ADDITIVE MANUFACTURING

A study on the materialistic properties of Inconel and titanium fabricated through additive manufacturing.

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Abstract

Over the past decades, Inconel 718 and titanium 6Al4V have established their roles as prefered material in the gas turbine industry. Production of complex parts with these alloys using conventional production however is time consuming and expensive. With AM fabrication of metals developing fast, the possibilities for application in the repair or production of gas turbine parts grow. The aim of this research is to prove the capability of laser cladding, selective laser melting, and wire feed electron beam welding as suitable alternatives to conventional production using wrought material. All three methods show promising results, proving capable of producing material with minimum or near minimum material properties. Laser cladding and wire feed electron beam welding achieve good values in Inconel 718, whereas selective laser melting produces good values in titanium 6Al4V, indicating process experience to be a major factor. Defects and porosity are found in some samples, showing the neccessity of optimalization and quality control. KLM and the NLR are recommended to commit to further research, as well as to keep exchanging information on quality and material properties.

Acknowledgements

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Finally, a special thanks goes out to my parents, for supporting me unconditionally during a period that wasn't easy for them.

This research is dedicated to my late grandfather Wim Habers, who passed away during the last month of this research at the age of 95. He was had a lifelong passion for flying.

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LIST OF ABBREVIATIONS AND ACRONYMS

KLM	Koninklijke Luchtvaart Maatschappij, Dutch airline.
NLR	Dutch National Aerospace Laboratory.
GE	General Electric.
AM	Additive Manufacturing.
WFEB	Wire Feed Electron Beam, an additive manufacturing technique.
SLM	Selective Laser Melting, an additive manufacturing technique.
6Al-4V	6 Aluminum, 4 Vanadium. Titanium alloy composition.
OEM	Original Equipment Manufacturer.
CPH	Close-Packed Hexagonal, crystal structure.
BCC	Body-Centered Cubic, crystal structure.
B transus	Temperature above which all titanium is fully BCC structured
UTS	Ultimate Tensile Strength

1 INTRODUCTION

1.1 Problem statement

Over the past decade, the use of additive manufacturing processes, such as laser cladding, WFEB and SLM, has increased significantly. Application of these processes for the repair of gas turbine components has become more prevalent. Using AM to fabricate gas turbine parts offers the possibility to produce structurally complex parts with high accuracy, leading to lower overall production times. The mechanical properties of cast and wrought alloys typically used in gas turbine parts are well known. Properties of both the untreated and annealed states of Inconel 718 and titanium 6Al-4V have been researched and documented extensively. AM-processes generally involve a large amount of heat input, as well as a different cooling process than conventional methods of production, leading to altered mechanical properties. These properties have not been researched nearly as much as those of parts that were produced conventionally. Certain parameters in the AM-processes also have a significant impact on these properties, leading to varying mechanical properties in parts created with different parameters. Currently, only some repairs at KLM are performed using AM, due to the need for approval by the OEM. Most of these AM-repairs are done using the WFEB method, the others using laser cladding. No repairs are currently allowed to utilize the SLM method. Theoretically, AM could be a better alternative for some repairs that are currently being done using conventional production methods. However, in order to get OEM approval for these repairs, the mechanical properties of AM-produced parts need to be documented more extensively. Approval for repairs will only be given by OEMs when the mechanical properties of the particular AM-produced part and their consistency can be proven.

1.2 Research outline

Using the aforementioned three AM-methods, Inconel and titanium material will be built up in different orientations. This material will then be inspected for internal defects. After selecting the parts of material without defects, tensile testing rods will be fabricated out of both the AM-fabricated material and conventionally produced (wrought) material. Subsequently, half of the rods will be subjected to typical heat treatment. Tension tests and metallurgic research will be used to accurately determine their mechanical properties. The results gathered by analyzing the test parts will then be used to answer the following research questions:

Main research question:

What are the differences in mechanical properties between AM-fabricated and conventionally produced Inconel and titanium parts?

First sub question:

What are the differences in mechanical properties between parts produced with the individual AM-methods?

Second sub question:

Which repairs currently using conventional production would benefit from using AM production?

1.3 Report structure

This report will be structured around answering these research questions as accurately and completely as possible given the available data. The methodology that was used to gather the necessary data for this research is discussed first, along with the problems encountered during the research. Subsequently, the results of the research are presented and discussed. Next, the research questions will be answered and conclusions will be drawn. Finally, recommendations are made to KLM and NLR. The appendices will include all data gathered during the tests, as well as all images, tables and other items that were excluded from the main report.

2 METHODOLOGY

The tests that have been performed for this research were preceded by a significant amount of preparation. This chapter provides an in depth description of the boundaries and limitations of the research, as well as the steps that were taken to get to the end result. The problems that arose during production and processing are also discussed, as they play a role in the comparison between the methods, as well as in the applicability of the different AM-methods for certain repairs.

2.1 Boundaries and limitations

This subchapter addresses the boundaries and limitations that were set up for this project. These boundaries were created to ensure a profound and complete research, while keeping the amount of work feasible for the given time period of 17 weeks. The AM-methods that have been researched are laser cladding, WFEB-welding and SLM. Two alloys frequently used in gas turbine manufacturing and repair have been researched, namely Inconel 718 and Titanium 6Al-4V. In chapter 3 the compositions of these alloys are displayed. Compositional variations in the alloys were neglected. With the AM-methods mentioned above, test specimens were fabricated in two different orientations. Half of the specimens were built up horizontally, while the other half were built up vertically, as depicted in figure 1. In horizontal samples, the direction in which layers are built up is perpendicular to the direction of pulling during tensile testing, whereas in vertical samples, the direction of layer buildup is parallel to the direction of pulling. Testing rods made of conventionally produced material did not need to be produced in different orientations. The test specimens were subjected to tensile testing and microscopic analysis. While high temperature properties are important, tensile tests of the samples have only been performed at room temperature. The material properties of samples produced by these AM-methods were compared both to conventionally cast and wrought samples, as well as to each other. During tensile testing, the material properties that were researched are the 0.2% yield strength, ultimate tensile strength (UTS), Young's modulus, elongation at break and reduction of area. Fatigue characteristics have not been researched due to a lack of time. Microscopic analyses were only performed on untreated rods, as the differences in microstructure are clearer before heat treatment. Microscopic analysis will be limited to porosity of the specimens, grain size and grain orientation. A

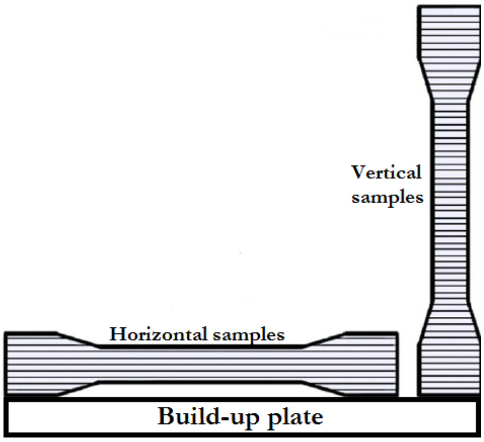

Figure 1 – Sample orientations

total of three rods have been tensile tested for each combination of method, material, orientation, and treatment. For each combination, one rod was microscopically analyzed.

2.2 Production of material

The material build-up characteristics of each AM-method are unique for each combination of production method, build-up orientation, and material. In this subchapter, a short description of the production method as well as its characteristics for the production of materials is presented. The difficulties encountered during the production are also discussed.

2.2.1 Laser cladding

The laser cladding (or laser metal deposition) production method relies on the use of a 1kW laser to create a melt pool. Using a conical cladding head, carrier gas supplies a steady flow of alloy in powder form. The powder is melted by the laser while being deposited on the melt pool. The cladding head is mounted on a 6 axis robot. The production of horizontal material was done by creating multiple parallel cladded tracks, forming a build-up of material roughly rectangular in shape. This rectangular shape was built up until beam shaped parts with an adequate height were formed, and they were removed from the build-up plate. For the vertically produced material, square bars were built up on a build-up plate. The removal of the built-up material from the base plates proved a rather time consuming process. The horizontally produced material was produced in single batches, meaning the material for the different tensile rods had to be taken out of this single piece. This was done using a computer controlled circular saw. Because of the costs of the materials and the machines involved in

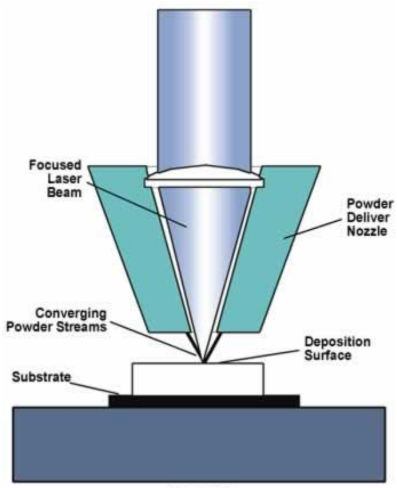

Figure 4 – Laser cladding process

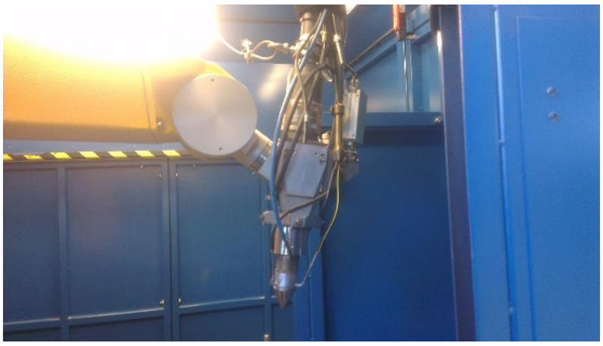

Figure 5 –Laser cladding head

Figure 2 – laser cladding, 0.7 mm track distance

Figure 3 – laser cladding, 1.2 mm track distance

the production, the amount of material supplied was also minimal, meaning the tolerances for separating the single block were very low. While producing the vertical titanium 6Al4V material build-up, consistency in thickness of the cladded layers was difficult to achieve. The reason for this is that the macros used for the robot have not yet been optimized for the production of vertically orientated parts. In combination with the unpredictable nature of the deposition of powder material, this caused the middle part of each layer to be significantly less thick. In order to achieve the best possible results from the laser cladded results, different parameters were first tested. Using different distances between cladding tracks as well as different laser intensity settings, laser focus distances and shielding gasses, samples were produced for microscopic analysis. Figures 2 and 3 show some of the microscopic images taken from these samples, in this case with different track distances (0.7mm and 1.2mm). After these tests were completed, the production using laser cladding was started. The laser cladding of Inconel did not bring up any issues, as it is the material KLM has the most experience with so far. Titanium production, however, proved to be a bigger challenge than previously anticipated. The material showed a tendency to be distributed unevenly. Depending on the chosen parameters, the material build-up height would be larger on either the start or end section of the cladding tracks. A good example of this can be seen in figure 8. The smaller bar sections on the back of the first build-up plate are severely slanted. Once this slanting has started to happen during the build-up, it is virtually impossible to correct it, and a new bar must be started. For the horizontally built-up material this issue was not too severe, as the required build-up height is significantly lower than for the vertically produced material. Even with tested parameters, it took several weeks to reach a stadium in which enough material could be built up to reach the required length of the tensile rods. Aside from the direct and major impact this

Figure 6 – Horizontally laser cladded Inconel

Figure 7 – Vertically laser cladded Inconel

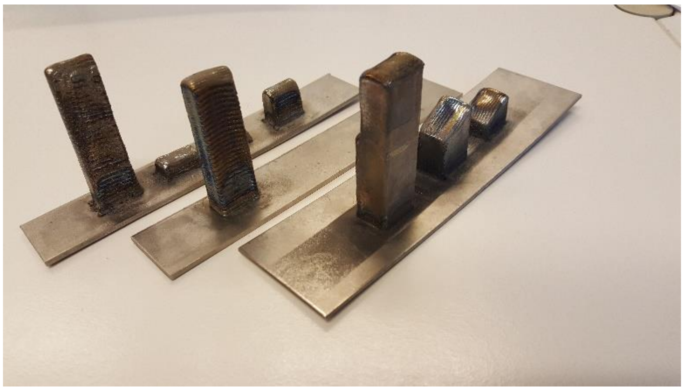

Figure 8 – Vertically laser cladded titanium

had on the time schedule of the research, it also had some consequences for the machining of the material, which will be discussed in the corresponding subchapter. The length of the production period for both the Inconel and titanium material had several causes and effects. The causes were first and foremost the difficulty in achieving the correct parameters for the production of (especially vertical) material. Secondly, as KLM's engine shop is always a hub of activity, a steady flow of production jobs and repairs had to be performed by KLM's single laser cladder and its operator. This left little room for planning the production of each batch, as the time necessary to get the production right was unknown. Finally, the production could only be done with some, in some cases even only one sample at a time. With a production time of several hours per batch or sample and the previously mentioned difficulties in achieving proper build-up, this added even more to the delay during the production phase. The effects of this were, firstly, that the production was severely spread out over time, meaning that most of the other steps in the production process of the tensile rods (machining to 9 millimeters, x-ray analysis and machining to final dimensions) had to be performed several times. Secondly, the heat treatment of the rods had to wait until the very last batch of material was produced in early December 2016 and went through the subsequent steps.

2.2.2 WFEB welding

Material build-up using WFEB welding relies on a concentrated beam of electrons to create a melt pool in the base material. Using coils, the electron beam is focused and deflected onto the workpiece. Wire material is added to the resulting melt pool to create material build-up. The horizontal pieces of material were produced using a steady substrate and beam deflection to move the focal point. The vertical pieces were produced by keeping the beam direction steady and rotating the table on which the workpiece is mounted. The production of Inconel samples using WFEB went relatively well. Both horizontally and vertically, the layer build-up was consistent and apart from some excess material on the produced bars, there were no significant issues. The production of titanium proved somewhat more problematic, however not as much

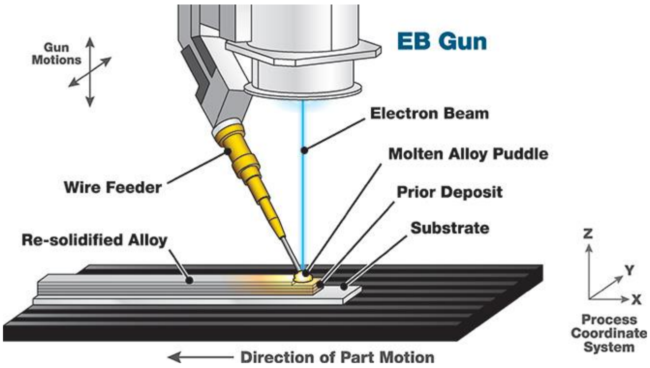

Figure 9 – WFEB welding process

Figure 10 – KLM's WFEB welding head and rotary table

Figure 11 – WFEB vertically produced Inconel 718

as with laser cladding. The problems with the production of titanium were caused mainly by the presence of gas inclusions in both the horizontally and vertically produced material. This will be discussed more in paragraph 2.3.

2.2.3 SLM

Similar to laser cladding, the SLM process makes use of a laser to melt alloy in powder form. Instead of depositing melted powder metal through carrier gas, however, the powder is placed in a thin layer on the build platform. The laser and mirrors are used to melt the powder at the right locations, before the build platform lowers and the powder scraper adds a new layer of powder metal. This results in a thinner layer build-up, but also in better precision. Furthermore, due to the support of the powder bed itself, support structures are not necessary with this method of manufacturing. Contrary to WFEB welding and (in this case) laser cladding, the material produced by the SLM project is near net shape. It needs little machining before being polished.

