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Chair of Drilling and Completion Engineering

Master's Thesis

Investigation of Additive Manufacturing of Components for the Oil & Gas Industry

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Abstract

Drilling operations and production facilities of the oil and gas industry are spread around the globe, also in remote locations, offshore or in the desert. In several cases, it is impossible to make the right component available at the right time to the right location, without enormous additional costs or effort. Manufacturing the required component to the exact specification directly at the location certainly adds huge benefits. Other industries such as automobile, aerospace have applied this just-in-time strategy very effectively by using the fast-developing additive manufacturing technologies.

This thesis is embedded in an overall project which is performed by the Chair of Drilling and Completion Engineering together with OMV E&P GmbH. It investigates the usage of additive manufacturing in the oil and gas industry.

The content of the thesis is divided into three main phases: testing of additive manufactured parts, an oil and gas specific SWOT-Analysis and a methodology describing the workflow for spare part manufacturing.

During the first phase of the thesis the additive manufactured parts, which were produced from the selected material, 1.4542 (17-4 PH), are evaluated and compared to a conventionally manufactured part and the metal grade API C-110, which is a controlled yield strength casing or tubing grade. This phase includes the preparation of the specimens, testing and analysis of the results. The behavior of the material in hardness, tensile and Charpy-V notch impact tests is evaluated. Sulfide stress cracking (SSC) and hydrogen-induced cracking (HIC) tests were conducted in an external lab.

For the second phase, a SWOT-Analysis is performed to evaluate the general opportunities and shortcomings of this manufacturing method, as well as the specific chances for embedding it into the supply chain of an oil and gas production or service company.

During the third phase of the thesis, a methodology or workflow to produce an additive manufactured part is evaluated and established. The workflow starts at the point where it is recognized that a specific component is needed at the rig or the production facility and ends when the manufactured part can be delivered to this location. Therefore, different methods are investigated and researched to create a 3D model where a blueprint may not be available for a variety of reasons.

The main objectives of the thesis are to gain knowledge about the properties, particularities and limitations of additive manufactured parts, especially for the application in the oil and gas business. Furthermore, the benefits of integrating this technology in certain areas are shown to get one step closer to a safe and efficient way to use it in the oil and gas industry.

Zusammenfassung

Bohrungen und Förderanlagen der Öl- und Gasindustrie sind über die ganze Welt verteilt, auch an abgelegenen Orten, auf Hoher See oder in der Wüste. In einigen Fällen ist es unmöglich das richtige Teil, zur richtigen Zeit, an der richtigen Stelle zur Verfügung zu haben, ohne enorme zusätzliche Kosten und Aufwand. Die Herstellung des benötigten Teiles direkt vor Ort würde einen großen Vorteil bringen. Diese „just-in-time“ Strategie wird bereits in anderen Bereichen, wie der Automobilbranche oder der Luftfahrtindustrie, durch den Einsatz von Additiver Fertigung angewendet.

Diese Masterarbeit ist Teil eines Projektes, welches vom Lehrstuhl für Drilling and Completion Engineering zusammen mit der OMV E&P GmbH durchgeführt wird. Ziel ist es, den Gebrauch von Additiver Fertigung in der Öl- und Gasindustrie zu untersuchen.

Der Inhalt der Masterarbeit ist in drei Phasen aufgeteilt: Testung der durch Additive Fertigung hergestellten Teile, eine Öl und Gas spezifische SWOT-Analyse und einer Methodik die den Arbeitsablauf für die Ersatzteilherstellung beschreibt.

Während der ersten Phase der Arbeit werden die additiv gefertigten Teile, welche aus dem ausgewählten Material, 1.4542 (17-4PH), hergestellt wurden, getestet und mit konventionell hergestellten Teilen sowie der API C-110 Klasse, einer geregelten Casing und Tubing Klasse, verglichen. Das Verhalten des Materials wird mit Hilfe von Härtetests, Zugversuchen und Kerbschlagbiegeversuchen ermittelt. Weiters wurden Tests zur Spannungsrisskorrosion und Wasserstoffinduzierten Korrosion in einem externen Labor durchgeführt.

Für die zweite Phase wurde eine SWOT-Analyse durchgeführt, um die generellen Möglichkeiten und Mängel die dieses Fertigungsverfahren mit sich bringt zu untersuchen, aber auch um die speziellen Chancen, die sich aus der Verwendung dieser Technologie in der Lieferkette von Öl und Gas Produktions- oder Service-Firmen ergeben, aufzuzeigen.

In der dritten Phase der Masterarbeit wurde eine Methodik bzw. ein Arbeitsablauf erarbeitet. Dieser startet an jenem Punkt an dem erkannt wird, dass ein bestimmtes Teil am Bohrturm oder der Förderanlagen gebraucht wird und endet, wenn der additiv gefertigte Teil geliefert werden kann. Es werden dabei auch verschiedene Methoden untersucht und erläutert, die verwendet werden können, um das benötigte 3-D Model des Teiles zu erzeugen wenn dieses nicht verfügbar ist.

Das Hauptziel der Masterarbeit ist es einen Einblick in die Eigenschaften, Besonderheiten und Limitierungen von Additiver Fertigung und den resultierenden Teilen zu bekommen, mit dem Fokus auf dem Einsatz in der Öl- und Gasbranche. Darüber hinaus sollen die Chancen die durch die Verwendung dieser Technologie in gewissen Beriechen entstehen gezeigt werden, um einen Schritt näher an einen sicheren und effizienten Gebrauch dieses Verfahrens in der Öl- und Gasindustrie zu kommen.

Acknowledgements

First of all, I want to thank my supervisor Univ.-Prof. MBA, Ph.D. Kris Ravi for, letting me be a part of this interesting and future-oriented but also challenging project. Additionally, I am thankful for his guidance and important input during the whole time.

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Contents

Chapter 1 Introduction

The ongoing development in the sector of additive manufacturing (AM) leads to a growing usage area of this technology and the transition from a rapid prototyping technology to a full-grown production technology that should be integrated into the supply chain of a modern company. The thereby growing flexibility regarding the geometry of the part, its manufacturing time and the production amount lead to interesting possibilities for the industry.

In the oil and gas sector, possible lead times can be very high due to operations in remote areas, like the sea or the desert. Additionally, those result in downtime of a drilling rig or a production facility, which leads to enormous additional costs or the loss of essential revenues. A just-in-time and also possible on-location manufacturing technology would, therefore, be quite promising. Besides the location and the time flexibility advantages, oil and gas companies would also benefit from the possible reduction of the warehouse size and the reduction of limitations during the manufacturing process.

Even though AM is already used in various areas, such as aerospace or for medical purposes, there are still significant uncertainties and much diverse information. The goal of the project in which this master thesis is embedded is to evaluate the feasibility and benefits but also shortcomings of using parts that are AM in the oil and gas industry. Additionally, to identify the necessary steps to implement and apply this manufacturing technique. The content of this master thesis is split into three main parts, the material testing phase, SWOT analysis and a workflow for the reproduction of a part using AM.

In the introduction chapter, background information, like the material and the shape of the parts, which were manufactured, using selective laser melting (SLM), and afterwards used for the tests, are provided.

In the testing phase, AM parts are tested and compared to the conventional manufactured one in regards to their mechanical properties. The purpose is to get an overview of the comparability of products from the different manufacturing processes. The SWOT-Analysis will highlight possibilities but also the limitations and challenges which come along with AM, specifically for the usage in the oil and gas industry. The last part, the workflow, will explain the necessary steps from a part that is needed to an AM spare part that arrives at the location.

1.1 Additive Manufacturing - Method

In general, AM processes are methods where parts are manufactured by adding elements and segments of a specific material. These materials can be polymeric, plastic, ceramic and metallic. For the present thesis and the overall project, the focus is on AM technologies using metal as feedstock material. The 3D model of the part is sliced into layers of a certain thickness, which is dependent on the material and the AM method used. The part is then manufactured layer by layer until it is completed, this process is the significant difference to conventional manufacturing and the reason for the different behavior of the parts regarding their mechanical, thermal and chemical properties under static and dynamic conditions. (Dehghanghadikolaei et al. 2018) The necessary process steps from to manufacture an AM part are further explained in Chapter 4.

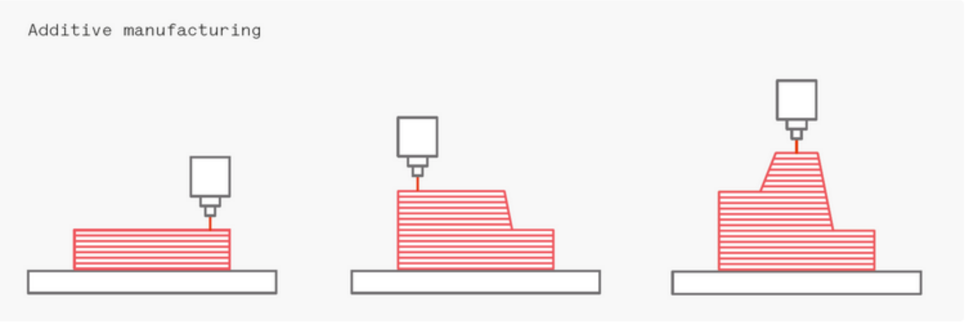

Figure 1: Schematic of the Additive Manufacturing Process (3D Hubs website)

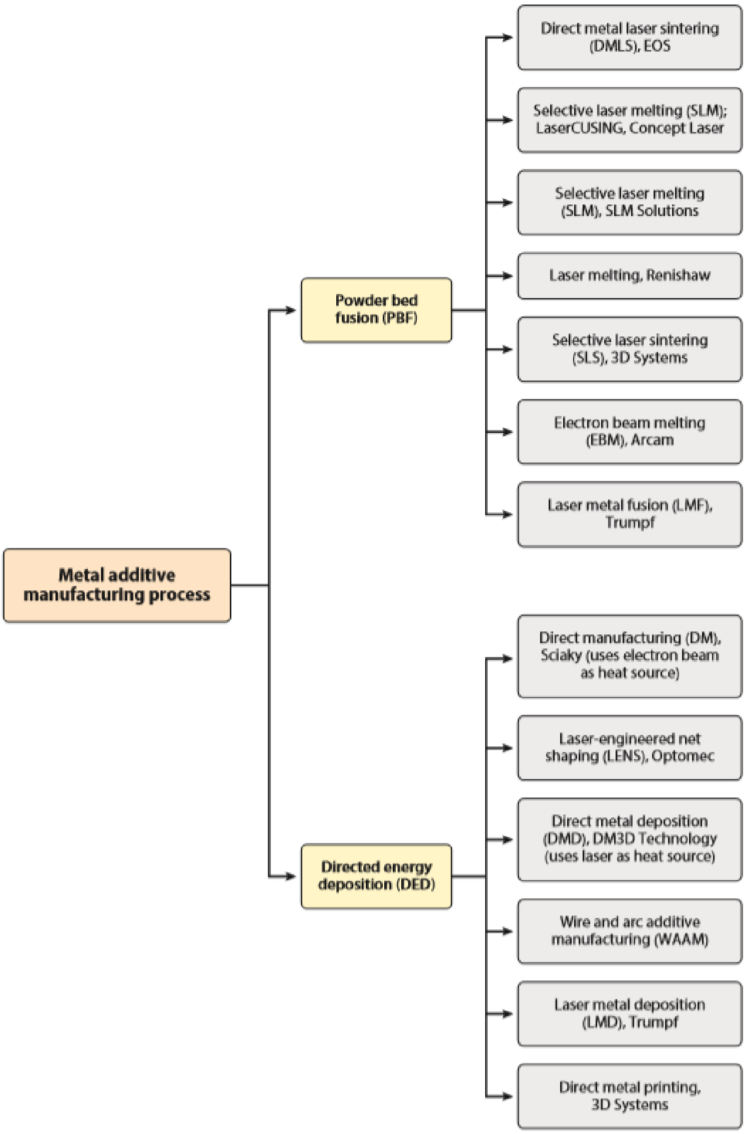

Figure 2: Different AM process (Lewandowski et al. 2016)

Figure 2 shows different AM methods. The main difference between the powder bed fusion (PBF) technologies and the directed energy deposition (DED) is the application of the material. In the PBF group, the material is fed over the whole production area and only the necessary structures are melted. DED technologies apply the material near the energy source, only where it is actually needed. (Lewandowski et al. 2016)

The parts produced for this project were manufactured using the SLM method. This method is powder-based, which means the material feedstock is a metal powder, which is fed into the build chamber by a roller or coater. The file with the sliced model provides the information for every layer. The laser receives this information and moves on the defined path. The powder which was in contact with the laser melts and the rest remains untouched and can be used again. This process is repeated layer-by-layer. The direction in which the part is growing layer-by-layer is called the building direction. During those steps, the chamber is under a controlled atmosphere, either vacuum or an inert gas, like nitrogen, at air pressure. With this method, a density of over 99% is achievable. The advantages of this method, compared to other AM methods, is the high flexibility in geometry as well as the accuracy of the final part, additional this method has a high process speed compared to other AM technologies. SLM machines can fabricate multiple parts at ones. However, the limiting factor is the size of the build chamber. Figure 3 represents a schematic of this process. (Dehghanghadikolaei et al. 2018)

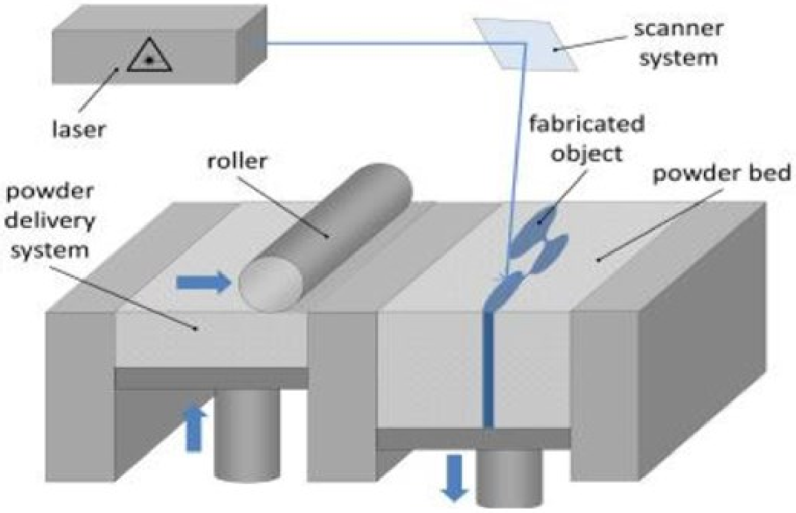

Figure 3: Schematic of the SLM method (Dehghanghadikolaei et al. 2018)

1.2 Material

The selected material for the experiments is 1.4542 / 17-4PH / AISI 630 / X5CrNiCuNb16-4 / UNS S17400, which is a precipitation hardened stainless steel. In general, it is corrosion resistant and has excellent mechanical properties, but it is also known for being susceptible to stress corrosion cracking (SCC) and also sulfide stress cracking (SSC) under certain circumstances. (Pfennig et al. 2017) In the oil and gas industry

17-4PH is used in wellhead components, valve assembly systems and the drill string. (Coseglio 2017)

	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	Nb	Fe
Min. (%)						15.00	3.00		3.00	5xC	bal.
Max. (%)	0.07	0.70	1.50	0.04	0.015	17.00	5.00	0.60	5.00	0.45	bal.

Table 1: Chemical composition of the material 17-4PH in weight % (Thyssenkrupp 2018)

ThyssenKrupp produced the powder, which was used for the manufacturing of the parts in this project and Figure 4 shows the metal powder under the scanning electron microscope (SEM).

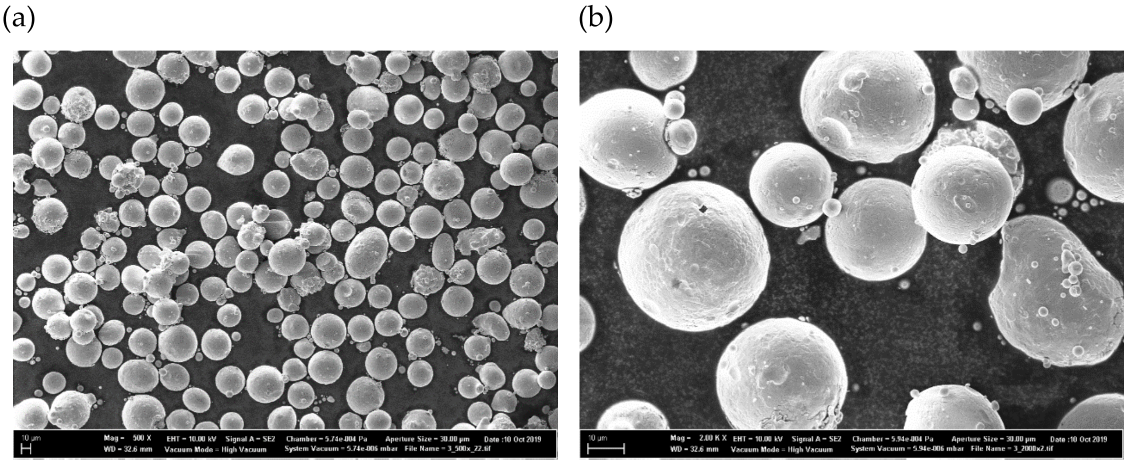

Figure 4: SEM image of the used metal powder (a) Magnification 500 (b) Magnification 2000 (Courtesy Fraunhofer)

D10	D50	D90
23.5 µm	34.4 µm	50.0 µm

Table 2: Particle size distribution (Thyssenkrupp 2018)

1.3 Process parameters

A variety of process parameters have a significant influence on the AM parts and its mechanical properties. These parameters are further discussed in Chapter 4.4. One of these parameters is the layer thickness, which was 30 µm in this case. Layer thickness describes the size of every new layer, which is fed into the chamber before the laser starts to scan.

Another critical factor that needs planning is the laser path or usually called scan strategy. This is usually performed with the support of the software used to command the AM machine. The scan strategy controls the melting and solidification process and has, therefore, an influence on the microstructure and the properties of the AM parts. The direction and stripes change after every layer. Figure 5 represents an extraction of the scan strategy for the manufactured parts. Herby, it is possible to see that the direction of the stripes changes every layer by 90 degrees and also, the stripes move by 1 mm. This is used to ensure that no local weak points are created and to reduce the number of pores that are systematically built. (Keshavarzkermani et al. 2019)

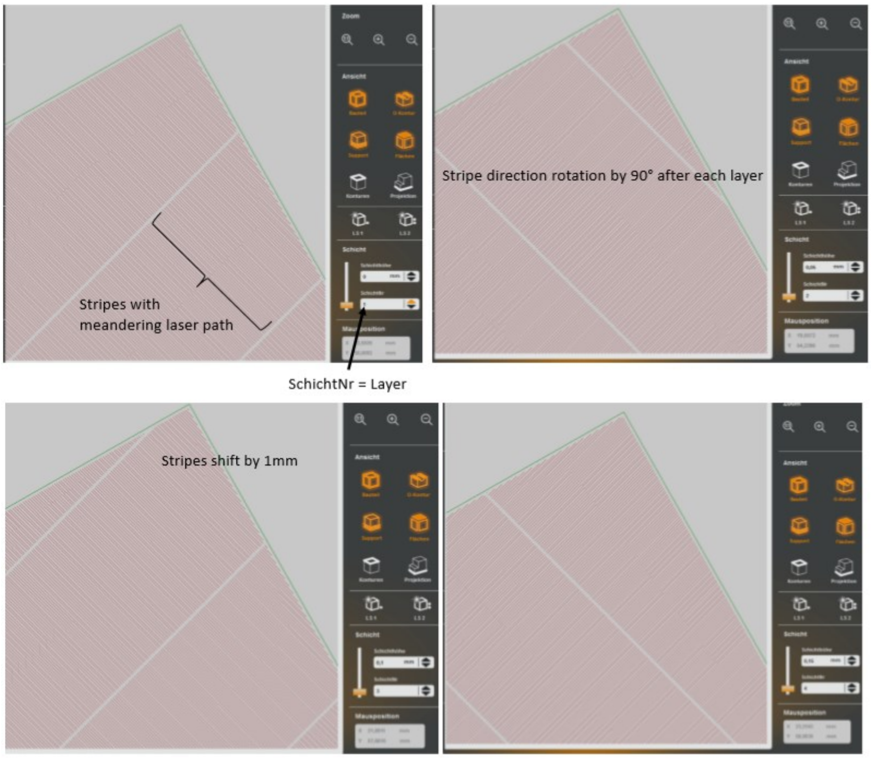

Figure 5: Laser path design – Change of the direction and stripes for different layers (Courtesy Fraunhofer)

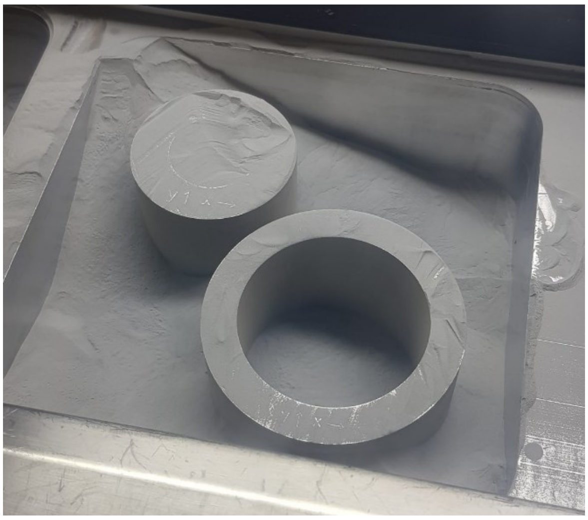

Figure 6: AM pipes in the manufacturing unit (Courtesy Fraunhofer)

Figure 6 shows two hollow cylinders in the manufacturing unit directly after the manufacturing process. A fraction of the residual, unmelted powder is still in the chamber.

After the AM process, heat treatment was performed to increase the strength and hardness of the material. The heat treatment included solution annealing at 1040°C for 45min and H900 precipitation hardening according to ASTM A564, which is at a temperature of 480°C for 1h. (A01 Committee 2019)

1.4 Additive Manufacturing parts

The parts selected for printing are shown in Table 3. Two hollow cylinders with different dimensions and five plates were printed. The hollow cylinders were manufactured to keep the cutting of the specimens simple. The plates were used to perform the tensile tests, also perpendicular to the building direction. The definition of the building, respectively, printing direction are shown in Figure 7 on the example of a cylinder. The reason for the tests in different directions is to evaluate the influence of building and printing direction onto the mechanical properties of the part. This is, therefore, interesting as the building process is entirely different in those two directions. In the building direction layer after layer is attached, perpendicular to that, the printing direction, we have a continuous surface.

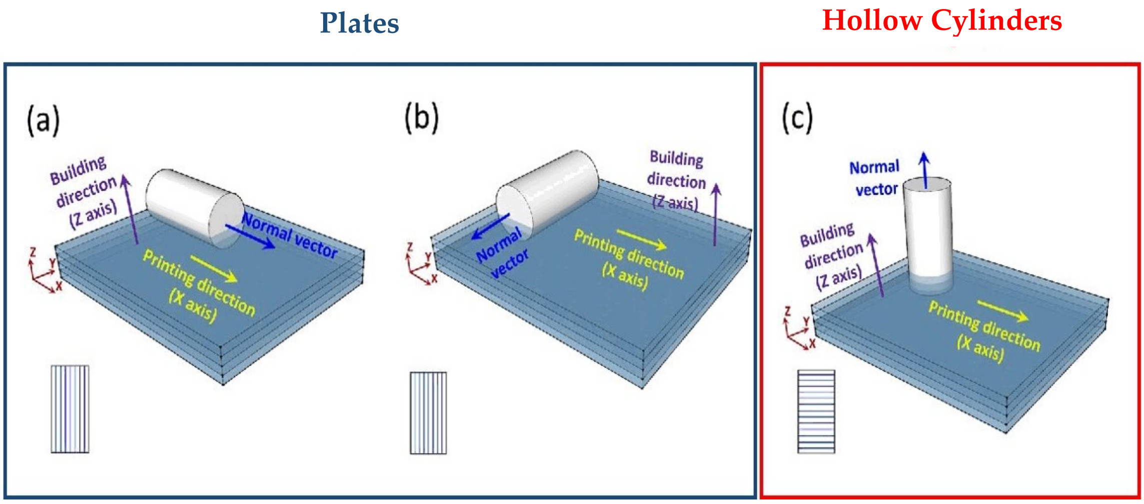

Figure 7: Building direction on the example of a cylinder – the plates were manufactured laying like in (a) and (b) and the hollow cylinders standing like (c) (Courtesy Fraunhofer adapted from Wang et al. 2017)

Hollow Cylinders			
Part number	OD (mm)	Wall thickness (mm)	Height (mm)
1	127	17.26	100
2	88.9	20.53	100
Plates			
Part number	Length (mm)	Width (mm)	Height (mm)
1	100	55	15
2	100	30	15
3	100	15	15
4	100	15	15
5	100	15	15

Table 3: Characteristics and dimensions of the manufactured hollow cylinders and plates

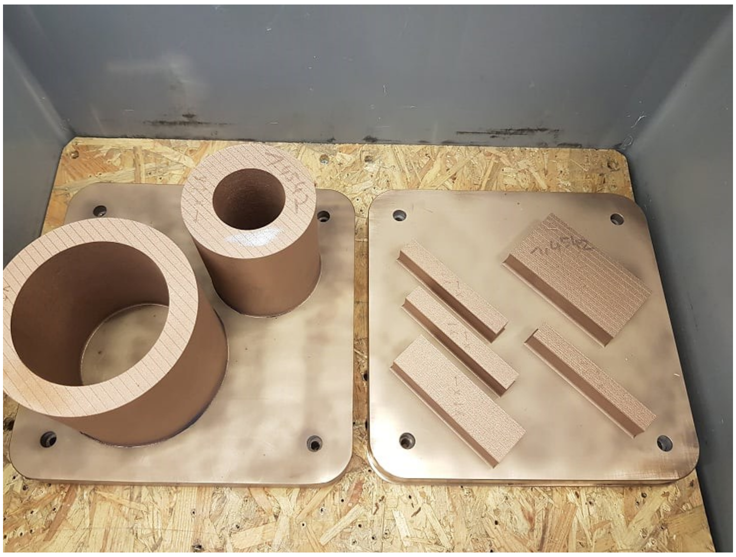

Figure 8: AM parts on the base plate after the heat-treatment (Courtesy Fraunhofer)

Figure 8 represents the parts still attached to the base plate. They were later separated by wire discharge machining. Two printing jobs were necessary to manufacture all parts. Thus, two build plates are in the image. The colour of the parts is resulting from an oxide layer due to heat treatment.

