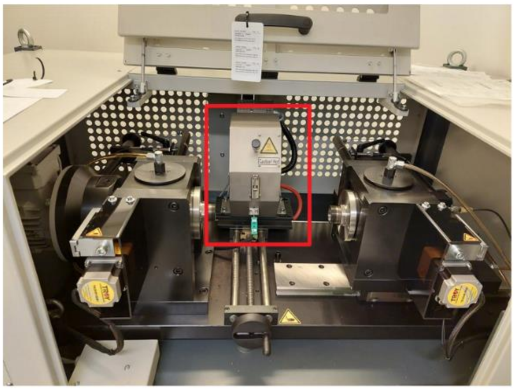

Figure 3.4-3 *Furnace marked in red*

Because of the specimen's small size, we had to remove the furnace which can be used to expose the specimens to a heated environment, marked with a red square in figure 3.4-

3, as it hindered the chucks from moving as close as needed. The specimen was then fastened, and the bending moment was applied by adding weights wired to the chucks as shown on picture 3.4-3.

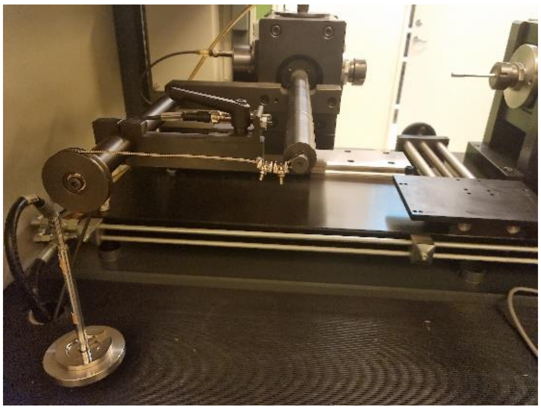

Figure 3.4-4 *Weights wired to apply bending stress*

Figure 3.4-5 *Placement of weights for bending moment*

3.5 Microstructural examination

The microstructural examinations were conducted using a Zeiss Stemi 2000-C Stereo Microscope, as well as using the camera on the telephone Samsung A52 through the microscope lens to take photos. We examined both the unprocessed green part and the sintered part.

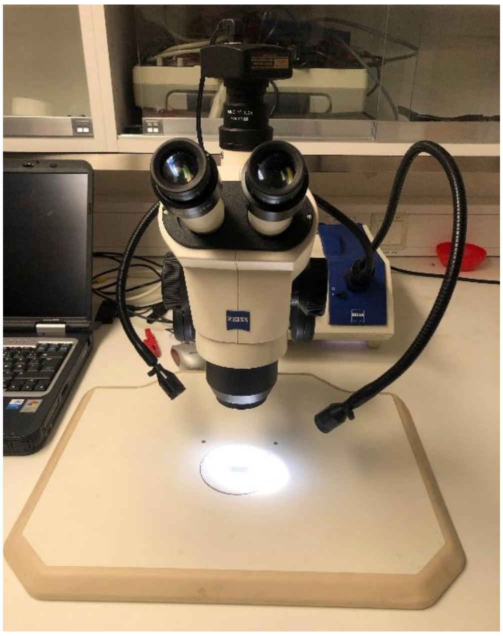

Figure 3.5-1 *The Zeiss Stemi 2000-C stereo Microscope*

In preparation for the microstructural examinations of the sintered part, one of the specimens was cut perpendicular to the printing direction. It was then sanded with a 1200 grid paper to reveal pores and internal structure.

4 Results

In this chapter, our experiences during the project and results from experiments are presented.

4.1 Printing

Printing

Multiple parameters were tested for printing the test specimens. The first tests were printed horizontally. This was unsuccessful because the printed sample started warping and delaminating from the glass plate it was printed on. This caused the extruder to move the sample around, making deposition of material in the right spot impossible. As one can see in figure 4.1-2. The warping is likely a result of thermally induced tension.

Figure 4.1-1 *Failed specimen 1*

Figure 4.1-2 *Failed specimen 2*

Figure 4.1-3 *Failed specimen 3*

A heated chamber and/or building platform, kept at temperatures below the material's melting point, but above room temperature promotes adhesion to the printed bed and reduces thermally induced stresses (Gonzalez-Gutierrez, et al., 2018). Therefore, this could probably be resolved with testing other printing parameters like higher bed temperature or higher infill rate. However, as the materials and time were limited, it was not possible to perform these tests. To counteract the warping, prints were performed upon a special printing sheet made of a heat resilient, clear polymer, as can be seen on figure 4.1-5. This sheet was then glued to the heated glass plate, with the intention of making the extruded material stick to the surface.

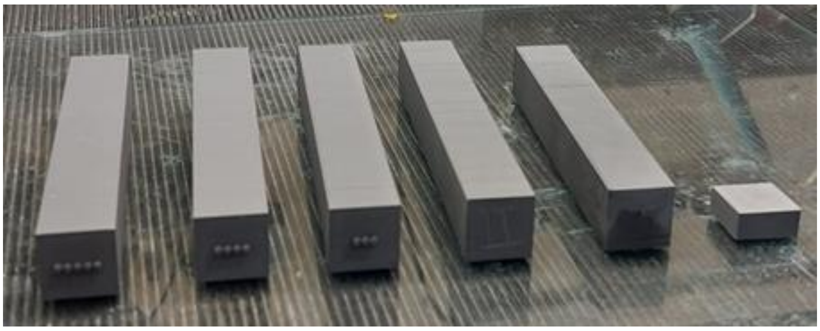

Figure 4.1-4 *All test specimens*

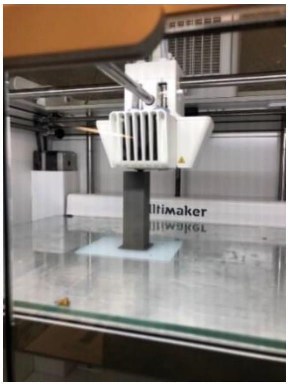

Figure 4.1-5 *The printing process*

Printed Material

After printing, the specimens were inspected and measured precisely. The printed material was heavy and seemed rigid. The surface showed clear signs of being printed, as it was rough and uneven. At the top of the specimen, small gaps between the strands could be observed (Figure 4.1-7). The five printed cylinders on top of the sample is the markings to differentiate the samples before and after sintering. The roughness of these cylinders may suggest that the geometrical deposition of filament is somewhat inaccurate when printing very small structures. This could possibly be improved with changing printing parameters, like the nozzle diameter, printing speed or temperature.

Figure 4.1-6 *Sideview of the cross section of specimen 5*

Figure 4.1-7 *Upper cross section of specimen 5*

4.2 Debinding and sintering

When the specimens came back from the external firm, they had twisted and warped during the sintering and debinding process. This is most likely because of the meshing algorithm, which rotated the printing layers in only one direction 45° for each layer. The temperature gradient caused by the slow subsequent layering of the material, might have reinforced the twisting. The temperature differences can result in shrinkage which again can lead to dimensional inaccuracies warping and displacement of the specimen during printing (Ziółkowski & Dyl, 2020). If the rotation of the layers had been alternating instead of going in one direction, the twisting might have been mitigated.

