CHRISTIAN RENÉ JAKOBSEN GRASHEI

SUPERVISOR: PROF. R.M CHANDIMA RATNAYAKE MUDIYANSELAGE

Subtractive Manufacturing and Additive Manufacturing Within The Framework of LCA and The Principles of The Circular Economy

Qualifying part accordance to DNV-ST-B203

Bachelor Thesis 2024 – 20 Credits (ECTS)

B.Sc. Mechanical Engineering (Y-vei)

Faculty of Science and Technology

Department of Mechanical and Structural Engineering and Materials Science

Partners – Without You This Thesis Would Not Be Possible!

Abstract

Life cycle assessment (LCA) is the future of calculating the environmental impact of industrial processes such as additive and subtractive manufacturing. By using designated software to accomplish an easily readable scoring system and do on-demand design alterations or change manufacturing methods to get direct environmental data.

The principle of the circular economy is also discussed at the micro level, considering material handling, and some macro considerations like material waste management outside of the company structure. Discussing recyclability and how increasing sustainability by greener production can contribute to circularity.

The valve wedge part was manufactured at Stamas Solutions AS with the subtractive manufacturing method using CNC Mill, and at AM North AS using powder bed fusion laser beam method. The valve wedge was manufactured in 316L material for both processes.

The additive manufacturing categorization (AMC) was done using a chart and conducting a risk assessment of the different considerations mentioned in the DNV-ST-B203 Additive manufacturing of metallic parts standard. The findings gave a result that indicated the need for AMC 2 level testing and qualification. A BPQ was printed, and tests were conducted at Quality Lab Stavanger and at University of Stavanger laboratory facilities at Department of mechanical and structural engineering and material science. Destructive testing such as tensile, impact, hardness, micro and macrostructural, and non-destructive tests such as visual, volumetric, and surface were performed to complete the BPQ and part testing. The BPQ is to give a basis for the mechanical properties of the printed parts.

The Dassault systems: 3DExperience software was used to simulate and analyze the environmental impacts of additive manufacturing and subtractive manufacturing using the EF 3.0 impact assessment method and ecoinvent library for the LCA category processes. The LCA yielded a total environmental footprint score of 3.8e-3 points for AM, 1.30e-4 points for SM and a total difference of 3.7e-3 points. Although the AM process is 'less' environmentally friendly than the SM process trade-offs should be considered in the selection process of manufacturing methods.

The BPQ and part testing requirements according to DNV-ST-B203 was to print the testing specimens according to the SQB specifications and perform testing according to the selected AMC 2 level for the part testing requirements. The BPQ tests were as follows: Tensile, impact, hardness, microstructural analysis and macrostructural analysis. Where the results were: 464,6 MPa yield strength, 598,0 MPa UTS, 43% elongation, 60,5% reduction of area, 114 J average, 221 HV10 average, macrostructural gave visible fusion lines and weld pools as described in the standard, and the microstructural analysis at 150x gave no indication of poor material properties. Whilst for the 1kx magnification on microstructural analysis gave some indication on oxides in the structure. EBSD was also performed and gave indication on 99.3% austenitic properties in the structure and 0.7% of other phases in the material (likely to be ferrite) or badly indexed phases. Lastly, the EBSD indicates that the average grain size is around 13,8μm.

Keywords: Additive manufacturing, Subtractive manufacturing, Life cycle assessment, Circular economy, AMC, qualification, BPQ, SQB, manufacturing technology, material technology, EBSD, SEM.

Acknowledgements

Thank you to the University of Stavanger with the Department of Mechanical and Structural Engineering and Materials Science for access to labs, and to all faculty for chats, help, and guidance. Especially to Navid Sayyar and Espen Undheim for their expertise in material science, and for educating me on the subject.

Thanks to Stig Vagner Rasmussen from PLM group for valuable insights into the 3DExperience software.

Thanks to Sastry Y Kandukuri from DNV AS for providing relevant information towards qualification.