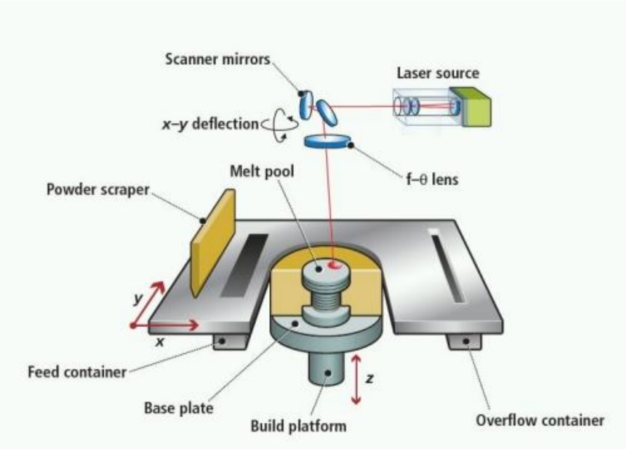

Figure 12 – The SLM process

2.3 Processing

2.3.1 X-ray analysis

To make sure the results gained from tensile testing are an accurate representation of the material properties of AM-fabricated parts, it is crucial to inspect the produced material for internal defects before machining the material to tensile testing rods. X-ray photographs were taken of the produced material and inspected for the presence of gas pockets. The Inconel material did not show any internal defects. Some WFEB-produced titanium pieces, however, did show several gas inclusions. X-ray images of sections of

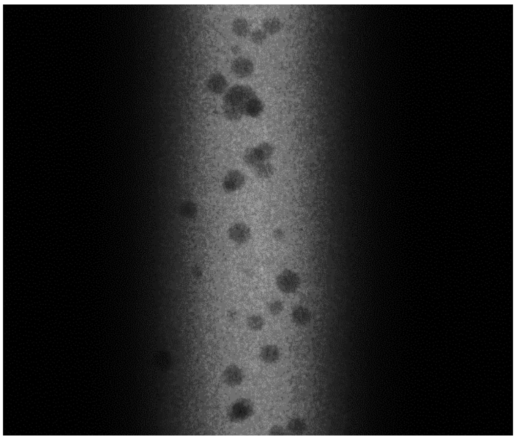

Figure 13 – WFEB titanium X-ray, lower section

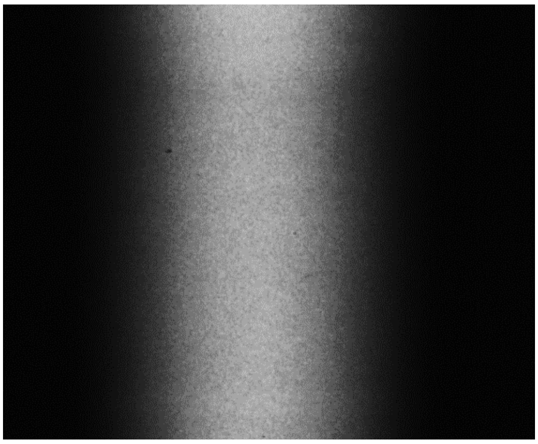

Figure 14 – WFEB titanium X-ray, upper section

the first piece of vertical titanium to be produced are shown in figures 13 and 14, as the gas inclusions were most prevalent in this piece. Remarkably, the inclusions were not homogenously spread throughout the length of the material, but rather appeared to be grouped in the lower half of the material. With the weld parameters remaining constant during the production of this entire piece, the phenomenon is unlikely to be caused by bad parameters. After deliberation with the WFEB operators and KLM engineers, the most likely cause is believed to be contamination of the wire, as it was not kept in an argon environment during storage, as recommended by GE. Another possible explanation is the evaporation of the metal itself due to the sheer heat involved in the process. Because of the irregular appearance of the inclusions however, this is thought to be less likely to be the cause. Apart from a few of the vertically produced and one of the horizontally produced pieces of WFEB titanium, no other material showed significant gas inclusions or other internal defects during X-ray inspection.

2.3.2 Machining

The tensile tests were done according to ASTM E8. In order to improve the results of the X-ray inspection, the pieces of material were first turned to 9mm round bars. The location of internal defects could then be better interpreted to be either inside or outside the net shape of the tensile rods. As depicted in figures 6, 7, 8 and 11, the material produced with laser cladding and WFEB welding has a significant amount of excess material that had to be removed by machining before the net shape could be achieved. A significant number of the 9mm round bars were then machined to size using a CNC lathe. However, the other part of the tensile rods had to be machined out of pieces of material that were only barely long enough for the tensile rods. The mandrel used on the CNC lathe was not capable of holding the tensile rods firmly enough due to the small grip surface and the inability to apply a center on pieces this small. This inability to apply a center on the CNC lathe caused a slight variation in the gauge diameter of the tensile rods, due to slight movement of the unsecured end of the rods. It also meant that about half of the tensile rods produced at KLM (conventional, laser cladded and WFEB samples) had to be machined to final dimensions using a manual lathe machine. Whereas the KLM's service hangar could find time in their schedule to incorporate the CNC lathe machining,

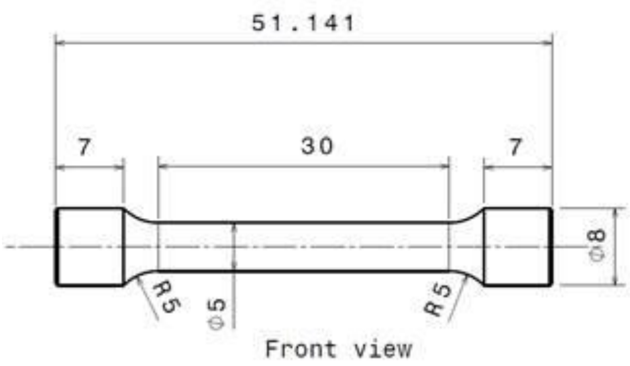

Figure 15 – Tensile testing rod dimensions

Figure 16 – Machined tensile rods

the manual lathe machining could not be performed there due to production work having priority over this research. It could have been outsourced to another company had there been time for that, but there was not. This again added big amounts of time to the already vastly surpassed time schedule of the research.

2.3.3 Heat treatment

Gas turbine components made from Inconel 718 or titanium 6Al4V usually receive heat treatment before being built into an engine. These heat treatments are used to achieve the required mechanical properties in the material. While titanium only receives relief of the internal stresses created during production, yield strength, UTS, elongation and Young's modulus are drastically improved when Inconel is heat treated. To do this, the treatments are designed to create a desired grain size and morphology, as well as to let certain elements in the alloy precipitate. Half of the rods were left untreated. The other half was subjected to heat treatment typical for parts of the same material. This was done in order to use both treated and untreated conditions to identify differences between the 4 production methods. The titanium rods were subjected to a single stress relief treatment at 735°C for 2 hours. Unfortunately, no graph of this treatment is available. The reason for this is that the treatment was not performed in the main furnaces at KLM's engine shop, but at the laboratory. The main furnaces normally used for the heat treatments were all broken down at that moment in time. As there was very little time between when all titanium rods were machined and when the tensile tests had to be performed, the titanium treatment had to happen in a small oven at the KLM's laboratory. The data logger used to try to monitor the temperature using a thermocouple stopped registering at temperatures higher than 400°C for reasons currently unknown. The Inconel rods were given stress relief treatment, as well as solid solution and aging treatments, in accordance with GE and KLM's standard treatment of Inconel 718 parts. The stress relieve treatment consists of heating to 1060°C, holding for 1.5 hours, followed by quenching to 538°C at not less than 17°C/minute. This treatment is shown in figure 17. The solid solution treatment consists of heating to 954°C, holding for one hour, again followed by quenching to 538°C at not less than 17°C/minute afterwards. The aging treatment consists of two phases. First heating to 760°C, holding for 5 hours and afterwards vacuum cooling to 650°C, holding for one hour and quenching. These two treatments are shown in figure 18. As discussed briefly before, the heat treatment of the rods had to wait until the last batch of material had been produced. Some things to be noted are the dates of the heat treatments. In order to try and minimize the time and money spent on these heat treatments, the stress relief treatment was performed as soon as all the Inconel material had been produced and x-rayed for defects. The solid solution and aging treatments had to wait until after all the machining on the rods was done, as these treatments typically double the hardness of the Inconel, making machining even more difficult that in stress relieved condition.

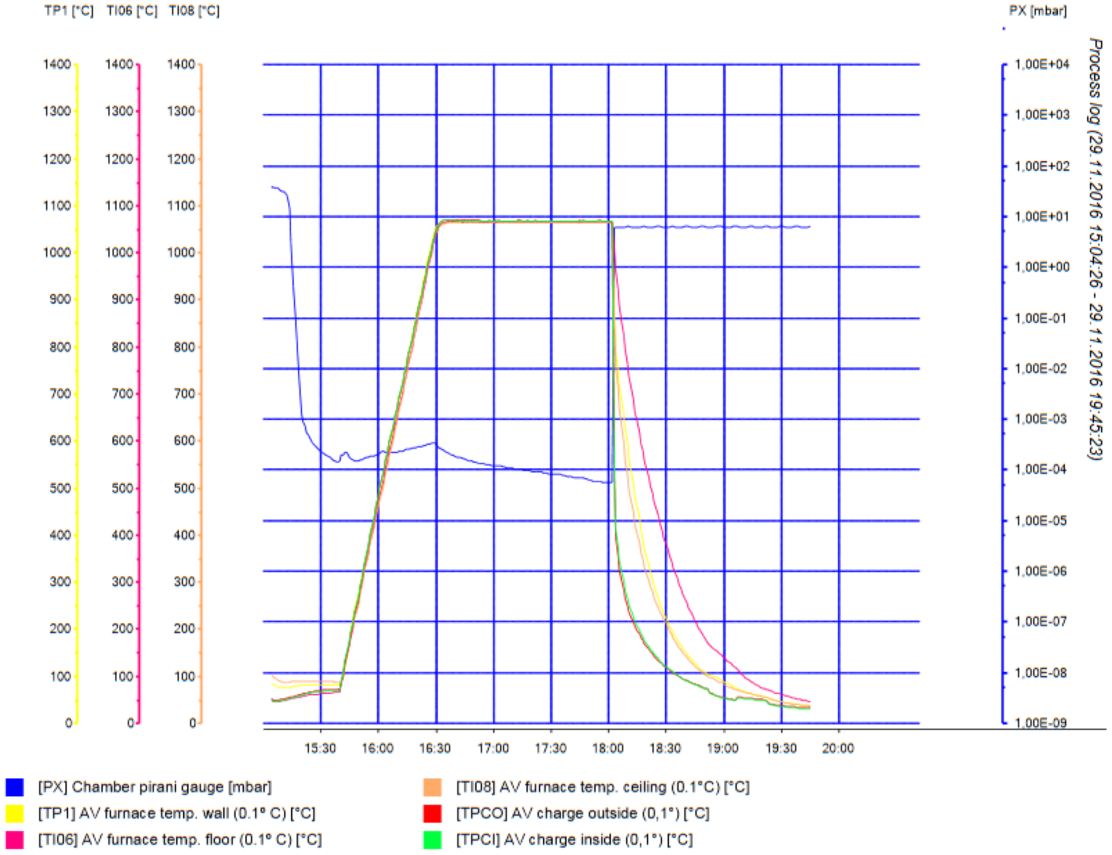

Figure 17 – Inconel stress relieve treatment

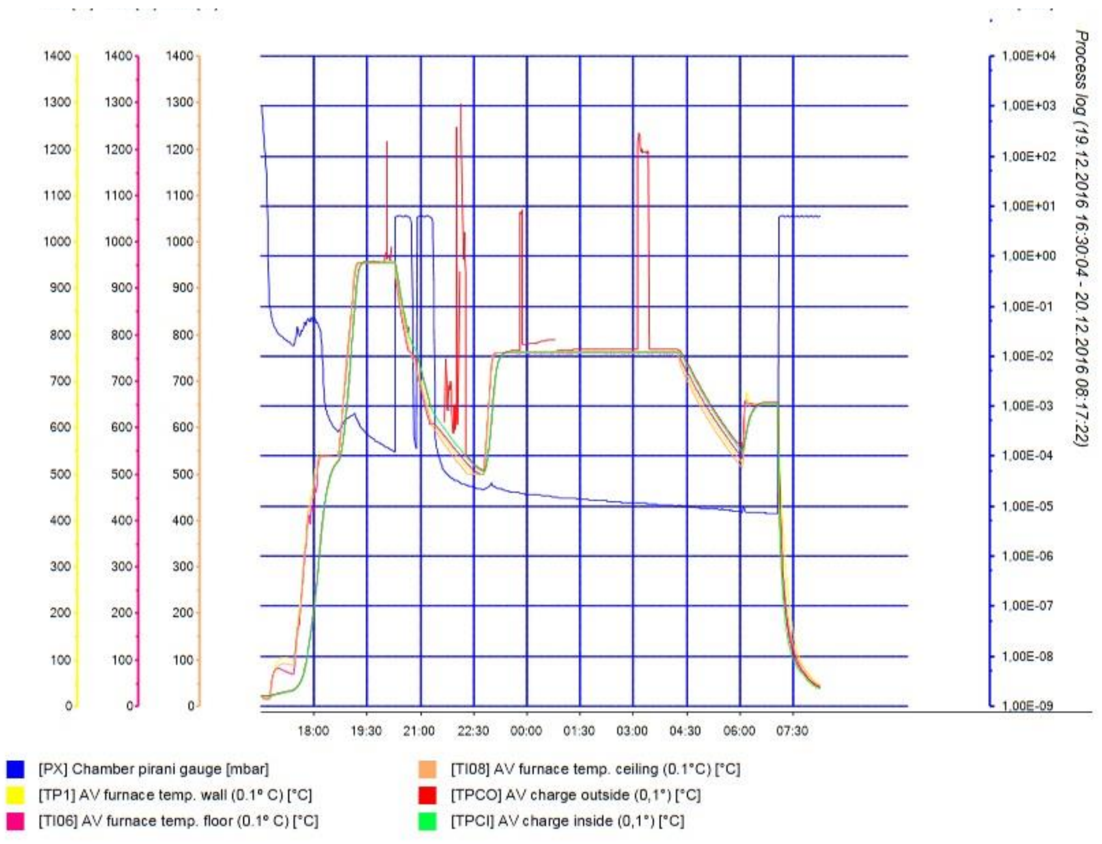

Figure 18 – Inconel 718 solid solution and aging treatments

2.4 Testing

2.4.1 Geometrical analysis

Figure 19 – All tensile samples, with exception of the SLM samples

As mentioned earlier, the gauge diameters of the tensile rods showed slight variations. In order to achieve the most exact results possible, the diameter of all tensile rods was measured at multiple positions along the gauge section. These measurements were performed using a micrometer. The smallest sections were determined and the new gauge area for each tensile rod was calculated. Another geometrical issue that arose was the fact that, although the gauge section length was equal in all samples, not all pieces of material were long enough to achieve the total length necessary for the end parts of the rods. This had consequences for the placement in the testing bench which will be discussed in the next subchapter. Figure 19 shows all tensile rods fabricated by KLM. It should be noted that one batch has only two instead of three tensile rods to be tested. The third sample of this batch was unfortunately destroyed during machining, and there was no time left to go through the prior production steps again.

2.4.2 Tensile testing

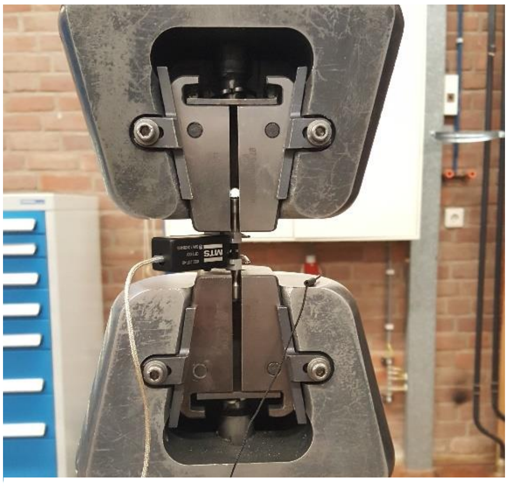

Figure 20 – Clamps holding tensile rod with extensometer mounted

The tensile tests were performed at NLR’s research facility in Marknesse, Flevoland. There was, however, an issue that arose shortly before performing the tensile tests. The initial design supplied by NLR was agreed upon, but when planning a date for the tests, it turned it this was not the design NLR was planning on testing. Fortunately, the difference was limited to length of the end parts of the rods, and the presence of thread. The length and diameter of the gauge section in both designs was equal, making it a problem of placement in the tensile testing bench, rather than a difference in properties received from the tests. There was however no time left to thread all end parts on the unthreaded samples. Whereas the SLM samples had threaded end parts that could be screwed in place in their holders, the unthreaded samples had to be clamped in place. This had some consequences for the setup and the results of the tensile tests. Firstly, the elongation measurement made by the tensile testing bench itself is only accurate after the sample enters plastic transformation, as during elastic transformation, the sample is still being settled in the clamps. Typically, the setup of clamps and sample would therefore move slightly during the first part of the tensile tests, and for this part an extensometer was placed on the samples when possible. As visible in figure 20, the extensometer only barely fits between the clamps at the start of the test. However, some of the sample batches, as mentioned earlier, had shorter end parts. This meant the clamps had less surface to grip on, and the gripping force caused the end parts to be slightly deformed into an oval shape. The effect this had was that the breaking surface of those rods was too irregular to take accurate measurements of. This was the case for the vertically laser cladded and WFEB welded Inconel samples. Of the SLM produced Inconel samples, no reduced area measurements were given either. It also means that the elongation results are not as accurate as they could have been had all the samples had threaded heads. During tensile testing, one sample out of a batch of three was unfortunately bent while being put in the clamps.