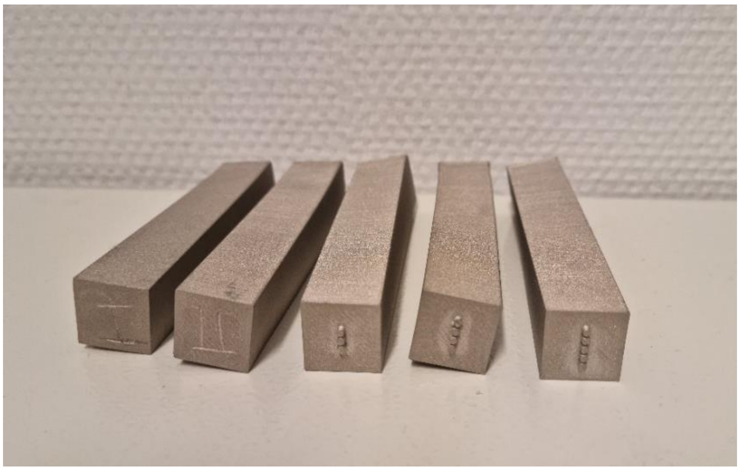

Figure 4.2-1 *Specimens after sintering*

The specimens all looked very symmetrical when in the green part state, but the state of the internal microstructures like for example inhomogeneous distribution of binder in the filament could also be a reason for the warpage (Cho, Park, Rho, & Park, 2019). During their study on warpage in powder injection molding manufactured parts, Cho et al. found that reducing the heating rates in both the thermal debinding and the sintering phase reduced the warpage.

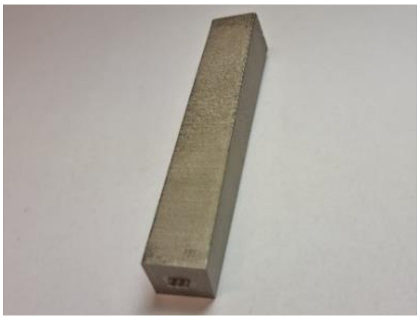

Figure 4.2-2 *Specimen 3 from above*

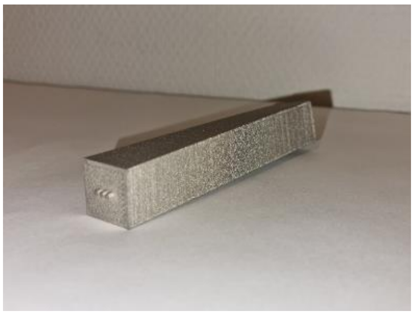

Figure 4.2-3 *Warpage in specimen 3 seen from the side*

After receiving the twisted specimens, the expected performance in the fatigue test was lowered due to the unexpected results and what effect it may have had on the internal structures.

Figure 4.2-4 *Sideview of specimen 3 after sintering*

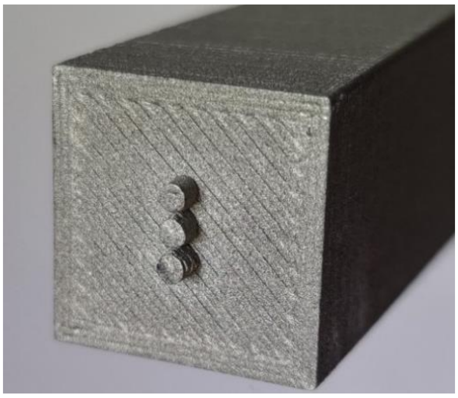

Figure 4.2-5 *Upper cross section of specimen 3 after sintering*

4.2.1 Shrinkage

After receiving the specimens from debinding- and sintering processing, they were measured again using a digital caliper, and the shrinkage was calculated. In average the shrinkage was approximately 15% in Y direction, 16,5% in X direction and 19% in Z direction (see table 2). This is due to the reduction of porosity and densification. Compared to the shrinkage percentage given by manufacturer of the filament BASF, this is 1,5% more shrinkage in X-direction and 1% less shrinkage in Z-direction. A possible cause of this could be the gaps between the deposited strands from the printing pattern. The fact that the shrinkage in Y direction matches with the length of the specimens is also caused to believe that they were in fact sintered up-right, even though IGO3D spoke against this.

4.2.2 Density

The density of the specimen was calculated with volume and weight, using the measurements taken after the fatigue test. The volume of the sample was measured by immersing the sample in water and measure the difference in weight of the water. Then volume was calculated by using the known density of water, and the difference in weight. Density was calculated to be 7,79 g/cm^3. BASF states that the density of the sintered material should be 7,85 g/cm^3, when measuring with the ISO 1183-1 standard (BASF, 2021). Given that our measurements are correct and sufficient compared to the ISO standard, the density differs 0,77%. This is a very small difference that could have been caused by the difference in measuring method, or a higher number of internal pores. If internal pores are the case, it could affect the fatigue properties of the specimen.

Table 3 *Measurements of the parts pre- and post-processed with shrinkage*

Specimen	**1**	**2**	**3**	**4**	**5**	**Average**
Length pre [mm]	119,9	129,56	129,56	129,58	129,55	
Length post [mm]	96,0	103,6	104,0	103,6	103,7	
Shrinkage Z [%]	19,73	20,04	19,73	20,05	19,96	**19,002**
Height pre [mm]	19,84	19,98	19,99	19,98	19,99	
Height post [mm]	16,84	16,84	16,89	16,88	16,86	
Shrinkage Y [%]	15,12	15,72	15,51	15,52	16,66	**15,01**
Width pre [mm]	20,07	20,06	20,07	20,07	20,07	
Width post [mm]	16,73	16,75	16,79	16,78	16,76	
Shrinkage X [%]	16,64	16,50	16,34	16,40	16,50	**16,48**

4.3 Fatigue test

Out of the five test rods, only three of the tests were completed conventionally. The reliability of the results of the fatigue tests are therefore clearly affected by the small quantity of test specimens.

The initial intention with the tests was to get data that could be used in a S-N diagram. Therefore, the load was varied throughout the test. However, complications during testing changed the strategy, as the samples reactions differed a lot from expectations. The first specimen was exposed to 2 N of load, which translates to 47,4 MPa in bending stress. Because of the early fracture in the first test, the second specimen was tested at 1 N and 23,7 MPa. The third specimen got tested at 5N and 118,5 MPa, the fourth at 2 N and 47,4 MPa, and fifth at 1 N and 23,7 MPa. In retrospect it would have been better to test all the specimens with the same load to check for dissimilarities in the specimens. This will be commented on later.

Table 4 *Fatigue testing results*

Sample	Number of cycles	Load	Stress [MPa]	Diameter [mm]	Remarks
1	5700	2N	47,4	5,99	
2	58200	1N	23,7	5,99	
3	1900	5N	118,8	5,99	Sample bent, triggering stop-switch before fracture.
4*	12100	2N	47,4	5,99	Result not reliable due to sample slipping and abnormal stop of machine
5	32100	1N	23,7	5,99	

Specimen 1

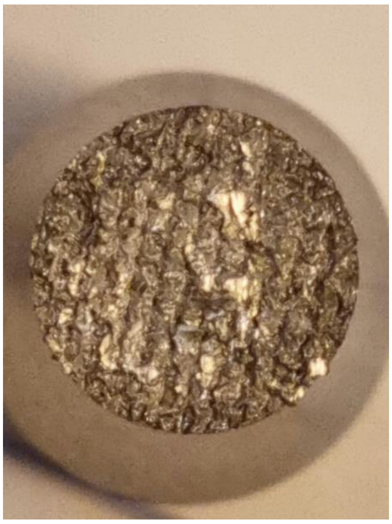

Figure 4.3-1 *Fracture surface of specimen 1*

The first specimen fractured after 5700 cycles with a bending stress of 47,4MPa.

Even though the printed steel was easy to process and looked like conventionally produced steel after machining, the provoked fracture surface shows clear signs of the specimen being printed. The printing pattern is visible as parallel lines, and it seem like that strands and layers have not fully melted together.

Specimen 2

The second specimen was exposed to a bending stress of 23,7MPa and fractured after 58200 cycles. The fracture surface show signs of better adhesion between the printing layers than of specimen 1.

Figure 4.3-2 *Fracture surface of specimen 2*

Figure 4.3-3 *Specimen 2 after test*

Specimen 3

Figure 4.3-4 *Specimen 3 after test*

The third specimen bent while exposed to 118,5 MPa in the test machine, this caused the arm holding the weights to trigger the stop switch before fracture.