Chapter 2 Material testing

To evaluate the possibilities and shortcomings of the 17-4Ph AM material, a series of tests were performed to be able to evaluate their properties in comparison to a conventional manufactured material, which was also tested in parallel. The AM material was also compared to the standardized properties of a C-110 API grade, a common grade in the oil and gas industry. Literature values shown in some test results in this chapter and also in the first row of Table 4, are the minimum values a conventional 17-4Ph material needs to have.

The tests, except for the SSC and the HIC, which were outsourced to Voestalpine Tubulars, were all performed in the OMV TechCenter in Gänserndorf. The SEM images were taken at the Montanuniversität Leoben. Before the tests, the chemical composition of the additive and the conventional material was measured to ensure it meets the required values.

2.1 Expectations

One reason to conduct the tests and to determine the mechanical properties during this phase was that there are no clear standards or values an AM material needs to meet. The mechanical properties vary with different parameters used in the AM process. Table 4 shows values regarding the tensile test and the hardness of 17-4PH material from different sources.

Source	Material	Yield point/ $R_{p0,2}$ [MPa]	Tensile strength/ R_m [MPa]	Hardness [HV]
Deutsche Edelstahlwerke	Conventional Manufactured – H900[1]	≥ 1170	≥ 1310	≥ 406
SLM solutions	AM 30 µm layer – H900	mean 1024	mean 1308	mean 352
	AM 50 µm layer – H900	mean 897	mean 1189	mean 367
Amteq[2]	AM – H900	≥ 1200	≥ 1300	-
EOS	GP1 [3] – Stress relieved	mean (weaker direction) 550	mean (weaker direction) 980	mean 250
Thysen Krupp	AM – as printed	550-590	750-910	220

Table 4: Mechanical properties of 17-4PH from different sources and suppliers (Conventional, AM H900, AM; Deutsche Edelstahlwerke 2018, SLM Solutions; EOS GmbH 2009, Thyssenkrupp AG website)

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[1] Heat treatment according to ASTM A564, solution annealing and precipitation-hardening at a temperature of 900°F

[2] AM company – anticipated value for their products

[3] Powder name from EOS, composition corresponds to 17-4PH

2.2 Nomenclature of the specimens

All tests were prepared and conducted in different axis, in building direction as well as perpendicular to it. These additional tests are performed to measure the influence of building direction and its impact on the properties and the microstructure. The specimens for the AM part were machined out of a pipe and a plate. For the conventional material, they were machined out of a rod.

Every specimen has a particular name. The first letter always indicates the manufacturing process "A" for AM and "C" for conventional manufacturing. The metallic cuts are named further by the axis, which is perpendicular to the surface of the cut. The Charpy-V notch impact tests and the tensile test were also performed in two directions with the AM material, where "L" means lengthwise, which is parallel to the building direction and "Q" stands for transversal, which is perpendicular to the building direction. For the conventional material, these tests were only performed in one direction as the diameter of the rod was too small. However, for the results, this is irrelevant as no significant performance difference is expected in the different axis of the conventional manufactured one. The number at the end of some specimens is a continuous number if more tests were performed in the same direction.

Code	Explanation
Cuts	
AR	Additive radial
AT	Additive tangential
AZ	Additive building direction
CL	Conventional lengthwise
CQ	Conventional transversal
Tests	
AL	Additive lengthwise (in building direction)
AQ	Additive transversal
CL	Conventional lengthwise

Table 5: Overview of the nomenclature of the specimens

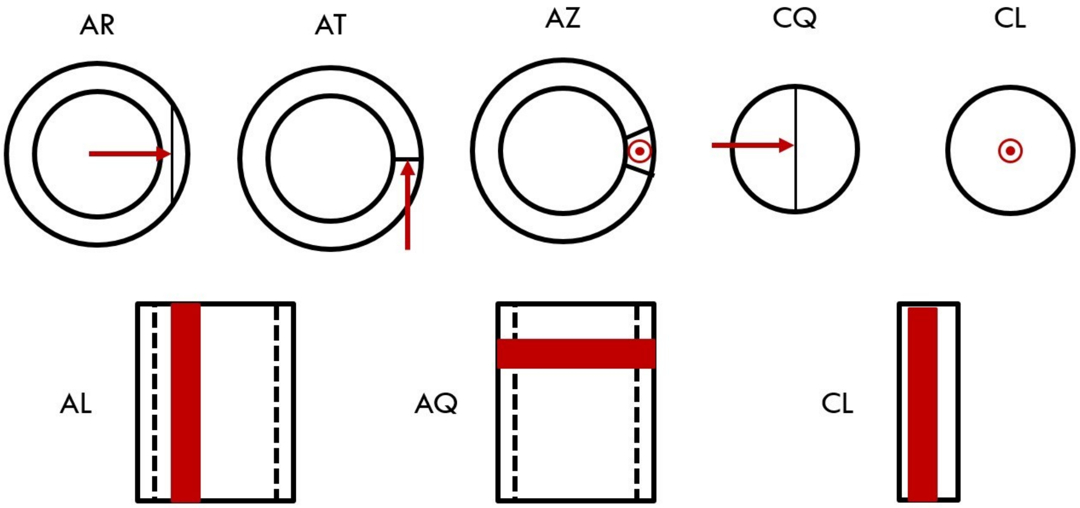

Figure 9: Nomenclature and direction of the metallic cuts in the first row and the test specimens in the second row

2.3 Tensile test

The purpose of the testing phase is to evaluate the limits and the behavior of the AM material compared to the conventional manufactured one. Therefore, a tensile test is an essential basic test to evaluate this. The concept of this test is that a tensile force is applied to the specimen causing the material to elongate until it is no longer able to withstand the stress. The force and the elongation of the material are measured, recorded and plotted. (Joseph 2017) Besides the tensile strength (Rm), the maximum stress that the specimen can withstand and the offset yield point (Rp0.2), the stress vs. strain curve shows the behavior of the AM material over the testing time and allows to compare it to the conventional material very well. The offset yield strength is an approximation of the elastic limit of the material. It is the intersection of the stress vs. strain curve with a line that is parallel to the linear region of the curve and has a predefined offset. For Rp 0.2, this offset value is 0.2 % strain, which is also the most common offset. The value of Rp 0.2 was calculated automatically by the testing software. (ASM International 2002)

The tensile tests were performed and prepared according to the standard EN ISO 6892-1. With the AM material, three tests were performed in the printing direction and two crosswise. With the conventional material, two tests were performed.

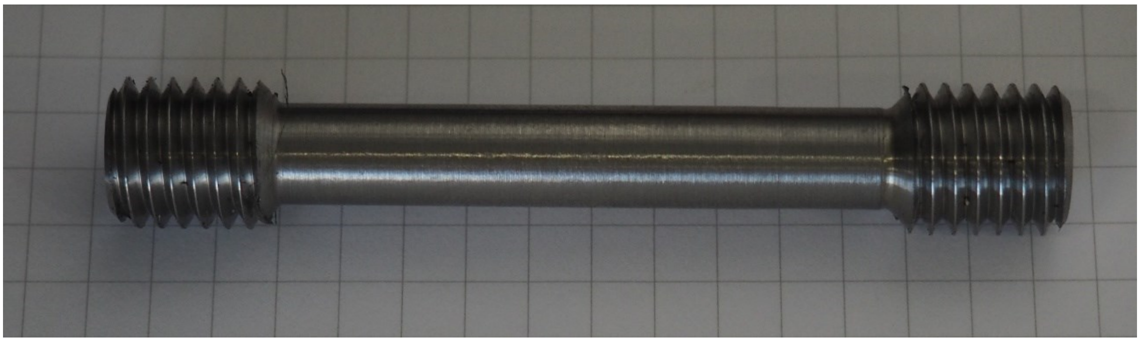

Figure 10: AL 1 tensile test specimen

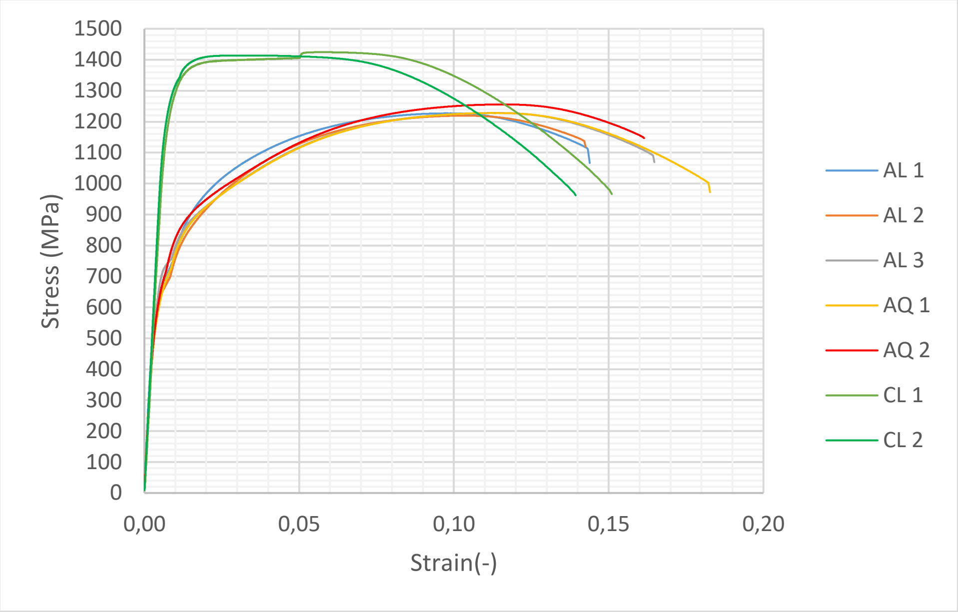

Figure 11: Tensile test curves from all specimens

All stress-strain curves are displayed in Figure 11. It can be seen that the test results were homogenous for the conventional as well as for the AM material. There are no significant outliers visible. At first sight, it is possible to recognize that the AM parts behave and perform entirely differently than the conventional ones. On the one hand, the printed parts are deviating from a rather linear and, therefore, elastic behavior much earlier than the conventional ones. Therefore the Rp 0.2 or the offset yield point is almost only half of the value from the standard minimum value. On the other hand, the Rm or ultimate tensile stress is close to the literature value. The percentage value in Table 6 shows the ratio between test results and literature value. Compared to the C-110 API grade, the yield strength is about 100 MPa lower. However, the tensile strength is higher for the additive manufactured one by approximately 400 MPa.

Specimen	**Rp 0.2 (MPa)**	**Rm (MPa)**	**Rp 0.2 percentage of literature value (%)**	**Rm percentage of literature value (%)**
AL	650	1,225	56	93
AQ	635	1,242	54	95
CL	1,260	1,420	108	108
Literature	1,170	1,310		
C-110	758	793		

Table 6: Average results and percentage of the standard literature value for the conventional manufactured material
(red: < 75%, yellow: 75–99%, green >=100%)

All the detailed test results are listed in Appendix A2.

Another essential aspect that can be derived from the stress-strain curve is that the AM material properties do not significantly vary in the different two different axes. Therefore, it can be assumed that, with this manufacturing process and the conducted heat treatment, mentioned in Chapter 1.3, the building direction is not influencing the tensile strength significantly.

The stress-strain curve of the AM material showed another unusual behavior as a dent occurs in the stress-strain curve after the elastic region. It is marked in Figure 12. This dent occurs in every curve of the AM specimens in a similar position. This is probably due to Lüders-Strain, at the transition from elastic to plastic deformation. The conventional material shows only a slight indication of this behavior in comparison with the AM ones. Interactions between dislocations and solute atoms are the reason for this. In this area, the material gets plastically deformed only localized. Low carbon steels are prone to this behavior. (Hertzberg, et al. 2012)

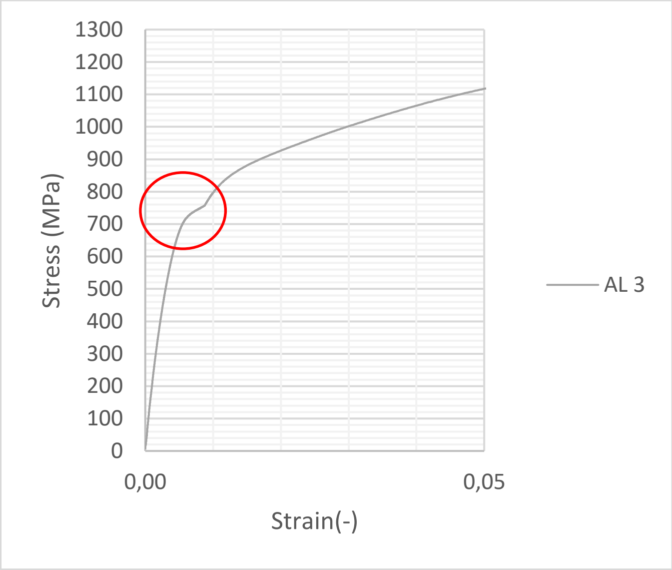

Figure 12: Marked dent in the stress-strain curve of the AL 3 specimen

After the tests, the fracture profiles of AL 1, AQ 1 and CL 1 were analyzed and compared. Figure 13 shows the fracture surfaces from AQ 1 and CL 1 under the scanning electron microscope (SEM). It is clearly visible that the AM material has a significantly smaller grain size than the conventional manufactured one. Additionally, an air inclusion or pore with a diameter of approximately 30 µm is visible. The size of the pore, as well as the edge, indicates that there was no contact before the tensile test. This means the pore was already in place after manufacturing and did not occur during the test. The surface of AL 1 looks similar to the surface of AQ 1, the same structure and there are also gas inclusions visible. On both surfaces, dimples and a honeycomb pattern is visible. These are indicators of a fragile or ductile fracture. The same behavior was also observed from Hu et al. (2017) when they investigated SLM 17-4PH stainless steel. In the conventional material, some inclusions are visible inside the dimples.

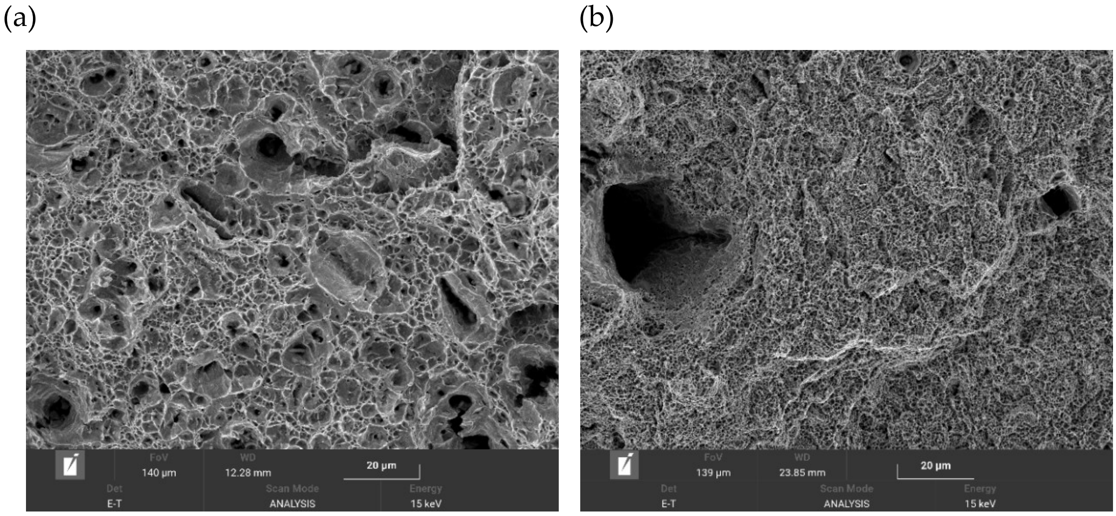

Figure 13: SEM images of the tensile test fracture surface (a) CL 1 (b) AQ 1

The tensile test showed a performance gap between the AM parts and the conventional one. However, not only the absolute values of the test results differ, the material, even though the chemical composition is the same, behaves differently over the complete stress-strain curve. One observation was the smaller grain size in the AM part. The analysis of the fracture surfaces showed that the lower strength could be due to the presence of pores in the AM parts. Another explanation could be the influence of residual stresses inside the AM parts due to the manufacturing process. An issue with the heat treatment, which is explained in Chapter 2.10.2, could also be the reason for the lower properties.

2.4 Charpy-V notch impact test

The Charpy-V notch impact test is a high strain rate test. For this test, the specimen is machined with a 2 mm deep notch. A pendulum hits the specimen and the height of the resulting swing is measured. This height correlates to the amount of energy which is absorbed by the specimen during fracture. The purpose of the Charpy-V notch test is to evaluate if a material can be classified as either brittle or ductile. The result is based on the absorbed energy as well as the fracture surface. In general, this test is more qualitative and is used to compare materials. It can be performed for various temperatures because certain materials show a transition. (TWI 2016) The tests for this thesis were conducted under room temperature.

The Charpy-V notch test was performed again in both directions for the AM parts, in building direction and perpendicular to it, and following ISO 148. Out of each direction and the conventional material, three specimens were prepared.

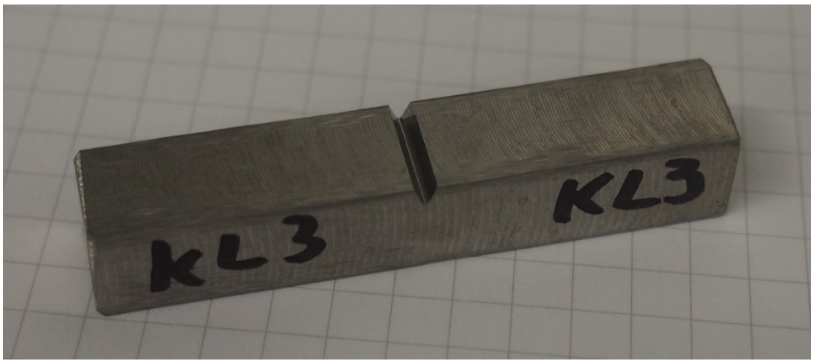

Figure 14: Charpy-V notch impact test specimen CL 3 – KL 3 was the German abbreviation

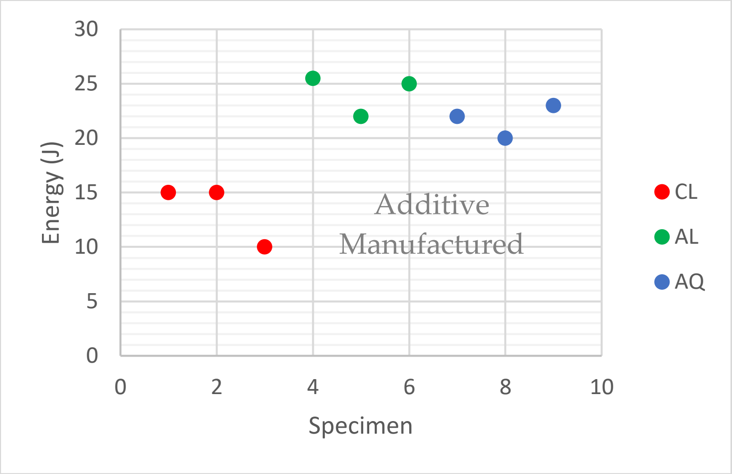

Figure 15: Results of the Charpy-V notch impact test

The results showed again only slight differences of maximum 5 Joules between the two testing directions of the AM material and the values are attached in Appendix A3. The conventional material absorbs less energy than the printed, which indicates that its behavior is rather brittle and the AM one more ductile. This is also following the higher tensile strength and hardness of the conventional part.

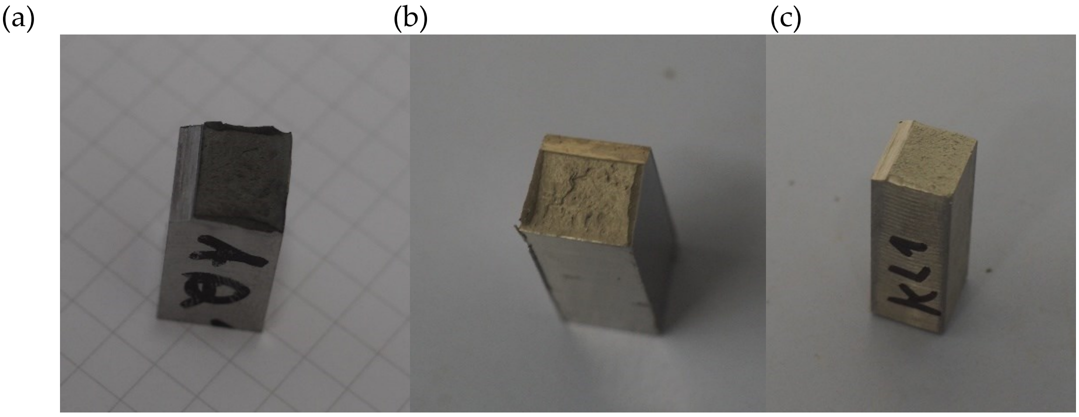

Figure 16: Charpy-V notch test specimens after failure (a) AQ 1 (b) AL 2 (c) CL 1

The fractures of the AM samples, in Figure 16 (a) and (b) indicate a ductile behavior by the stronger deformation on the edges of the fracture surface and deep dimples inside the face. The conventional the edges are barely deformed and the surface is a rather smooth and homogenous mat. (Emre et al. 2015)

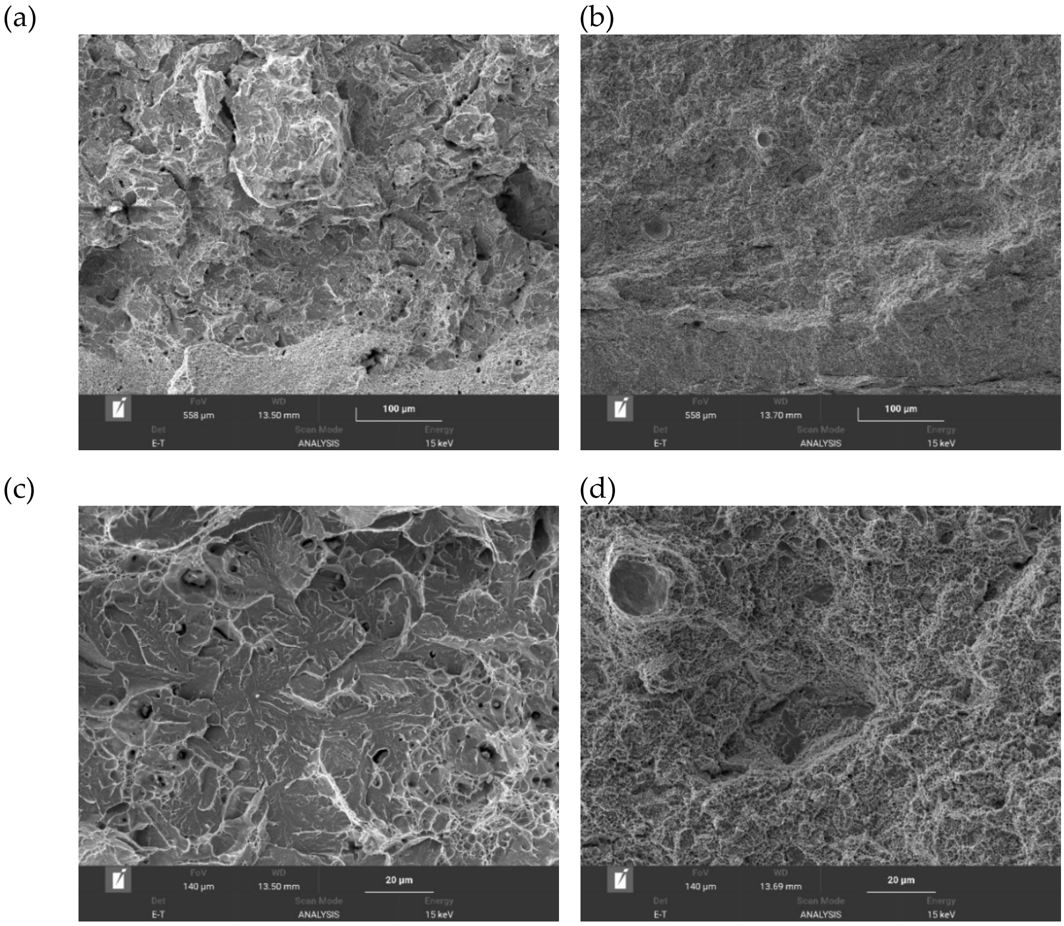

Figure 17: SEM Charpy-V notch impact test fracture surface (a) CL 3 (b) AL 3 (c) CL 3 (d) AL 3

The AM material on the right side, Figure 17 (b) and (d), has a honeycomb pattern again with dimples comparable to the tensile test, only in some areas a brittle behavior of the material is visible. However, the conventional material on the left, Figure 17 (a) and (c), shows a pure transcrystalline fracture surface. This corresponds with the lower values of the Charpy-V notch test. Furthermore, the difference in the size of the grains between the conventional material and AM material is again clearly visible.