Thanks to Rolf Lohne from IKM Flux AS who provided me with valves, and valve data.

Thanks to Matteo Vanazzi from F3nice who provided me with valuable insights in recycle powder and LCA.

Thanks to Petter Lunde at Quality Group Stavanger for the express delivery of DT and NDT.

Special thanks to Pål Svanes (external supervisor), Ingrid Åsen and Ole Friestad from Stamas Solutions AS for manufacturing and various mails, discussions, meetings and LCA help along the way!

Special thanks to Jan-Inge G. Kongsbak (external supervisor) from AM North for manufacturing and all the hard work you have put in the documentation regarding AMC 2 and BPQ qualification.

An incredibly special thanks to Trine Boyer (external supervisor) from Vår Energi, without you this project would not have been possible. You opened your professional network and allowed me to participate in a large cooperative push towards AM. Also, thank you for funding this project.

Thanks to Professor R.M Chandima Ratnayake Mudiyanselage for all discussions, for always keeping your door open, and for taking this exciting project to the next level.

To my mentor and dad Jan-Tore Jakobsen, for you guidance, love and support for the last 3 years, you constantly pushing me to do my best has been essential for me achieving my bachelor's degree.

To my love Helle Skjølberg, thank you for being by my side through thick and thin and the sacrifices you have made the past 3 years while I have pursued academia are not forgotten, and I am grateful that you were by my side through it all.

To family and friends thank you for the support!

Christian René Jakobsen Grashei, Stavanger, June 5th, 2024

Table of contents

List of Figures

List of Tables

List of Equations

Nomenclature

Acronyms

AM	Additive Manufacturing
AMC	Additive Manufacturing Categorization
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CE	Circular Economy
CM	Conventional Manufacturing
CNC	Computer Numerical Controller
DED	Direct Energy Deposition
DLD	Direct Laser Deposition
EBSD	Electronic Backscatter Diffraction
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
GBW	Global Warming Potential
JIT	Just-in-time
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSS	Lean Six Sigma
PBF	Powder Bed Fusion
PBF-LB	Powder Bed Fusion – Laser Beam
PLM	Product Life Cycle Management
SEM	Scanning Electron Microscopy
SLM	Selective Laser Melting
SM	Subtractive Manufacturing

Symbols

α	Alpha
ε	Epsilon
σ	Sigma

Chemistry

C	Carbon
CO_2	Carbon dioxide
Cr	Chromium
H^+	Hydrogen
Mn	Manganese
Mo	Molybdenum
mol	amount of substance
Ni	Nickel
O	Oxygen
P	Phosphorus
PO_4	Phosphate
S	Sulfur
Sb	Antimony
Si	Silicon
N	Nitrogen

Unit abbreviations

µm	Micrometer (1/1000 mm)
CTUe	Comparative Toxic Unit for ecosystems
kg	Kilograms
MJ	Megajoules
mm	Millimeter (1/1000 m)
rpm	Revolutions per minute

1 Introduction

1.1 Background

Higher demand for efficient manufacturing methods introduces new and informative software and solutions to guide manufacturers to implement greener production and products (Guinée *et al.*, 2011; Saade, Yahia and Amor, 2020). Therefore, this research aims to do a feasible study implementing the Dassault systems 3DExperience platform to gather the life cycle data for a small offshore relevant part (GT valve wedge) to research the environmental impacts for comparative study of subtractive and additive manufacturing using ecoinvent database, and the Environmental Footprint 3.0 Impact assessment method. Additionally, the principles of the circular economy in connection with material management are progressively more important, by considering recycling materials and end-of-life considerations (Alexander, Pascucci and Charnley, 2023; *Circular economy: Technology - Economy - Environment*, 2023). After speaking to a representative from Dassault Systèmes it became known that this thesis is the first in northern Europe to research the given software.

The research was developed through software learning, and meetings with manufacturers (Stamas and AM North) to get valuable information on the methods and the DNV standard. Literature reviews were done to get a better understanding of the LCA and principles of the circular economy. Material testing was done to conform to the AMC qualification.