This gives reason to believe that the load was too high for the sample. Which might imply that bad adhesion between the layers can affect the ductility of the material.

Specimen 4

Figure 4.3-5 *Fracture surface of specimen 4*

Due to specimen 3 bending at 118.5 MPa, the load for specimen 4 was reduced back to 47,4 MPa. However, the results for specimens 4 were deemed unusable due to the sample slipping in the chucks as well as the machine having an abnormal stop before restart. The warning lamps for oil temperature and problems with the oil pump lit up during the test.

Specimen 5

Figure 4.3-6 *Fracture surface of specimen 5*

Specimen 5 was exposed to 23,7 MPa and fractured after 32 100 cycles. The printing pattern is also slightly visible as lines going vertically on the fracture surface in figure 4.3-6.

4.4 Microstructural Analysis

4.4.1 Green part

After closer examinations with a microscope, it is clearly visible that the printing process has created some gaps in the material of the green part. Both internally and on the surface. From the examination of the green part, it is expected that the test rods will not endure a lot of loading and bending stress due to the stress concentrations that will occur at these gaps.

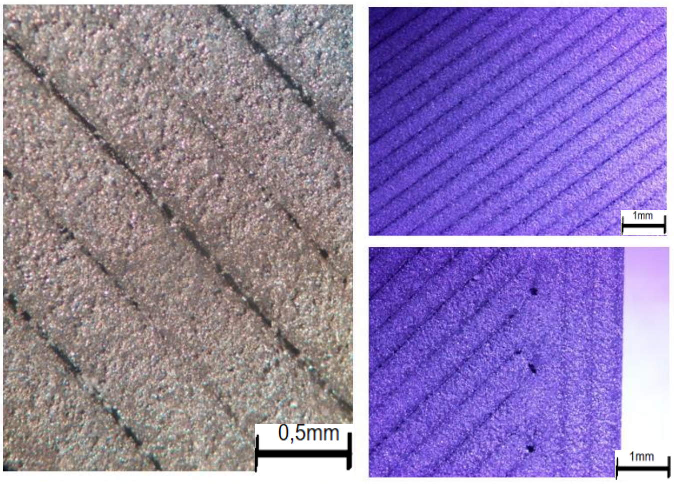

Figure 4.4-1 *Gaps in the printing pattern of the green part*

It is expected that the level of adhesion between some of the layers of the print will be insufficient after sintering, because of the gaps in the green part. It is also possible that there is some residual binding material that has not been properly removed during debinding, and this will cause the finished part to not withstand as much load and fatigue.

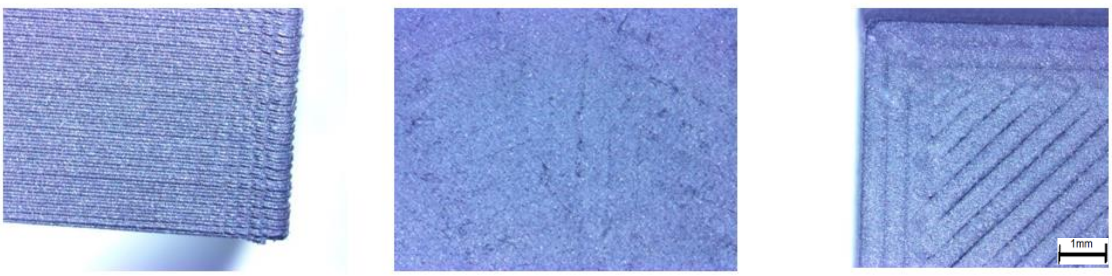

Figure 4.4-2 *Left: The layers in Z-direction makes an uneven surface Middle: After grinding the internal printing patterns and gaps are still visible Right: Printing pattern of corner of specimen*

4.4.2 Sintered part

The microscope picture shows the X-Y plane one centimeter inside the specimen from the end of the specimen. Here, a clear formation of voids can be observed in figure 4.4-3. The voids formations are visible as parallel white lines in the X-Y plane. This shows that the voids have formed in gaps between the strands of extruded material that were created during printing and seen in the green part.

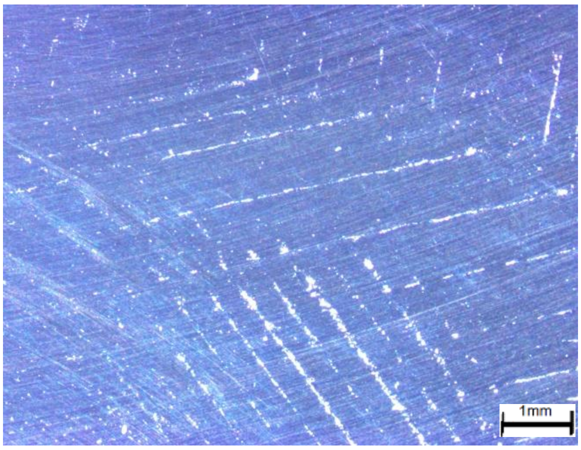

Figure 4.4-3 *Microscopic picture of sintered part*

The pore formations can be seen going in multiple directions in the same plane. This is likely due to the that the cut was made some degrees away from perpendicular to the Z-axis, which makes multiple layers of filament visible.

5 Discussion

In this chapter the results from the experiments will first be discussed. Secondly, the feasibility of the fused filament fabrication technology as a solution for the navy is discussed. Lastly, it is debated whether selective laser melting could be a good alternative for additive metal production.

5.1 Results and method

Fatigue

Results from the fatigue test shows that metal produced with BASF Ultrafuse 316L withstands very few fatigue cycles. In this case, the specimens could at most withstand 58200 cycles at 23,7 MPa. This is low compared to the industrial standards of 316L, which is around 270 MPa (British Stainless Steel Association, 2021). The test results were also inconsistent, making it pointless to create an S-N curve. The inconsistency of the results indicates that the process has a lot of unknown variables that affect the outcome.

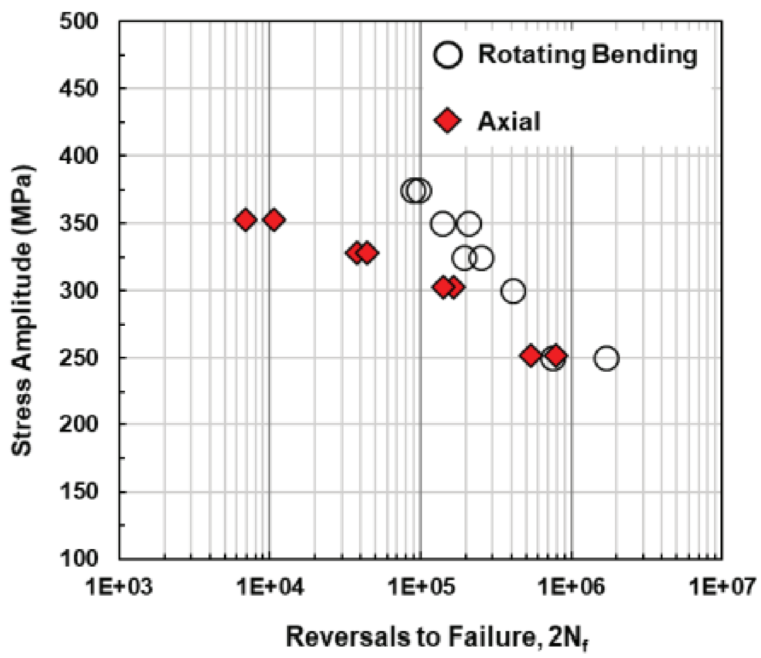

Figure 5.1-1 *Axial- and rotating bending fatigue test results for LB-PBF manufactured 316 steel* **(Shrestha, Simsiriwong, & Shamsaei, 2019)**

Figure 5.1-1 shows the results of a study on the fatigue life of selective laser melting manufactured specimens. They were subjected to rotating bending- and axial loading, and the experiment was done by Shrestha et. al. They tested on as-built parts, meaning that no surface treatment was done after printing. Their conclusion was that all the cracks in the specimens were initiated at the surface, where the maximal bending stress appears in a bent cylinder (as seen in figure 5.1-2). After the fracture surfaces was examined with a microscope, they found that the layers from the AM process caused micro-notches on the surface which may have been the driving factor in the fatigue failure of the parts.