The fracture surface of the AM part indicates with the honeycomb pattern a ductile behavior. However, the transcrystalline fracture surface of the conventional part means that it behaves brittle in the Charpy-V notch test. (Zarębski et al. 2019) This shows that the different parts respond differently to the test and are again evidence for a different behavior due to the diverse manufacturing processes.

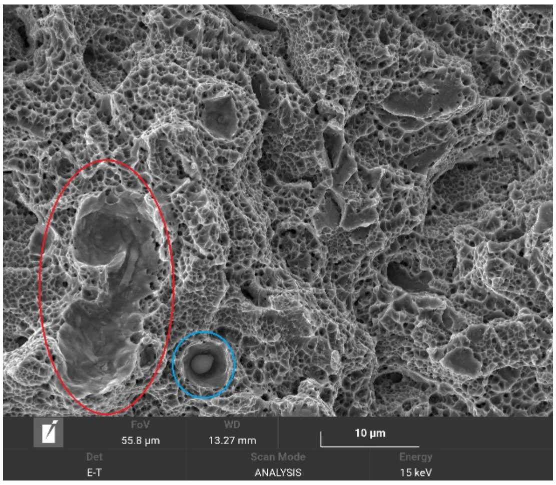

Figure 18: SEM Charpy-V notch impact test fracture surface AQ 3, with pore (red) and inclusion (blue)

Figure 18 indicates additional information which can be retrieved from the fracture surface. The red circle marks a pore in the AM material and the blue circle an inclusion which is present. Even though most of the area shows a ductile behavior, on the right, a few small spots show an indication of a transcrystalline fracture surface.

The results of the Charpy-V notch test are, as mentioned earlier in this section, more qualitative than quantitative, as they describe the fracture behavior of the material. The results show a different response of the conventional and the AM part as the second one is behaving more ductile.

2.5 Hardness test

For the hardness testing of the material used in this project, the testing procedure after Vickers was conducted, this is a hardness testing method well suited for all metals. For this method, the test force is applied by a straight diamond pyramid with a square base. The opposite faces have an angle of 136°. The form of this pyramid has the advantage that the resistance of the material is proportional to the applied force. To evaluate the hardness of the material, by the testing machine, the diagonal length of the impression is measured. The exact testing method was HV 10, which means a force of 98.07 N was applied. (Herrmann 2011)

The Vickers hardness testing was performed in accordance with ISO 6507. The test specimens were cut out from the AM as well as from the conventional manufactured material from all three axes and embedded in the thermoplastic mounting compound EpoMet. Afterwards, the specimens were polished for the test. For every specimen, six hardness tests were performed on different positions of the surface.

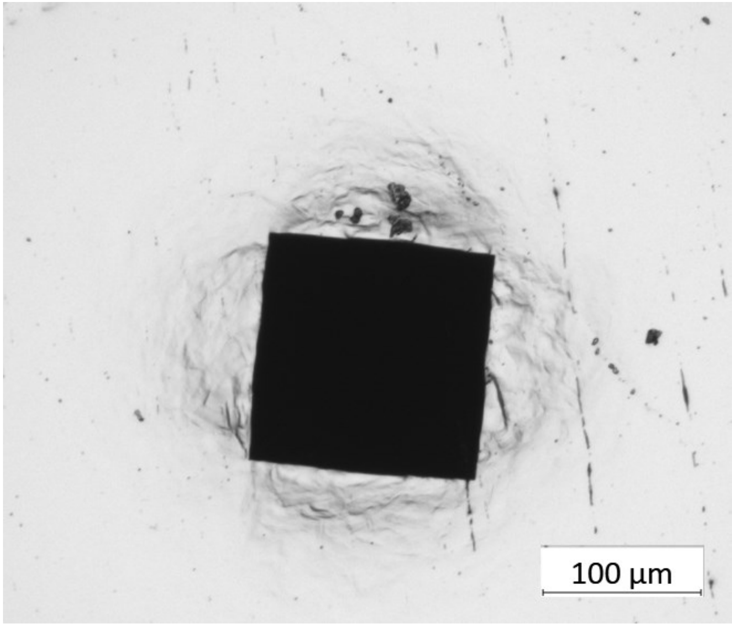

Figure 19: Vickers hardness test on CL with deformed zone

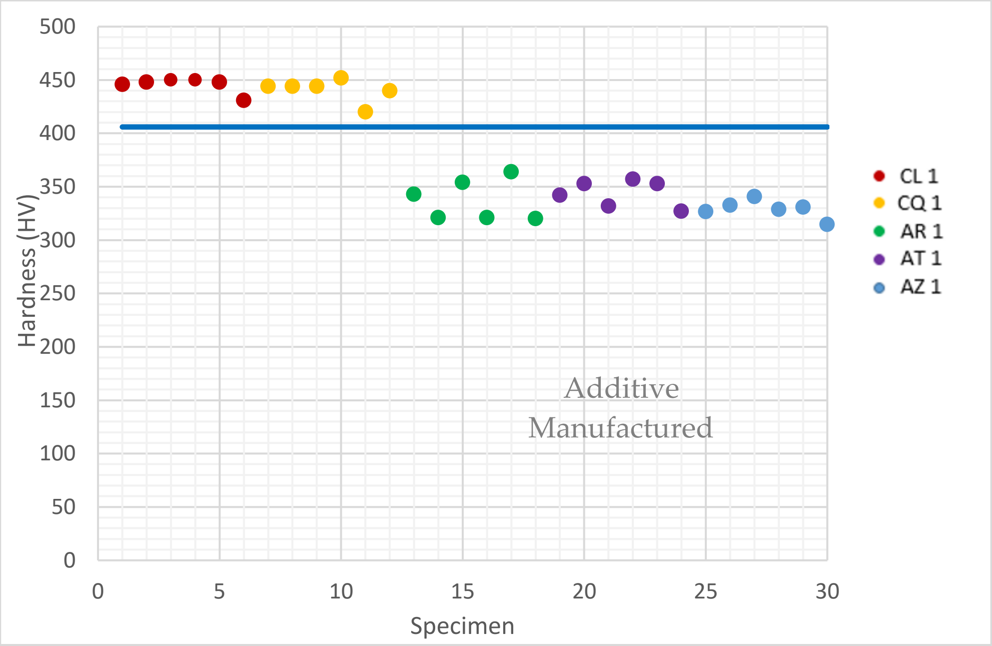

Figure 20: Hardness test results

The test results showed a more substantial dispersion in the AM parts than in the conventional, where only one respectively two values vary from a very narrow set of results. This is means that the material is more heterogeneous and can possibly indicate the presence of pores and segregation.

Specimen	Vickers Hardness
CL	446
CQ	441
AR	337
AT	344
AZ	329
Literature	406

Table 7: Average hardness

The results, presented in Figure 20 and Table 7, show again that the AM material has more than 20% lower values than the conventional material and the literature value for this material, which is indicated by the blue line. The tested conventional parts reach the literature value for the hardness of a 17-4PH material with H900 heat treatment. For the AM parts, the hardness is only about 82% of this value. The difference between the hardness in the different axes of the AM part is also in this test, only around 4%, which is very low. All results are attached in Appendix A4.

There is also a strong correlation between the hardness of a material and its tensile strength. (Khodabakhshi et al. 2015) Therefore, the results of the performed hardness test show a similar outcome and proof the results of the tensile tests.

2.6 Sulfide stress cracking test

The Sulfide stress cracking (SSC) test was outsourced to Voestalpine Tubulars. The tests were conducted in accordance with NACE standard TM0177-2016 Method A.

Therefore, the specimens get exposed to a 100% H_2S environment and tensile loaded. The tests were conducted under room temperature and the test solution pH was between 2.7 and 2.9. Material is stated to be resistant against SSC for a specific load if it withstands 720 h without failing. The tensile loads used for the tests were 80% of the yield strength of an API C-110 grade and 80% of the yield strength of an L-80 grade. (Thompson et al. 1991)

Specimen number	Test stress [MPa]	Failed time [h]
1	644	2
2	644	2
3	644	2
4	442	5
5	442	6

Table 8: Results of the SSC tests, performed under different loads

Figure 21: Failed SSC specimen

The test was performed with 644 MPa and because this was almost 100% of the yield point, we measured in the tensile test it was repeated with the SSC tensile test load for an L80. However, also for this load, the material performed poorly regarding SSC and the results are far away from the 720 h.

Even though the 17-4PH material is known for its excellent corrosion resistance, because of its high chromium and nickel count, it is still susceptible to SSC. In the NACE standard MR0175-88, the maximum allowable hardness for 17-4PH is stated with 33 HRC, which is equal to 311 HV. From the hardness tests, we know that the AM material used in this project is around 330 HV, which is above this threshold. Also, the hardness of the conventional material is significantly above this threshold and the material is therefore susceptible to SSC. In a similar test series, conducted by Thompson et al. (1991), with conventionally manufactured 17-4PH, which was H1150 heat-treated, the specimen failed with a load of 326 MPa, which is 40% of its yield strength, within 220 h. NACE MR0175 also permits to use the material only in a double age-hardened condition. So one conclusion would be to treat the material differently and reduce the hardness, this could lead to better SSC test results. (Thompson et al. 1991)

2.7 Hydrogen induced cracking

The hydrogen-induced cracking (HIC) test was also outsourced to Voestalpine Tubulars. The test was conducted in accordance with NACE standard TM0284-2016. This test is used to measure the resistance of a material against corrosion in a hydrogen sulfide environment and the associated cracking by hydrogen absorption. The test duration is 96 hours. The pH of the test solution was between 2.7, at pre-purging, and 3.8 after the test. The results of a HIC test are crack length ratio (CLR), crack thickness ratio (CTR) and crack sensitivity ratio (CSR).

For evaluating our material, two specimens were tested and the results are presented in the following Table.

Specimen number	Section number	CSR (%)	CLR (%)	CTR (%)
1	1	0.00	0.00	0.00
	2	0.00	0.00	0.00
	3	0.00	0.00	0.00
	mean	0.00	0.00	0.00
2	1	0.85	40.89	2.22
	2	1.40	76.15	4.29
	3	3.30	74.26	7.93
	mean	1.85	63.76	4.81

Table 9: HIC test results

In the book "Oil and Gas Pipelines and Piping Systems" the maximum values are defined as followed:

- CLR 15%
- CSR 1.5%
- CTR 5%

Another limit is the maximum individual crack length, which should not be higher than 5mm.

For this project, we have two specimens that show very different results. The ones from the first specimen look very promising. However, this is due to the fact that the cracks, as shown in Figure 22, occurred on the surface of the specimen and according to the standard, they are not counted.

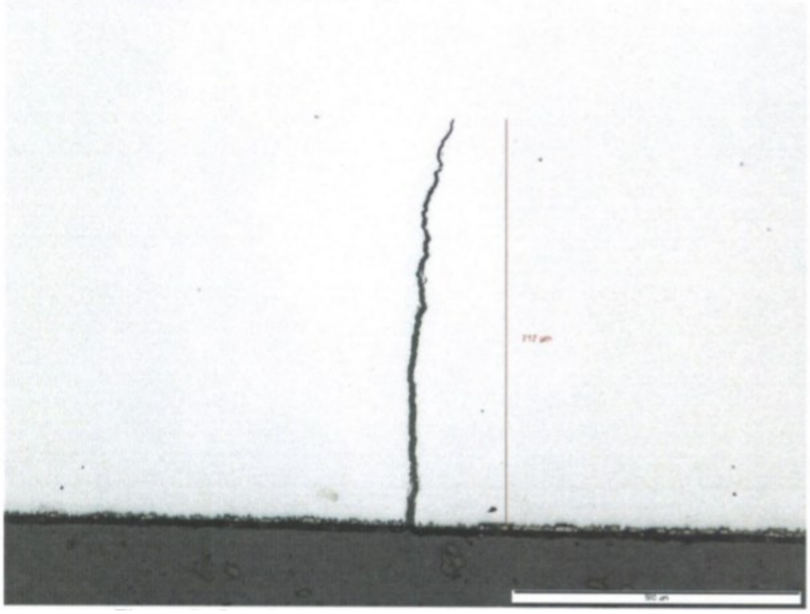

Figure 22: HIC test surface-crack Specimen 1, section No. 3 (Courtesy Voestalpine Tubulars)

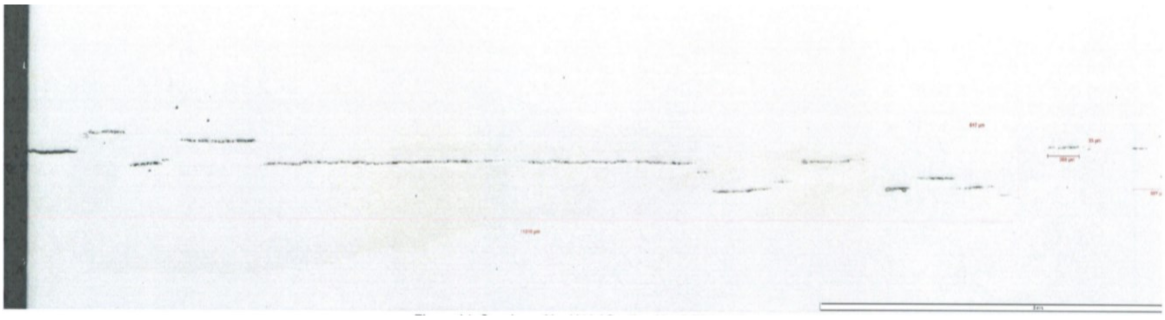

Figure 23: HIC test surface-crack Specimen 2, section No. 2 (Courtesy Voestalpine Tubulars)

The second specimen failed at least one criteria regarding CLR, CSR or CTR in every section. Usually, if one specimen fails the test the whole heat of steel, which is represented by the specimen, has failed the test. (Bahadori 2017)

2.8 Metallography

From the static test results and the Charpy-V notch impact test, we saw that the AM material behaved entirely different than the conventional one. This trend is also visible if we continue to analyze the microstructure of the material. The metallography analysis is based on light microscope as well as SEM images.

To prepare the specimens for the metallography investigations, the AM hollow cylinders, as well as the conventionally manufactured rod were cut so that samples from every direction, which were described in Chapter 2.2, were available. The metallographic cuts were then mounted, by using the thermoplastic mounting compound EpoMet. For the studies, they were then ground to remove the effects of the cutting process. Afterwards, they were polished to reduce the roughness to 1 µm. Metallic cuts from all axis were also etched for the metallographic studies.

First of all, it needs to be mentioned that there is no significant inhomogeneity in the AM material, which is related to the building process in either direction. There is no layer structure visible. This observation is most probably due to the effect of heat treatment, which has a considerable influence on the microstructure.

2.8.1 Etchants

To etch the parts, two different Etchants were used. Those two were Kalling 2 and V2A-stain. The compositions are displayed in Table 10 and their impact on the steel is described below.

Etchant	Composition	Concentration
Kalling 2	Copper(II) chloride	5 g
	Hydrochloric acid (32%)	100 ml
	Ethanol	100 ml
V2A-Stain	Hydrochloric acid (32%)	200 ml
	Distilled Water	200 ml
	Nitric acid (65%)	20 ml
	Pickling inhibitor (after Dr. Vogels)	0.6 ml

Table 10: Composition of the used Etchants

Kalling 2 was used because it is well applicable for Steels with a Chrome content. The etch effect is that the acid attacks the ferrite in the material and the copper of the etchant precipitates on it. Carbides are not affected and the austenite is slightly attacked.

For the etching with the V2A-Stain, the fluid was heated before. It was selected because it works properly for Cr-Steels and CrNi-Steels and it was used to evaluate the grain sizes. (Petzow 2015)

2.8.2 Grains

As already indicated during the test analysis, there is a significant difference between the grains of the conventional manufactured material and the AM one. Without analysis, it is already visible that the microstructure and the grains are completely different between the manufacturing methods.

The size of the grains is one of the first points which differs entirely from the conventional one. To evaluate the different pore sizes, the idea of the "Jeffries planimetric method" was used to measure the grains per unit area and to relate it to the ASTM grain size number scale. First, a circle is drawn onto the microscopic image and the grains which are inside are counted. The grains which intersect with the circle are also counted, but the amount is divided by two. With the sum of these two values, the number of grains per square millimeter (N_A) can be calculated by dividing it through the observed area. The ASTM grain size number G is then calculated, as shown in equation (1). (Vander Voort 1999)

$$G = [3.322 \log(N_A)] - 2.95 \tag{1}$$

For preparing the specimens, they were etched with V2A, to make the grains visible. The software ImageJ was used to evaluate the size of the area, but the counting itself needed to be performed manually.

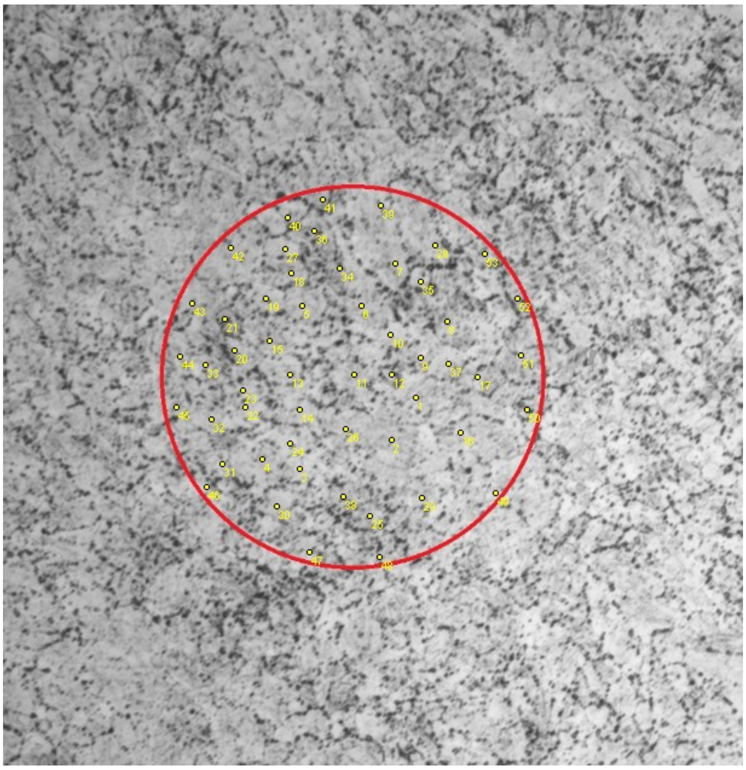

Figure 24: Grain counting AT

Material	Inside Circle (-)	Intersecting Circle (-)	Area (mm^2)	N_A (grains/mm^2)	G (-)
AM	37.5	13	546.18	80560	13.35
Conventional	34	15	1522.066	27266	11.79

Table 11: Mean results of the grain size evaluation

This grain size number is connected to specific grain-size data obtained from the ASTM E112. 13.35 was rounded to 13.5 and 11.79 to 11.8. The reason for the different areas between the conventional and the AM part is that the grain size varies strongly. Therefore, the selected area for the conventional was larger to get also a grain count between 30 and 40.

Material	G (-)	Nominal diameter (µm)	Feret's diameter[4] (µm)	Average area of grain section (µm^2)
AM	13.5	3.3	3.7	11.1
Conventional	11.8	6.0	6.8	36.0

Table 12: Grain-size data from ASTM E112 (extracted from Vander Voort 1999)

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[4] Feret's diameter is the height between tangents of the grain boundaries

The results of this grain size evaluation show what already could have been anticipated, the difference in the size of the grains between the AM material and the conventional is significant, where the diameter is only half for the AM material.

2.8.3 Pores

In general, three types of pore can occur during the AM process. Those three types are gas, keyholes (KH) and lack of fusion (LoF) pores. The difference between them is their source, shape and size. Gas pores are due to trapped gas either in the powder or during the melting process. They have a spherical shape and are the smallest of the three types. The KH pores are due to an excess of input energy during the manufacturing process. The pores are relatively large and circular in the horizontal direction and elongated vertically. The LF pores are caused by, opposite to the KH pores, a lack of input energy. (Snell et al. 2019)

To evaluate the pores, two values were used. On the one hand, the microscopic images were analyzed and, on the other hand, the results which were calculated by Pankl, the company which performed the HIP[5]-treatment on the AM parts, was taken. This treatment is explained in chapter 2.9. The first method had the purpose of analyzing the pores qualitative, the second one to estimate the total porosity of the sample.

For the optical 2D analysis, the image processing software ImageJ was used. Therefore, the images were adjusted with a certain threshold that only the dark places in the pictures which indicate the pores were still visible. These remaining “particles” can be counted and evaluated by the software. With this method, 25 microscopic images were analyzed with a total area of around 26.87 mm^2.

For the evaluation of the pore type, the data set was filtered regarding their circularity, Aspect ratio (AR) and their size. LoF pores have a high AR and a lower circularity. Their length is usually high. KH pores are well rounded have a moderate AR and are bigger than gas pores which are therefore the smallest and have the highest circularity. There are also pores that could not be assigned to a specific type, which is a large amount of very small pores. Because of their size, the uncertainties in the analysis of their shape are higher. (Snell et al. 2019) It is also not a hundred percent sure that no other inclusions are counted as pores during the analysis as the difference in colour is only very slight, which is also a more significant issue for the smaller pores, respectively, the inclusions. Because of these shortcomings, only points with a length of more than 5 μm were counted because they can be found and defined as pores very accurate. What needs to be mentioned is that the limits for the pore classification, even though there are some literature values are still subjective. The term length in this chapter is referred to as the maximum diameter of the pore. This means the largest distance between two points on the pore edges.

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[5] Hot isostatic pressing

Pore type	count	pore area (μm^2)	pore area fraction (%)
Gas	93	2181.07	0.0081
KH	13	4835.43	0.0180
LoF	18	7120.07	0.0265
unclear	183	2771.47	0.0103
Sum	307	16908.05	0.0629

Table 13: Pore count

Figure 25 to Figure 27 describe the shape of the visible pores. Only those are included, which could be linked to one of the pore types described earlier in this chapter.