2.4.3 Microstructure analysis

In order to perform this analysis, sections of the rods to be analyzed were taken. These sections were embedded and polished, as shown in figure 21. The surface of the Inconel 718 samples was then etched using 'kalling' etchant ($CuCl_2$, hydrochloric acid and ethanol). For titanium 6Al4V, Kroll's reagent (distilled water, nitric acid and hydrofluoric acid) was used to etch the surface. Analysis of the microstructure, grain boundaries and grain orientation was subsequently performed using a strong optical microscope and the corresponding computer software, shown in figure 22.

Figure 21 – Sample polishing

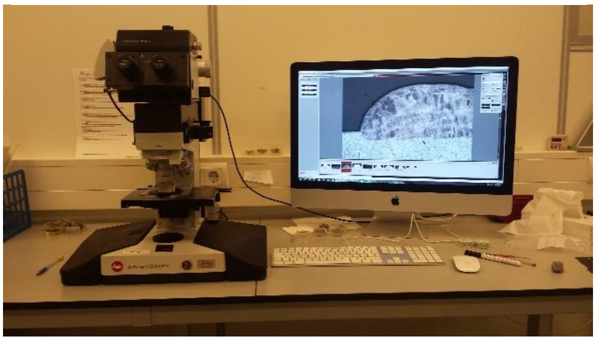

Figure 22 - Aristomet optical microscope

3 THEORETICAL BACKGROUND

The behavior of Inconel and titanium components when in operation in a gas turbine are heavily dependent on the composition of the specific alloy as well as the microstructural phases present in the alloy. In this chapter, the alloying elements serve a specific purpose in altering the mechanical properties of the alloy. In this chapter the different alloying elements in Inconel 718 and titanium 6Al-4V are presented and their influence is discussed. The microstructural phases that can be present in the alloys are also presented and their influence on mechanical properties discussed.

3.1 Inconel 718

Table 1 – Inconel 718 composition

Inconel 718		
Element	Min (weight%)	Max (weight%)
Carbon	-	0.08
Manganese	-	0.35
Silicon	-	0.35
Phosphorus	-	0.015
Sulfur	-	0.015
Chromium	17	21
Nickel	50	55
Molybdenum	2.8	3.3
Niobium	4.75	5.5
Titanium	0.65	1.15
Aluminium	0.2	0.8
Cobalt	-	1
Tantalum	-	0.05
Boron	-	0.006
Copper	-	0.3
Iron	Remainder	Remainder

Due to the ever present desire to increase gas turbine performance, nickel based superalloys were developed to fill the requirements. By adding alloying elements to nickel, the behavior of the metal is significantly altered. Due to the need for different mechanical properties in different parts of the gas turbine engine, various different nickel based superalloys with varying compositions were developed. The mechanical properties of these alloys can be altered through heat treatment to transcend properties of pure nickel, as well as untreated alloy. With mechanical properties such as high strength at high temperatures and good resistance against hot corrosion and oxidation, nickel base superalloys can currently account for up to

50% of the total weight of a gas turbine engine. Of these nickel superalloys, Inconel 718 is used most in gas turbine engines. First introduced in the early 60's, Inconel 718 (or alloy 718) is presently the most produced composition of the nickel superalloys. Most of the alloying elements in Inconel 718 (table 1) show a significant margin, causing different batches of material to have slightly different compositions and microstructures, and therefore different mechanical properties. This difference was, as noted in chapter 2, not researched in this study. The alloying elements all serve specific purposes in the alloy. Through solution treatment and precipitation treatment, desired microstructural phases can be achieved in the alloy. In order to correctly analyze and interpret the effect of different AM methods on the microstructural phases, the different phases that can occur in the alloy are discussed.

3.1.1 Gamma matrix

The austenitic γ matrix is the primary structure in nickel based superalloys. It has a FCC structure (figure 23) and retains this up to its melting point. The FCC structure of the γ phase allows for strengthening of the matrix through solution hardening. Several of the alloying elements (Fe, Al, Ti, Mo, W, Cr) can strengthen the matrix by solid solution hardening.

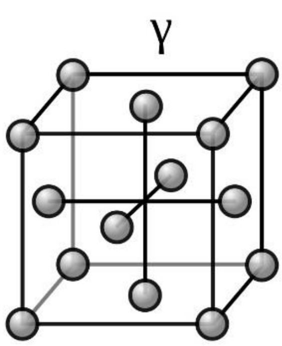

Figure 23 – FCC structure

3.1.2 Intermetallic phases

The properties of Inconel 718's γ matrix can be improved by the presence of certain desirable intermetallic phases. Two phases in particular form the main strengthening of the alloy, the γ' (gamma prime) and γ'' (gamma double prime) phases. Alongside these two strengthening phases, secondary phases such as the δ-phase, μ-phase, carbides and nitrides can be present in the material.

The γ' phase consists of Ni_3Al and $Ni_3(Al/Ti)$. Like the γ matrix, it is FCC shaped. Due to its slight oversize of the γ' matrix compared to the γ matrix, there is a γ/γ' matrix mismatch. The shape of the γ' phase is dependent on the size of the γ/γ' mismatch, and can range from cuboidal to spherical. In Inconel 718 the mismatch is generally relatively big, and γ' therefore cuboidal. γ' precipitated in the temperature range of 600ºC to 900ºC.

Whereas the γ' phase acts as the main strengthening mechanism in most nickel based superalloys, γ'' assumes this role in Inconel 718. The composition of γ'' is Ni_3Nb and it has a disk-like shape. The γ'' phase has a BCT structure (figure 24) and

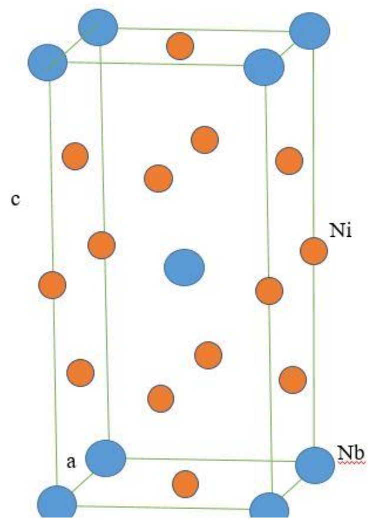

Figure 24 - BCT structure

precipitates in the range of 705ºC to 900ºC. It is the metastable phase of the Ni_3Nb composition.

The stable phase with a Ni_3Nb composition is the δ-phase. The δ-phase generally has a needle-shaped morphology. It precipitates from the γ matrix at temperatures between 700ºC and the δ-solvus temperature, which varies between 980ºC and 1050ºC due to compositional variations. The δ-phase has an orthorhombic structure and is therefore, unlike the γ' and γ'' phases, incoherent with the γ matrix. Although this causes undesirable materialistic properties, the δ-phase does serve an important purpose in achieving the desirable amount of γ' and γ'' precipitation. During solution treatment, the γ' and γ'' precipitates dissolve, while a small amount of δ-phase precipitates at the grain boundaries.

3.2 Titanium 6Al4V

Titanium alloys are generally categorized as α-alloys, β-alloys or α-β alloys, depending on the role of the alloying elements. The alloying elements in titanium alter the microstructure and grain morphology, leading to altered mechanical properties. Pure titanium is allotropic. Up to 885 ºC, it forms a CPH structure (α-phase). When brought to higher temperatures, the crystalline structure changes to a BCC structure (β-phase). These structures are depicted in figure 27 and 28. The alloying elements in titanium 6Al-4V are aluminum and vanadium, making it an α-β alloy. The aluminum acts as the α phase stabilizer. It raises the β transus temperature, as well as creating a temperature range where both α and β phase are present. Vanadium acts as the β phase stabilizer, lowering β transus temperature and extending the α+β temperature range further downwards. Figure 25 shows the resulting phase diagram for this alloy. At 4 weight percentage vanadium and 6 weight percentage aluminum, the alloy has a β transus temperature of around 1000 ºC, and retains a small percentage of its β structure at room temperature. Grain growth above β transus temperature is uninhibited as there is only one microstructure present. Growth of the α phase during cooling is greatly dependent on the cooling rate. The slower the cooling process, the more time is available for α phase structures to nucleate and grow into lamellae in the existing β structure. This means that a slower cooling process leads to shorter and thinner α phase lamellae, resulting in a higher yield strength. Fast cooling (3.5K/s or more) results in the formation of the undesirable martensitic α' and α'' structures.

Table 2 – Titanium 6Al4V composition

6Al-4V		
Element	Min	Max (weight%)
Aluminum	5.5	6.75
Vanadium	3.5	4.5
Iron	-	0.3
Oxygen	-	0.2
Carbon	-	0.08
Nitrogen	-	0.05
Hydrogen	-	0.0125
Yttrium	-	0.005
Other elements	-	0.4
Titanium	Remainder	Remainder

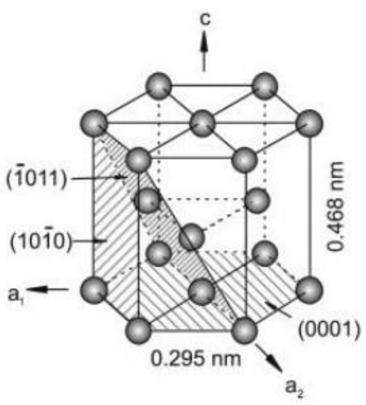

Figure 25 - CPH structure

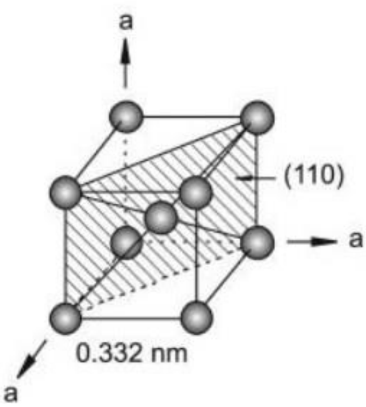

Figure 27 - BCC structure

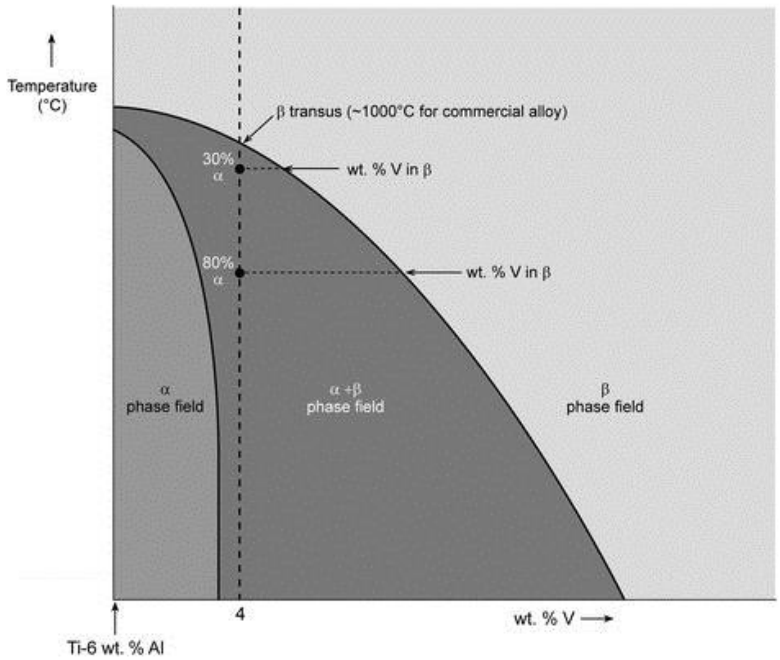

Figure 26 - Ti 6Al-4V phase diagram

4 RESULTS

In this chapter, the results of the tensile tests will be presented and discussed. Along with the tensile test data, photographs of the microstructure of relevant samples will be given where deemed necessary. The complete tensile data set is provided in appendix 2. All microstructure photographs that are not included in the main report are provided in appendix 1. The samples are divided into batches, each with its own properties, and indicated with a batch label. The batch labels are specified in the table below.

Table 3 – Batch labels and descriptions

Label	Description
LIHA	Laser cladded, Inconel, horizontal, annealed.
LIVA	Laser cladded, Inconel, vertical, annealed.
LTHR	Laser cladded, titanium, horizontal, stress relieved.
LTVR	Laser cladded, titanium, vertical, stress relieved.
EIHA	WFEB produced, Inconel, horizontal, annealed.
EIVA	WFEB produced, Inconel, vertical, annealed.
ETHR	WFEB produced, titanium, horizontal, stress relieved.
ETVR	WFEB produced, titanium, vertical, stress relieved.
SIHA	SLM produced, Inconel, horizontal, annealed.
SIVA	SLM produced, Inconel, vertical, annealed.
STHR	SLM produced, titanium, horizontal, stress relieved.
STVR	SLM produced, titanium, vertical, stress relieved.
CI-A	Conventionally cast and wrought from bar, Inconel, annealed.
CT-R	Conventionally cast and wrought from bar, titanium, stress relieved.

During tensile testing, some observations were made that need to be taken into account when interpreting the data results:

- The laser cladded, vertically produced titanium rods consistently broke almost immediately after starting their tensile tests. These samples show (almost) no reduction of area or elongation.
- The horizontally produced, WFEB Inconel rods show an irregular shape of the reduced area (slanted +- 45°)

- Data produced by heat treated tensile rods shows more accurate and consistent data.
- The shape and diameter of the reduced area in testing batches (SIHA, LIVA and EIVA) proved too irregular to take an accurate reading of.
- Some samples show some non-linearity in the plastic deformation area, making Young's modulus readings on these samples inaccurate. This will be discussed where applicable.
- The conventionally cast and wrought Inconel samples show some inferior properties, like Young's modulus for example, when compared to properties specified in literature. This will be taken into account in the comparison.

Due to these observations and the absence of untreated SLM specimens, the decision was made to present and discuss the data of the treated specimens in the main report, while providing the data of untreated rods in the appendices.