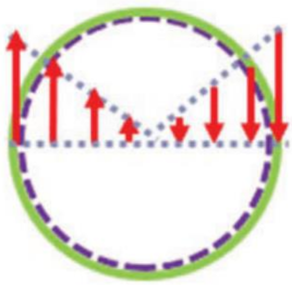

Figure 5.1-2 *Distribution of bending stress in cylinder* **(Shrestha, Simsiriwong, & Shamsaei, 2019)**

When comparing the results of the axial loaded SLM specimens from Shrestha et al.'s experiments (marked with red diamonds on figure 5.1-1) to the results from the same test preformed in Jiang's studies on the FFF manufactured specimens (table 5), it is very clear that the axial fatigue strength in the FFF manufactured specimens is much lower than the SLM manufactured. Fracture occurs already at 10^4 cycles at 120 MPa loading in the FFF specimens, while the SLM specimens are not even tested at loadings under 250 MPa. This is of course a different type of loading than the one tested in this thesis, but the material properties are related. If the material was homogenous and without defects, tensile and flexural strength would have been the same, but as tensile stress is equally distributed over the cross section the tensile strength suffers more from defects and is consequentially usually lower than flexural strength.

Table 5 *Results of axial fatigue test on FFF produced 316 steel* **(Jiang & Ning, 2021)**

Stress level	Test method	Number of cycles to failure
120 MPa	Tensile	1.05×10^4
100 MPa	Tensile	1.04×10^5
80 MPa	Tensile	$>10^6$

When comparing these results to ones for axial fatigue strength on AISI SS 316, the results are similar to the ones presented in section 2.3. The SLM manufactured SS 316 shows greater fatigue life than both the AISI SS 316 and the FFF SS 316. The AISI SS 316 has an endurance limit of about 150 MPa, the SLM SS 316 250 MPa and the FFF SS 316 80MPa roughly.

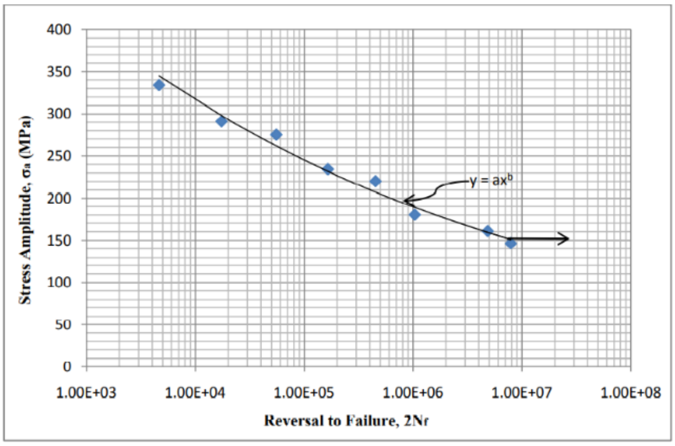

Figure 5.1-3 *S-N curve of AISI SS 316*
(Mohammad, Ali, Sahari, & Abdullah, 2012)

Lastly, looking at the results from Jiang et al.'s result from the flexural fatigue test on the FFF built specimen, it does show greater fatigue strength for flexural fatigue than for axial. The specimens did not even fracture at 120 MPa (table 6). The FFF technology is still in its early stages for metal production, and there is therefore not a lot of literature or research comparing properties with parts constructed with traditional manufacturing methods or other AM techniques. In this thesis we could not get to any loading close to what Jiang et al. exposed their test specimens to, and this probably because of the printing direction, which will be discussed below.

Table 6 *Results of flexural fatigue test on FFF produced 316 steel* **(Jiang & Ning, 2021)**

Stress level	Test method	Number of cycles to failure
150 MPa	Flexural	1.37×10^5
120 MPa	Flexural	$>10^6$
100 MPa	Flexural	$>10^6$

Printing orientation and layer direction

When the samples were printed, complications with printing horizontally, mentioned in section 4.1.1 made it only possible to print vertically with the timeframe given. By printing in this direction, the sample consists of many fine layers printed in the same plane as a fracture surface usually occurs during a rotating-bending fatigue test. The chances of a fracture occurring from an insufficient lamination between layers is therefore greater than if the samples were printed horizontally, where the layers would be perpendicular to the fracture surface.

Examples of the layering directions effect on mechanical properties can be seen in a study from Kurose et al. Their tensile strength test specimens were printed in three different layering directions and two different thicknesses, as seen in figure 5.1-4. The results from the tensile strength test showed that the layer directions had a significant influence on the mechanical properties. Only the specimens printed in the layer direction parallel to the tensile test direction exhibited poor mechanical properties, and the highest strength were obtained in the parts with layer direction perpendicular. The difference in tensile yield strength was as big as 300MPa between the T-specimen and L-specimen (see figure 5.1-5).

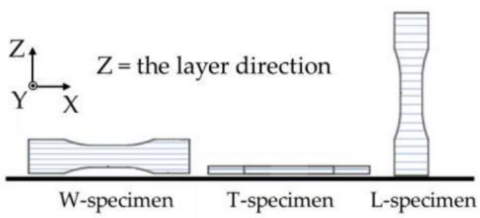

Figure 5.1-4 *Different layering directions* **(Kurose, et al., 2020)**

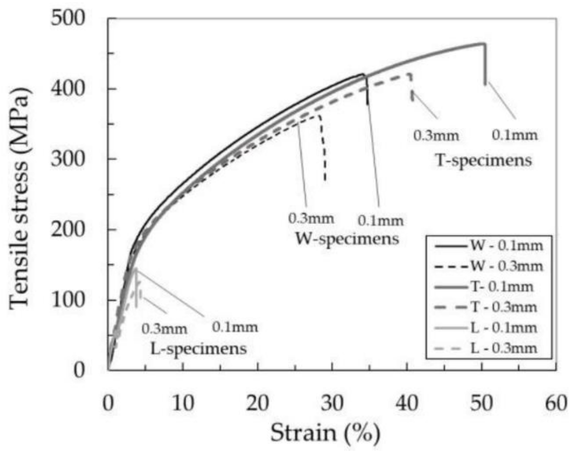

Figure 5.1-5 *Tensile stress-strain curve of specimens with different layering directions* **(Kurose, et al., 2020)**

Several other studies support this, and among them are Tosto et al.'s study on the difference between 316L steel and 17-4P steel manufactured with fused filament fabrication.

The graph in figure 5.1-6 shows the stress-strain curve of their 316L specimens, which were printed in the same filament used in this thesis, the Ultrafuse 316L filament. The blue curve is for a specimen printed upright and the red is for one laying down. The specimens printed up-right displayed the lowest values with a yield strength of 113,75 MPa, compared to 148,01 MPa for the ones printed flat (Tosto, Tirillò, Sarasini, & Cicala, 2021). For the record, none of specimens showed the mechanical properties stated by BASF for the Ultrafuse 316L filament.