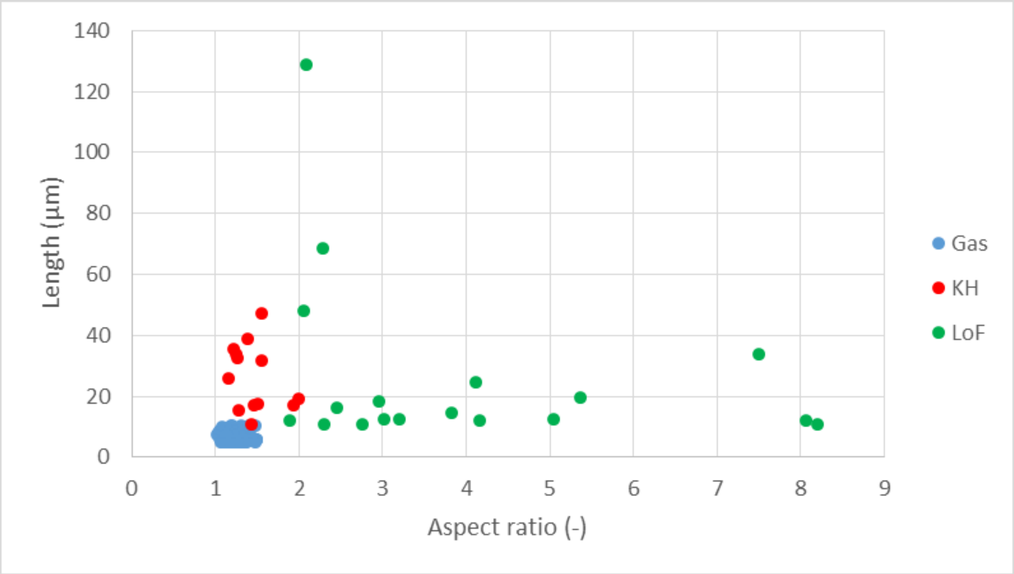


Figure 25: Pore evaluation – Length vs. Aspect ratio

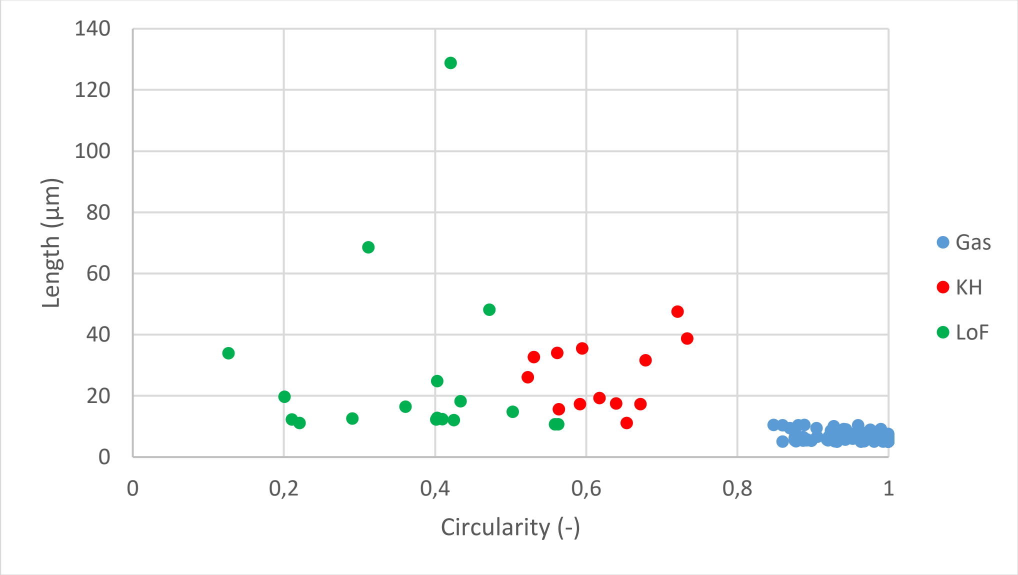


Figure 26: Pore evaluation – Length vs. Circularity

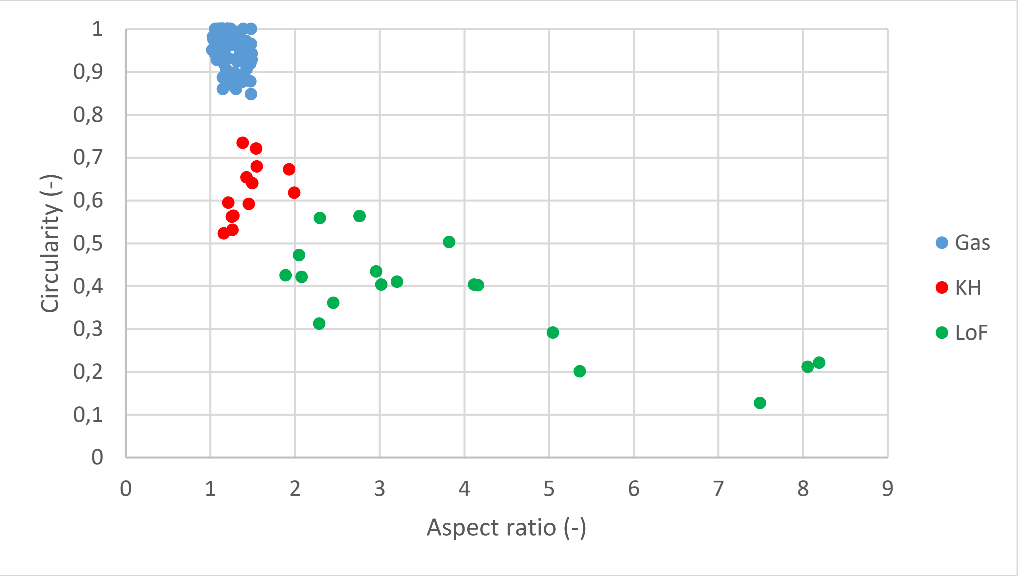


Figure 27: Pore evaluation – Circularity vs. Aspect ratio

In general, the pore amount is not too significant even though the count is quite high the area is very small, the largest fraction is the number of pores that look like gas pores, but especially those tiny pores are the reason for the high count results. The total count of pores, which were larger than 10 µm is 38. The number of pores with a shape that indicates LoF is 18 and there are 13, which look like KH pores. The amount of LoF and KH pores is very similar, which indicates that the input energy was appropriate as no excessive pattern was visible in any direction. (Snell et al. 2019) If one of those two types would be significantly larger, the input energy needs to be adjusted. From the number of pores, the unclear fraction looks very large, but as the comparison of the area indicates the most significant amount of them are the smallest pores, where the lack of accuracy makes it difficult to classify them.

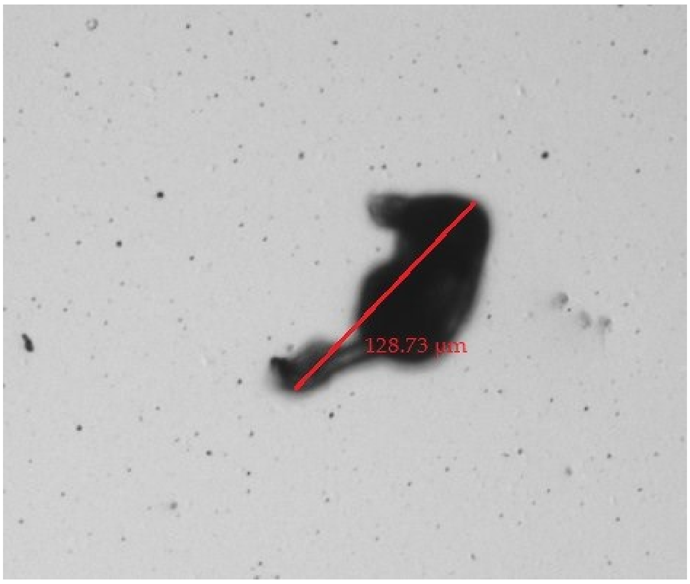


Figure 28: Largest evaluated pore

During the analysis, only a few big pores were measured, the largest one with a length of 128.73 µm and a fraction of the total investigated area of 0.016%. As shown in Figure 28, the pore has an irregular shape and the most probabilistic reason for its occurrence is LoF.

The pore calculation performed by Pankl was on the second Pipe with optical measures using a digital microscope. The result of this calculation is that the porosity of the part is 0.0298%. With the pore classification, a porosity of around 0.063% was calculated, which is double the value of the one Pankl calculated. It needs to be mentioned that two pores in the performed study made up one-third of the total pore space and these pictures were selected on purpose during the microscopy to evaluate these pores. This means the value would reduce significantly without those outliers. Furthermore, the evaluation was not conducted on the same specimen. There is no specific standard for a maximum porosity that an AM part should have, but a typical threshold is 0.05%, so with our parts, we should have met those requirements.

In the conventional manufactured material, nearly no pore-like structures that meet the defined parameters were detected. If all measurable spots are included, it can be derived that a possible porosity is below 0.01%. This value may be significantly lower as there were a large number of inclusions that could not be separated optically from pores by the program. Another outcome is that the spots, in case they are pores, are very small in the conventional material in comparison, with a size of maximum 1/10 of the length of the largest pore in the AM material. So the influence of these pores on the properties is also very low.

To sum it up, the number of pores in the AM part was moderate even though a few of them were bigger. There was no clear dominant type of pore even though the number of pores that could be formed due to trapped gas had a significantly higher value, but this is the norm according to the literature and their area is also small compared to the other types. Pores play a massive role in AM because of the aim to accomplish the highest tensile resistance as well as long fatigue life. Therefore, porosity determination is an essential part of AM quality control. (Sola et al. 2019)

2.8.4 Inclusions

The samples were etched with Kalling No. 2. In the images of the AM, carbide was visible. The interesting thing is that the structure and presence of the carbides vary very strongly within the part. The carbides appear bright in the secondary emission image shown in Figure 29 of the AR specimens. There they are very fine and spread over the whole sample. In Figure 30, which was taken with the same settings at the same magnification, carbides were hardly visible, only some structured bright spots.

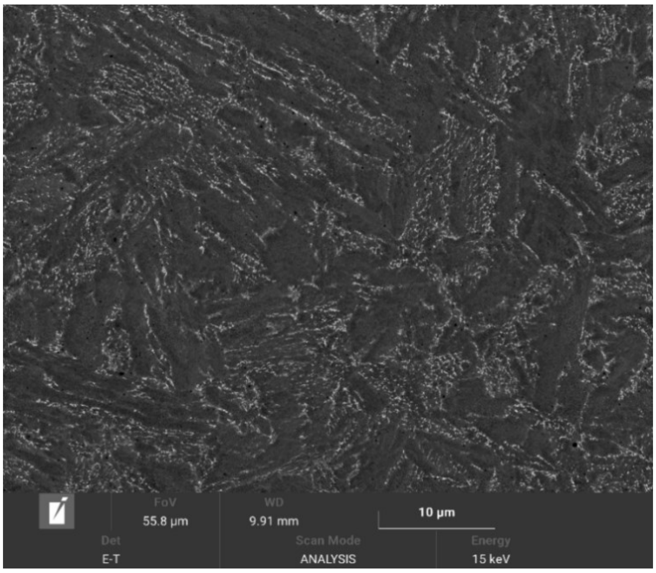


Figure 29: SEM image - Carbides in AR

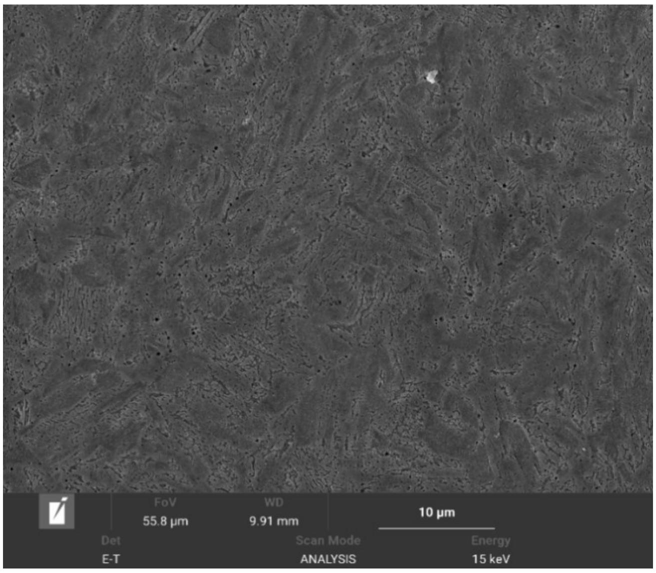


Figure 30: SEM image - Carbides in AT

Carbides comparable to the ones found in the AT sample were also visible in the samples of the conventional manufactured material in both directions. Furthermore, elongated inclusions, which are most probably silicates, were observed in the SEM images as well as the ones from the light microscope. (Taken from Olympus website) The inclusions in the conventionally manufactured parts were larger than in the AM parts.

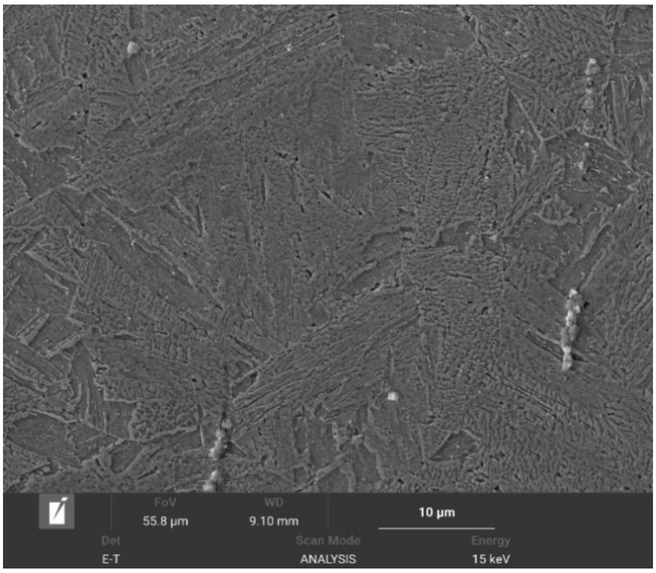


Figure 31: SEM image - Silicates in KQ

2.9 HIP-Treatment

HIP stands for hot isostatic pressing and is a form of heat treatment where simultaneously heat and pressure are applied. An inert gas induces this pressure. The benefit of this process compared to the usual heat treatment is that the porosity gets reduced and the density of the AM part increases. Therefore, the mechanical properties, static as well as dynamic of the treated material increase. A HIP treatment also reduces the statistical spread associated with AM material properties, which increases the reliability and efficiency of the parts. (Inside Metal Additive Manufacturing 2014)

During the project, which involves this thesis, parts of the AM material were also HIP treated. Tests conducted on this treated material will help to evaluate pore influence onto the mechanical properties. Especially as pores were also visible on the fracture surfaces of the tensile and Charpy test.

The company Pankl performed the treatment on pipe number two and plate number two. With this HIP process, it was possible to reduce the porosity from 0.0298% to 0.0012%. With the treatment, the hardness increased from 37 HRC to 43 HRC, respectively 351 HV to 424 HV. (Winklmayr 2020) From the treated material, we expect better results regarding the tensile stress of the material. Due to the closing of pores, the size of the parts changed. Those changes in the second pipe are shown below. The overall shape change is shallow, only in certain areas changes up to 0.171 mm are visible. The detailed size changed is shown in Figure 32 and 33.

Theoretically, it is possible to correlate the hardness to the tensile strength. From a conversion table, it is possible to anticipate the tensile strength of the parts which were HIP-treated. The approximated tensile strength, according to DIN 50150, is around 1350 MPa, this would be an increase of more than 100 MPa. Furthermore, with this value, the tensile strength would be higher than the minimum standard value for 17-4PH conventional manufactured material. (Conversion table from B.B.S. I Halmstad AB website)

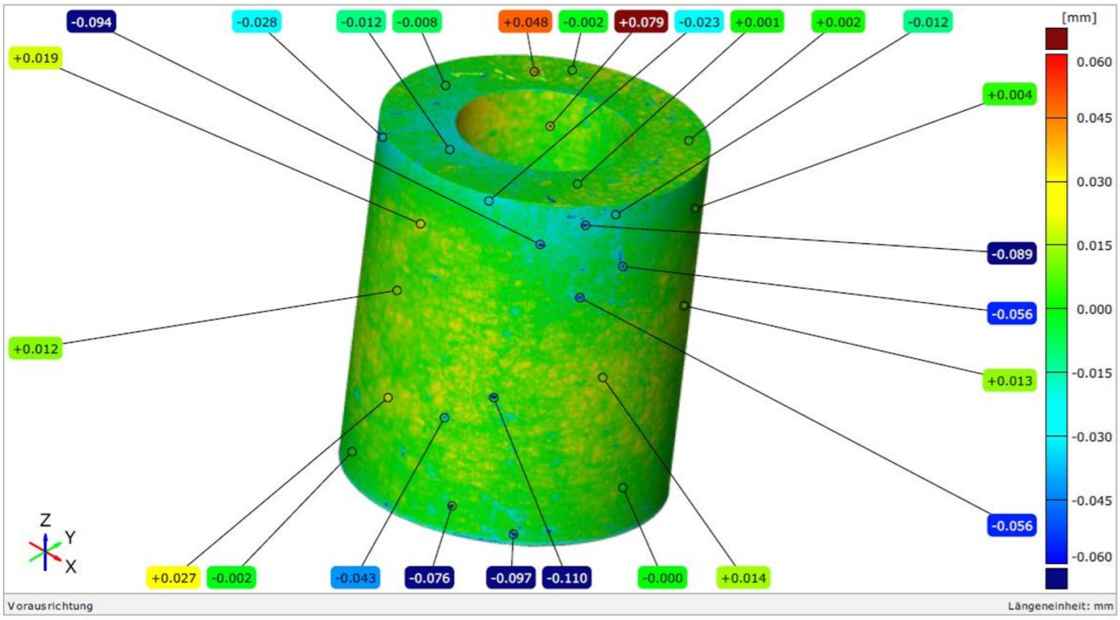


Figure 32: Size changes due to HIP-treatment (Courtesy Pankl)

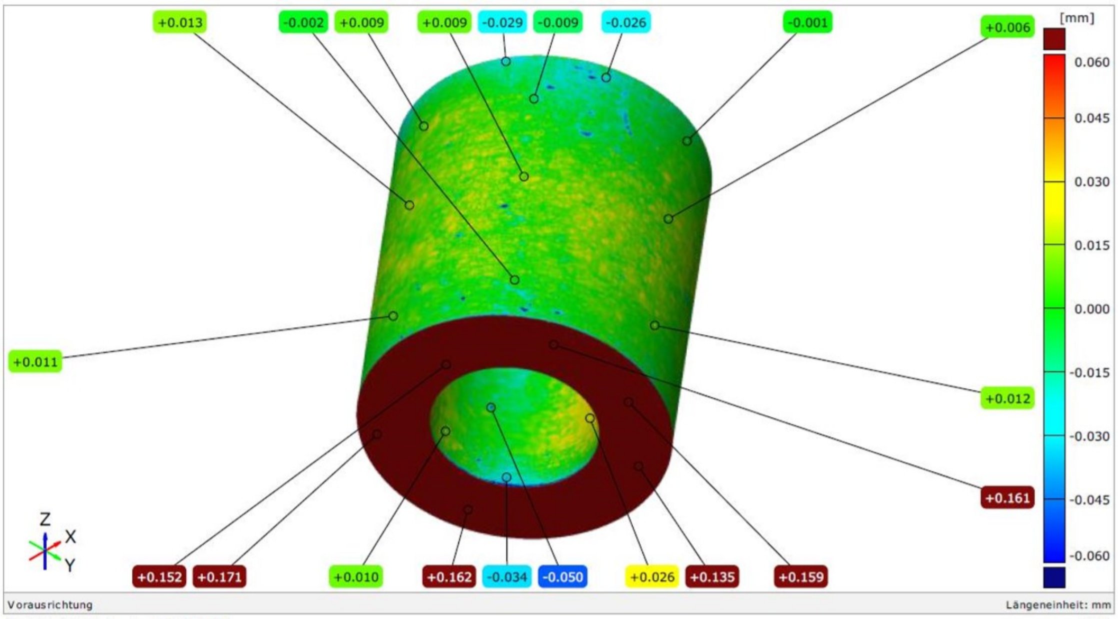


Figure 33: Size changes due to HIP-treatment (Courtesy Pankl)

2.10 Conclusion – Testing

One point which can be derived from the results of the tests is that the mechanical properties for our AM part with the performed heat treatment are not significantly depending on the printing direction. Tensile, Charpy-V notch impact test, as well as hardness test, showed no significant differences between the specimens, which were cut out in building direction and perpendicular to it. This observation was not expected as the bonding in the different directions ought to be quite different due to the manufacturing process, where we have on the one hand layer after layer “welded” together and, on the other hand, a plane structure produced by the laser. It needs to be mentioned that most probably, the heat treatment, which was performed in our case, contributed to these results.

Another observation was the different behavior of the AM parts compared to the conventional ones as well as the different microstructure. Therefore, so even though it might sound obvious, it needs to be mentioned that for the AM material, the same properties as a conventional manufactured one cannot be taken for granted.

The hardness and the tensile strength of the material were significantly lower than the values from the conventionally manufactured part. The different parameters and processes which are related to the manufacturing process, as well as the different microstructure, make it difficult to evaluate the exact reason for the lower mechanical properties of the AM parts compared to the conventional one. Especially the tensile test, where the yield strength of the AM parts was only half of the conventional parts showed shortcomings. The pores which were visible on the fracture surface and the metallic cuts could have played a role. The overall pore fraction, however, was not bad, with about 0.03%. The test results of the HIP-treated material will give further insight and it can be assumed that the properties after this treatment are significantly higher and close to the conventional ones. Another possibility could be a not perfect performed heat treatment further explained in chapter 2.10.2. Residual stresses in the material due to the manufacturing process, which decreased the mechanical properties are also an issue at AM but should be released by post-processing. Nevertheless, it is obvious from the expectations of the different sources that the material should have performed better than in our tests.

Compared to the C-110 grade, the AM parts had almost the same yield strength and higher tensile strength. However, the AM was not successful at the SSC and HIC test. This is probably due to the presence of pores and the high hardness of the material, which increases the susceptibility to SSC. Also, the smaller grain size and grain size distribution can play a role in the fracture propagation. This part of the mechanical tests needs further investigation and also to test the HIP treated material with less porosity and higher expected tensile properties will give further insight.

2.10.1 Meaning of the results for a spare part

These test results and observations have a massive impact on the consideration and the design of an AM spare part.

One thing is that the lack of standardization of the manufacturing procedure makes it necessary that the material of the spare parts which are produced is tested and evaluated. Also, quality control during the manufacturing process is necessary to reduce the potential defects which come along with AM. Therefore, pore evaluation is an essential criterion.

Another important outcoming of this testing phase for our future project and the usage of AM material in the oil and gas industry is that it is very likely that different materials need to be used to reproduce parts. As the requirements for the usage probably cannot be met with the AM material like with the conventional material. So, therefore, additional testing and evaluation are necessary to specify the AM material.

To reduce the necessary effort and increase the knowledge about different materials, respectively the opportunities, one idea would be to print testing “coupons”. Those should only have the for the tests necessary dimension. With those coupons, more tests and material evaluations can be performed and also different post-processing can be tried and compared. It is necessary to have a wide range of materials with specified properties in order to select the right candidate for each spare part.

2.10.2 Issues with heat treatment

One thing which cannot be excluded is that the heat treatment was not performed perfectly after the parts were manufactured, the behavior of the material would indicate this during the tensile test and the hardness. This was brought up by an expert from Pankl, the company which performed the HIP-treatment. He mentioned that this treatment should not increase the hardness that much if the material had a perfect heat treatment before, as only the pores should be closed. The hardness increase they measured was from 37 HRC to 43 HRC, respectively 351 HV to 424 HV. The reduction in the porosity could explain a small hardness increase (Cherry et al. 2015), but in the manufactured material, it was already quite low before the HIP-treatment.

To evaluate this further, a second solution annealing and H900 heat treatment were performed on an AM part, which was not HIP treated. Table 14 represents the mean hardness values at different stages. The measurements before the second heat treatment and after HIP treatment were performed by Pankl and the one after the second heat treatment in the OMV TechCenter.

Hardness before second heat treatment (HV)	Hardness after second heat treatment (HV)	Hardness after HIP treatment (HV)
351	382	424

Table 14: Mean values of the hardness measurements

The increase in hardness after the second heat treatment is supporting the theory that the first one did not work as it should. The highest values are still after the HIP treatment, which shows the benefit of this post-processing method. The result shows that HIP treatment could improve the properties in a way that the AM material performance comes close to the conventional manufactured material. The observations are based on one experiment and further investigations are highly recommended.

Chapter 3 SWOT-Analysis

The possibility to use AM to manufacture metal parts offers a lot of specific opportunities but also significant shortcomings and insecurities. Therefore, this chapter covers a SWOT analysis to evaluate and display the current state of AM for the exploration and production sector of an oil and gas company.

3.1 SWOT-Analysis general

In the beginning, a general SWOT analysis for AM is carried out and later the adapted one for the oil and gas industry. This helps to get a bigger overview of AM. In some areas, they will match, but in others, they will not. The reason for that is the different desires and intentions for selecting AM. The analysis, even it is kept very general, is focused on SLM technology.