4.1 0.2% yield strength and ultimate tensile strength

4.1.1 Inconel 718

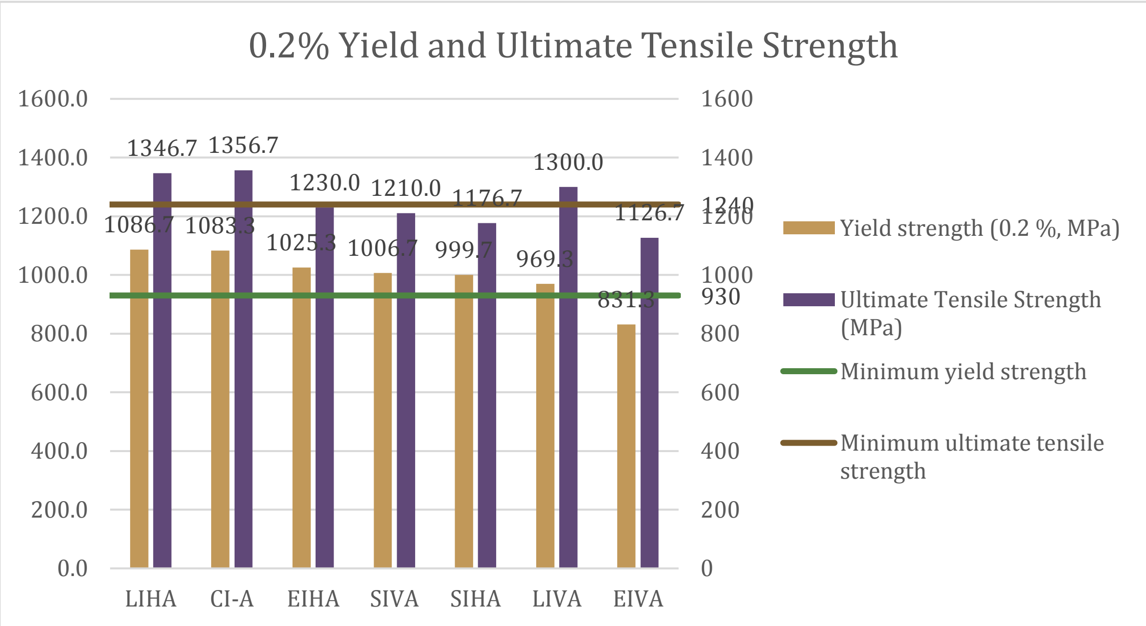

Figure 28 – Yield strength and ultimate tensile strength of Inconel 718

ASTM F3055 indicates that the required minima for yield strength and UTS are 940MPa, 1240MPa and 920MPa, 1240MPa for longitudinal and transverse specimens respectively. Longitudinal meaning in the direction of the grains, in this case it symbolizes the horizontally produced specimens. Transverse represents the vertically produced specimens. This specification is for SLM produced parts, but will be used as a general minimum requirement in this research for an accurate comparison. The first observation to be made is that only the CI-A, LIVA and LIHA samples prove to reach the required minimum UTS. LIHA shows comparable properties to the conventional samples. While the LIVA samples show UTS values above minimum requirements, the vertically produced samples (SIVA, LIVA and EIVA) seem to show values inferior to horizontally produced samples. With regard to the orientation, the SLM samples (SIVA and SIHA) show the least directional dependency. The differences in WFEB and laser cladding samples are more significant. Whereas only three sample types achieve the minimum UTS, all but one achieve the required minimum yield strength. EIVA being the only type not to achieve minimum yield strength, a closer look should be taken at the microstructure present in both the CI-A (images 29) and the EIVA (images 30) samples, for comparison. The difference in properties between the two samples shows itself in the microstructure. In the CI-A sample, the grain morphology seems to be consistent and omnidirectional, and grain size is decently large. In the EIVA sample, it seems grain growth happened vertically. This appears to have created long, vertical dendrites, making tensile properties very directional. Because these images were taken in the direction of these dendrites, they

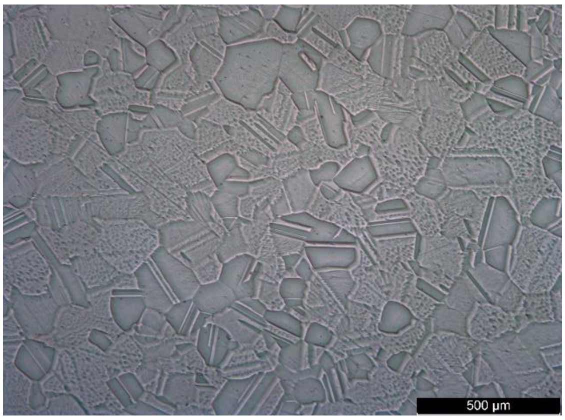

Figure 31 – CI-A sample, 50x magnification

Figure 29 – EIVA sample, 50x magnification

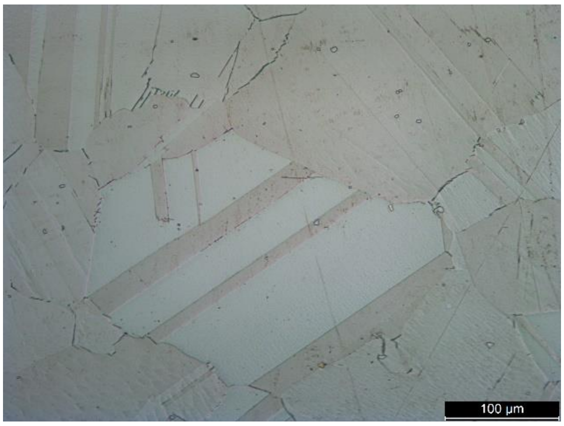

Figure 32 – CI-A sample, 200x magnification

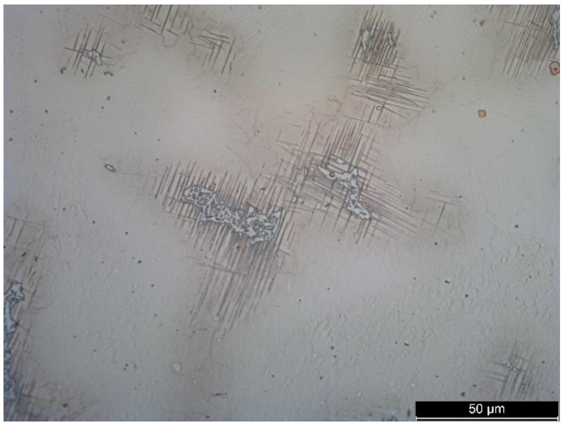

Figure 30 – EIVA sample, 500x magnification

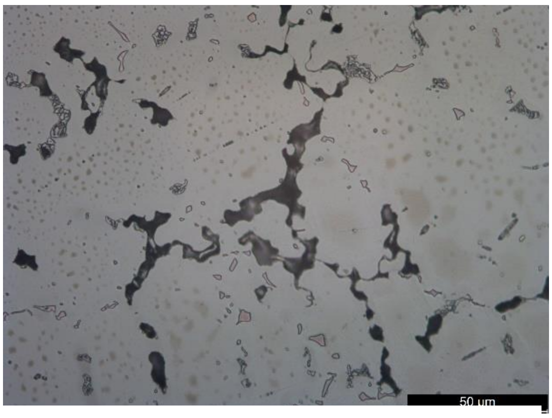

Figure 33 – EIVU sample, 1000x magnification

appear as small grains. With a larger magnification, an increased formation of δ-phase at these dendrites of the EIVA sample becomes clear in (image 32). A few δ-phase particles can also be seen in the CI-A sample in (image 31), but not nearly as much. In some areas of the material, this extremely directional formation of grains led to some areas in the material cooling down so much faster than others that small voids between the fast solidifying dendrites were formed. While not visible in the EIVA sample made, these were incredibly apparent in parts of the untreated sample, EIVU, as shown in (image 33). It must be noted that not finding defects in the EIVA sample does not mean that these defects were not present in the other parts of the sample or the other rods in the EIVA batch. Heat treatment does not repair defects like the ones found in the EIVU sample, EIVA is therefore likely to also suffer from parts of material having these defects

4.1.2 Titanium 6Al4V

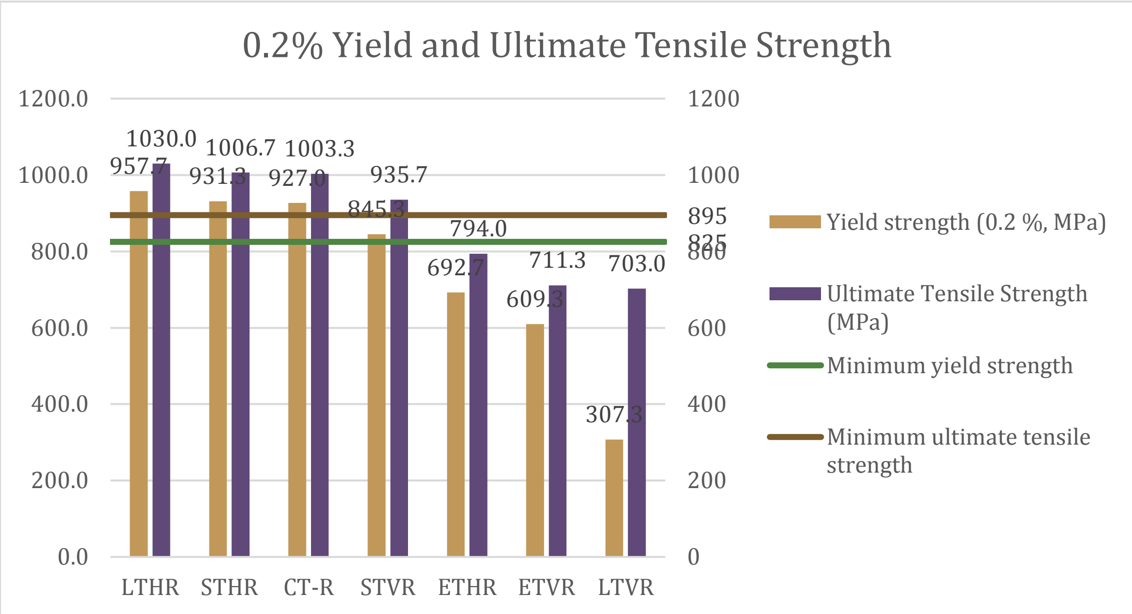

Figure 34 – Yield strength and ultimate tensile strength of titanium 6Al4V

In the case of titanium, ASTM2924-14 again supplies minimum values for SLM produced parts, which will be used as a comparison. It gives minimum yield strength and UTS values of 825MPa and 895MPa for both horizontally and vertically produced parts. The conventional CT-R (image 35 and 36) as well as the LTHR, STHR (image 37) and STVR samples exhibited acceptable values for both yield strength and UTS. The WFEB

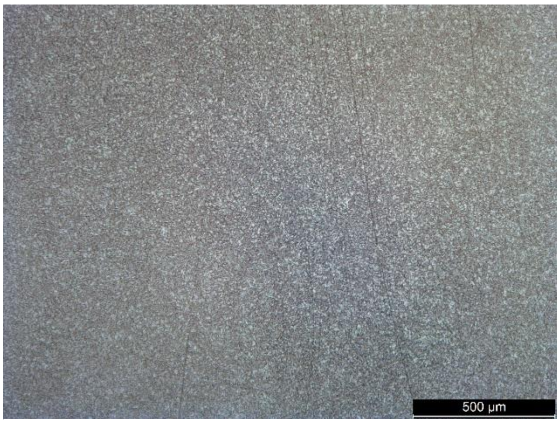

Figure 35 – CT-R sample, 50x magnification

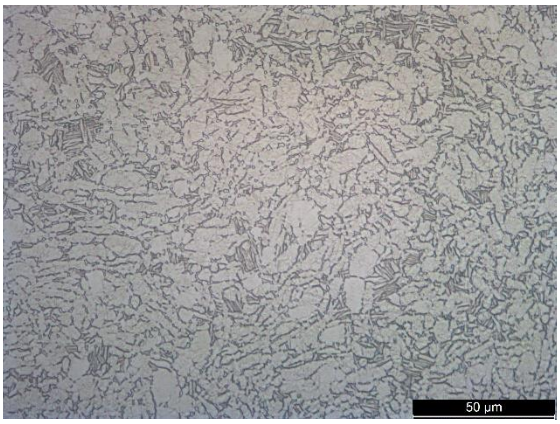

Figure 36 – CT-R sample, 500x magnification

produced ETHR and ETVR (image 38) samples show values far under minimum requirements. The LTVR sample shows even worse values, which conforms to the observation of these samples breaking even before showing signs of elongation. The CT-R sample shows a fine and evenly distributed α-phase build-up. The STHR sample shows a less evenly distributed yet fine α-phase build-up. The ETVR sample however, shows the more coarse structure buildup in these samples, suggesting the presence of α’ or α’’ phases. The poor performance of the LTVR samples is explained perfectly by the microstructure analysis (image 39). In this particular part of the sample, the cladded layers appear to be separated by small voids, causing a severe lack of fusion, and therefore inferior tensile properties.

Figure 38 – STHR sample, 50x magnification

Figure 37 – ETVR sample, 50x magnification

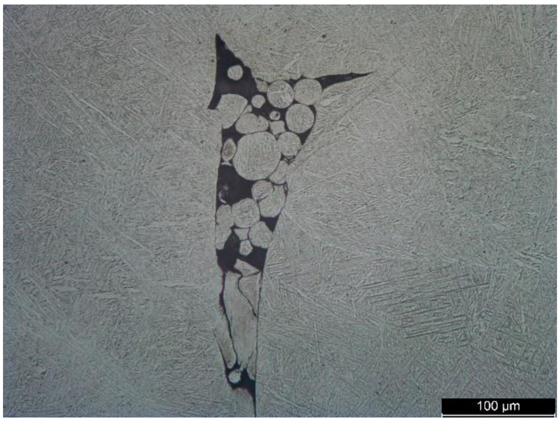

Figure 39 – LTVR sample, 200x magnification

4.2 Reduction of area and elongation

4.2.1 Inconel 718

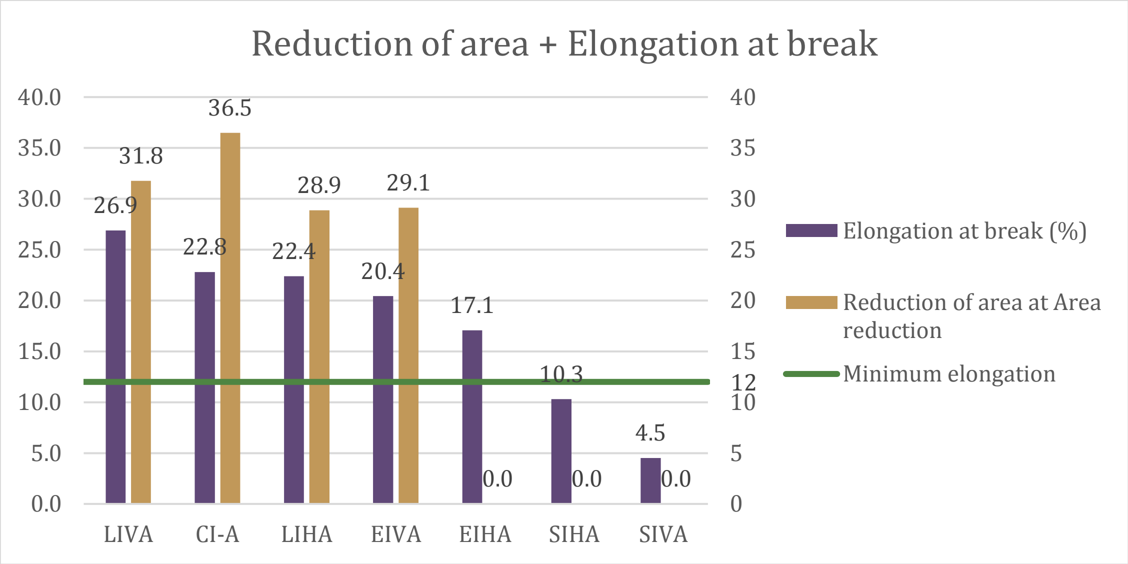

Figure 40 – Elongation at break and reduction of area for Inconel 718

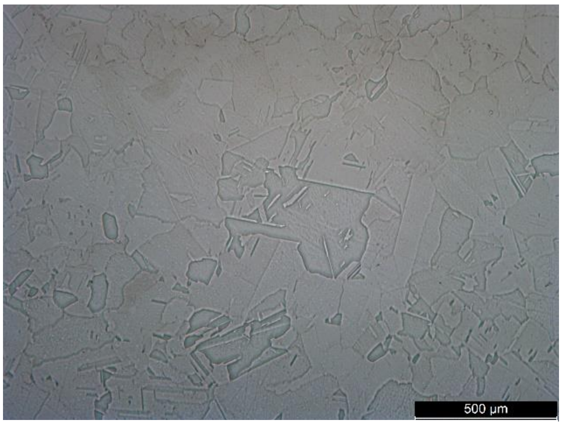

Figure 41 – LIVA sample, 50x magnification

The required elongation at break for Inconel, stated by ASTM F3055, is 12%. This goes for both vertical and horizontal samples. The results of the tensile tests clearly indicate that only the vertically produced LIVA and EIVA samples show inferior elongation. The conventional CI-A sample shows a value close to the average value suggested by literature, 22% (source 16). The LIHA samples show an even higher average elongation value, outperforming literature values for conventional material by almost 5%. A look at the microstructure present in the LIVA sample (image 41) shows a grain structure similar in size and morphology to that of the conventional samples (image 29). An interesting observation to be made is again the high directional dependency in both laser cladding and WFEB samples, while in the SLM samples, the vertical samples even outperformed the horizontal samples. As explained earlier, reduction of area measurements could not be taken of all the samples, the SIHA, SIVA and EIHA samples are not present in this graph.