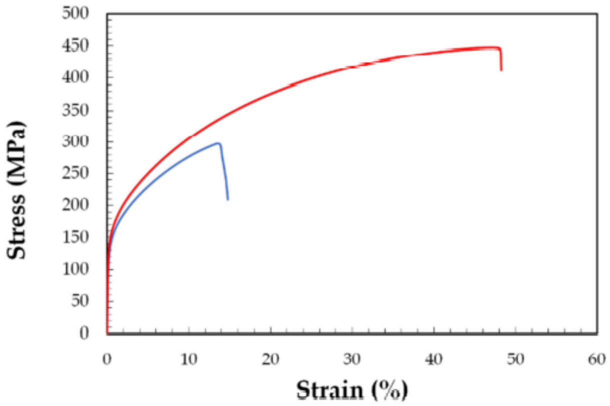

Figure 5.1-6 *Tensile stress-strain, blue: up-right, red: flat* **(Tosto, Tirillò, Sarasini, & Cicala, 2021)**

In their study, Jiang et al. specified the importance of considering the relationship between loading direction and the printing direction before applying PDS-built components. The printing orientation also effects mechanical properties, and two studies from Vălean et al. and Kiendl and Gao tested toughness and strength relative to the strand layup. This is regarding the angle of the strands in the printing pattern. The tensile strength test shows the same results as the ones on layering direction mentioned above.

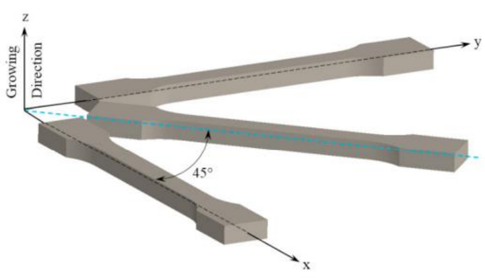

Figure 5.1-8 *Different printing orientations* (Kiendl & Gao, 2019*)*

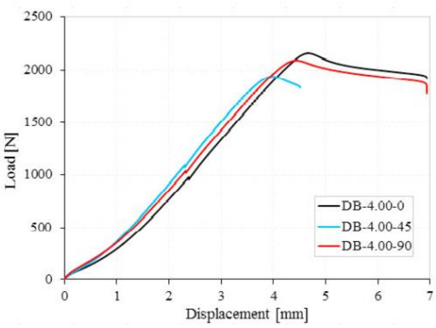

Figure 5.1-7 *Stress-strain curve of specimens printed with different orientation* **(Kiendl & Gao, 2019)**

That is, that the specimens with strands in parallel to the loading direction showed the best results. Printing upright has already proven not to be a good choice but choosing the right printing orientation can also be deciding for fatigue life when printing laying down. It is important to take such variables into consideration already in the design phase of PDS-built parts, and this was not considered prior to printing the specimens in this thesis.

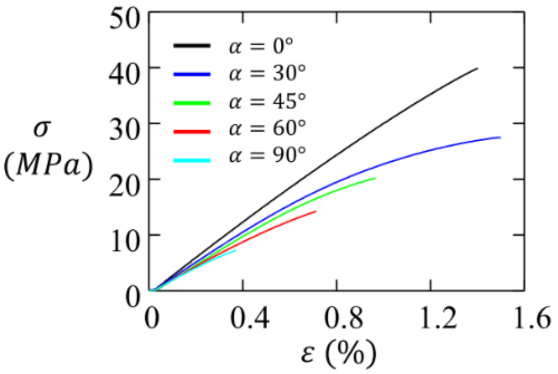

Figure 5.1-9 *Stress-strain curve of specimens with different printing orientation* **(Văleana, et al., 2020)**

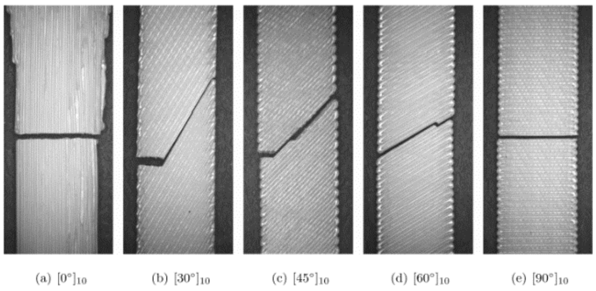

Figure 5.1-10 *Fractures of specimens with different printing orientation* **(Văleana, et al., 2020)**

Microstructure

"*The measured fracture strengths for most materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies*" (Callister & Rethwisch, 2011). This is due to microscopic cracks or flaws in the materials microstructure. The size, orientation and number of cracks and flaws severely affects the strength of the material, because flaws and cracks can cause stress concentrations which further can induce crack growth.

When producing a part with fused filament fabrication this is especially relevant since it has been reported that the production method suffers from insufficient lamination between layers or impurities introduced during printing. Tosto et al. did a microscope examination of the Ultrafuse 316L after printing and observed the same voids between the strands as was seen in this thesis. Despite the full sintering cycle the cross section of their dogbone-shaped specimen printed flat, also exhibited micro porosity and voids (figure

5.1-11). It is thought to be a result from the incomplete fusion of the strands observed in the green part (Tosto, Tirillò, Sarasini, & Cicala, 2021). Gong et al. also printed with the Ultrafuse 316 and measured 1,5% of residual porosity, contrasting their selective laser melting prints which were fully dense (pictured in figure 2.3-2).

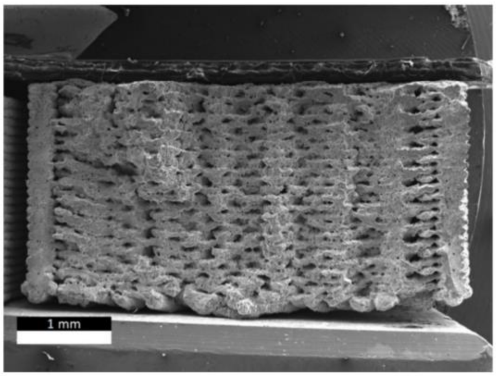

Figure 5.1-12 *Cross section of dogbone specimen printed flat* **(Tosto, Tirillò, Sarasini, & Cicala, 2021)**

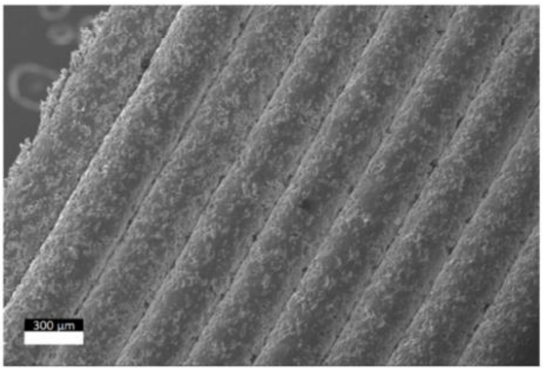

Figure 5.1-11 *Microscope picture of green part in Ultrafuse 316L* **(Tosto, Tirillò, Sarasini, & Cicala, 2021)**

This could possibly have been reduced by changing some of the parameters. As described by Thompson et al., a higher extrusion multiplier factor could have made the sample denser and prevented the observed gaps in the surface. In their study they used an extrusion multiplier of 105% which may have contributed to a microstructure with less defects. This is supported by Godec et al., who optimized printing parameters for tensile properties of FFF manufactured 17-4P steel. When increasing the extrusion multiplier, it resulted in more compact specimens because the deposited strands were better connected and overlapping, reducing the voids. This is what had the strongest effect on the tensile properties.

It is clear that the quality of the print is highly dependent on printing parameters, and therefore the operator's skill. This also applies for the debinding and sintering, as the heating rates and final temperatures need to be adjusted precisely to avoid defects that were not present in the printed green part (Thompson, Gonzalez-Gutierrez, Kukla, & Felfer, 2021).

Surface roughness

The specimens in this thesis were lathed and were not tested as-built. Consequently, the defects in the material causing the fractures must be internal. It is therefore believed that the cause of the fracture is pores or poor layer adhesion. For parts that are as-built the surface will be a critical aspect of its fatigue strength.