Strengths	Weaknesses
Complex shapes and geometries	Relatively rough surface finish
Reduction of manufacturing Steps - No tooling needed	Post-processing operations
Material efficiency - Reduced material waste	In-process monitoring
Flexibility in manufacturing location	Costs per unit – Complex economics
	Significantly low fabrication speeds
	Limiting factors and part dimensions
	Lack of repeatability – Influences and parameters
	Material and parameter availability
Opportunities	Threats
Customized products	Reliability of the parts and standardization
Part optimization and lightweight construction	Quality control
Rapid prototyping	Hype and unrealistic expectations
AM of intelligent material – include electronics or combine materials	Intellectual property
Growing potential - Developing of new materials	Ethical constraints (gun printing)
On-demand production - Extending applications to print spare parts directly in-situ	Cybersecurity risks (CAD drawing piracy)
Suitable for small production volumes	Not fit for mass production

Table 15: SWOT-Analysis AM general (modified from Al-Makky et al. 2016)

3.1.1 Strengths

One of the biggest strengths of AM is clearly the ability to print or manufacture complex parts and geometries where the material is only applied where it is actually needed. Furthermore, this geometry can be changed and adapted from part to part, which brings a huge benefit when it comes to part optimization. (Al-Makky et al. 2016) Another advantage is that the higher complexity in shape does not mean that the manufactured part gets more expensive. (Buchmayr et al. 2015) Even though the possible complexity of parts is enormous, there are still restraints and the design of the manufacturing needs to be planned very accurately.

Due to the possible complexity in shape, this manufacturing method also reduces the material waste by the decreased amount of work steps and tooling, which is needed. This waste material can be up to 70% of the total material used for conventional manufacturing a complex part. (Sharma 2017) For example, cavities can be created to a certain extend by AM. Apart from the material waste, which is not necessary, the reduction in assembly time and the disappearing of the tooling reduces the time. The main strength is the reduction in process steps to achieve a specific geometry. (DigitalAlloys 2018c)

Apart from this flexibility regarding the shape of the part, the flexibility of the AM production facility regarding different objects is a significant strength of this technology, as numerous different parts can be manufactured from different materials with the same machine. Therefore customized products become affordable. The relatively small size of this facility also creates the opportunity to be independent regarding the location.

3.1.2 Weaknesses

Regarding the weaknesses, it needs to be mentioned, that the poor or rough surface finish is always dependent on the printing method and parameters as well as the material used. If necessary, post-processing jobs can improve surface smoothness and add finer features, which initially may not be possible. Those secondary operations to enhance the as-printed state lead to additional costs and also time. (DigitalAlloys 2018b)

Another shortcoming of AM is the difficulty of in-process quality control, which means that if an error occurs during the manufacturing process, the part is still completed. The error is only, if it is not a visible failure, recognized when testing the properties of the created part. (Buchmayr et al. 2015) Technologies that cover this weakness are already under development and explained in Chapter 4.7.1.

The costs of metal AM is one of the most significant issues when trying to apply it. Therefore, the use of AM instead of conventional manufacturing needs to have another benefit. This benefit could be possibly increasing product performance or saving time by reducing the lead. The production speed itself is also low compared to conventional mass production, but it is again necessary to apply this technology in the right area. (DigitalAlloys 2018b)

The biggest weakness is the questionable reproducibility and the lack of standardization. Different printing processes and process parameters lead to different properties of parts manufactured out of the same material. Therefore, those parameters and the processing needs to be standardized. The mechanical properties may also vary with the size and shape, which means that every newly designed part needs to be tested and evaluated. Furthermore, the already mentioned lack of in-process monitoring alters the risk of defects. (DigitalAlloys 2018b)

The most significant limiting factor when it comes to the design of an AM part is the dimension of the part. The size of the building chamber controls this. Even though we mentioned that the possible part complexity in design is an advantage of AM, there are still some limiting factors:

- Minimum wall thickness
- Minimum pin diameter
- Maximum hole sizes
- Escape holes (remove unmolten powder from hollowed parts)
- Overhanging surfaces
- Unsupported Edges
- Aspect ratio
- Achievable tolerance

The absolute values of these properties are dependent on the machine and the material used. (Redwood/Taken from 3D Hubs website)

Another weakness of AM is that there are still not that many materials available and when new material is used, the parameter selection process can take some time. The variety of strength, composition and finishing procedures is necessary to extend the areas where AM can be applied. Not all materials can be processed into powders. (DigitalAlloys 2018b)

3.1.3 Opportunities

The general opportunities of AM are most probably in the area of creating complex and customized tools and the usage of high-tech material.

AM also has a significant advantage for part optimization as the shape can be changed more precisely and weight reductions can be performed, to sum it up with this technology the freedom of design is drastically increased. Parts with a complex structure are probably the area where AM is most competitive with conventional manufacturing as usually for conventional parts, post-processing is necessary or some shapes are simply not possible. Because of these reasons, AM is already a fixed part of the manufacturing chain of medicine and aerospace industry. (Camisa et al. 2014) Parts can be manufactured in one step, with shapes that can only be achieved conventional when multiple parts are produced and then assembled. This results in additional assembly time. The higher freedom of design connected with the possibility to adapt the design from part to part is a big benefit when it comes to part optimization and also to reduce the weight of a part. (DigitalAlloys 2018a)

Figure 34 shows the optimization of an antenna bracket, where AM was used to manufacture the whole bracket as one piece. This leads to a reduction in assembly time. Furthermore, the design was adapted to reduce weight.

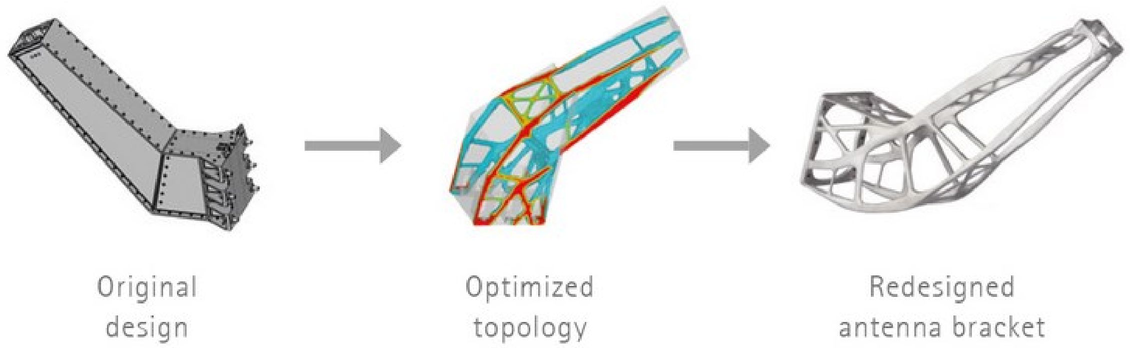


Figure 34: Design optimization of an antenna bracket (courtesy EOS GmbH)

Prototyping is also an application where AM has big advantages and is already used a lot, as it can be performed rapidly without the need for constructing or adapting a machine. Therefore, AM can accelerate product development. Not only prototyping but also to manufacture low production volumes with AM is competitive, as no expensive tooling is necessary.

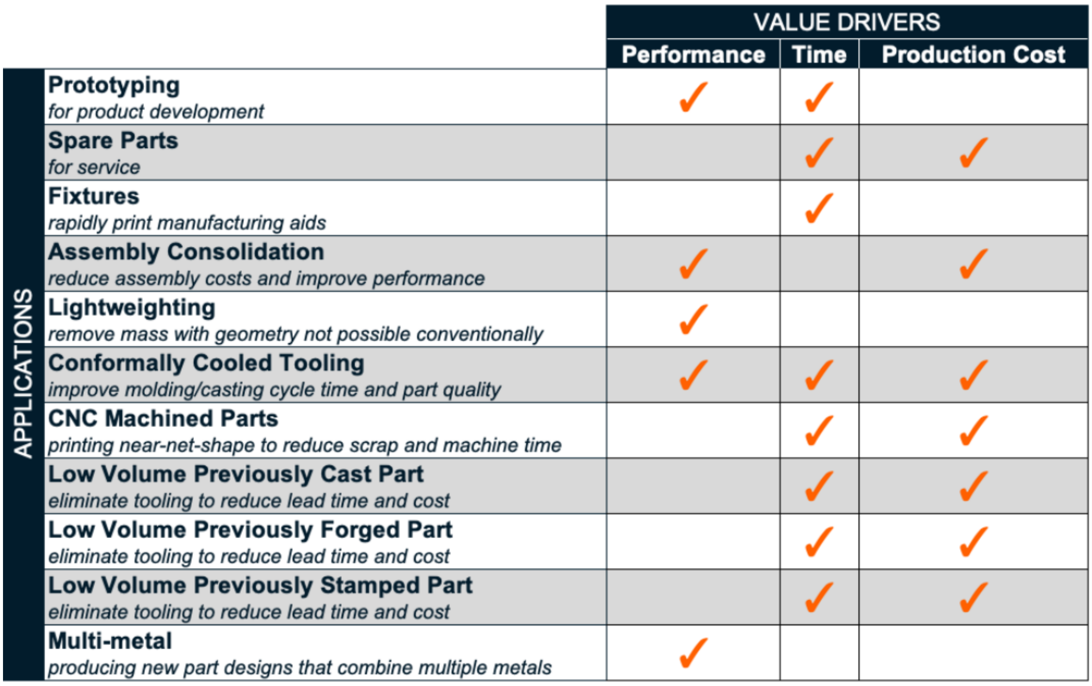
One big opportunity for AM, but still mostly under research, is also the possibility to include electronics, batteries and to combine materials. (Al-Makky et al. 2016)

The ongoing development regarding AM is a massive opportunity for customers as well as for the manufacturers. The application areas will increase with the creation of new material powders as well as with the development of quality control within the manufacturing process. Furthermore, if the possibilities of this technology are more and more recognized and integrated into the engineering world, the market for AM will also increase. Another point is that with further development, the costs per unit will decrease, which increases the ability to compete with conventional manufacturing. (Buchmayr et al. 2015)

The opportunities of in-situ spare part manufacturing and the lead-time reduction will be discussed in the oil and gas industry analysis as it plays a more significant role in this sector.

AM is, of course, not suitable to replace conventional manufacturing completely. It is an efficient and helpful complement, which, when it is used in the right area, is able to reduce time and cost as well as to increase the possibilities for the user. So AM should be used in the supply chain together with conventional manufacturing, based on their individual advantages. (Buchmayr et al. 2015)

The general opportunities, respectively, the applications of AM are summed up in Figure 35. Furthermore, on the right site, the benefits of using this technology in this area are shown.



	VALUE DRIVERS		
APPLICATIONS	Performance	Time	Production Cost
Prototyping *for product development*	✓	✓	
Spare Parts *for service*		✓	✓
Fixtures *rapidly print manufacturing aids*		✓	
Assembly Consolidation *reduce assembly costs and improve performance*	✓		✓
Lightweighting *remove mass with geometry not possible conventionally*	✓		
Conformally Cooled Tooling *improve molding/casting cycle time and part quality*	✓	✓	✓
CNC Machined Parts *printing near-net-shape to reduce scrap and machine time*		✓	✓
Low Volume Previously Cast Part *eliminate tooling to reduce lead time and cost*		✓	✓
Low Volume Previously Forged Part *eliminate tooling to reduce lead time and cost*		✓	✓
Low Volume Previously Stamped Part *eliminate tooling to reduce lead time and cost*		✓	✓
Multi-metal *producing new part designs that combine multiple metals*	✓		

Figure 35: Applications for AM (DigitalAlloys 2018a)

3.1.4 Threats

Threats of AM are, of course, the reliability and also the reproducibility, which therefore is also a safety question. A failure of a critical part due to a defect can lead to accidents and risk of injury. Some legal aspects make the usage of AM parts difficult, like the necessary testing or how to ensure the quality of the printed part, as well as the necessary in-process quality control. Additional intellectual property concerns, if parts are reproduced, can show up and become a problem. (Al-Makky et al. .2016)

One of the biggest threats is the lack of standardization regarding AM, so there are a lot of different values and expectations of properties as well as a significant amount of parameters that can be changed, e. g. layer thickness, laser intensity, the time between two layers. This lack of certainty or the result variation makes it very difficult to use the parts in a safe way and to print additional samples for testing with every part manufactured, is very costly and time-consuming and, therefore, not a permanent solution. It is possible that if we compare two different AM parts of the same material with the same heat treatment or without any and we have completely different mechanical properties. (Jacobs 2016) All these issues are reasons that quality control is essential and the problem with in-process monitoring was already mentioned along with the weaknesses.

CAD files and models will become the goal of piracy, which leads to intellectual property issues. The possibility that AM can be used to manufacture things like guns or weapons is also a big concern. (Al-Makky et al. 2016)

The fact that AM is not competitive in mass production regarding the costs per unit is generally correct and also the time it takes to manufacture one part usually takes longer. However, it is always dependent on the application and how urgent the part is needed. Also, the price per unit is not always higher. For low production volumes, the cost per unit could be less for AM than for conventional manufacturing. For large production volumes, these changes. (Conerly 2014)

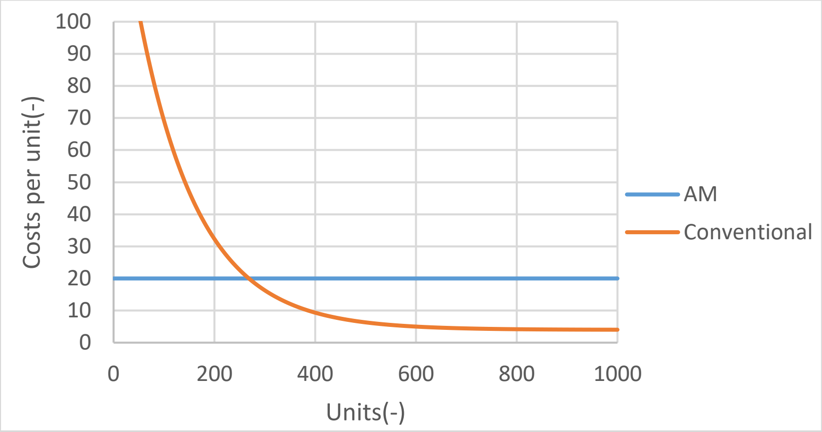


Figure 36: Hypothetical cost per unit comparison

3.2 SWOT-Analysis Oil & Gas industry

As indicated in the previous part in this chapter, the strengths, weaknesses, opportunities and threats of using AM in the oil and gas industry should be highlighted. Some points overlap with the general SWOT-Analysis. The influence of this technology in this industry is also difficult to express because a company can occupy different roles, as a customer or a manufacturer. Table 16 shows the SWOT-Analysis for AM in the oil and gas industry. The points from the table are discussed in detail afterwards.

Strengths	Weaknesses
Complex shapes and part optimization	limited powder suitable for the oil and gas industry
Flexibility – different parts	Time-consuming parameter testing required
Low production runs	Consistency-Reproducibility
Less supplier dependent – in-house manufacturing	Tolerances and accuracy
Less part stock – reduction of dead capital	Low acceptance of new technologies
Opportunities	**Threats**
High price objects – low amount	Reliability of the parts and standardization
Downtime/Lead time reduction	Quality control procedures
Reduction of warehouse size and part on stock	Safety
Design optimization	Post-processing
Reverse engineering	

Table 16: Swot analysis for the use of AM in the oil and gas industry

3.2.1 Strengths

For the oil and gas industry, complexity and optimization are not the most critical strengths of AM. There are still some areas where a customized part is necessary or adds a benefit as well as in the research and developing sector for new parts. Also, the creation of parts that need to be assembled if they are conventionally manufactured but can be printed as one can mean a benefit for the industry as the assembly time gets reduced. (Taken from GE Additive website)

The more interesting point is the flexibility which is achieved with AM because of a wide range of parts which can be created with one starting material and only one machine. So with one AM unit, a lot of different spare parts can be covered. Furthermore, if we assume that an oil and gas company uses the AM technology by itself, they become a "manufacturer", which means that they are no longer dependent on suppliers in some areas. In this case, due to the benefits of AM, the low production volumes are also not an issue. In general, it is possible to decrease the steps required in the manufacturing chain. (Sharma 2017)

3.2.2 Weaknesses

The powder availability is still a challenge for the oil and gas industry as many alloys and high-quality stainless steel are usually used in the other branches, like the medicine or aerospace sectors. The material needs of the oil and gas industries are quite different from them and the materials need to withstand very harsh environments like high pressure, temperature and corrosive agents. Additionally, if a new powder is available, it is still necessary to evaluate and test the properties of parts out of this powder with different manufacturing parameters to select the right ones. This process is again time and cost consuming. (Jacobs 2016)

For the usage of AM in the oil and gas industry, especially as a manufacturer, it needs to be sure that the consistency is ensured. Every part manufactured the same way, needs to have the same mechanical, chemical and physical properties. Also, the properties within the parts need to be constant. These points are still a weakness of AM technologies. (DigitalAlloys 2018b)

Tolerance and printing resolution is also an important thing which needs to be considered. Some parts need to be manufactured very accurately to make sure that they fit and perform as they should. The resolution is strongly dependent on the technology used as well as the material and the parameters. If the tolerances cannot be obtained as-printed, the part needs to be post-processed, which needs additional time and tools at the manufacturing location. (DigitalAlloys 2018d)

Another weakness or challenge which is not directly related to AM but more to the whole oil and gas industry is a low acceptance, respectively, the problematic implementation of new technologies. The oil and gas industry was generally plodding regarding the usage of innovative technologies to optimize the performance and increase the efficiency of their projects. The approach "if it is not broke, do not fix it" is no longer state of the art and innovative and ambitious technologies need to be integrated into the industry, especially in those challenging times. (Gates 2018) AM with its unique possibilities and improvements can have a positive impact on the productivity and efficiency of a company. However, it is possible that in the short term basin, the oil and gas industry will rely on AM service providers before implementing this manufacturing method in-house, which is related to significant expenditures.

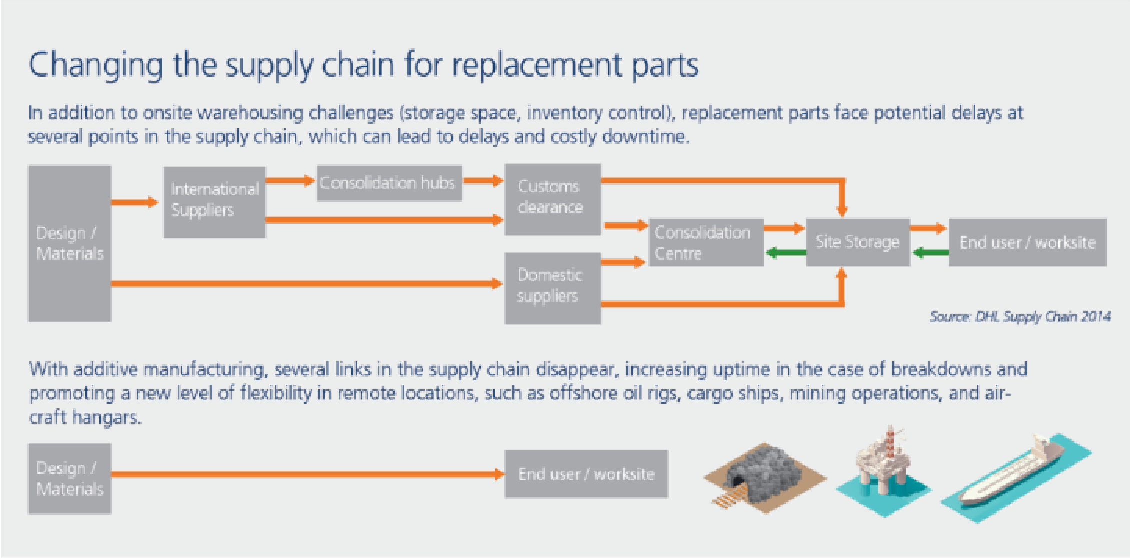
3.2.3 Opportunities

The opportunities of AM in the oil and gas industry vary a lot because, on the one hand, the many different fields within the industry have other challenges and desires, like research and development or maintenance. On the other hand, the technology itself offers different possibilities and chances.

The general approach to describe the biggest opportunity of AM and the area where it is highly competitive to conventional manufacturing is “high complexity/low units”. Therefore it needs to be mentioned that with the complexity, it is meant that a part has low material and high manufacturing costs, as with conventional machines, more manufacturing processes are necessary. (Sharma 2017)

The most significant opportunities for AM in the oil and gas industry is the use of this technology regarding spare part management and lead time reduction. Stocking and the according strategy is extremely important, especially downturns increase the desire and the pressure to reduce the inventories of spare parts. However, the right stocking is delicate because overstocking, too much or unnecessary spare parts, so to say, means that many company resources are bound within the spare parts. Understocking, whereas means that in case something breaks and the necessary spare part is not available in the company, it needs to be ordered and brought to the location. This could lead to significant downtime and, therefore, a loss of revenues. (Taken from GE Additive website) If AM is implemented in the spare part management of the company, it could reduce the warehouse stocks significantly by on-demand printing. So the certain spare parts which can be manufactured with AM technology are removed from the warehouse. It is still necessary to store powder, but the advantage is that the application of the powder is flexible and not committed to one specific part. Therefore, the overall bound capital on spare parts can be reduced. Other terms for this on-demand manufacturing are “Rapid Manufacturing” or “Direct Digital Manufacturing”. (Gibson et al. 2015)

Further development would be to manufacture the part not only on-demand but on-site. So an AM facility is placed at strategic points or even directly at a production plant or the rig, then time and logistic effort to bring a necessary part to the location can be further minimalized. (Silva et al. 2013) This is also especially interesting for the oil and gas industries as many operations are conducted in remote locations, like offshore, the arctic or in the desert, where the logistics are incredibly challenging and time-consuming. When a critical part has a failure, it is possible that a spare part needs to be flown many miles to the rig or the production facility. (Taken from GE Additive website) So this reduced lead time and supply chain enhancement by AM can save much money. The import of parts can also lead to longer lead times in certain countries. (Silva et al. 2013) The independency on part suppliers, reduction in logistics and the flexibility regarding the manufacturing location offer the possibility to enhance the supply chain. Possible supply chain improvement is shown in Figure 37.



Changing the supply chain for replacement parts

In addition to onsite warehousing challenges (storage space, inventory control), replacement parts face potential delays at several points in the supply chain, which can lead to delays and costly downtime.

Source: DHL Supply Chain 2014

With additive manufacturing, several links in the supply chain disappear, increasing uptime in the case of breakdowns and promoting a new level of flexibility in remote locations, such as offshore oil rigs, cargo ships, mining operations, and aircraft hangars.

Figure 37: Supply chain comparison – conventional and AM (Lloyd's Register 2017)

Another strength of additive manufacturing is "Reverse Engineering", where a part is optically or tactile scanned and recreated as a model and afterward printed. This is a big opportunity for in situ spare part manufacturing as well as to recreate parts that are no longer available on the market. By editing the digital model, optimizations and adoptions can be performed to increase the efficiency or the suitability of the part. The recreation of such a model will take time, but after it is created one time, it can be used for infinite parts. (Buchmayr et al. 2015)

3.2.4 Threats

The threats of using AM are very similar to the general ones. There are mainly legal and regulatory issues. There are no clear standards and the lack of reliability of the properties of the products can be a safety risk. As health safety and environment (HSE) is an essential part of the oil and gas industry and the risk should always be minimized, this is, of course, a huge issue. There needs to be further development and strategic quality control to integrate AM in the supply chain. (Jacobs 2016)

With the role change of the company from a customer to a manufacturer, it can print their own parts without being dependent on a supplier, but the design of the part is still the intellectual property of the original manufacturer. Even though reverse engineering is, in general, not prohibited, there still can be issues with patent owners of parts or if it is allowed to print parts for own use. So there are still some legal aspects or license arrangements that have to be clarified and made to use the model and the part or if it is allowed for personal use. (Taken from GE Additive website)

The possible need for post-processing is also a threat regarding the use of AM in the oil and gas industry. This means that additional equipment and expertise are necessary and that makes it more challenging to establish an AM unit directly on location.

An additional point is that it is essential to evaluate which parts are suitable for AM, as there are some shortcomings and limitations from the manufacturing as well as on the legal side. The selection of an appropriate part, in order to ensure that manufacturing it with AM technologies, leads to a benefit is described in Chapter 4.2.

3.3 Conclusion – SWOT-Analysis

The SWOT analysis showed that the opportunities of AM in the oil and gas sector differ a bit from the general ones. The remote operating locations, together with the losses due to downtime, lead to the fact that AM is a strong tool to improve the spare part management and to reduce lead-times. Especially if it is considered to use a mobile manufacturing facility, for example, in a shipping container, to realize on-demand and on-site production of spare parts, this flexibility is a massive benefit of AM compared to conventional manufacturing techniques. The possibility to create complex designs and optimize it is shifted a little bit in the background for this industrial sector.