4.2.2 Titanium 6Al4V

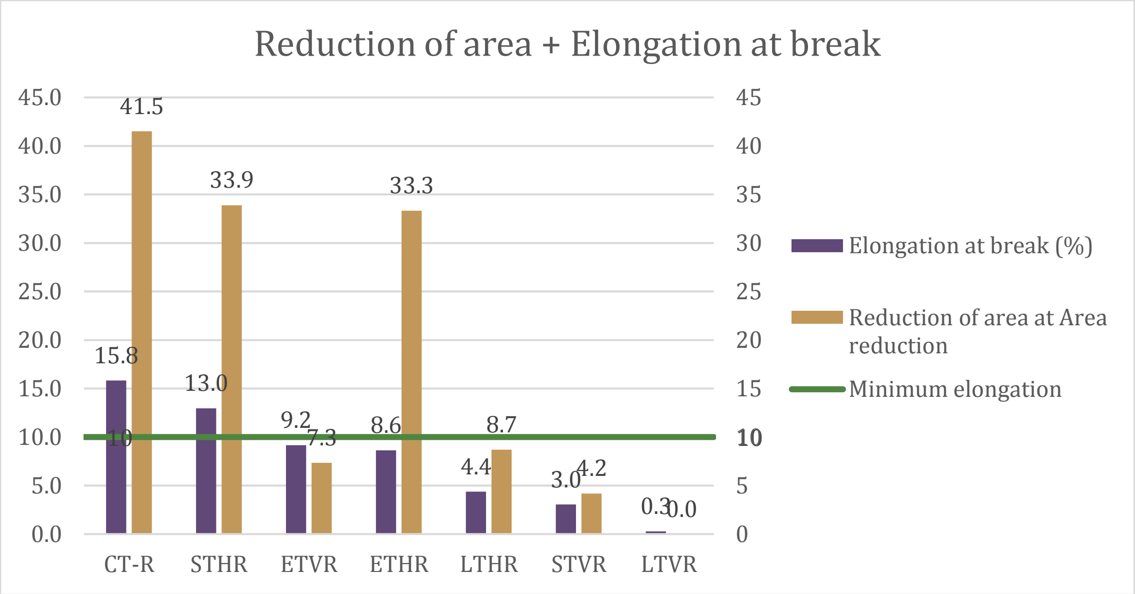

Figure 42 - Elongation at break and reduction of area for titanium 6Al4V

For titanium, the required minimum elongation before break is given by ASTM2924-14, and is 10% for both vertical and horizontal samples. Where the Inconel samples only had 2 batches that didn't achieve the minimum, the titanium samples show the exact opposite. Only the conventional samples and the horizontal SLM samples achieved elongation values high enough. While both horizontal and vertical WFEB samples do come rather close to the minimum and some samples do exceed the minimum, the average is just too low. The laser cladded samples, as well the vertical SLM samples don't nearly come close to the required minimum. As expected due to the observations during testing, the LTVR samples did not show any elongation before failing.

4.3 Young's Modulus

4.3.1 Inconel 718

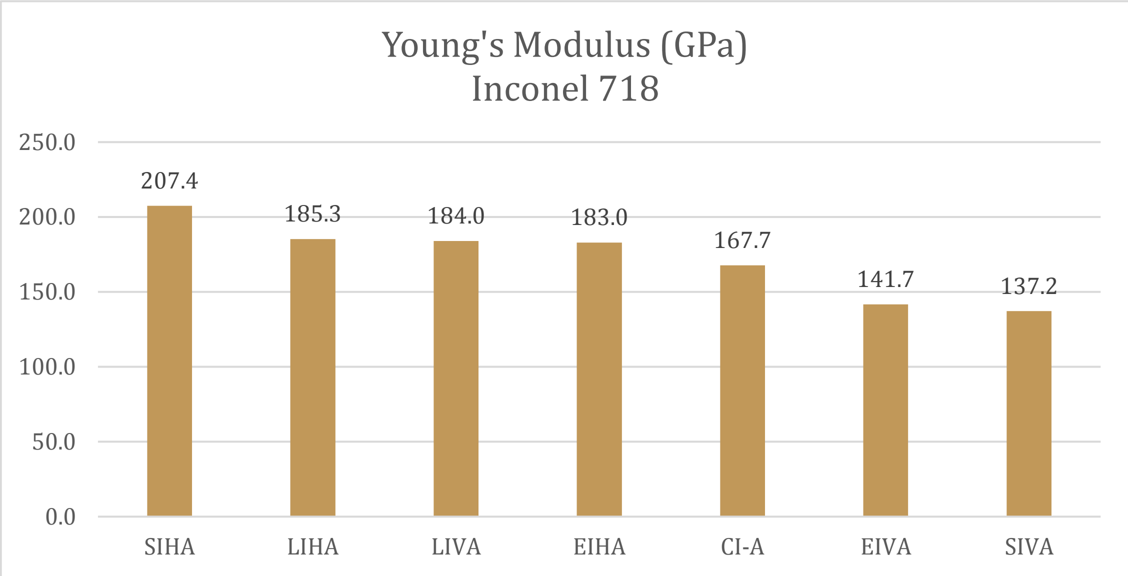

Figure 43 – Young's modulus for Inconel 718

When analyzing the Young's modulus data, the observation of some samples showing non-linearity in the elastic deformation area must be taken into account. After the tensile tests were performed, the reference points on each samples chart used to calculate the Young's modulus were manually adjusted to give the most accurate value possible. The data show that, as previously mentioned, the conventional CI-A batch does not seem to represent an accurate value when compared to standard values suggested by literature, which is 208GPa (source 17). A possible explanation for this could be that the batch of supplied material has a composition that does not produce good Young's modulus values, but this is not certain. When compared to the literature suggested standard value, all horizontal samples seem to come close to the standard value, with the SLM batch almost equaling it. When it comes to the Young's modulus, the vertical laser cladding sample also seems to hold up decently, but both SLM and WFEB welding seem to be very directionally dependent. The explanation for this directional dependency is clearly visible in the SIHA samples microstructure (image 44). The grains have formed in a long, stretched out manner. They appear to have formed in the direction of the powder bed plane,

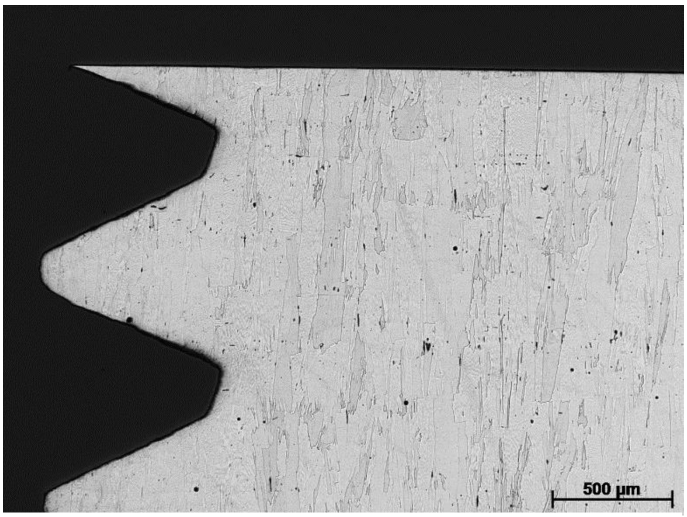

Figure 44 – SIHA sample, 50x magnification

suggesting the cause to be the very small layer build-up involved in the SLM process. Though not having a major impact on yield and ultimate tensile strength, this does appear to have a large influence on the Young's modulus. The directional dependency in the WFEB samples complies with the results found for yield and ultimate tensile strength, and can also be blamed on the dendrite buildup in the vertical samples

4.3.2 Titanium 6Al4V

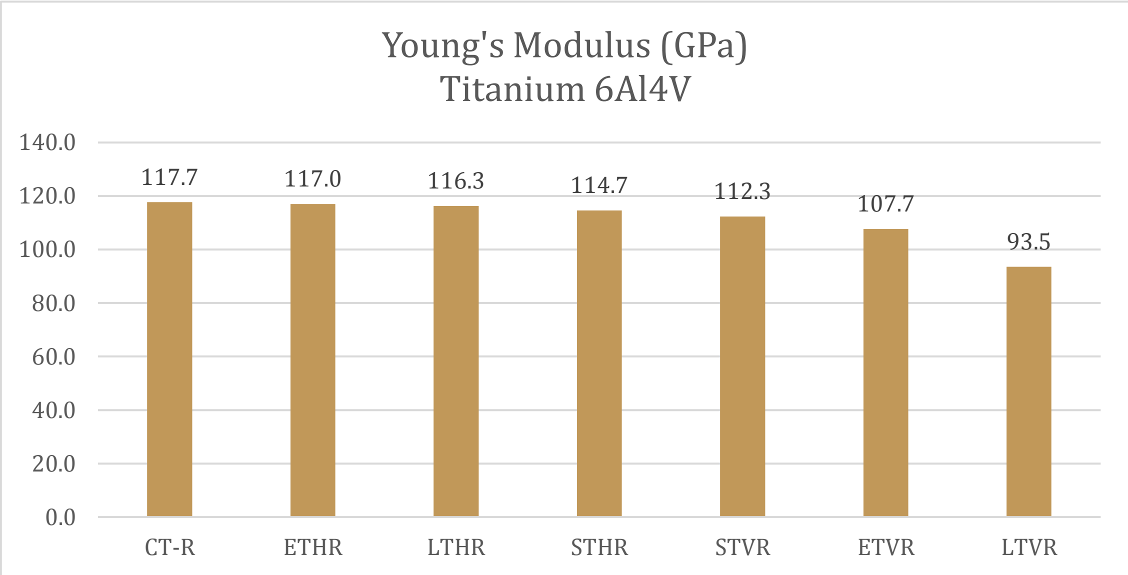

Figure 45 – Young's modulus for titanium 6Al4V

Literature (source 18) suggests an average Young's modulus for titanium 6Al4V of 120 GPa. Even though the data of the Young's modulus analysis might not be as accurate as preferred, they do show consistent results. Both the conventional CT-R and all horizontal samples come very close to the suggested standard Young's modulus. Even the vertical SLM sample doesn't fall far behind. The LTVR sample data are very inaccurate due to the earlier described premature failing of the samples. Interesting to note is the tiny difference between the horizontal and vertical SLM titanium samples, especially when compared to the big difference that was found in the SLM Inconel. This suggests that the directional dependency of SLM parts is very material specific.

4.4 Porosity

When it comes to the porosity of the samples, it must be noted that there was simply no time left after performing the tensile tests, sample preparation and production of microscopic images to perform accurate measurements on all the pores present in the samples. In order to still be able to draw conclusions about the porosity, a visual count was performed, estimating the size of the pores visually. Unfortunately however, only images were supplied of the SLM produced Inconel samples, but since no material could be supplied by NLR, a porosity count could not be made of these samples. However, the images (image 48 and 49) do indicate severe porosity in these samples. Microscopic

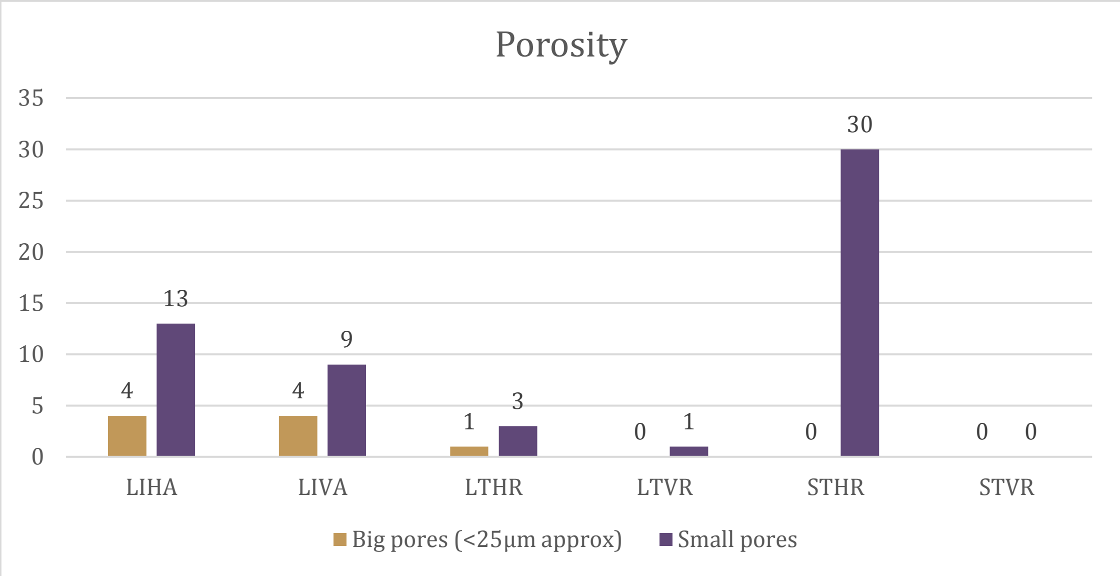

Figure 46 – Porosity count

analysis revealed that, as expected, no porosity is present in the conventional and WFEB samples, as it seems to be limited to the additive manufacturing methods using powder material. Porosity is not to be confused with either the gas inclusions that were so prevailing in some parts of the horizontal titanium WFEB material or with the defects present in laser cladded and SLM produced material. The second observation to be made is that the amount of pores in the titanium samples is lower than the Inconel samples, except for the STHR sample. This sample showed a concentration of an estimated 30 small pores, all concentrated on one side of the sample, suggesting powder contamination. Some of these pores are shown in image 49. It must be noted that powder contamination is a suspicion the NLR already had after performing the tensile tests on the SLM titanium samples. The reason for their suspicion is that the SLM titanium properties received from these samples is lower than values that were achieved in earlier tests. These earlier tests showed even higher yield and ultimate tensile strengths and more consistent elongation. It must also be noted that a powder contamination in the SLM produced titanium might show up in the porosity results only for the horizontal sample, but still might be present in all tested SLM titanium samples, including vertical ones. The powder quality used during production appears to be the dominating factor in determining the porosity of the material.