As mentioned, the surface roughness presents a challenge for FFF produced parts, and the condition of the surface is particularly important when subjected to bending loads. The surface properties of the FFF printed parts are not yet satisfactory without after treatment if the part is going to be used for surface-critical applications. Burkhardt et al. has investigated different surface treatments in the green state and found that laser polishing is the most feasible surface treatment method. A combination of green part printing and surface polishing procedure in one print head is therefore under development (Burkhardt, Freigassner, Weber, Imgrund, & Hampel, 2021).

On the other hand, the green part state presents the opportunity to treat the surface when the part is still soft enough to easily cut, sand or polish. Jiang et al. wrote that the most effective way to enhance the fatigue properties of their printed 316L would be to reduce the number of surface pores by different surface finishing technologies.

Shrinkage

The shrinkage in the test specimens was significantly different from the percentages stated by the manufacturer of the filament. The inaccurate anisotropic shrinkage makes the FFF printed metal not suitable for parts where tolerances are crucial. Trials should therefore be conducted before production to optimize the final shape. Also, applying layer by layer relatively slow will cause a temperature gradient in the manufactured part and shrinkage, which may lead to dimensional inaccuracies, warping, displacement during printing and cracks (Ziółkowski & Dyl, 2020). All of which was observed during this experiment where the shape retention of the specimens was very poor.

Sources of error

Due to some of the choices made regarding the manufacturing of the test specimens the reliability of the results can be questioned. The results do not showcase the potential of metal production using the fused filament fabrication, more so, they demonstrate the many variables in material properties that are dependent on a skilled operator.

Printing orientation and pattern was not considered prior to manufacturing, and ultimately this resulted in twisting in the specimens. The layering direction was also crucial to the specimen's performance in the fatigue test and printing up-right would not been done if the time would allow it.

The specimens were not tested as-built and were lathed to fit the test standards. This altered the original surface to a much finer surface. The effects of surface roughness, which usually affects crack growth, are therefore not displayed in the results of the fatigue test. Experiences with printing parts that needs support structures are also not included.

In hindsight, it would be better to conduct all tests with the same load, and look for difference in results, rather than attempting to create a S-N curve, because of the number of specimens. The samples reacted very differently compared to each other, and the fracture surface differed a lot, even for the specimens tested at the same load.

Even though all specimens were printed with the same parameters and went through the same debinding and sintering process, the displayed different results. This leaves the question whether unknown parameters affect the material. Like placement in the oven during debinding and sintering, or humidity and temperature during printing.

Furthermore, the specimens that only endured a small number of rotations are likely to have a high margin of error. This is because the fatigue testing machine applies load only when the rotation has reached the set speed, but the odometer will still count the rotations before load is applied.

5.2 Feasibility of FFF technology

During the AMMA conference the representative from General Electric (GE) claimed that between 2011-2019, over 50% of all US military aircrafts did not meet their mission readiness goals because of hard to obtain spare part. The global maritime group Wilhelmsen has also commented on the state of the maritime industry in an article about their collaboration with Thyssenkrupp on 3D printing; "*Based on current data the maritime industry spends billions of dollars every year on spare parts; with 50% of these vessels being older than 15 years, availability of parts are limited. This makes fulfillment of orders for maritime spare parts costly and complicated, and in fact, the supply chain overheads involved may often far outstrip the cost of the part itself. Moreover, traditional manufacturing processes such as machining and casting often involve long lead-times stretching into months.*" (Wilhelmsen, 2020).

A lot of the participants at AMMA argued that the lead time is more important than prices in a military context, and that 3D printing could be a good alternative to reduce the lead time. As previously discussed, the main advantage with AM is the possibility to produce geometrically complex parts in a relatively short time. Additionally, it would be possible to make the latest updated version of a spare part "instantly" as designed by the producer (Green ship of the future, 2017). This technology has the potential to reduce downtime for ships and reduce the dependence on external manufacturers, when in need of spare parts. Given that the products have a good enough quality to replace the original part.

For use in a naval context there are some requirements for fire, smoke, and toxicity properties that the 3D printing facilities and the printed material needs to meet due to the harsh environment, and safety being the priority. The maritime industry is based on old, reliable techniques, and implements new solutions very carefully. Additionally, shipbuilding in general face high classification requirements, and technologies that guarantee repeatability and quality is therefore needed (Ziółkowski & Dyl, 2020). Several standardization agencies, such as American Society of Testing and Materials (ASTM) international, are actively involved in the development of guidelines to qualify and certify AM parts with optimal mechanical properties under various loading conditions (Shrestha, Simsiriwong, & Shamsaei, 2019).

As earlier mentioned, the FFF material can contain a lot of defects such as poor adhesion, voids, porosity, warping, and twisting that can affect the material properties drastically. This makes it hard to guarantee reliability and repeatability, as could be seen in this thesis in the printed specimens after sintering. The development of regenerated parts that is no longer manufactured is not yet mature enough to be widely used and is still in an experimental state (Ziółkowski & Dyl, 2020). As a result, the question of whether the printed part is a permanent or a temporary solution is therefore raised.

Regeneration of emergency parts will enable the continuation of short-term operation with temporary solutions, before reaching the shipyard for more permanent repair. For use in the navy, it is also important to take the conflict state into consideration, that is if it is a state of war or peace. Parts that are subject to failures from the ship's operation specifically, are often dependent on requirements of classification societies (Ziółkowski & Dyl, 2020). During war time on the other hand, it would be possible to go outside of these requirements in critical situations if the risk is accepted by the captain of the ship.

The material quality of the printed part is not the only challenge, but the 3D printing itself poses some difficulties regarding onboard manufacturing. These include limited space, the high humidity environment, high sea states, vibrations onboard and the effects of temperature fluctuations, which can differ a lot due to seasons, time of the day or geographic position. The printer must be calibrated and positioned to ensure high quality results, and the personnel operating the printer must be properly trained (Ziółkowski & Dyl, 2020). For the FFF technology it also includes the debinding- and sintering furnace, which additionally will hold high temperatures and gasses that need proper storage.

Implementing 3D printing facilities for occasional use onboard may not be economically justified, and one could reconsider the need for the printer to be onboard the ship. The benefits of 3D printing could still give valuable outcome when placed on land, and the disadvantages of carrying the facilities onboard could be avoided. Also, the personnel at the workshops in the bases have a high level of understanding of materials and technical skills.

This experiment, though it is lacking in many areas and not of statistical significance, gave an impression of the manufacturing method, and academic research and conversations with experts in this field widened the impression. Though the FFF technology is used broadly in the field of additive manufacturing, the production of metal parts is still relatively new. And even though it may seem as simple as to plug in your 3D drawing, the finished part may not have the mechanical properties needed.

There are several areas of optimization that can improve the FFF technology. For example, the development of improved simulation tools with the ability to predict mechanical properties of printed parts by knowing material properties, processing parameters and build strategies. Moreover, a simulation program for the debinding and sintering process could allow optimization before printing. A monitoring system that can stop the printing and adjust processing parameters could reduce the number of defects in the printed parts (Gonzalez-Gutierrez, et al., 2018). This could also reduce the number of attempts before getting a successful print, as we struggled with.

Surface roughness is also, as mentioned, one of the downsides of the FFF technology. This could be resolved by developing mechanisms to smoothen the surface of the strands when deposited, additionally lessening the need for aftertreatment (Gonzalez-Gutierrez, et al., 2018). Advancement in the binder system for filaments, making them easier and faster to remove, for example using water as solvent, could also improve the manufacturing method. To achieve a reliable metal manufacturing process with fused filament fabrication there are areas in research and development that should be improved.

When optimizing the process, metal manufactured with the fused filament fabrication method show good results. Thompson et al. writes in their paper that their printed steel show deflections similar to conventionally manufactured stainless steel at lower strength. Jiang et al. also concluded in their study on fatigue strength that post processing with surface grinding and heat treatment could extend the fatigue life. The PDS process could be a promising technique for production of metal parts with further research and development.