However, the analysis showed clear areas where AM technology needs to be improved to be able to integrate it into the supply chain of a company fully. It is necessary that the output of this technology is reliable and that it is safe and also legally approved to use it in the field. Therefore the manufacturing process needs to be standardized. To describe it exaggerated, the next important step in the development of this technology is that it finds its way from a high-tech one part creation technology to an accepted or common manufacturing process with clear standards and reliable output.

Chapter 4 Workflow

In this chapter, a possible workflow and the different process steps from a needed part to the delivery of an AM one should be described. A lot of internal and external factors influence those steps. The general approach for this is called reverse engineering, where an existing part is used to create a 3D model to manufacture a new part.

4.1 Overall Workflow

The process of creating an adequate AM is strongly dependent on the actual situation and the available technologies as well as facilities in the company or the service provider. As already mentioned, the geographical location where the part is needed and the location of the manufacturing facility have much impact. Logistics plays a massive role in spare part management and lead-time reduction. A general overview of the different steps which are necessary from the identification of a needed part to the delivery of the AM replacement is shown in Figure 38.

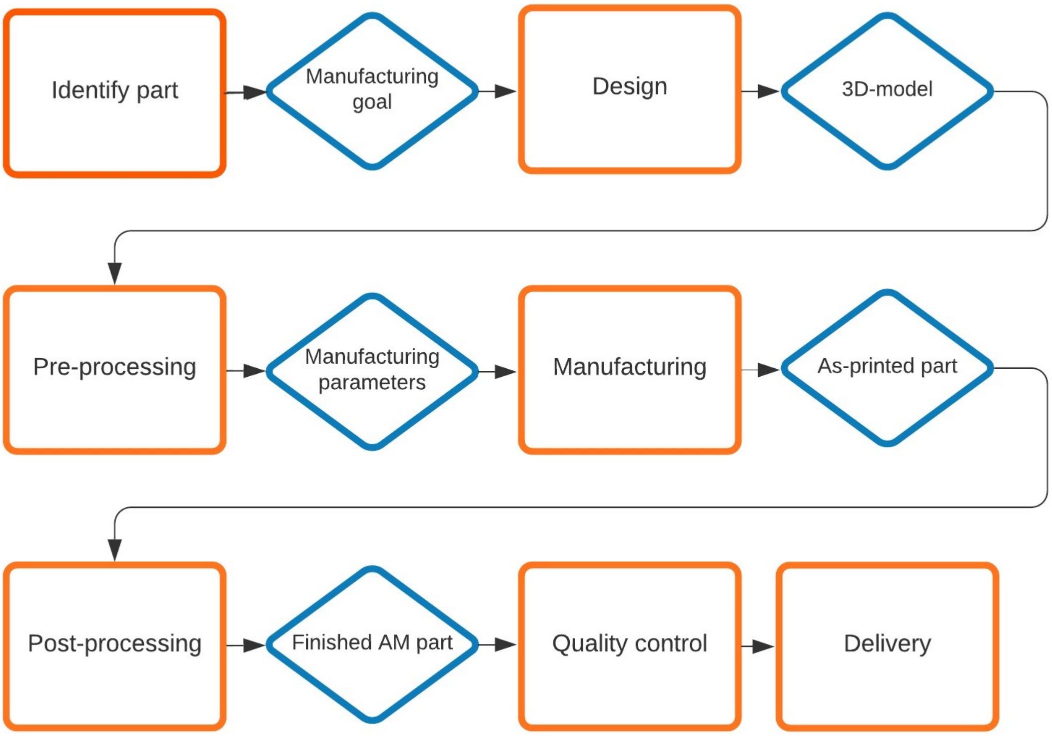


Figure 38: Workflow for an AM spare part (orange square = process step, blue rhombus = sub-target of every process step)

4.2 Identify part

For identifying the right part for AM, two things need to be considered. On the one hand, the technical limitations of AM and, on the other hand, the benefit gained due to it. Identifying the part should already start before a specific part fails because it is beneficial to decide in advance if this part can be produced using AM.

4.2.1 Technical limitations

With technical limitations, it is meant that it is necessary to evaluate if the available AM technology can print a specific part. This is dependent on the size of the part and if the design is not hurting the manufacturing limitations. Those were presented during the SWOT-Analysis in Chapter 3.1.2. Another factor is the available powder material and if its properties fit the needs of the part. These attributes restrict the selection of candidates for AM and have to be fulfilled. Otherwise, the part cannot be manufactured using AM. (Knofius et al. 2016)

4.2.2 Improvement

The second aspect is more of an economic issue. Therefore, it needs to be evaluated if manufacturing a part with AM brings a benefit to the company. This benefit can be a reduction in costs, a decrease in downtime or to secure the supply of spare parts that are no longer produced.

The reduction in costs can be due to a reduction in the manufacturing costs itself. This is mostly relevant for low volume costs where AM has the advantage that setup and tooling costs of the machines get reduced. Another point is the reduction of the costs for the safety stocks, so the number of parts, which have an extended lead time but also a small demand, can be reduced and the bound resources of the company are decreased. An additional possibility of how AM can also reduce the costs is if the manufactured spare part has a higher mean time between failure (MTBF), due to part optimization or the possibility to manufacture complex parts. (Gibson et al. 2015)

The downtime reduction can be achieved by improving the supply chain by increasing the responsiveness. On-demand manufacturing can secure the part supply while reducing the warehouse. Especially if a part is no longer produced, the security of supply is a significant benefit. In case the AM unit is close or directly where the part is needed, the time and costs for logistics get reduced enormously. With conventional manufacturing, it was necessary, that if an essential part failed, to emergency-ship it or to have an inventory close to the facility. Another possibility to use AM parts is to overcome lead times if a spare part is necessary it is manufactured additive, even though the properties of this part are lower, and used till a conventional part is delivered at the location. In general, it can be summarized that with AM, an oil and gas company is less dependent on suppliers and can reduce bound resources by adding flexibility to their supply chain. (Walter et al. 2004)

A summary of the improvement areas, where AM brings a benefit related to spare part attributes, is presented in Table 17.

Spare part attributes	Improvement potential						
	Reduce manufacturing/ order costs	Reduce direct part usage costs	Reduce safety stock costs	Improve supply chain	Postponement	Temporary fix	Reduce effect of supply disruptions
Demand rate	Low		Low		Low		
Resupply lead time			Long	Long	Long	Long	
Agreed response time			Short	Short		Short	
Remaining usage period		Long					
Manufacturing/ order costs	High						
Safety stock costs			High		High		
Number of supply options	Few			Few			Few
Supply risk				High			High

Table 17: Spare part properties correlated to improvement potential (orange=reduce costs, green=reduce downtime, blue=secure supply; Knofius et al. 2016)

4.2.3 Spare part ranking

The selection of an appropriate part is somewhat subjective and, therefore, a ranking method would be beneficial. The ranking method can also be split into technical limitations and the benefit of AM for the company. The first ones are so-called Go/No go attributes, which means that the part can either be printed or not, according to technological constraints. There are basically two attributes that need to be considered regarding that, the material type and the part geometry, especially the size. The classification of the benefits is a little more complicated. The attributes of the spare parts need to be weighted according to the company goals. (Knofius et al. 2016) Figure 39 presents an example of a weighting system, for an oil and gas company, it is presumed that the percentage of reducing downtime is even higher and the cost reduction lower.

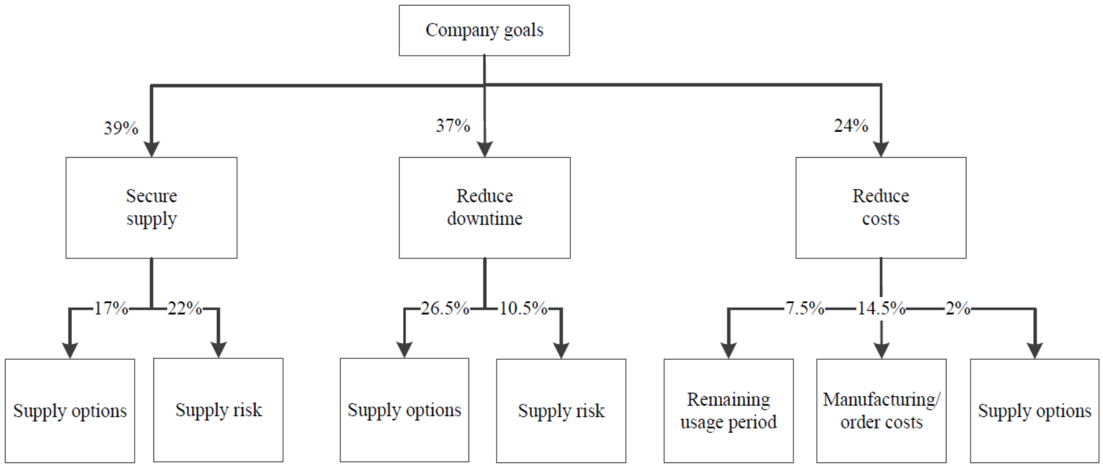
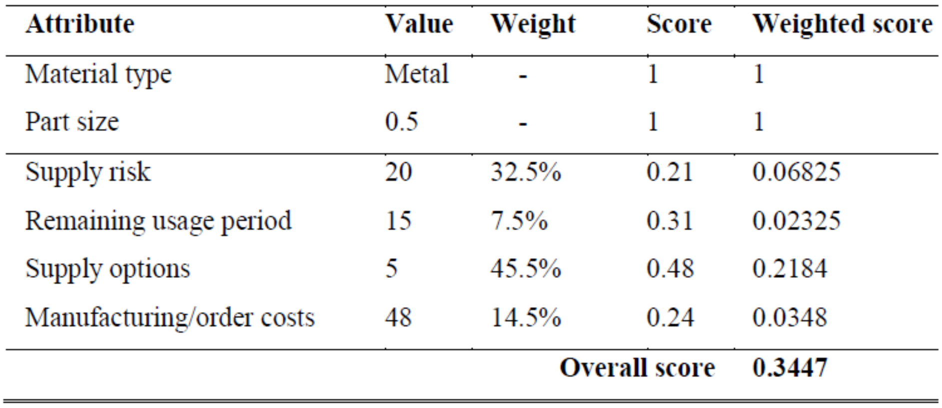


Figure 39: Example of attribute weighting (Knofius et al. 2016)

It is still necessary that the score for each attribute needs to be assigned individually and is, therefore, also subjective. The established score is then multiplied with the weighting to ensure the consideration of the company goals in the ranking. All the values are then summed up to get an overall result. The value for the technical limitations is either 0 or 1, as there is no grading on how good a part can be manufactured. The ranking method helps to compare different spare parts regarding the benefit of manufacturing it with AM. One example of a ranking for a potential spare part is shown in Figure 40. (Knofius et al. 2016)



Attribute	**Value**	**Weight**	**Score**	**Weighted score**
Material type	Metal	-	1	1
Part size	0.5	-	1	1
Supply risk	20	32.5%	0.21	0.06825
Remaining usage period	15	7.5%	0.31	0.02325
Supply options	5	45.5%	0.48	0.2184
Manufacturing/order costs	48	14.5%	0.24	0.0348
			Overall score	**0.3447**

Figure 40: Example score of a spare part (Knofius et al. 2016)

4.3 Design

Even though designing is maybe not always the right word to describe this step, for every part which is manufactured using AM, a 3D-Model needs to be created at least once. This process can be quite different as the goal can be to either design a completely new part or to recreate an existing part as precisely as possible. However, it is necessary to have a Computer-Aided Design (CAD) of the part that needs to be manufactured. (Gibson et al. 2015)

To design a completely new part, it is always necessary that, even though the complexity of parts that can be created using AM is very high, the balance between part functionality and manufacturability needs to be considered. The design capabilities are always dependent on the material and technology used. For part optimization, it is nearly identically as an existing design that needs to be adapted digitally. The limiting factors in design were already discussed.

For using AM to recreate an existing part, there are different approaches and ways how the model can be available. They can be diverted into scanning, drawing, database or license solutions, as shown in Figure 41. The selection of the method is mostly dependent on the part and the actions which were taken in advance. There are a lot of legal issues that need to be addressed before recreating a part like copyright protection but also technical issues to ensure a correct spare part. The details of the different ways are presented below.

Regardless of which scenario is present and the method used during this process, the output should be a 3D CAD file of the object which needs to be manufactured.

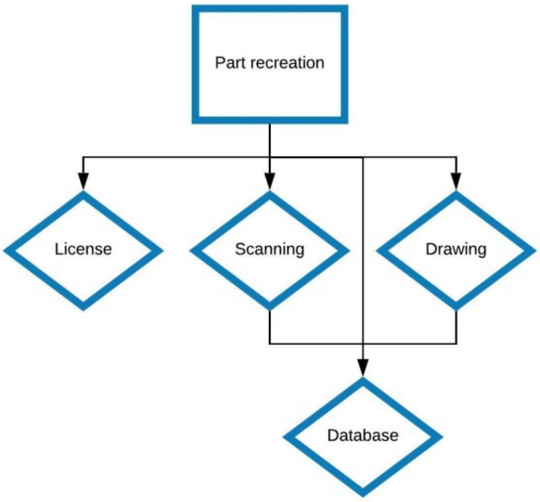


Figure 41: Overview of spare part model options

4.3.1 Scanning

Scanning is usually the method used if a part needs to be replaced and there is no existing model available only the needed part which needs to be recreated because it failed or to create a model already in advance. The result is usually a point cloud and then recreating a 3D model out of those measured points. However, different technologies are available to perform this measurement, which have different concepts and therefore vary in their application field. A general classification system of different 3D scanning techniques is presented in Figure 42. (Chougule et al. 2018)

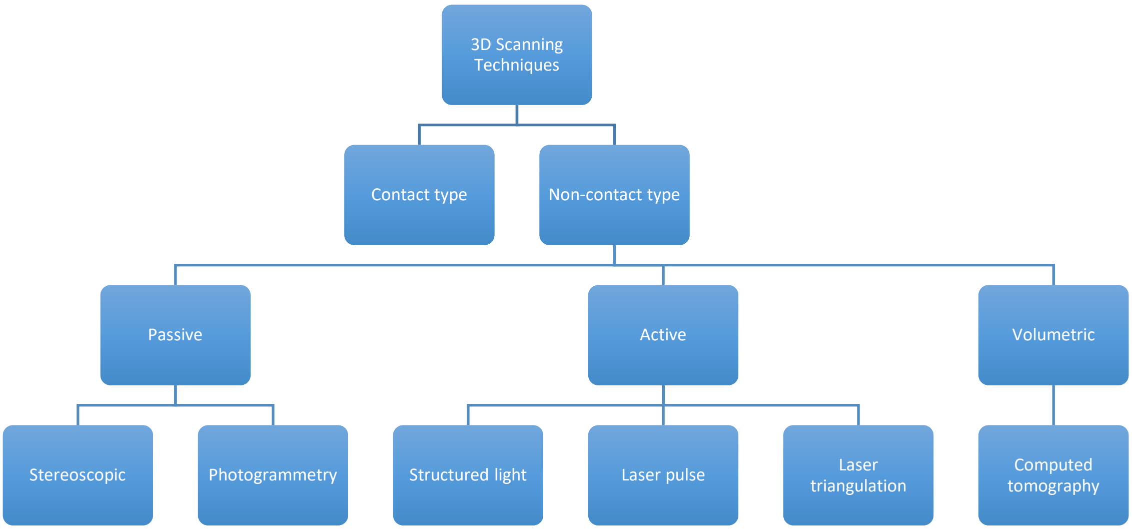


Figure 42: 3D scanning techniques classification (adapted from Chougule et al. 2018)

Some common methods are compared regarding time, cost and accuracy in Table 18. Creating a model to manufacture a technical spare part with AM, especially the accuracy, is extremely important. (Chougule et al. 2018)

Types	Major Hardware	Time required	Cost	Accuracy/ resolution
Laser triangulation	Line laser, camera, processor	High	Low	Medium
Structured light	Projector, two cameras	Low	High	High
Photogrammetry	Camera, processor	Low	Low	Low
Laser pulse	Laser source, Laser Detector	High	Low	High
Contact based	Measuring probe	High	High	High

Table 18: Comparison of different 3D Scanning Techniques (Chougule et al. 2018)

One problem with the creation of appropriate models from scans is if there are internal structures that cannot be seen from outside. In such a case, the optical methods and contact-based reach their limits. Below the working principle of the different methods is explained.

4.3.1.1 Contact

The principle of contact-based scanning techniques is rather simple, as the name already indicates it uses the physical contact between the probe and the object to get the surface information. The probe gets moved over the surface and slightly deformed by the contact. The disadvantage of this method is that the probe needs to be able to get to the whole surfaces, which is especially tricky for internal structures. However, this method can also be used for transparent or reflecting objects in contrast to many other methods. The accuracy of this method is relatively high, but it is also very time-consuming. (Arrighi 2020)

4.3.1.2 Photogrammetry

For photogrammetry based methods, it is necessary to take several images from different views and angles, with a reference point. The model is then created out of the images via software. The object needs to be a clear and well-lit place. This method is rather time and cost-efficient, but the accuracy is not high compared to other methods. (Chougule et al. 2018) There are also applications and software available which allow it to use a phone camera to take the images for the 3D model. The idea itself would be interesting primarily if it can be used directly at a rig or production facility in case a part breaks, where no model is available.

4.3.1.3 Stereoscopic

Stereoscopic scanning is a passive method that uses two cameras. The concept is mirroring the human visual system. With the two different 2D pictures, it is possible to estimate the position of a point on the object with triangulation. (Lanman et al. 2009)

4.3.1.4 Structured light

At structured light scanning, a light grid pattern is projected by a stable light source onto the object, which needs to be scanned. Cameras are used to measure the deviation of the grid in response to the object and convert the results into coordinates for the model. (Raychev et al. 2017)

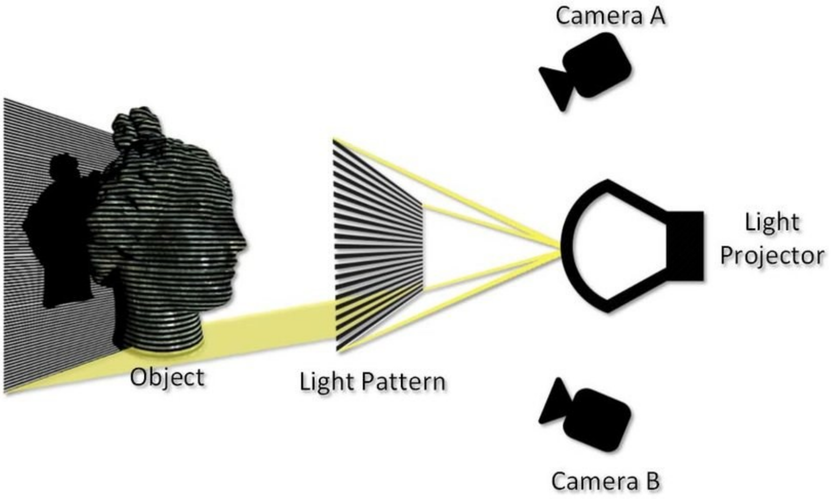


Figure 43: Working principle of structured light scanning (Raychev et al. 2017)

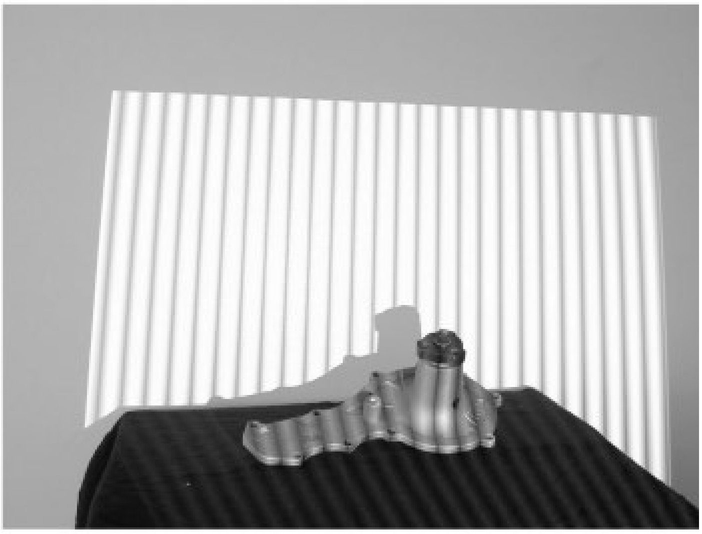


Figure 44: Example of a structured light Scanning (Page et al. 2005)

4.3.1.5 Laser pulse

Laser pulse-based scanners are also often called time of flight scanners. With the laser, the distance to the object is measured by emitting a laser pulse to the object and timing the trip time of the reflected light until it reaches the detector. The position of the laser needs to be changed or mirrors need to be used to track different points. (Page et al. 2008)

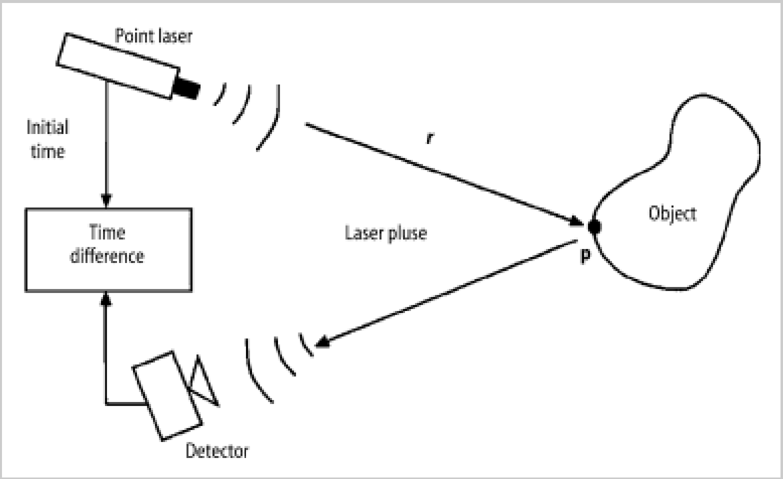


Figure 45: Working principle of a laser pulse or time of flight system (Page et al. 2008)

4.3.1.6 Triangulation

For triangulation scanning, a laser is used to emit a point onto the surface. The camera recognizes the point and with that, the distance can be measured over the calibrated and measured angles. It is therefore called triangulation, because the laser source, the camera and the object form a triangular. (Page et al. 2008)

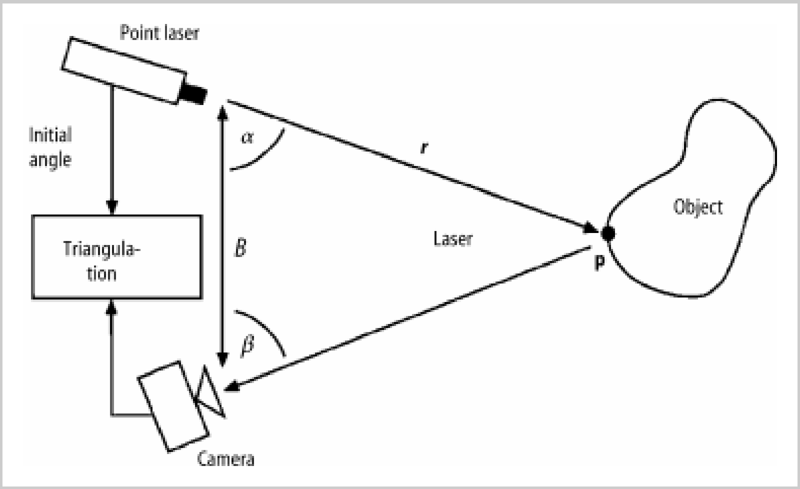


Figure 46 Working principle of a triangulation system (Page et al. 2008)

4.3.1.7 Computed tomography

X-ray computed tomography (micro CT) can be used to create a model of the necessary object, including their internal structures. The difference between a micro CT scanner and a medical CT scanner is that the micro CT has a smaller scale and a higher resolution. The resolution can be up to one micron. (Bagnell 2018) A CT scanner works with X-rays, which are shot through the object. A part of the X-rays is absorbed by the object, depending on the density. The detector measures the returning portion. The object is placed on a rotating platform to get this information from all angles. Not only surface information can be derived from that, but also internal structures can be scanned. Due to this possibility, CT scanning is also a method for non-destructive inspecting an AM part. This usage is further explained in Chapter 4.7.2. A problem with CT scans can be the limited dimension of the object, which is restricted by the detector size and the energy of the X-rays. Especially for high-density parts, like the metal parts in the further project, the energy needs to be high enough. (Ramsey et al. 2017)

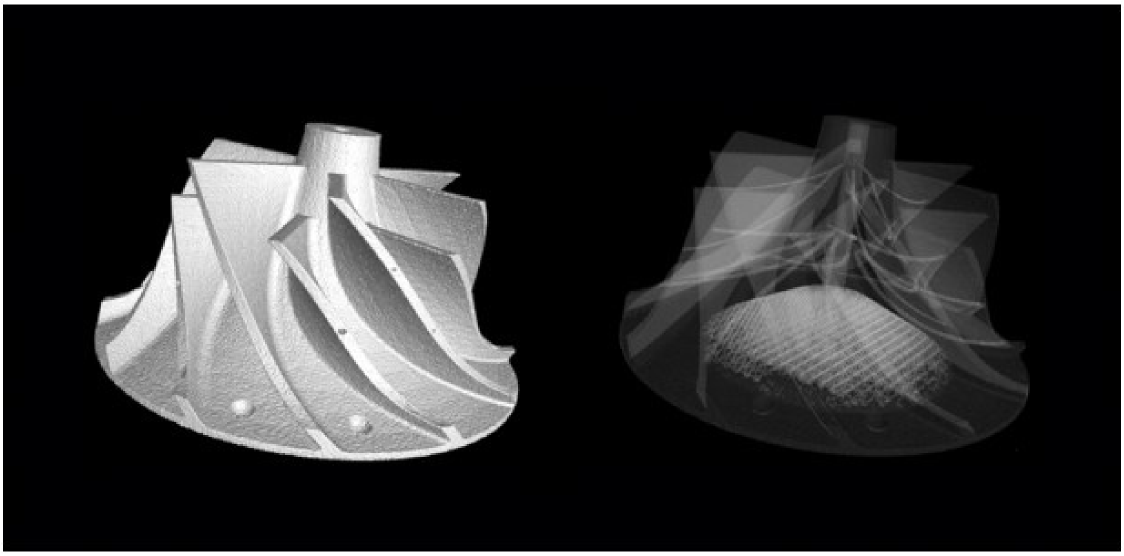


Figure 47: CT scan of an AM to recreate the surface as well as to detect internal flaws (Ramsey et al. 2017)

4.3.2 Draw

A rather simple concept would be to create the model from scratch. Therefore, it is necessary to measure the properties of the desired part and recreate it with a modeling software. The disadvantage and shortcomings of this method are that it can be challenging to be precise and to recreate complex structures. It is as well very time consuming and requires adequate personnel. On the other hand, no tool or scanning technology is necessary except for the software.