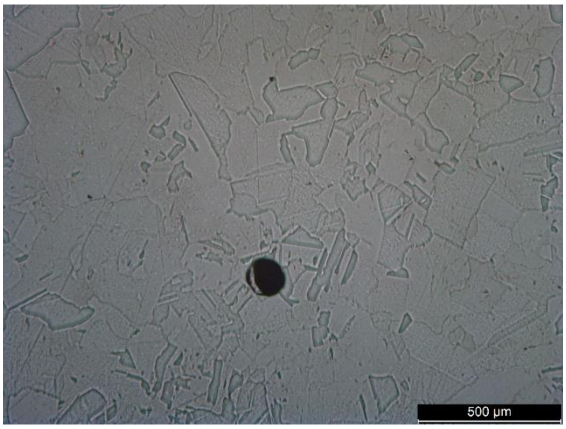

Figure 48 – Pore in Inconel laser cladded sample, 50x magnification

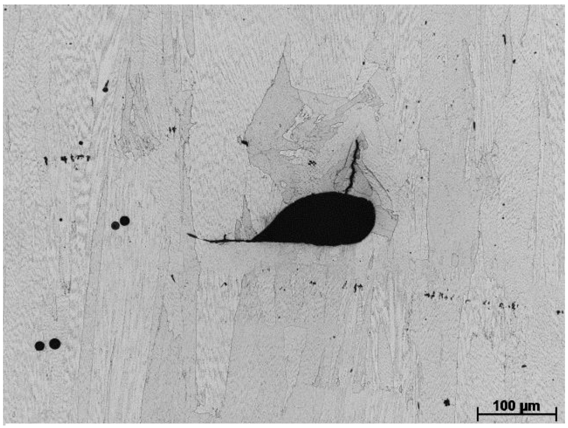

Figure 49 –Pores and defect in Inconel SLM sample, 200x magnification

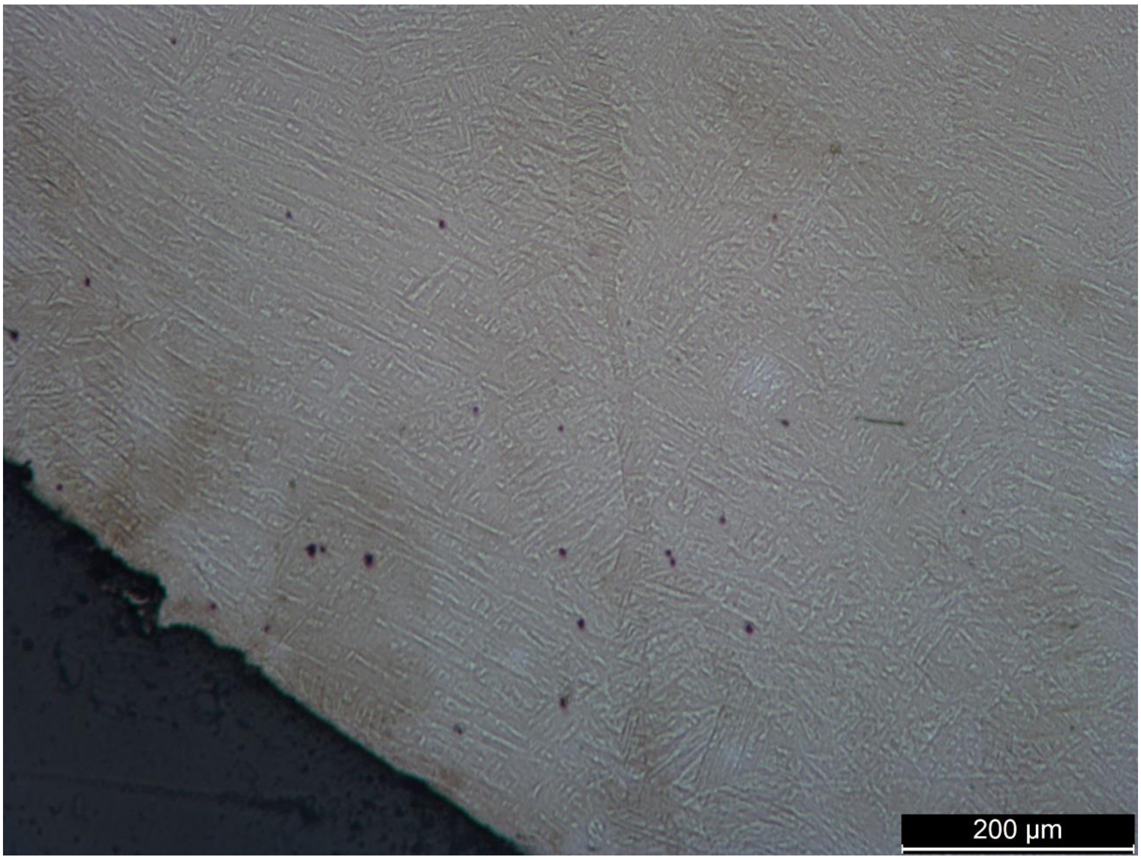

Figure 47 –Concentration of pores in STHR sample, 100x magnification

5 CONCLUSION

When combining the different observations made and results gathered, conclusions can be drawn. It must however be noted that these tests were performed using only three samples for each combination of variables. Although bigger batches would give more accurate results, the conclusions drawn from these results are still a good indication for future work. To formulate the conclusions, the main research question and the first sub question will first be answered. Then, general conclusions will be drawn. The second sub question shall be answered in the recommendations, through showing some repairs that could be performed using the researched AM-methods.

5.1 Main research question

What are the differences in mechanical properties between AM-fabricated and conventionally produced Inconel and titanium parts?

The prevailing difference between the AM-fabricated parts and the conventionally cast and wrought ones is the directional dependency that can be found in all methods to a certain extent. The differences are the most severe in the titanium 6Al4V parts, but do also show up in the Inconel parts. Horizontally fabricated material seems to nearly always outperform vertically produced material, and show promising results.

In Inconel 718, minimum UTS seems to be harder to achieve than minimum yield strength, which all methods prove to achieve. Elongation at break gives diverse results, with two out of three AM methods achieving minimum value. The found Young's modulus values, although less reliable than the other results, seem acceptable. Porosity does prove to be a consistent problem in powder manufactured Inconel, with powder contamination as the suspected main cause.

In Titanium 6Al4V, although consistent Young's modulus values are achieved, achieving minimum values for yield strength and elongation at break proves slightly harder than in Inconel 718. Minimum yield strength and UTS are however achieved by some AM samples. Minimum elongation is still harder to achieve. Porosity seems generally low, with the exception of the single concentration of pores found in SLM material.

5.2 First sub question

What are the differences in mechanical properties between parts produced with the individual AM-methods?

When it comes to Inconel 718, all AM methods prove capable of reaching the required minimum for yield strength. The same applies to the case of laser cladding for UTS. The elongation achieved was best in laser cladding as well, with the horizontal samples topping conventional ones. The WFEB samples do not fall far behind, but the SLM samples do. For the Young's modulus, all methods approach the standard values to an acceptable level. Porosity seems most severe in SLM produced material. When it comes to the material buildup process and the defects caused by them, SLM seems to have the most difficulties with producing defect free material.

For titanium 6Al4V, a big directional dependency is found in the yield strength and UTS values. SLM and horizontally laser cladded material achieves minimum values, but WFEB does not. WFEB does however show better elongation results, as does horizontal SLM. Vertical SLM performs badly, which might be caused by powder contamination. Whereas SLM had defects in Inconel 718, defects in titanium 6Al4V seem the biggest problem still for both laser cladding and WFEB welding.

5.3 General conclusions

The first general conclusion drawn from both the results and the observations and experiences during the production and testing phases is that the processes all prove capable of delivering material with investigated properties close to, or even better than, conventionally cast and wrought material. These results show that AM-production of parts could form a feasible alternative to conventional production. There is, however, much optimization to be done. KLM has more experience with the laser cladding and WFEB production of Inconel 718 and delivers better results there, whereas the NLR shows its experience in producing titanium 6Al4V using SLM and delivering better results there. This suggests that the amount of experience operating a certain process currently still has a large impact on the material properties. Aside from process experience, quality of used material has a large influence. However, the positive effect of research and experience is proven to improve results and should encourage both companies to commit to further optimization of their processes.

The second conclusion is that the time needed for this research turned out to be much longer than expected initially. Not only did production of the raw material take weeks longer than expected, but also the machining, X-raying and heat treating of the material took significantly longer due to the material going through the processes in separate batches. Finally, at multiple stages in this research there were moments where the slightest bit of extra delay would have meant that the material would not be ready in time for heat treatment or tensile testing. This should be taken as a learning experience for all parties involved, and future research should be planned with appropriate time buffers.

6 RECOMMENDATIONS

6.1 General recommendations

Following the conclusions drawn from the gathered results, recommendations can be given to both companies collaborating in this research. The first recommendation is to both companies, and is to improve quality control on the materials used in additive manufacturing processes. Whether it is the powder material used in laser cladding and SLM, or the wire material used in WFEB welding, the potential effect of low quality or contaminated material is detrimental for material properties in the produced parts. It is recommended that KLM and the NLR exchange experiences and quality test results on powder suppliers in order to ensure high quality delivered material and therefore minimize porosity. Regular testing of powder material should be performed to minimize the chance of powder contamination affecting produced parts. Furthermore, it is recommended that KLM achieve controlled gas storage of wire feed material for the WFEB process to prevent the found gas inclusions in the titanium 6Al4V material.

Secondly, it is recommended to both KLM and the NLR to commit to further research to investigate more properties such as tensile properties at elevated temperatures, creep behavior and fatigue properties. More important, however, is additional research on process parameters and their influence on build-up quality. While AM fabrication is still a young and unoptimized technology, experience with the processes and the machines used for them proves to be the biggest influence on achieved quality. Researching material produced with different power settings, welding speed, track distance or material feed speeds could result in increased properties and drastically reduce the chance of defects occurring.

6.2 Possible AM repairs

While the NLR is a company based around research and does not produce or repair parts for customers, the KLM does. Some repairs currently done at KLM may benefit from the use of AM-production in the repair process. In this subchapter, some these repairs will be discussed shortly.

The first one is a repair being performed on the turbine rear frame. Some areas of this frame piece tend to show fatigue cracks. This section is then cut out, and a so called ‘TRF patch’ is welded in using EB welding and some manual TIG welding. This is shown schematically in figure 50, and figure 51 shows a turbine rear frame with a patch welded in. Due to the geometry of the turbine rear frame, no single TRF patch is equal in shape. The surface of the patch needs to be a plane curved in multiple directions. Currently these TRF patches are produced using conventionally wrought Inconel 718 blocks, which are 5-axis CNC machined down to the exact required dimensions before being sanded and polished. Due to the lack of 5-axis milling capabilities, this production process is currently also outsourced, and only the weld repair is performed at KLM’s engine shop. This is a very costly process and could benefit from using a TRF patch produced with AM. An additional benefit is that the 3D measuring data of the pre machined area, currently required for CAD/CAM processing for the 5-axis milling operation, can immediately be used for the AM-manufacturing process without extensive 3D modelling in Autodesk Inventor and subsequent CAM processing. The recommendation is to use the laser cladding process to build up a TRF patch for this repair. The properties in the researched horizontal laser cladding material are very promising, and due to the curved but relatively flat geometry of the TRF patches, this would be an ideal part to produce horizontally using laser cladding. This would leave only minor machining before the patch can be welded into the rubine rear frame. Replacing conventional TRF-patch production with production using laser cladding would not only save KLM money, but also time by eliminating time consuming outsourcing of the TRF patch production.

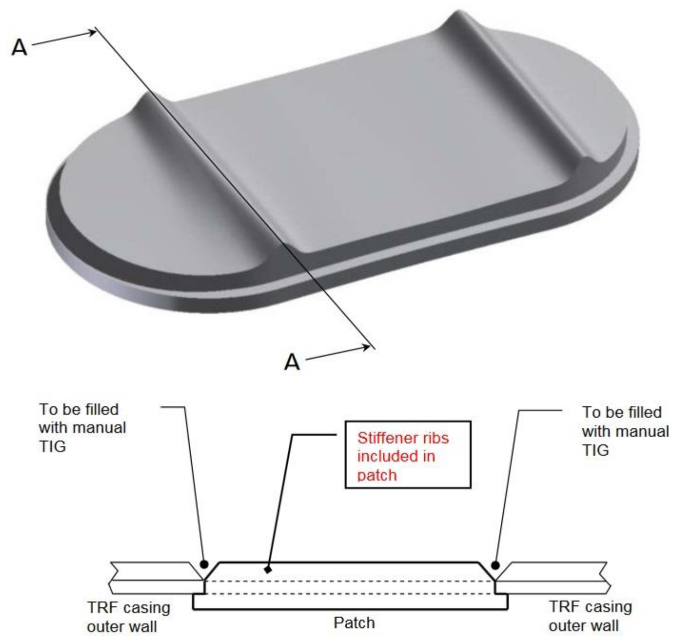

Figure 50 – Schematic TRF patch repair


Figure 51 – Welded patch in turbine rear frame

Another other repair that benefits from the use of AM is a repair being performed on stationary CDP seals. Figure 52 shows a cut through section of one of these CDP seals, and figure 53 shows one of the seals itself. The honeycomb backing strip, indicated in the figure, wears down during removal of the honeycomb being replaced during repair. When it gets below minimum dimensions, the seal has to be replaced. The strip could however be built back up using AM to prevent the seal from being scrapped. This repair has been attempted using WFEB material build-up to achieve required dimensions before machining the strip down to exact dimensions. Consistency in the achieved material has recently been being proven to GE however. I reccomend KLM continue research on similar AM repairs, as WFEB showed promising results in this research. With minimum yield strength and elongation acquired and a UTS close to minimum, horizontal WFEB material build-up shows it is capable of delivering adequate properties to be used in repairs like the CDP seal repair. Being able to repair these seals using AM will result in saved money through preventing these expensive parts from being scrapped.

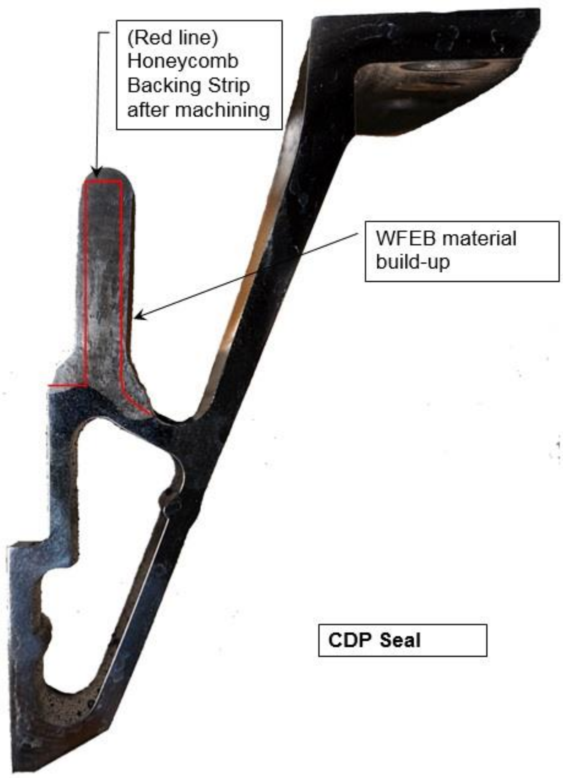

Figure 52 – CDP seal section

Figure 53 – CDP seal

The third and last repair in this report that benefits from AM production is a repair on Inconel 718 rotating seals. Figure 54 shows one of these rotating seals. The repair on these seals is currently being performed using automated conventional TIG welding. Tests have however proven the capability of the laser cladding machine to perform the required material buildup 8 times as fast as using conventional methods. Images of the test repair using laser cladding is shown in figures 55 and 56. On top of this reduced production time, post processing time would improve with at least a factor of 3. Currently, a testing schedule has been arranged with GE to prove consistent results of this repair method, and it is recommended KLM continues this research in order to reduce the time needed for this reseach and maximize the delivered quality.

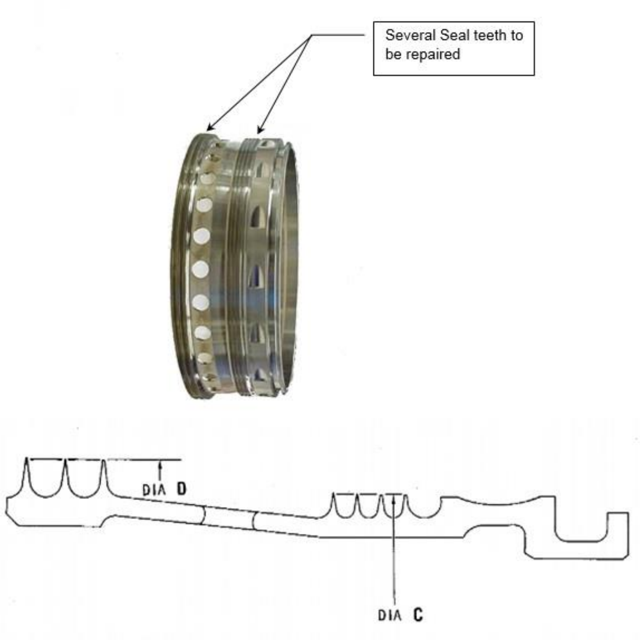

Figure 54 – Rotating seal teath repair schematic

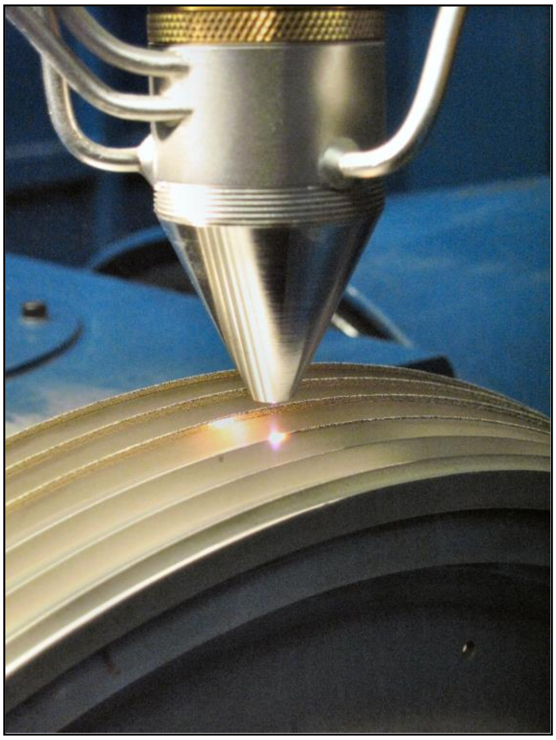

Figure 55 – Cladding head during seal teath repair

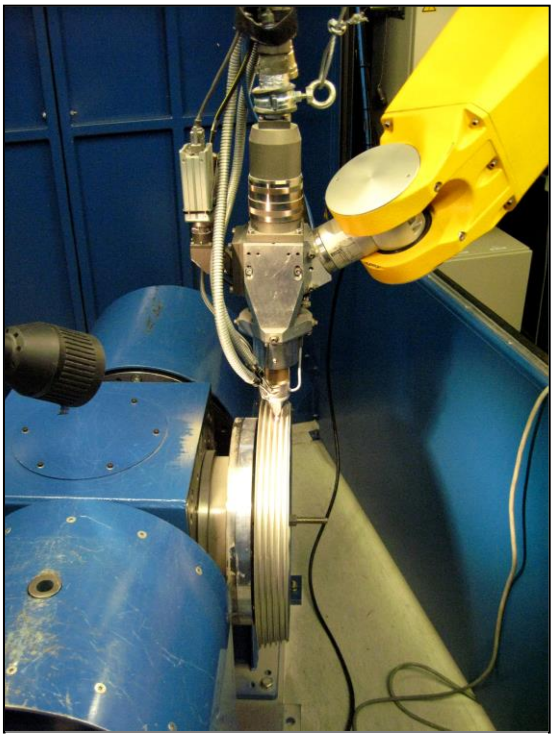

Figure 56 – Seal teeth repair using laser cladding

7 COMPETENCES

This report serves as the graduation report for bachelor in mechanical engineering. Part of graduating from this study at the HHS Delft is achieving a certain set of competences that is expected of all graduates. These competences are discussed in this chapter, and argumentation will be given as to how I achieved these competences. The first competence that is discussed, ‘Professionalizing’, is the only competence that has to be improved from competence level 2 to level 3. Out of all the other competences, two have to be chosen in which the competence level must at least remain at the level it had before the start of the graduation project. As these two competences I chose ‘Researching’ and ‘Advising’.