Though steel and other metals hold several properties that are beneficial and critical for many parts onboard a ship, there are composites with great material strength that can replace a lot of metal parts. Printing in nylon and then reinforcing the part with for example carbon fiber, Kevlar or glass fiber, would result in a part with very high mechanical properties and the ability to bear heavy loads. The materials are also relatively cheap and the FFF machines show great results printing with composites.

Markforged has published the results from their test with different reinforcements. They claim that their nylon composite reinforced with carbon fiber showed ten times greater strength than the pure nylon one. And as shown on the graph below, it exhibited even better strength than the aluminum alloy 6061-T6 (Ziółkowski & Dyl, 2020).

Figure 5.2-1 *Different reinforcements done by Markforged* **(Ziółkowski & Dyl, 2020)**

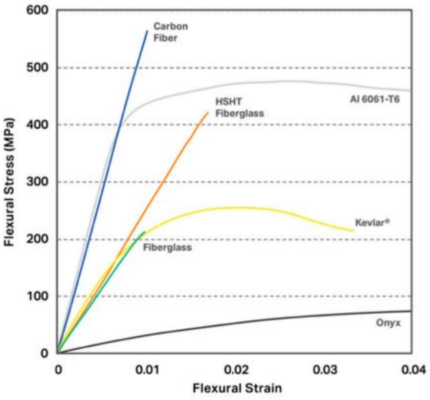

Figure 5.2-2 *Tensile stress-strain curve for different reinforcements* **(Ziółkowski & Dyl, 2020)**

Printing with reinforced composites is already a focus area in the Norwegian Navy, printers have been bought, and operations and tests have been conducted. The technology has been found to make good use in the special forces, and the representatives at AMMA from Stratasys UK, the Bundeswehr and Fieldmade had the same experience, especially in terms of customized equipment. The Norwegian minesweepers have also had troubles with marine life in their seawater intake, and printed filters have helped reduce this problem.

Printing composites would likely be the most feasible way to implement fused filament fabrication onboard ships as of today. Parts like for example handles, fixtures, covers, gaskets, washers, and O-rings could easily be produced in composites. NAVSEA (Naval Sea Systems Command) of the US Navy is reporting having 182 approved 3D-printable parts in their database, and more than 600 parts undergoing engineering reviews (NAVY LIVE, 2020). The US Navy is also going to install over 25 Stratasys F900, one of the biggest polymer printers on the marked, within the next five years as a part of a 20-million-dollar contract (Griffiths, 2021). Several other countries are also looking into the possibilities that 3D printing gives.

5.3 Alternatives for metal production

There are many good AM alternatives to producing metal parts with the FFF method. One of the more promising technologies in metal AM is, as earlier mentioned, selective laser melting (SLM). Multiple companies have had success with using SLM in later years, also for fatigue critical parts. One of these are General Electric Additive. According to the head of sales in GE that spoke at AMMA2021, they have successfully made parts for high load scenarios. One example was additive made turbine blades for a jet engine. These are exposed to multiaxial dynamic loading, which proves that it is possible to achieve good mechanical properties with using SLM manufacturing.

Although SLM produces good results, the process may be more demanding than other methods, as there are many variables that needs to be controlled to achieve a good outcome. This makes the equipment for SLM very complex, and therefore also the required knowledge to operate the machine more advanced. The handling of the printing powder also demands personnel with competence because of the health risks related to the powder.

With SLM there is no need for debinding and sintering. Which is a process that is both energy and time consuming. This makes SLM able to produce parts faster than FFF technology. There are also fewer possibilities of human error with SLM, as there are less steps that need involvement of the operator. The CEO of Fieldmade also stated that the furnaces needed for sintering contain a lot of fragile components that might not survive the stresses caused by transportation through rough seas.

With SLM, the user can make many different metals with the same machine. Some of these are: steel, aluminum alloys, brass, copper alloys and titanium alloys. (Ziółkowski & Dyl, 2020). Although, compared to changing materials in a FFF printer, the process is a quite time consuming and complex. To change materials in a FFF printer, you only need to change the filament and extrude material for a few seconds to clear out the nozzle. To change materials in a SLM system, one must clean out all the old powder from the system. This is especially important when changing between two metals that can react with each other. According to the representative for FFI at AMMA2021, changing the printing material in their SLM machine takes around 8 hours. This varies, as it only takes 2 hours with the Lasertec 30 used at Fieldmade (lasin, 2021).

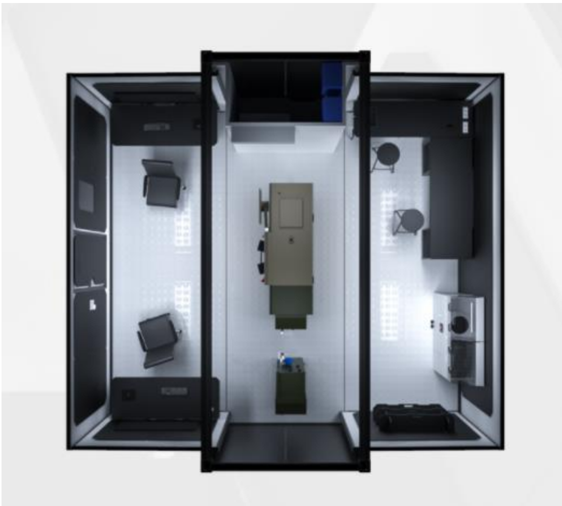

Figure 5.3-1 *Fieldmades container solution NOMAD 03* **(Fieldmade, 2021)**

SLM can also be used for repairs on damaged parts by printing on top of it, making the technology very useful regarding repairs on corroded components as it is possible to add material where the corrosion has taken place. Nevertheless, there are still some challenges that needs to be farther examined. One of these is whether or not SLM equipment can print when exposed to the movement and vibrations that occur on a ship. As seen with the NOMAD 03 concept delivered by Fieldmade, it is possible to compact a SLM system into a relatively small, portable system. Fieldmade has achieved placing a LASERTEC

30 SLM machine in a standard 40ft container together with all support systems needed for cleaning the part of accessory powder after printing, and powder recycling. According to a technician at Fieldmade, the container solution has been through tough testing, that consisted of driving the container around in tough terrain and unloading the container at steep angles. Fieldmade also states that the container can be transported by air, sea and land (Fieldmade, 2021). Therefore, it would be possible to put the system on a naval ship. And although it may prove impossible to print during transit, the SLM system would still be useful when the ship is in port.

6 Conclusion and recommendation for further investigation

6.1 Conclusion

Due to the limited amount of data and the inconsistent results it is not possible to draw any statistically significant conclusions. Nevertheless, some interesting observations have been made regarding different parameters effects on the final results.

The impression gotten from the experiment and discussions with experts in the additive manufacturing field is that the maturity of the fused filament fabrication method for production of metal parts is not at a level where the products are reliable. Nevertheless, it is a promising technology, and will probably reach both reliability and repeatability in the future.

A good alternative is to focus on reinforced composites, which show great strength and can carry heavy loads. The Norwegian Navy has already invested in several printers for composites and making them a part of a naval exercise would help to map out the parts which are possible to regenerate.

If the Norwegian Navy was to procure metal additive printers as of today, the selective laser melting printers could be a good alternative. It is an established technology showing results with great mechanical properties but is a considerable expense as the machines are advanced and expensive.

6.2 Recommendation for further investigation

Before investigating further into the fused filament fabrication technology for metal manufacturing specifically, it would be wise to do a profound analysis of parts on naval ships that are possible to construct or regenerate using additive manufacturing in general. The parts should then be prioritized based on criticality, typical lead times and availability of the spares in question. After such an analysis, the material needed for the parts should be decided based on what types of loading it would be subjected to, and the required strength and properties. Then, the suitable technologies could be chosen. As mentioned early in the thesis, all the different AM technologies have their targeted application.