4.3.3 Database

The part database implements a system where the work of "design" or rather model building is already performed before the part is actually needed. So all parts which fulfill the properties to be created by AM are modeled as soon as possible. Every new part, which is used in the company, should be either scanned or delivered with a model. Therefore the name database, all models, would be stored within the company. So in case a part fails or a part is needed for any other reason, the necessary models are available and this saves a lot of time. Still, it is necessary to do the work once and keep the database updated. The significant advantage of AM is that if the model is owned once as many parts as necessary can be manufactured.

4.3.4 License

Another way to get the model of a part is to integrate or arrange a licensing system or sometimes also called the "iTunes" approach. The company would pay the owner of the CAD data to use it. Therefore, it would be secured that the exact right design is used. The time, which is needed to scan and to prepare the model of the part disappears. Also, the necessary expertise and technology inside the company are reduced. (Taken from GE Additive website)

One way to perform such an approach is to use Blockchain-technology for encoding and licensing data, a technology that is mainly used in the finance sector to prove the authenticity of financial transactions. Figure 48 shows such a concept with an example, where "Alice" is the owner of the printing data and the model and "Bob" wants to manufacture four parts. The technology secures that only Alice and Bob can read the information and the AM production unit only starts printing when the license is verified. So, therefore, it is necessary to include the machine suppliers to ensure a secured transfer from the copyright holder to the manufacturer and implement a so-called chain of trust for AM. (Martin et al. 2017)

Figure 48: Licence concept using Blockchain-Technology (Martin et al. 2017)

4.3.5 Project – Impeller model

For the ongoing project, the next step would be the recreation of an impeller used at OMV E&P. For this part, the modeling phase is quite challenging, as there is no model from the manufacturer available. The big difficulty with recreating a model of the impeller is the inner blades that cannot be tracked by the visual scanning methods completely. A possible solution is to scan the part as far as possible and to interpolate the rest of the part using CAD software. Another possibility would be, is to cut the impeller in half to scan it separately and then generate the model out of those two. For this method, the part needs to be destroyed and is therefore attractive if a part is already broken. Computed tomography is also capable of scanning the inner surface, even though the machine used needs to be able to have sufficient energy for metal parts.

Figure 49: Impeller similar to the one which should be produced using AM (Indiamart 2020)

4.4 Pre-Processing

The purpose of the pre-processing phase is to create a connection between the design and the manufacturing process. The 3D CAD file, which was created in the previous step needs to be transformed into instructions for the AM machine. Therefore, the model needs to be edited by a "slicer", a software that creates layers out of the design and a toolpath for the manufacturing process. (DigitalAlloys 2018c)

Additionally, it is necessary to evaluate if a support structure is necessary and to design it. Support structures are not a functional part of the AM end-part. They are necessary to hold the part in place and to overcome the limits, which were already indicated in Chapter 3.1.2, especially overhangs and hollow parts need a support structure. These structures are not only used to ensure a stable printing process but also to transport the heat and therefore reduce the temperature difference and the residual stresses due to the manufacturing process. The design of support structures is essential as they should fulfill their primary purposes, but it is also crucial that they can be removed easily. This means the contact area between the support structure and the AM end-part should be kept small. This ensures that it can be removed easily and the surface quality of the part is not affected too much. There is also software available which plans the support structure automatically, but it can have problems with complex geometries and can overestimate the necessary structure. (Järvinen et al. 2014)

Figure 50: Support structure attached to an AM part (3D Hubs/Redwood 2018)

Another important step within this pre-processing phase is to define the parameters for manufacturing. These parameters have to be defined before printing for the used material and the testing phase is very time-consuming. Nevertheless, this parameter selection is critical as the mechanical properties can be susceptible to these parameters. (Gibson et al. 2015) The AM parameters which have an influence on the properties are presented in Figure 51. The process parameters are still a critical issue when it comes to industrial use of AM, the lack of standardization for these parameters leads to a wide variety of possible results.

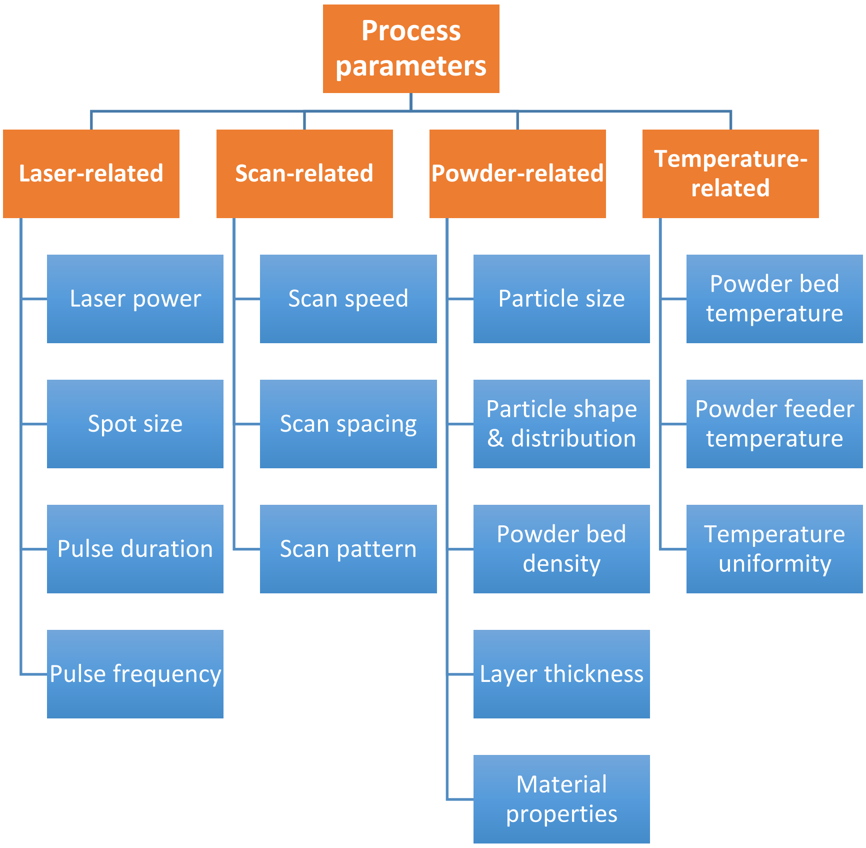


Figure 51: Process parameters (Aboulkhair et al. 2014)

Apart from planning and setting up the instructions and the parameter design, the machine needs to be prepared for the manufacturing process. It is necessary to load and align the build plate, the atmosphere in the printing chamber needs to be prepared and the feedstock of the machine needs to be filled with the selected metal powder. The metal powder needs to be handled as they are probable toxic, flammable and their susceptibility to oxidize. (DigitalAlloys 2018c)

4.4.1 Project – Impeller Pre-Processing

Regarding the manufacturing of the impeller for the further project, several supports are required due to the complex geometry. The support structures are necessary to build the hub of the build platform and in the flow path of the impeller, shown in Figure 52, where Laney et al. (2016) created an impeller segment using AM.

Figure 52: Support structure of an AM impeller (Laney et al. 2016)

4.5 Manufacturing

The manufacturing method itself, SLM, was already discussed in Chapter 1.1 from a technical perspective. From an operational point of view, the manufacturing or printing process itself is the step that needs the least attention. During this step, the machine works on its own and no operator is required. The time for this process is strongly varying. It can take minutes to many days to manufacture the part. This is depending on the part size or rather height but also on the technology used and the selected parameters, especially layer thickness and scan velocity. (DigitalAlloys 2018c)

The possibilities for an oil and gas company are varying on the grade of implementation of AM technologies into their supply chain. Especially in short term use of AM, there will be some restrictions as implementing in-house technologies is connected to high costs. The lowest level of implementation is to use the parts produced by contractors, respectively, other companies. Another option for them would be to use AM technologies to manufacture their own parts. The highest level of implementing AM into the supply chain would be to manufacture parts directly on-site at the drilling operation or the production facility.

4.5.1 Rig-site

One way to realize such on-site manufacturing is to use shipping containers as a remote AM facility. Containers can be transported easily to remote locations or offshore platforms. Furthermore, they are big enough to hold the necessary equipment and are able to withstand harsh environmental conditions. By including these containers in a rig move, a large number of spare parts could be manufactured on-site and therefore reduce the expensive downtime in case a part fails. (Lloyd's Register 2017)

Figure 53: On-site AM essentials (Lloyd's Register 2017)

An overview of the total equipment, which is necessary to realize such a remote AM facility, is presented in Figure 54. There are five main types of equipment that need to be included.

First of all, design equipment, which includes a laptop that controls the AM machine is necessary. In case the part model is not in the database or a license agreement is available between the company and the manufacturer, scanning equipment is also necessary. The usage of photogrammetry could, therefore, be an interesting option for the future, if the accuracy is sufficient.

Consumables that are mainly gas, which is necessary to create the required atmosphere in the build chamber and the metal powder with its related equipment, are also necessary.

The AM machine is, of course, an important part, this tool can also fit inside the container even though the actual size varies strongly with the AM method used.

Another important point which is also crucial is the post-processing equipment. This includes machines to perform a heat treatment or tooling equipment, for example, to remove support structures.

The last group is safety equipment, which is also necessary due to the fact that the person who is working there can be exposed to metal powder, gas, flammable materials or high voltage.

AM Stage/Component Group key 🟦 Design ■ Consumables 🟧 Build 🟩 Post-processing 🟪 Safety

Laptop and docking station
Needed to send AM machine readble design files to the AM machine.

Powder storage
The material required for AM is in powder form. It is important that metal powders are stored in their original, sealed (vendor-supplied) containers in a designated dry storage area. Preferably inside an approved metal, flammable storage cabinet that is cool, dry, and ventilated. The cabinet should protect against physical damage and be isolated (with a door) from sources of heat, ignition, moisture and contamination.

Gas supply
Gas supply (typically bottles) are required in the printing chamber to create a controlled, inert environment. This is commonly done with argon or nitrogen.

Powder recycling unit
The fine metal powder that is used for laser melting is expensive so waste should be avoided (for both financial and environmental reasons). Due to the inert environment within an AM machine it might be possible to sieve and reuse the metal powder.

AM machine (printer)
The most crtitical and expensive asset of the setup. With several options available, the size of the machine will depend on the process (e.g. laser, PBF, FDM), source, build material and build envelope.

Power source
To be able to run all the required machines the container will require a significant amount of power, therefore it is important to have a strong power source connected to the container.

Humidity and temperature control
The permitted room temperature when the system is in operation is limited to 20°C to 25°C when there is a 60% humidity and between 25°C and 30°C when there is a 45% humidity When the system is not in operation the temperature may vary between 10°C and 40°C and the humidity may vary from 20% to 80% (See NIST 1801). In order to control these variables additional air conditioning may need to be installed.

Compressor (air blower)
After the product build, air compression is the best method to remove unfused metal powder, particularly after Powder Bed Fusion.

Heat treatment
As the laser moves, the melted metal will cool more rapidly at the surface of the melt pool than at the causing variations in the parts microstructure. Heat treatment can remove residual stresses and disperse the tension accumulated during manufacturing by carrying out a stress relieving heat treatment. With a second heat treatment it is also possible to increase the strength and durability of an AM produced parts.

Post-processing and finishing
Some form of finishing (driling, milling, turning, smoothing) will likely be required. The finishing tool and process must be non-sparking to prevent the risk of fire and explosion due to the metallic powder.

Personal Protection Equipment (PPE)
Protective Clothing: Protective Clothing should be worn when there is a risk of skin coming into contact with metal powder. Rubber gloves (e.g. latex), steel-toed safety shoes and a standard lab coat willsuffice for cases where heat is not an issue. When moving hot build platforms or if there is a greater potential for fire (e.g. using aluminium / titanium alloys), the user should wear heat-resistant clothing (welding gloves, etc.).
Respirators: To protect the user from inhaling metal powder the user should wear the proper breathing apparatus. For particles smaller than 20 microns it is essential that a self-contained breathing apparatus is used. For particles bigger than 20 microns a mask respirator will be sufficient.
Protective glasses: To protect the user from metal powder or other small particles (during finishing for example.

Fire extinguisher
To protect the user in case of a fire a fire extinguisher (class D) should be present in the room. Due to the weight and size of the extinguisher it is advised that this is positioned on the ground and placed so the extinguishing medium is able to reach all areas of the container without the cylinder being moved.

Anti-static floor mat
An anti-static floor is required to insulate workers, protecting them from potentially deadly shocks generated by high voltage equipment.

Gas detection and extraction
The inert gas in the printing chamber presents a hazard to personnel if inhaled. For this reason it is essential to remove the gas before opening the chamber, and on detection of a gas leak, a detection and protection system must be in place. Since Argon is heavier than air, a suggested solution is to install a ventilator on a wall at the top of the container as an air inlet, and an extraction (outlet) for the air at the bottom of the container. Any emergency exits within the confined space must open outwards in order to mitigate the risk of suffocation from a gas leak.

Figure 54: On-site AM essentials – explanations (Lloyd’s Register 2017)

The exact equipment that is necessary is always depending on the technology which is used and the parts that need to be created. A broader spectrum of spare parts and different materials also leads to more machines and consumables that are required.

4.5.2 Manufacturing plant

Oil and gas companies also have the possibility to create manufacturing plants at specific strategic locations, for example, in countries where the import of parts is time-consuming. The advantages of this would be that with one plant, more rigs and production facilities can be provided with parts and more equipment, as well as expertise, can be concentrated at specific points. Therefore, a wider range of parts could be manufactured. The oil and gas companies would be less dependent on external suppliers or an excessive warehouse. One disadvantage is that compared to the on-site manufacturing, there is more logistic effort and the possibility for more extended downtimes.

4.5.3 Service/Part provider

The most straightforward use of AM parts in the supply chain is to outsource the manufacturing process. The advantage of this method is that the expertise and equipment are not required within the company and a specialized company provides the parts. The disadvantage is that a considerable strength of AM gets lost because the flexibility and the logistic benefit can be lost. Even though the manufacturing process is outsourced, there is still a lot of planning and testing to do. The project showed that the material requires a lot of testing and the parameters need to be evaluated. This means that it can take some time in case this is not prepared in advance.

4.6 Post-Processing

The post-processing of AM part plays a huge role, but the variations are again huge between different post-processing operations. This process step can lead to a drastic increase in the overall production time and costs. The most frequent operations which need to be performed during post-processing are removal of the support structures, accuracy or aesthetic improvements and techniques to improve the mechanical properties of the AM part. (DigitalAlloys 2018c)

Not only the support structure needs to be removed when powder-based technologies are used, but also the loose powder around the manufactured part. Usually, the part is taken out of the building chamber and the remaining loose powder is removed using brushes, compressed air and light bead blasting. There are also automated or semi-automated systems available nowadays, which are directly integrated into the machines. If a part requires a support structure due to its geometry, this structure needs to be removed in this process step. For metal AM, they can be quite strong, even though they are kept as little as possible. Therefore, the usage of band-saws, cut-off blades, wire electrical discharge machining (EDM) or other metal cutting methods can be necessary. (Gibson et al. 2015) Additionally, the produced AM part needs to be removed from the build plate, which can be performed with similar techniques.

It can be necessary to improve the surface texture or the accuracy for performance and tolerance reasons. The improvement of the surface texture can be necessary due to the stair steps because of the layer-based manufacturing process, powder adhesion or marks from the removed support structures. The type of method which is used is dependent on the desired outcome. For a simple improvement and a mate structure, bead blasting can be good enough. To achieve a polished surface, wet or dry sanding and manual polishing are necessary. There are also some automated methods, like abrasive flow machining, which can be used to improve the internal surface. Certain parts were a high accuracy is necessary, which cannot be reached with the AM technology used, can also be machined to reach the desired outcome. This can be achieved using techniques like milling. (Gibson et al. 2015)

To reach the desired mechanical properties of a metal AM part, heat treatment is used. Therefore, conventional heat treatment can be used to improve or change these properties. The results of a conventionally manufactured part and an AM part treated with the same heat treatment are varying, which means that the selection of the right one requires testing. Additionally, to conventional heat treatment procedures, special techniques for AM parts were developed. In Chapter 2.9, HIP treatment was already discussed. This method is used to increase the density of the AM object by reducing the porosity within the part. During the HIP treatment, pressure is applied together with temperature to achieve this outcome. (Gibson et al. 2015)

Many AM parts that might be used in the oil and gas industry will require post-processing operations to meet the desired properties. The selection and planning of the different technologies used are extremely important as they lead to a significant increase in the costs and time of the whole manufacturing process.

4.6.1 Project – Impeller Post-Processing

Apart from the heat treatment to meet the necessary mechanical properties, the support structures of the planned impeller need to be removed. Laney et al. (2016) removed the support structure mechanically from there impeller after the heat treatment. They still had a residual roughness from the structure, which can be seen in Figure 55. To improve the surface further and reach a smooth flow path, abrasive flow machining is recommended.

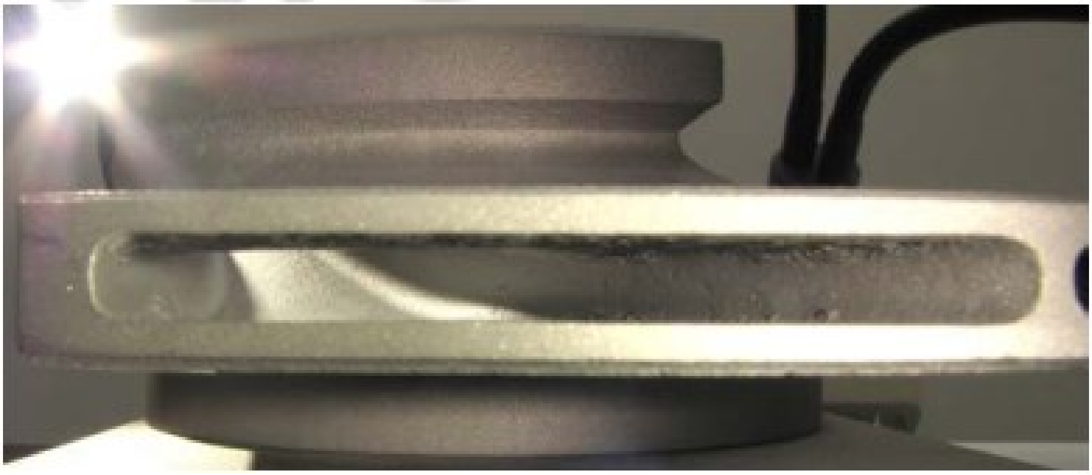


Figure 55: Post-processed impeller – supports were removed (Laney et al. 2016)

4.7 Quality assurance and control

One thing which was already shown during the testing phase is that quality assurance, respectively, control is an essential part that creates a lot of issues and uncertainties. However, the limited reproducibility of the properties makes it essential. As there are no manufacturing standards and the result vary strongly with process parameters but also with the hard to control in-process differences. (DigitalAlloys 2018c)

A high standard of AM parts can only be reached if quality assurance and control are performed adequately. Quality assurance is important during the whole process change and even in advance, it is necessary that parameters, the material and all activities are planned and structured according to a precise procedure or standard. It is also necessary that the equipment is maintained correctly and the staff is trained. Quality control also starts during the manufacturing process with in-process monitoring but also measures to make sure the requirements are fulfilled. (Wang et al. 2012)

4.7.1 In-process monitoring

As already mentioned during the SWOT-Analysis, the difficulties regarding in-process monitoring is a weakness of AM. One control factor is to observe the melt pool. Optical monitoring systems can be used to track the geometry of the melt pool area. Thereby it is possible to detect process failures and pores. By implementing an infra-red camera into the system, the process can be monitored more precisely by capturing the temperature distribution in the melt pool and measure the influence of scanning speed and laser power. Closed-loop systems were also developed to adapt the process parameters during the manufacturing process to improve the quality of the part. (Chua et al. 2017)

4.7.2 CT Scan

CT scanning would be an alternative method, for quality assurance, to destructive testing. With a micro CT scanner, it is possible to recognize if voids and inclusions, like pores, contaminations or cracking, are present and how big they are. Furthermore, with such a scanner, it is possible to check the dimensions of the part and if it fits the requirements. With this method, the part can be checked for failures during the manufacturing process without destroying it. (Ramsey et al. 2017) Therefore in case, it is tested that a particular AM part with no defects has defined properties and it can be ensured, using CT methods, that the next produced one has no defects, those properties can be anticipated.

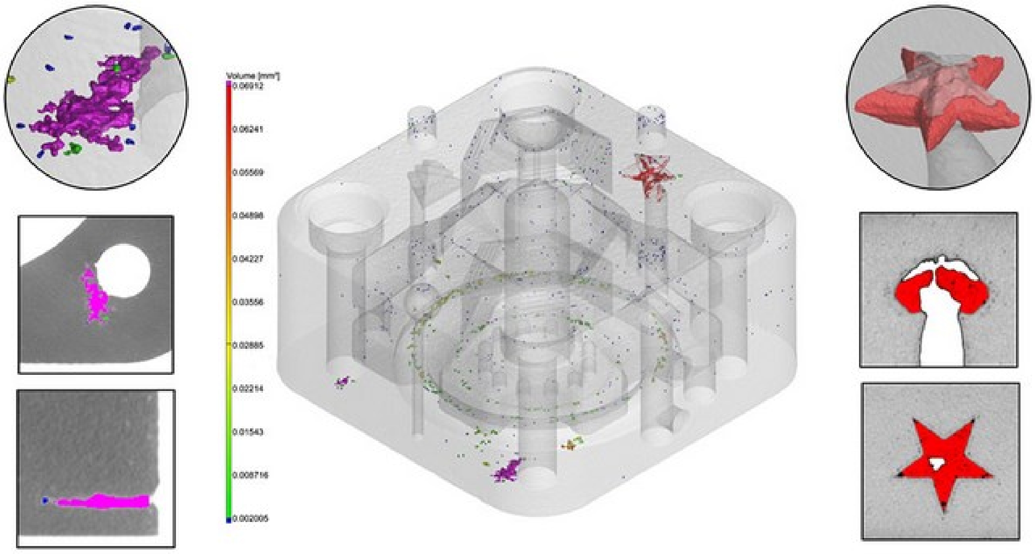


Figure 56: CT scan of an AM aluminium block – Purple indicates porosity and missing material, red indicates unfused powder (Delphi Precision Imaging website)

4.8 Delivery

The delivery of the AM part is the last point in the process chain, which is usually not a big deal, but especially in the oil and gas industry. This can be the decisive factor for using AM. During the manufacturing step of the workflow, the different levels of implementations were pointed out. Drilling and production projects are carried out in remote locations, where the logistic effort is enormous. This leads to downtime and costs. Therefore, on-site manufacturing would be an enormous advantage when it comes to delivery. Not only are logistics important when it necessary to deliver the part, but also administrative issues need to be considered when a part needs to be imported to a particular country. (Taken from GE Additive website)

4.9 Outcome - Workflow Oil and Gas industry

The workflow showed the never-ending possibilities in the process of AM. Many decisions need to be taken and planning is required to implement this manufacturing technique into the supply chain of an oil and gas company.