7.1 Professionalizing

Professionalizing is, out of the three selected competences, the only one that I achieved level 3 in during my graduation project. This means I am able to perform complex and unknown or unstructured tasks independently.

The first argument for me achieving this, is the fact that I have worked fulltime for over 4 months at a big, international company, KLM. During the course of this research, there were several branches within KLM that I had to communicate and collaborate with. Firstly, there was the engineering department which I belong to. These were my direct colleagues that I engaged in conversation with on a daily base. Secondly, there are the laser cladding and WFEB operators, of whom I had to request vast amounts of time and energy, and with whom I also collaborated in making test samples to get the parameters for production right. There was the X-ray facility which is, like the laser cladder and WFEB welder, operated by a single operator. Next there was the machining department, which involves several operators, operating in shifts. Especially with this department it was crucial that each time I delivered one or more batches of material, it was known to the current operator what was expected to be done. There were also the planning department for the engine shop, the furnace operator, and last but not least the laboratory at which I made the samples for microscopic analysis and performed this analysis. All these departments and operators not only have different working schedules, but also different amounts and areas of knowledge, making it a very multidisciplinary group of people to work with. It required professionalization on my part to form the connecting element between all of these parties, and to ensure that every operator and department was supplied with the knowledge, drawings or material to perform the tasks I needed them to perform.

Besides working as a graduate intern at KLM, I was also in close contact with the NLR. The tensile tests were also performed at the NLR, resulting in multiple visits to their testing facility. The research planning, boundaries, limitations etc. I had to set up taking in account both KLM and NLR's capabilities and expectations. Managing this collaboration between these two companies, which involved multiple conference calls, regular calls and dozens of emails, was made especially difficult by the difference in the two companies. Whereas KLM is a strictly economic operation, the NLR operates from a more scientific and research oriented business model.

7.2 Researching

The competence researching had been improved to level 2 before starting my graduation research. In order to graduate, this level of competence must have at least remained the same, meaning I am capable of performing complex but structured tasks mainly independently, but with help where needed.

The first example of achieving this competence is my ability to perform independent literature research on a subject unknown to me before starting my research. While receiving a decent amount of education on general knowledge of materialistic properties and behavior of metals, it was mainly limited to steel and other common alloys. Knowledge on the researched alloys, the used AM methods and the effect of the heat treatments used had to be gained during this research. I had to find multiple sources not only in the form of books, but also in the form of reports, thesis's and other sources found online. I had to validate these different sources for reliability before using them. The second example is the fact that I gathered and interpreted the data in this research independently. The results gathered in the tensile tests had to be processed into usable data and graphs before I interpreted these data in order to form conclusions. These conclusions and recommendations were formed with the use of the complex research questions that I've established independently too. The third and last example to prove my researching competence level is my ability to report my work in the standards used in the field of work my research was performed in. I have shown to be capable of describing the research accurately and understandably in well written English, the main language in the aerospace industry. I have written this report independently, only receiving minor feedback from my supervisor during the final days of writing, proving my capability of delivering a high quality research report in the industries standards.

7.3 Advising

The last competence, advising, I have also maintained at competence level 2. I have achieved this by using the data gathered and the conclusions drawn in this research to form my recommendations. Firstly, I independently gave general recommendations to both KLM and the NLR on future research and quality control. These recommendations I had to back up with data and conclusions that I gathered during the research I performed. I have thereby had to convince KLM and the NLR of the validness of my research and the accurateness of my conclusions. These recommendations I had to form in a relatively small timeframe given the amount of time available between tensile testing and the due date for this report. I also had to form the recommendations based on a relatively low amount of researched data. A large amount of variables had to be researched in a small amount of time. Forming an advice based on them required sufficient understanding of KLM’s working environment as well as understanding of the NLR’s testing environment. Secondly, with limited guidance, I made recommendations to KLM on several repairs that would benefit from AM production. This required me to learn how the repairs are currently being performed. It also required me to understand how the AM processes would fit into the current repairs, but also to understand how the different build-up behavior and mechanical properties would influence the parts in question. I performed the process of writing both the general conclusions and repair advice independently, with guidance in the form of supplied information and images, and feedback on my work, which I then processed.

8 APPENDICES

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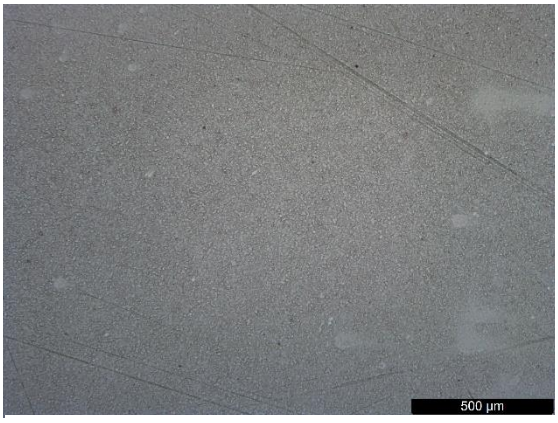
APPENDIX 1 – ADDITIONAL MICROSCOPIC IMAGES



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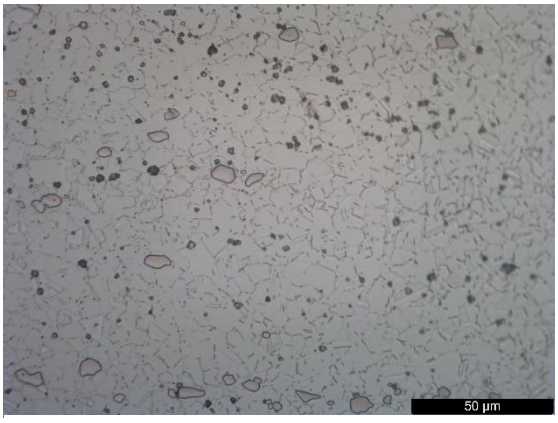

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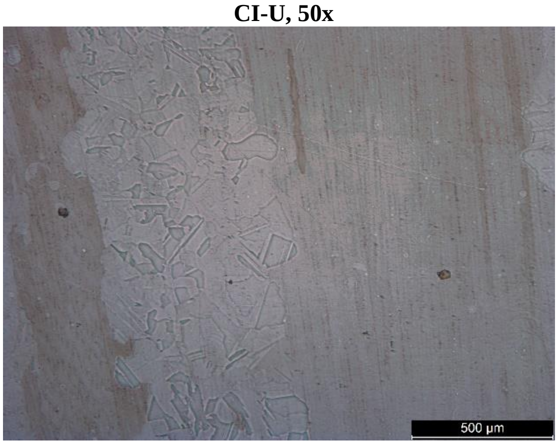

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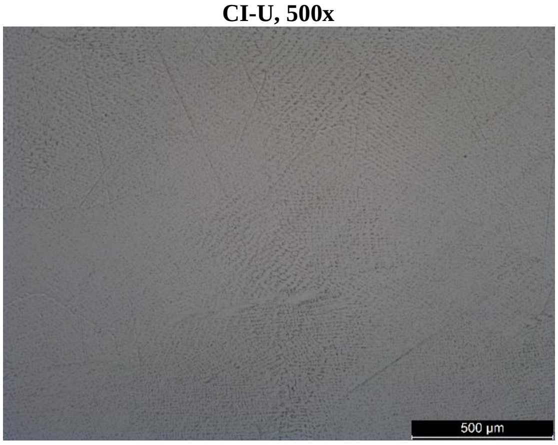

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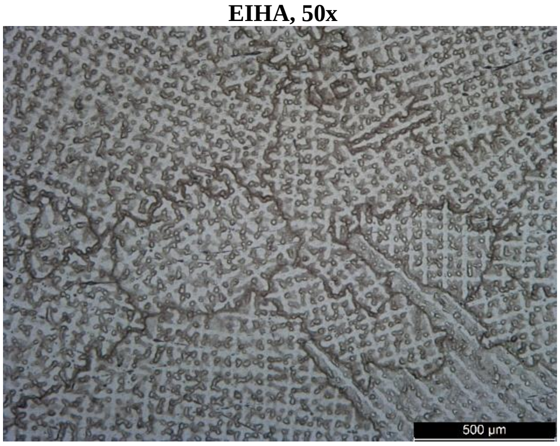

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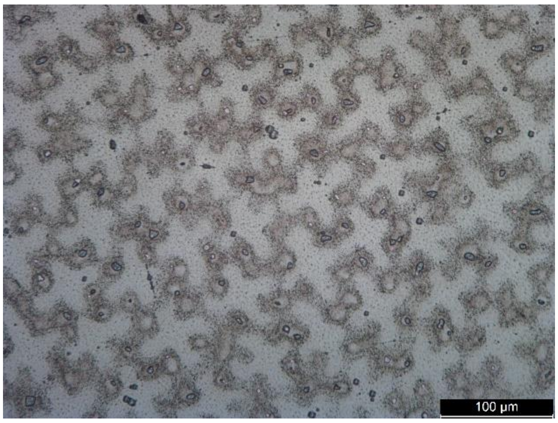

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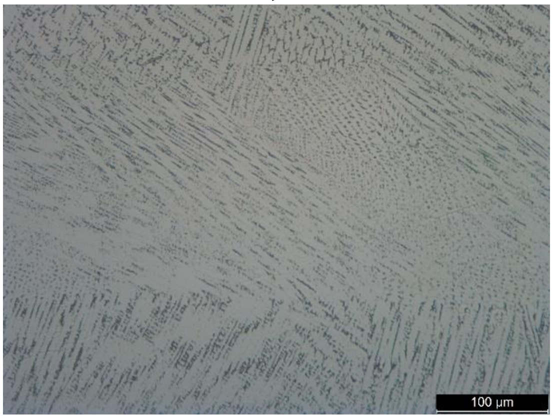

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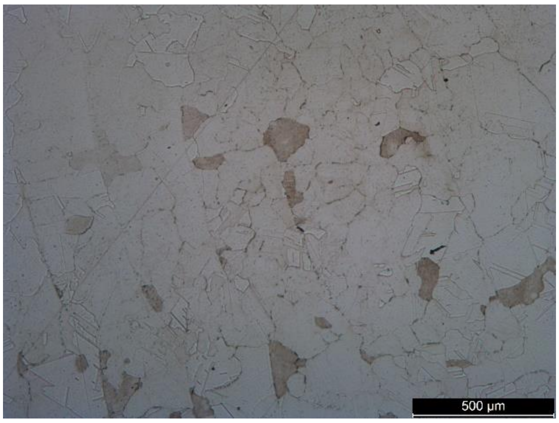

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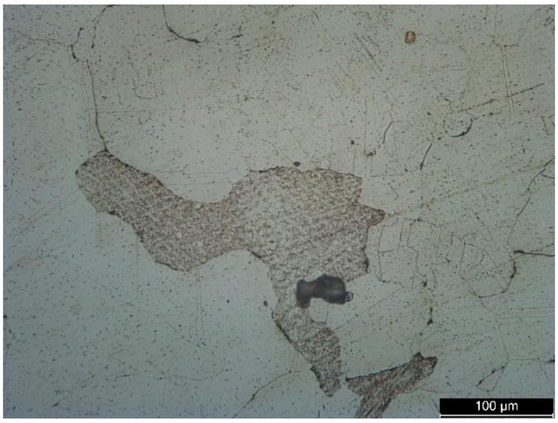

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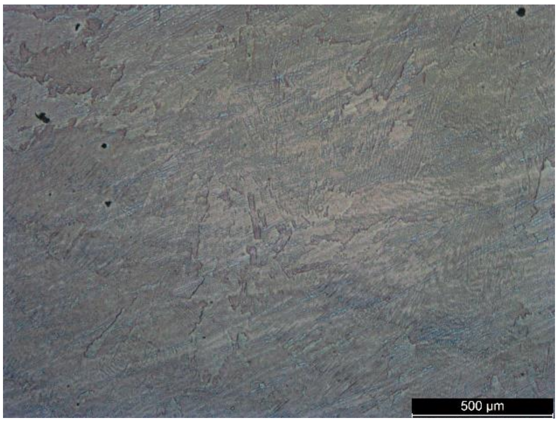

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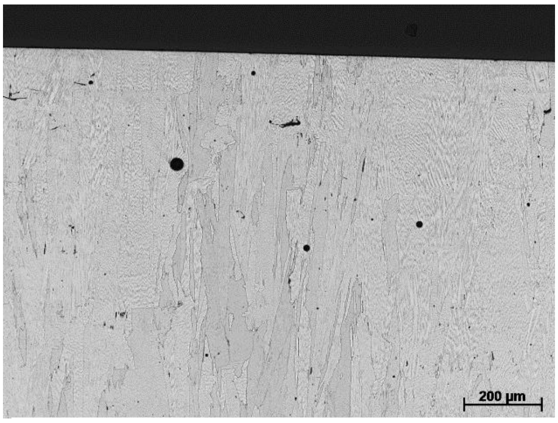

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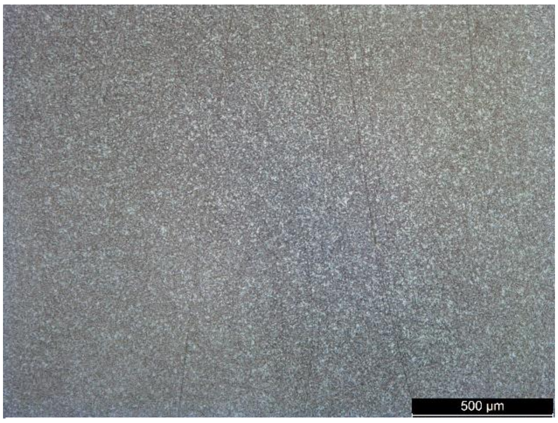

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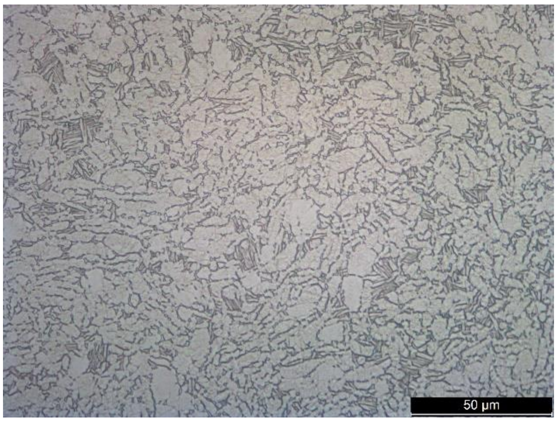

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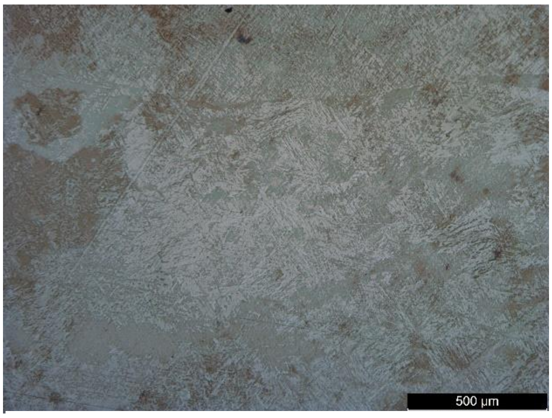