This has already been done to an extent with FFI and Fieldmade, but a more targeted and larger project would surely speed up the process. Placing one of the NOMAD-containers from Fieldmade on KNM Maud during a naval exercise can be one way to get results for such analysis. Purchasing polymer and composite 3D printers and placing them on different ships could also help to map out the areas where printing technology could be feasible, as well as increase awareness and interest in the manufacturing method within the crews.

References

Andås, H. E. (2020). *Emerging technology trends for defence and security.* Norwegian Defence Research Establishment (FFI).

BASF. (2021, 11 22). *Ultrafuse_316L_Technical_Data_Sheet_TDS.* Retrieved from ultrafusefff.com: https://www.ultrafusefff.com/wp-content/uploads/2019/07/Ultrafuse_316L_Technical_Data_Sheet_TDS.pdf

BASF 3D printing solutions GmbH. (n.d.). *Metal filaments*. Retrieved from Ultrafuse® 316L Process instructions: https://forward-am.com/wp-content/uploads/2021/01/Process-Guidelines-Ultrafuse-316L.pdf

British Stainless Steel Association. (2021, 12 02). Retrieved from org.uk: https://bssa.org.uk/bssa_articles/fatigue-properties-and-endurance-limits-of-stainless-steels/

Burkhardt, C., Freigassner, P., Weber, O., Imgrund, P., & Hampel, S. (2021, January 14). Fused Filament Fabrication (FFF) of 316L Green Parts for the MIM process. *World PM2016 – AM - Deposition Technologies.*

Callister, W. D., & Rethwisch, D. G. (2011). *Materials Science and Engineering Eighth Edition.* John Wiley & Sons.

Chakravorty, D. (2021, September 1). *All3dp.com*. Retrieved from STL (3D Printing File Format) – All You Need to Know: https://all3dp.com/what-is-stl-file-format-extension-3d-printing/#pointone

Cho, H., Park, J. M., Rho, J., & Park, S. J. (2019, October 25). Warpage of Powder Injection Molded Copper Structure. *Metals and Materials International*, pp. 1131-1137.

Deradjat, D., & Minshall, T. (2016, October 4). Implementation of Rapid Manufacturing for Mass Customisation. *Journal of Manufacturing Technology Management*.

Fieldmade. (2021, 12 5). *Fieldmade.no*. Retrieved from Filedmade.no: https://fieldmade.no/nomad03/

Fine technology. (n.d.). *Metal injection molding*. Retrieved from http://www.metalparts.net/metal-injection-molding

Flathagen, J., Norberg, C. D., Nilssen, J. R., Nonsvik, G., & Nordmoen, J. H. (2016). *Additiv produksjon av prototyper og reservedeler i felt.* Forsvarets forskningsinstitutt.

Frazier, W. E. (2014, April 8). Metal Additive Manufacturing: A Review. *Journal of Materials Engineering and Performance*, pp. 1917-1928.

Gong, H., Snelling, D., Kardel, K., & Carrano, A. (2018, November 2). Comparison of Stainless Steel 316L Parts Made by FDM- and SLM-Based Additive Manufacturing Processes. *Crossmark*, pp. 880-885.

Gonzalez-Gutierrez, J., Cano, S., Schuschnigg, S., Kukla, C., Sapkota, J., & Clemens, H. (2018, May 18). Additive Manufacturing of Metallic and Ceramic components by the Material Extrusion of Highly-Filled Polymers: A Review and Future perspectives. *Materials MDPI*.

Green ship of the future. (2017, 12 14). *Maritime industry leaders are addressing the challenge of 3D print and IP rights*. Retrieved from https://greenship.org/maritime-industry-leaders-are-addressing-the-challenge-of-3d-print-and-ip-rights/

Griffiths, L. (2021, September 3). *U.S. Navy to install 25 Stratasys F900 3D printers over next five years*. Retrieved from tctmagazine: https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/polymer-additive-manufacturing-news/u-s-navy-install-25-stratasys-f900-3d-printers-over-next-five-years/

Jiang, D., & Ning, F. (2021, April 1). Additive Manufacturing of 316L Stainless Steel by a Printing-Debinding-Sintering Method: Effects of Microstructure on Fatigue Property. *ASME Journal of Manufactoring Science and Engenieering* .

Kiendl, J., & Gao, C. (2019, October 25). Controlling toughness and strength of FDM 3D-printed PLA components through the raster layup. *Composites part B*, pp. 1-6.

Kierulf, P., & Langård, S. (2021, oktober 20). *Store medisinske leksikon* . Retrieved from https://sml.snl.no/formaldehyd

Kurose, T., Abe, Y., Santos, M. V., Kanaya, Y., Ishigami, A., Tanaka, S., & Ito, H. (2020, May 29). Influence of the Layer Directions on the Properties of 316L

Stainless Steel Parts Fabricated through Fused Deposition of Metals. *Materials MDPI*.

lasin. (2021, 12 01). *LASIN*. Retrieved from fs.uni-lj.si: https://web.fs.uni-lj.si/lasin/en/novi-3d-tiskalnik-kovin/

Mohammad, K., Ali, A., Sahari, B., & Abdullah, S. (2012). Fatigue behavior of Austenitic Type 316L Stainless steel. *International Conference on Mechanical Engineering Research 2011*. IOP Publishing.

NAVY LIVE. (2020, December 1). *U.S. Navy Accelerates Uptake of 3-D Printing for Spare Parts*. Retrieved from https://www.maritime-executive.com/editorials/u-s-navy-accelerates-uptake-of-3-d-printing-for-spare-parts

Roberson, D. (2021, May 6). *Ultimaker.com*. Retrieved from Learn: What filaments can be used for 3D printing? (ultimaker.com)

Shahrubudin, N., Lee, T., & Ramlan, R. (2019). An Overview on 3D Printing Technology: Technological, Materials and Applications. *Sustainable Materials Processing and Manufacturing 2019.* Johor, Malaysia: Elsevier.

Shrestha, R., Simsiriwong, J., & Shamsaei, N. (2019). Comparison of Rotating-Bending and Axial Fatigue Behaviors of LB-PBF 316L . *Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference*, (pp. 515-521).

Thompson, Y., Gonzalez-Gutierrez, J., Kukla, C., & Felfer, P. (2021, April 1). Fused filament fabrication, debinding and sintering as a low cost additive manufactoring method of 316L Stainless Steel. *Journal of Manufacturing Science and Engineering*.

Tosto, C., Tirillò, J., Sarasini, F., & Cicala, G. (2021, fabruary 5). Hybrid Metal/Polymer Filaments for Fused Filament Fabrication (FFF) to Print Metal Parts. *Applied Sciences MDPI*.

Văleana, C., Marşavina, L., Mărghitaş, M., Linul, E., Razavi, J., & Berto, F. (2020). Effect of manufacturing parameters on tensile properties of FDM printed specimens. *Procedia Structural Integrity 26*, pp. 312-320.

Wilhelmsen. (2020, September 28). *Wilhelmsen and thyssenkrupp step-up collaboration, establishing 3D printing joint venture targeting the maritime industry*. Retrieved from https://www.wilhelmsen.com/media-news-andevents/press-releases/2020/wilhelmsen-and-thyssenkruppstep-up-collaboration-establishing3d-printingjoint-venture-targetingthe-maritime-industry/

Yap, C. Y., Chua, C. K., Dong, Z. L., Liu, Z. H., Zhang, D. Q., Loh, L. E., & Sing, S. L. (2015). Review of selective laser melting : materials and applications. *Applied Physics Reviews*.

Ziółkowski, M., & Dyl, T. (2020, 12 12). Possible Applications of Additive Manufacturing Technologies in Shipbuilding: A Review. *Machines - MDPI*.