First of all, the selection of the components and spare parts is a critical point. If we look at the steps which are required till a part can be printed, it would be best to decide already in advance if a part should be replaced using AM or if a conventional spare part should be on stock. At least it is necessary to define the materials which should be used to evaluate and select the manufacturing parameters and the properties of the results. The reason for this is the time that is necessary to produce these parameters and to test it. Further development and especially standardization within the AM sector will help to reduce the necessary time and will increase the flexibility and reduce the time to implement new AM parts.

The creation of an appropriate 3D model is usually only a bit of an issue if it is a part of a complex internal surface. Otherwise, different scanning technologies are already well developed. For the oil and gas industry, especially portable scanning systems can be interesting. However, the most important thing is to reach a high accuracy, which should be the main criteria for the selection. Photogrammetry, where it is only necessary to take pictures on the rig site of the broken part to create a model, would be an exciting outlook for the future. However, a licensing system where the model is bought from the owner is still the most accurate way and requires the least equipment. If it is decided already in advance which parts are possible for AM, the scanning process can be done immediately and the model is fed into the database, at best, already with the defined manufacturing parameters. In case this part is needed, it is only necessary to transmit this data to the manufacturing unit.

Post-processing will also be a challenge when it comes to on-site manufacturing, as there are a lot of different possibilities that require different equipment. Post-processing is an essential part of AM, which is necessary to reach the desired outcome. Especially in the oil and gas industry where the parts need to withstand a harsh environment and have to meet exact tolerances to fit or to be even gas-tight. Also, special AM post-processing methods like HIP can bring a lot of benefits and need to be considered when using AM for producing parts.

Workflow

The further development in in-process monitoring and quality control technologies will lead to a safer use of AM parts. A reliable object is essential for the oil and gas industry and therefore, the reproducibility needs to be ensured.

Conclusion

AM offers a wide variety of possibilities for oil and gas production and service companies. The benefits regarding lead-time reduction or decrease the resources bound in warehouses. Due to these opportunities, AM will play a role in the future of this sector. However, until AM fully accomplishes the transition from a prototyping to a standard manufacturing method, a few insecurities need to be eliminated.

The lack of standardization and the big differences in process parameters and technologies make it hard to predict the properties of the manufactured part. It would be necessary that the same parameters and settings are used or given to ensure continuity. The material tests showed that not only the microstructure of the AM part is different compared to a conventionally manufacture one but also the behavior and the according properties. When selecting the right material for an AM part, it is, therefore, not always best to take the same material as for the conventionally manufactured part. The tested AM material showed significantly lower hardness and tensile properties compared to a conventional one. The increase in hardness, which was achieved via HIP-treatment, indicates that the possibilities are high and the evaluation and improvement of the material are critical.

Apart from the standardization, the repeatability of the AM parts is a problematic factor. This manufacturing method is vulnerable to small failures within the manufacturing process. The occurrence of defects or pores within the structure can lead to a drastic decrease in performance and need to be monitored. Especially the oil and gas sector, with its harsh environment, including pressures, temperature and sour media, requires reliable parts.

AM will not replace conventional manufacturing totally, but this is not the purpose of implementing this technique. Integrated into the supply chain of a modern oil and gas company, the benefits are, compared to other industry sectors quite different. The possibility to create complex shapes and the freedom of design are pushed a little bit in the background. As the reduction of costly downtime is a primary goal of every company, AM is an interesting technology. Using on-demand or even on-site manufacturing ensures the security of supply and fast spare parts without overstocking. This means the bound company resources within the warehouse can be decreased. This just-in-time approach is a huge advantage of AM and increases the flexibility of a company. Selecting the right parts for AM is essential, on the one hand, to ensure to gain a benefit out of using this technology and, on the other hand, to follow the design limitations of AM.

For implementing AM into the supply chain, the basic concept and the process steps are already well defined and known. The unique capabilities of AM technologies offer the possibility to realize this on-site manufacturing from the beginning to the end. The only issue is still the lack of standardization to ensure that the usage of the parts is safe. The technology also requires a lot of different equipment and expertise, from the beginning, the modeling of the part over pre-processing and manufacturing to post-processing. Especially in the beginning, it is probably better to implement AM step by step into the company to gain expertise and knowledge. If AM works probably and also standardization is present on-site manufacturing totally feasible.

AM will find its way into the oil and gas industry in the future and will then contribute to higher productivity and efficiency with its flexibility regarding the producible parts, the achievable geometries and the opportunity to transport a factory. This technology will offer the possibility to manufacture spare parts just-in-time and reduce downtime effectively.

Appendix A Test results

A.1 Prepared specimens

Material	Test	Dimension	Amount	Comment[6]
AM	Metallography	~ 20 mm	9	Kalling: 1 Z 1 R 1 T; V2A-Stain: 1 Z 1 R 1 T; SEM: 1 Z 1 R 1 T
AM	Hardness	~ 20 mm	3	1 Z 1 R 1 T
AM	Tensile	90 mm 15 mm diameter	5	3 L 2 T
AM	Charpy	55 mm 10 mm 10 mm	6	3 L 3 T
AM	SSC	100 mm 10 mm diameter	3	afterwards 2 additional
AM	HIC	100 mm 20 mm 20 mm	2	
Conv	Metallography	~ 20 mm	6	Kalling: 1 L 1 Q; V2A-Stain: 1 L 1 Q; SEM: 1 L 1 Q;
Conv	Hardness	~ 20 mm	2	1 L 1 Q
Conv	Tensile	90 mm 15 mm diameter	2	
Conv	Charpy	55 mm 10 mm 10 mm	3	

Table 19: Specimen preparation – necessary material

A.2 Tensile test

Specimen	Rp0.2 (MPa)	Rm (MPa)	A40 (%)	Z (%)
AL 1	630	1,227	13.9	26
AL 2	627	1,219	13.7	23
AL 3	693	1,228	16	27
AQ 1	616	1,228	17.8	44
AQ 2	653	1,256	15.6	29
CL 1	1,260	1,425	14.6	49
CL 2	1,260	1,414	13.5	54

Table 20: Tensile test results

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[6] Comments: Directions according to nomenclature and used etchant.

A.3 Charpy-V notch impact test

Specimen	Energy (J)
CL 1	15
CL 2	15
CL 3	10
AL 1	25.5
AL 2	22
AL 3	25
AQ 1	22
AQ 2	20
AQ 3	23

Table 21: Charpy-V notch impact test results

A.4 Hardness test

Specimen	Method	Hardness (HV)
KL 1	HV 10	446
KL 1	HV 10	448
KL 1	HV 10	450
KL 1	HV 10	450
KL 1	HV 10	448
KL 1	HV 10	431
KQ 1	HV 10	444
KQ 1	HV 10	444
KQ 1	HV 10	444
KQ 1	HV 10	452
KQ 1	HV 10	420
KQ 1	HV 10	440
AR 1	HV 10	343
AR 1	HV 10	321
AR 1	HV 10	354
AR 1	HV 10	321
AR 1	HV 10	364
AR 1	HV 10	320
AT 1	HV 10	342
AT 1	HV 10	353
AT 1	HV 10	332
AT 1	HV 10	357
AT 1	HV 10	353
AT 1	HV 10	327
AZ 1	HV 10	327
AZ 1	HV 10	333
AZ 1	HV 10	341
AZ 1	HV 10	329
AZ 1	HV 10	331
AZ 1	HV 10	315

Table 22: Hardness test results

Bibliography

A01 Committee. 2019. “Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes.” ASTM International. https://doi.org/10.1520/A0564_A0564M-19A.

Aboulkhair, Nesma T., Nicola M. Everitt, Ian Ashcroft, and Chris Tuck. 2014. “Reducing Porosity in AlSi10Mg Parts Processed by Selective Laser Melting.” *Additive Manufacturing* 1–4 (October): 77–86. https://doi.org/10.1016/j.addma.2014.08.001.

Al-Makky, M., and D. Mahmoud. 2016. “THE IMPORTANCE OF ADDITIVE MANUFACTURING PROCESSES IN INDUSTRIAL APPLICATIONS.” *The International Conference on Applied Mechanics and Mechanical Engineering* 17 (17): 1–14. https://doi.org/10.21608/amme.2016.35288.

Arrighi, Pierre-Antoine. 2020. “3D Scanning Technologies and the 3D Scanning Process.” ANIWAA. February 27, 2020. https://www.aniwaa.com/guide/3d-scanners/3d-scanning-technologies-and-the-3d-scanning-process/.

ASM International, ed. 2002. *Atlas of Stress-Strain Curves*. 2nd ed. Materials Park, OH: ASM International.

Bagnell, Ann. 2018. “What Is Micro-CT? An Introduction.” Micro Photonics. February 23, 2018. https://www.microphotonics.com/what-is-micro-ct-an-introduction/.

Bahadori, Alireza. 2017. *Oil and Gas Pipelines and Piping Systems: Design, Construction, Management, and Inspection*. 1st edition. Cambridge, MA: Elsevier.

B.B.S. i Halmstad AB. 2020. “Hardness Conversion Table.” Bbshalmstad. 2020. https://www.bbshalmstad.se/en/infocenter/hardness-conversion-table/.

Bournias-Varotsis, Alkaios. n.d. “3D Printing vs. CNC Machining | 3D Hubs.” Accessed May 25, 2020. https://www.3dhubs.com/knowledge-base/3d-printing-vs-cnc-machining/#selecting.

Buchmayr, Bruno, and Gerhard Panzl. 2015. “Eine SWOT-Analyse zum Einsatz der Additiven Fertigung für metallische Bauteile.” *BHM Berg- und Hüttenmännische Monatshefte* 160 (1): 15–20. https://doi.org/10.1007/s00501-014-0326-1.

Camisa, Joseph, Vinit Verma, David Marler, and Adam Madlinger. 2014. “Additive Manufacturing and 3D Printing for Oil and Gas - Transformative Potential and Technology Constraints.”

Cherry, J. A., H. M. Davies, S. Mehmood, N. P. Lavery, S. G. R. Brown, and J. Sienz. 2015. “Investigation into the Effect of Process Parameters on Microstructural and Physical Properties of 316L Stainless Steel Parts by Selective Laser Melting.” *The International Journal of Advanced Manufacturing Technology* 76 (5–8): 869–79. https://doi.org/10.1007/s00170-014-6297-2.

Chougule, V., H. Gosavi, M. Dharwadkar, and A. Gaind. 2018. “Review of Different 3D Scanners and Scanning Techniques.”

Chua, Zhong Yang, Il Hyuk Ahn, and Seung Ki Moon. 2017. “Process Monitoring and Inspection Systems in Metal Additive Manufacturing: Status and Applications.” *International Journal of Precision Engineering and Manufacturing-Green Technology* 4 (2): 235–45. https://doi.org/10.1007/s40684-017-0029-7.

Conerly, Bill. 2014. “The Economics Of 3-D Printing: Opportunities.” September 3, 2014. https://www.forbes.com/sites/billconerly/2014/11/03/the-economics-of-3-d-printing-opportunities/#67a1a6815021.

Coseglio, Mario Sergio Della Roverys. 2017. “Sulphide Stress Cracking of 17-4 PH for Applications in Oilfield Components.” *Materials Science and Technology* 33 (16): 1863–78. https://doi.org/10.1080/02670836.2017.1330230.

Dehghanghadikolaei, Amir, Navid Namdari, Behrouz Mohammadian, and Behzad Fotovvati. 2018. “Additive Manufacturing Methods: A Brief Overview” 5 (September): 123–31.

Delphi Precision Imaging. n.d. “Additive Manufacturing | CT & X-Ray Service |.” Delphi Precision Imaging. Accessed June 17, 2020. https://www.delphiprecisionimaging.com/additive-manufacturing-inspection.

DigitalAlloys. 2018a. “The Business Value of Metal Additive Manufacturing.” November 19, 2018. https://www.digitalalloys.com/blog/business-value-of-metal-additive-manufacturing/.

———. 2018b. “Application Criteria.” November 30, 2018. https://www.digitalalloys.com/blog/application-criteria-metal-additive-manufacturing/.

———. 2018c. “Process Steps in the Metal Additive Manufacturing Workflow | Digital Alloys.” December 13, 2018. https://www.digitalalloys.com/blog/process-steps-metal-additive-manufacturing-workflow/.

———. 2018d. “Design Rules for Metal Additive Manufacturing.” December 26, 2018. https://www.digitalalloys.com/blog/design-rules-metal-additive-manufacturing/.

Emre, Hayriye Ertek, and Ramazan Kaçar. 2015. “Effect of Post Weld Heat Treatment Process on Microstructure and Mechanical Properties of Friction Welded Dissimilar Drill Pipe.” *Materials Research* 18 (3): 503–8. https://doi.org/10.1590/1516-1439.308114.

EOS GmbH. 2009. “EOS StainlessSteel GP1 for EOSINT M 270 - Material Data Sheet.”

———. n.d. “Industrieller 3D Druck in Der Luftfahrt.” Accessed May 25, 2020. https://www.eos.info/de/3d-druck-beispiele-anwendung/innovation-stories/raumfahrt-3d-druck-satelliten-halterung.

Gates, Mark. 2018. “How to Achieve Technology Innovation in the Oil and Gas Industry - Sustainable Oilfield.” Sustainable Oilfield. September 22, 2018. https://www.sustainableoilfield.com/how-to-achieve-technology-innovation-in-the-oil-and-gas-industry/.

GE Additive. n.d. “3D Printing in the Oil and Gas Industry.” Accessed May 26, 2020. https://www.ge.com/additive/additive-manufacturing/industries/oil-gas.

Gibson, Ian, David Rosen, and Brent Stucker. 2015. *Additive Manufacturing Technologies*. New York, NY: Springer New York. https://doi.org/10.1007/978-1-4939-2113-3.

Herrmann, Konrad, ed. 2011. *Hardness Testing: Principles and Applications*. Materials Park, Ohio: ASM International.

Hertzberg, Richard W., Richard Paul Vinci, and Jason L. Hertzberg. 2012. *Deformation and Fracture Mechanics of Engineering Materials*. Fifth edition. Hoboken, NJ: John Wiley & Sons, Inc.

Hu, Zhiheng, Haihong Zhu, Hu Zhang, and Xiaoyan Zeng. 2017. "Experimental Investigation on Selective Laser Melting of 17-4PH Stainless Steel." *Optics & Laser Technology* 87 (January): 17–25. https://doi.org/10.1016/j.optlastec.2016.07.012.

Inside Metal Additive Manufacturing. 2014. "Post-Processing of AM Metal Components: HIPing." Inside Metal Additive Manufacturing. September 12, 2014. http://www.insidemetaladditivemanufacturing.com/1/post/2014/12/post-processing-of-am-metal-components-hiping.html.

Jacobs, Trent. 2016. "3D Printing in the Oil Field Kicks Into Production Mode." *Journal of Petroleum Technology* 68 (08): 30–35. https://doi.org/10.2118/0816-0030-JPT.

Järvinen, Jukka-Pekka, Ville Matilainen, Xiaoyun Li, Heidi Piili, Antti Salminen, Ismo Mäkelä, and Olli Nyrhilä. 2014. "Characterization of Effect of Support Structures in Laser Additive Manufacturing of Stainless Steel." *Physics Procedia* 56: 72–81. https://doi.org/10.1016/j.phpro.2014.08.099.

Joseph, Arthur. 2017. "Purpose of Tensile Testing." September 26, 2017. https://bizfluent.com/info-12146439-purpose-tensile-test.html.

Keshavarzkermani, Ali, Reza Esmaeilizadeh, Usman Ali, Pablo D. Enrique, Yahya Mahmoodkhani, Norman Y. Zhou, Ali Bonakdar, and Ehsan Toyserkani. 2019. "Controlling Mechanical Properties of Additively Manufactured Hastelloy X by Altering Solidification Pattern during Laser Powder-Bed Fusion." *Materials Science and Engineering: A* 762 (August): 138081. https://doi.org/10.1016/j.msea.2019.138081.

Khodabakhshi, F., M. Haghshenas, H. Eskandari, and B. Koohbor. 2015. "Hardness−strength Relationships in Fine and Ultra-Fine Grained Metals Processed through Constrained Groove Pressing." *Materials Science and Engineering: A* 636 (June): 331–39. https://doi.org/10.1016/j.msea.2015.03.122.

Knofius, Nils, Matthieu C. van der Heijden, and W.H.M. Zijm. 2016. "Selecting Parts for Additive Manufacturing in Service Logistics." *Journal of Manufacturing Technology Management* 27 (7): 915–31. https://doi.org/10.1108/JMTM-02-2016-0025.

Laney, Scot, Derrick Bauer, and Akiyoshi Ando. 2016. "Evaluation of Various Methods for Manufacturing One Piece, Small Tip Opening Centrifugal Compressor Impellers." https://doi.org/10.21423/R1KQ5P.

Lanman, Douglas, and Gabriel Taubin. 2009. "Build Your Own 3D Scanner: Optical Triangulation for Beginners."

Lewandowski, John J., and Mohsen Seifi. 2016. "Metal Additive Manufacturing: A Review of Mechanical Properties." *Annual Review of Materials Research* 46 (1): 151–86. https://doi.org/10.1146/annurev-matsci-070115-032024.

Lloyd's Register. 2017. "Portable Printing: How Do You Ship a Factory?" 25 2017. https://www.lr.org/en/insights/articles/how-do-you-ship-a-factory/?epslanguage=en.

Martin, Holland, Nigischer Christopher, and Stjepandić Josip. 2017. "Copyright Protection in Additive Manufacturing with Blockchain Approach." *Advances in Transdisciplinary Engineering*, 914–921. https://doi.org/10.3233/978-1-61499-779-5-914.

Olympus. n.d. "Nonmetallic Inclusion Analysis in Steel." Accessed April 14, 2020. https://www.olympus-ims.com/en/nonmetallic-inclusion-analysis-in-steel/.

Page, David, Andreas Koschan, and Mongi Abidi. 2008. "Methodologies and Techniques for Reverse Engineering–The Potential for Automation with 3-D Laser Scanners." In *Reverse Engineering*, edited by Vinesh Raja and Kiran J. Fernandes, 11–32. Springer Series in Advanced Manufacturing. London: Springer London. https://doi.org/10.1007/978-1-84628-856-2_2.

Page, David, Andreas Koschan, Sophie Voisin, Ngozi Ali, and Mongi Abidi. 2005. "3D CAD Model Generation of Mechanical Parts Using Coded-pattern Projection and Laser Triangulation Systems." Edited by E.R. Davies. *Assembly Automation* 25 (3): 230–38. https://doi.org/10.1108/01445150510610953.

Petzow, Günter. 2015. *Metallographisches, keramographisches, plastographisches Ätzen*. 7. leicht korrigierte Auflage. Materialkundlich-technische Reihe 1. Stuttgart: Gebrüder Borntraeger.

Pfennig, Anja, Helmut Wolthusen, and Axel Kranzmann. 2017. "Unusual Corrosion Behavior of 1.4542 Exposed a Laboratory Saline Aquifer Water CCS-Environment." *Energy Procedia* 114 (July): 5229–40. https://doi.org/10.1016/j.egypro.2017.03.1679.

Ramsey, Andrew, and Herminso Villarraga-Gomez. 2017. "The Inspection and Quality Control of Metal AM Parts with X-Ray CT" 3 (July): 105–11.

Raychev, Jordan, Georgi Hristov, Diyana Kyuchukova, and Plamen Zahariev. 2017. "Workflow for Development of a Virtual Museum That Will Provide Better Way for Learning the Cultural Heritage." In *2017 16th International Conference on Information Technology Based Higher Education and Training (ITHET)*, 1–5. Ohrid, Macedonia: IEEE. https://doi.org/10.1109/ITHET.2017.8067815.

Redwood, Ben. n.d. "How to Design Parts for Metal 3D Printing | 3D Hubs." Accessed June 15, 2020. https://www.3dhubs.com/knowledge-base/how-design-parts-metal-3d-printing/#introduction.

Sharma, Harshit. 2017. "Lucrative Use For 3-D Printing In Oil And Gas Industry." March 1, 2017. https://www.hartenergy.com/exclusives/lucrative-use-3-d-printing-oil-and-gas-industry-176387#p=full.

Silva, Jorge V.L., and Rodrigo A. Rezende. 2013. "Additive Manufacturing and Its Future Impact in Logistics." *IFAC Proceedings Volumes* 46 (24): 277–82. https://doi.org/10.3182/20130911-3-BR-3021.00126.

SLM Solutions. n.d. "Material Data SheetStainless Steel 17-4PH / 1.4542 / A564."

Snell, Robert, Sam Tammas-Williams, Lova Chechik, Alistair Lyle, Everth Hernández-Nava, Charlotte Boig, George Panoutsos, and Iain Todd. 2019. "Methods for Rapid Pore Classification in Metal Additive Manufacturing." *JOM* 72 (1): 101–9. https://doi.org/10.1007/s11837-019-03761-9.

Sola, Antonella, and Alireza Nouri. 2019. "Microstructural Porosity in Additive Manufacturing: The Formation and Detection of Pores in Metal Parts Fabricated by Powder Bed Fusion." *Journal of Advanced Manufacturing and Processing* 1 (3). https://doi.org/10.1002/amp2.10021.

Thompson, R. M., G. B. Kohut, D. R. Canfield, and W. R. Bass. 1991. "Sulfide Stress Cracking Failures of 12Cr and 17-4PH Stainless Steel Wellhead Equipment." *CORROSION* 47 (3): 216–20. https://doi.org/10.5006/1.3585248.

Thyssenkrupp. 2018. "Inspection Certificate to EN10204-3.1."

Thyssenkrupp AG. n.d. “Materialien.” Accessed February 18, 2020. https://www.thyssenkrupp-additive-manufacturing.com/de/materialien/.

TWI. 2016. “What Is a Charpy Impact Test?” November 2016. https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-charpy-testing.

Vander Voort, George F. 1999. *Metallography, Principles and Practice*. Materials Park, Ohio: ASM International.

Walter, Manfred, Jan Holmström, and Hannu Yrjölä. 2004. “Rapid Manufacturing and Its Impact on Supply Chain Management.”

Wang, Jian, James D. MacNeil, and Jack F. Kay, eds. 2012. *Chemical Analysis of Antibiotic Residues in Food*. Hoboken, N.J: Wiley & Sons.

Wang, Li, Yang Ju, Heping Xie, Guowei Ma, Lingtao Mao, and Kexin He. 2017. “The Mechanical and Photoelastic Properties of 3D Printable Stress-Visualized Materials.” *Scientific Reports* 7 (1): 10918. https://doi.org/10.1038/s41598-017-11433-4.

Winklmayr, Heiko. 2020. “17-4PH HIP@Pankl - Report.”

Zarębski, Krzysztof, Piotr Putyra, and Dariusz Mierzwiński. 2019. “Effect of Annealing on the Impact Resistance and Fracture Mechanism of PNC-60 Sinters After Cold Plastic Deformation.” *Journal of Materials Engineering and Performance* 28 (4): 2439–50. https://doi.org/10.1007/s11665-019-04017-y.

Acronyms

AL	Additive lengthwise
AM	Additive manufacturing
AQ	Additive transversal
AR	Additive radial
AT	Additive tangential
AZ	Additive building direction
CAD	Computer-aided design
CL	Conventional lengthwise
CLR	Crack length ratio
CQ	Conventional transversal
CSR	Crack sensitivity ratio
CT	Computed tomography
CTR	Crack thickness ratio
EDM	Electrical discharge machining
HIC	Hydrogen induced cracking
HIP	Hot isostatic pressing
HSE	Health safety and environment
OD	Outside diameter
SCC	Stress corrosion cracking
SEM	Scanning electron microscope
SLM	Selective laser melting
SSC	Sulfide stress cracking
WT	Wall thickness

Symbols

N_A	number of grains per square millimetre	[grains/mm^2]
G	ASTM grain size number	[-]

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