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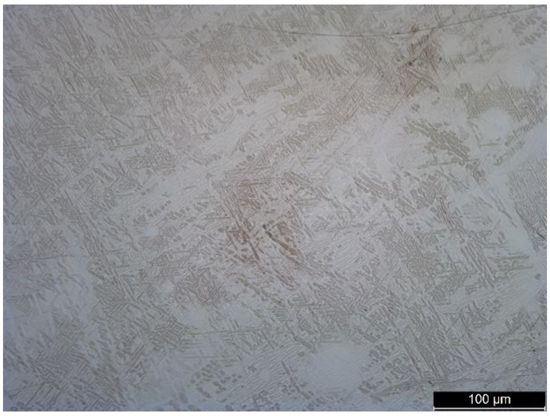
ETHU, 50x



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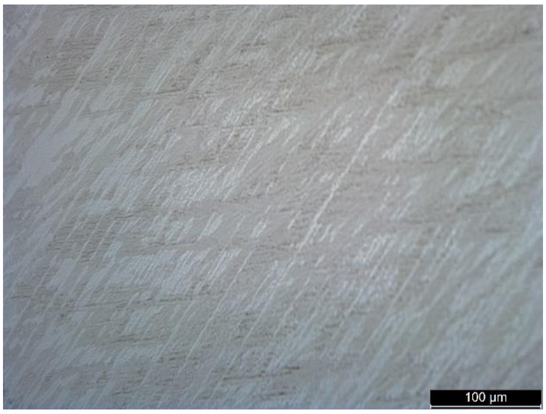

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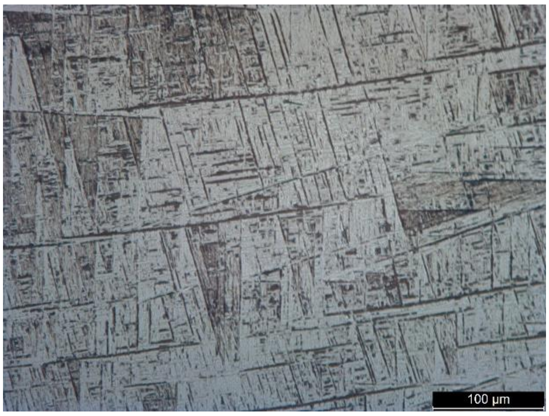

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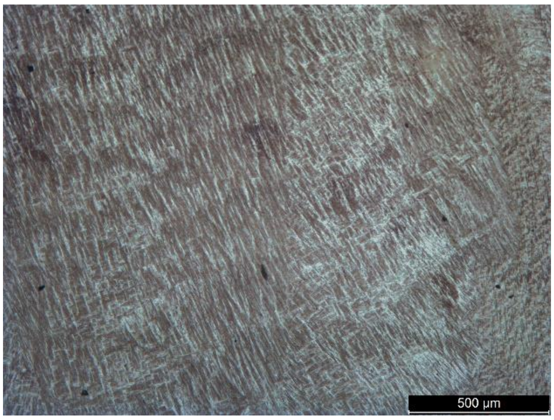

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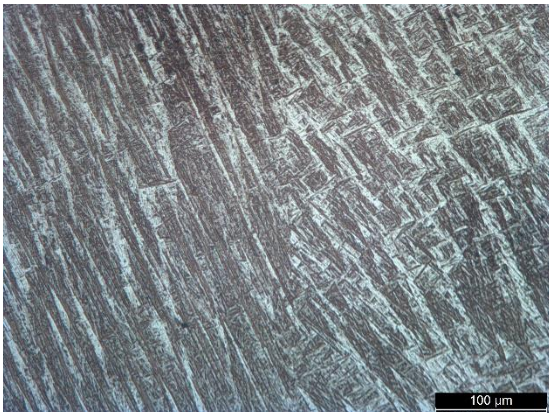

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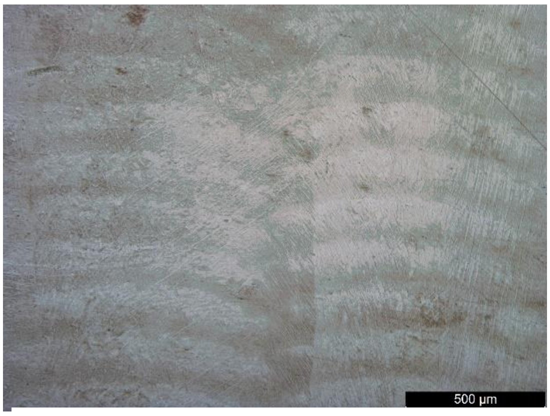

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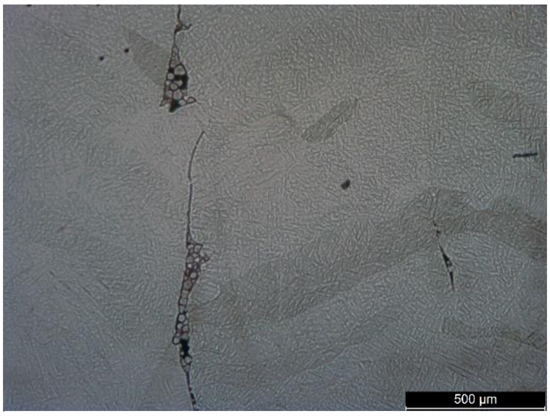
LTHU, 200x



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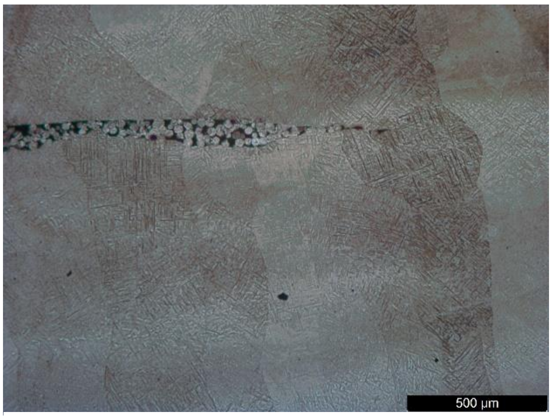

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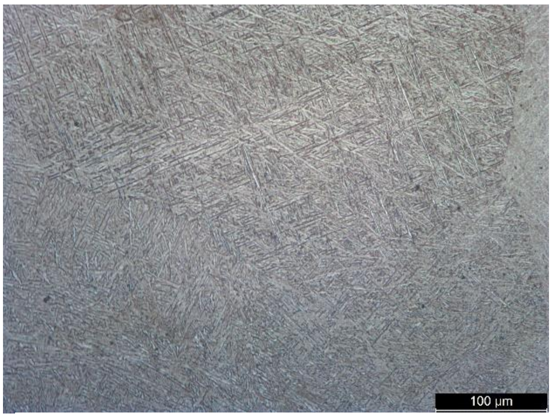

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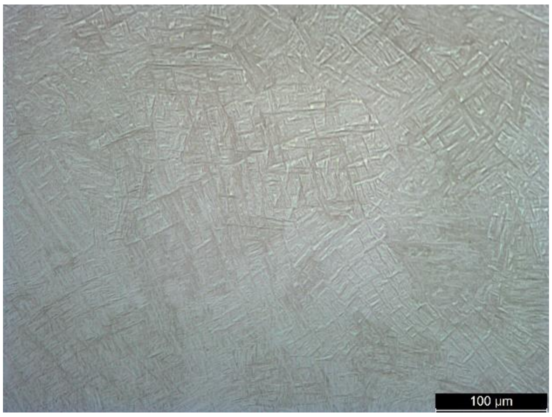

STHR, 200x

STVR, 50x

STVR, 200x

APPENDIX 2 - TENSILE DATA SETS

Sample code	Max. Load (kN)	Ultimate Tensile stress (MPa)	Modulus (Young's) (GPa)	Yield strength (Offset 0.2 %) (MPa)	% Elongation at break (Standard) (%)	Final diameter (mm)	Reduction of area at Area (%)	Diameter (mm)	Area (mm^2)
LIHU1	17.9	921	175	616	37.4	3.85	40	4.970	19.400
LIHU2	17.8	916	193	647	32.4	4.32	24.7	4.977	19.455
LIHU3	18.6	938	177	638	38.4	4.27	27.7	5.022	19.808
LIHA1	26.6	1360	190	1090	21.8	4.17	30.3	4.995	19.596
LIHA2	26.4	1340	184	1080	24.1	4.29	26.5	5.005	19.674
LIHA3	26.1	1340	182	1090	21.3	4.17	29.8	4.976	19.447
LIVU1	16	817	118	522	39.5	3.68	45.6	4.990	19.556
LIVU2	17	894	132	562	35.8	4.1	30.4	4.916	18.981
LIVU3	16	823	109	531	39.6	3.36	54.5	4.980	19.478
LIVA1	24.7	1270	182	838	25.1	4.35	23.3	4.968	19.384
LIVA2	25.7	1320	187	1000	29.5	3.96	36.5	4.969	19.392
LIVA3	25.4	1310	183	1070	26.1	3.99	35.5	4.968	19.384
LTHU1	21.4	1100	111	1010	3.91	4.68	11.2	4.966	19.369
LTHU2						4.957		4.957	19.299
LTHU3	21.4	1120	114	1000	4.95	4.75	7.77	4.946	19.213
LTHR1	19.5	1000	117	952	1.29	4.969	0	4.969	19.392
LTHR2	20.2	1040	114	972	5.71	4.58	14.7	4.959	19.314
LTHR3	20.4	1050	118	949	6.11	4.68	11.4	4.972	19.416
LTVU1	4.42	226				4.989	0	4.989	19.549
LTVU2	9.11	475	96.6	424	0.87	4.938	0	4.938	19.151
LTVU3	7.23	372	96.2	361	0.31	4.973	0	4.973	19.423
LTVR1	18.7	967	106	922	0.80	4.96	0	4.960	19.322
LTVR2	14.4	745	86.1		0	4.956	0	4.956	19.291
LTVR3	7.68	397	88.5		0.03	4.964	0	4.964	19.353
EIHU1	16.7	863	149	518	39.6	4.958	0	4.958	19.306

EIHU2	20.1	1000	206	622	29	5.051	0	5.051	20.038
EIHU3							0		0.000
EIHA1	23.6	1190	179	1000	18.4	5.034	0	5.034	19.903
EIHA2	26.1	1320	186	1080	18.5	5.019	0	5.019	19.784
EIHA3	23.3	1180	184	996	14.3	5.023	0	5.023	19.816
EIVU1	14.3	758	211	313	41.9	3.22	56.7	4.869	18.620
EIVU2	16.2	856	158	429	44	3.79	40.4	4.909	18.927
EIVU3	15.4	823	113	407	31.5	3.38	51.9	4.873	18.650
EIVA1	20.8	1130	159	884	15.2	4.39	18.1	4.851	18.482
EIVA2	21.2	1170	128	853	17.8	4.03	29.8	4.810	18.171
EIVA3	20.2	1080	138	757	28.3	3.79	39.5	4.873	18.650
ETHU1	15.1	754	127	553	14.1	4.03	36.4	5.053	20.053
ETHU2	14.6	745	113	568	14	3.24	57.9	4.993	19.580
ETHU3	15.6	759	129	562	10.1	4.24	31.3	5.117	20.565
ETHR1	15.2	805	118	685	9.12	4.06	31.6	4.909	18.927
ETHR2	15.1	795	118	676	11.4	3.65	44.8	4.912	18.950
ETHR3	14.8	782	115	717	5.42	4.3	23.6	4.918	18.996
ETVU1	13.9	743	116	632	6.37	4.32	21.7	4.882	18.719
ETVU2	14.2	749	115	588	11.7	3.85	38.7	4.917	18.988
ETVU3	16.7	861	105	718	9.48	4.3	24.9	4.962	19.338
ETVR1	13	673	102	573	8.62	4.7	10.5	4.969	19.392
ETVR2	12.7	675	117	569	10.6	4.67	9.06	4.897	18.834
ETVR3	14.9	786	104	686	8.27	4.86	2.46	4.921	19.019
SIHA1	23.5	1180	205.1	990	12.9				0.000
SIHA2	23.5	1200	208.3	1010	10.9				0.000
SIHA3	22.4	1150	208.8	999	7.1				0.000
SIVA1	23.1	1180	135.9	1000	4.04				0.000
SIVA2	24.1	1220	138.7	1010	4.8				0.000
SIVA3	24.1	1230	136.9	1010	4.7				0.000
STHR1	19.5	1000	116	929	12.5	3.878	39.2	4.974	19.431
STHR2	19.6	1010	114	930	13.6	4.126	31.2	4.975	19.439
STHR3	19.5	1010	114	935	12.8	4.122	31.3	4.973	19.423

STVR1	18.5	949	114	839	5.78	4.813	6.52	4.978	19.463
STVR2	17.9	919	113	845	1.32	4.938	1.52	4.976	19.447
STVR3	18.1	939	110	852	2.03	4.845	4.51	4.958	19.306
CI-U1	20.6	1050	119	629	48.1	3.68	45.9	5.005	19.674
CI-U2	20.7	1050	142	619	48.3	3.8	42.8	5.024	19.824
CI-U3	20.2	1040	155	617	47.1	3.78	41.9	4.959	19.314
CI-A1	26.3	1350	159	1080	24.6	3.99	35.6	4.972	19.416
CI-A2	26	1360	171	1090	21.7	3.87	38.5	4.936	19.136
CI-A3	26.2	1360	173	1080	22.1	3.98	35.4	4.951	19.252
CT-U1	14.5	732	117	642	10.6	3.66	46.9	5.021	19.800
CT-U2	19.7	1020	114	932	15	3.54	49.1	4.961	19.330
CT-U3	19.1	1020	110	917	9.18	3.74	41.7	4.897	18.834
CT-R1	20	1010	113	929	16.7	3.85	40.9	5.009	19.706
CT-R2	19.3	1000	125	926	15.2	3.77	42.1	4.954	19.275
CT-R3	19.5	1000	115	926	15.6	3.8	41.5	4.969	19.392

APPENDIX 3 – PROCESS PARAMETERS

EIHA:

* Beam Current = 15mA

* Gun Voltage = 30 kV

* Welding Speed = 450 mm/min

* Wirefeed speed in 450mm/min

* Work distance = 200 mm (sharp focus = 355 mm)

* Filler Wire Diameter = 1.1 mm, Inconel 718

EIVA:

* Beam Current = 15mA

* Gun Voltage = 30 kV

* Rotation speed of rotary table = 4.5 rpm

* Wirefeed speed in 450mm/min

* Work distance = 200 mm (sharp focus = 355 mm)

* Filler Wire Diameter = 1.1 mm, Inconel 718

ETHR:

* Beam Current = 20mA

* Gun Voltage = 30 kV

* Welding Speed = 150 mm/min

* Wirefeed Speed 150mm/min

* Work distance = 200 mm (sharp focus = 355 mm)

* Filler Wire Diameter = 1.1 mm, Titanium 6Al4V

ETVR:

* Beam Current = 15mA

* Gun Voltage = 30 kV

* Rotation speed of rotary table = 5 rpm

* Wirefeed speed in 500mm/min

* Work distance = 200 mm (sharp focus = 355 mm)

* Filler Wire Diameter = 1.1 mm, Titanium 6Al4V

LASER CLADDING INCONEL 718

Offset: 8. 5 mm (dus focus 8.5 mm boven het oppervlak)

Layer height: 0.28 mm

Laserpower: 500W

Shielding gas Argon: 35 l/min

Carrier gas Argon: 11 l/min

Welding speed 8 mm/sec

Powder: 25 mg/sec

Distance nozzle to part: 7 mm

LASER CLADDING TITANIUM 6AL4V

Offset: 8. 5 mm (dus focus 8.5 mm boven het oppervlak)

Layer height: 0.6 mm

Laserpower: 375W

Shielding gas Argon: 35 l/min

Carrier gas Argon: 11 l/min

Welding speed 7 mm/sec

Powder: 35 mg/sec

Distance nozzle to part: 7 mm

SLM TITANIUM

Laserpower: 350W

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