The main body of the thesis contains software implementation, a literature review, and some practical work.

Chapter 2 will include a description of LCA, Circular Economy, and manufacturing methods.

Chapter 3 will give a brief introduction to the old and modern technologies within manufacturing to give a deeper insight and understanding to the newer ones.

Chapter 4 will give the experimental part, here the LCA studies and DNV qualification will be explained.

Chapter 5 (result) the data, analysis, and the qualification report will be given. Chapter 6 there will be a discussion and conclusion of the thesis.

There are in total six appendices with additional information.

Appendix A provides the methodology report written in a summer intern position in the summer of 2023 at Vår Energi which is the feasibility study and motivation for this thesis.

Appendix B provides theory and equations to cover some of the less relevant information in the thesis.

Appendix C provides the LCA reports generated in the software, the LCA tutorial, and technical drawings.

Appendix D provides all production data and records tied to manufacturing from Stamas.

Appendix E provides all production data and records tied to manufacturing from AM North, and all BPQ documentation and part qualification documents.

Appendix F provides pictures that are not used in the thesis.

1.2 Problem Formulation and Goal

How can software comply with the future needs of life cycle considerations towards additive and subtractive manufacturing? How is the process of AM qualification according to DNV-ST-B203, and AMC considerations?

Due to high demand for greener production and products there is a climbing need in the industry to have more documentation of the impact categorization of raw materials, packaging and transport, manufacturing methods, product as a service, and end-of-life considerations. Also, the increasing demand for just-in-time production and digitalization of spare parts instead of conventional storage adds interest in the AM methods but increasingly does the environmental aspects of this method as well. The software 3DExperience was discussed as an opportunity in the summer of 2023 and a few videos were studied as feasibility research for the thesis. Thereafter, the software was bought, and this thesis was developed to both educate and expand knowledge on the software and topic of LCA.

Due to increasing interest in AM manufacturing technology, industry 4.0, and just-in-time manufacturing, the qualification process of metallic AM parts is new and not all manufacturers are familiar with this process. This thesis will ask the manufacturer (AM North) to comply with a chosen AMC level and develop the needed documentation and testing requirements that are within the DNV-ST-B203 standard for metallic AM parts. The AMC consideration will be solved using a matrix system to determine the level of risk in the given considerations from the DNV standard.

The goal of the thesis is to educate within LCA, CE, and industry principles (industry 4.0, just-in-time, lean, and six sigma) and deliver the LCA results that are directly gathered from the software (focusing on material cradle-to-cradle), give some principles of the circular economy on both manufacturing methods on the material side, find an AMC level and manufacture and test according to DNV-ST-B203 to give insights on the process of manufacturing both as a customer and as a manufacturer.

1.3 Limitations

While LCA data is valuable in terms of decision-support in a product life cycle, there are some limitations are important to address, some of which are:

- ✓ LCA relies on comprehensive and exact data. In another context, the analysis cannot be better than the data, and the data can be outdated or lacking.
- ✓ The system boundaries of an LCA can be subjective. Choose which categories (carbon footprint, energy use, depletion, to name a few) to be included or excluded, and what environmental impacts to address.
- ✓ Simplification and generalization to make the analysis workable – it is important to not oversimplify or overlook nuances that could spoil the data.
- ✓ Uncertainty and sensitivity in LCA result due to assumptions, variability, and data limitations, therefore it is important to source the uncertainty with a sensitivity analysis.
- ✓ Lack of consistency in methodologies – for the sake of consistency it is important to follow one guideline and framework.

Project Timeline

In Figure 1-1 below the projected timeline for the thesis is displayed. Within the experimental part are projected manufacturing (additive and subtractive) and various laboratory exercises needed to be done to configure and optimize the part in CAD software. The thesis is due on May 15th (middle of week 20).

In Figure 1-2 below the actual project timeline is shown. Due to some unforeseen waiting the due date was extended to June 5th (middle of week 24).

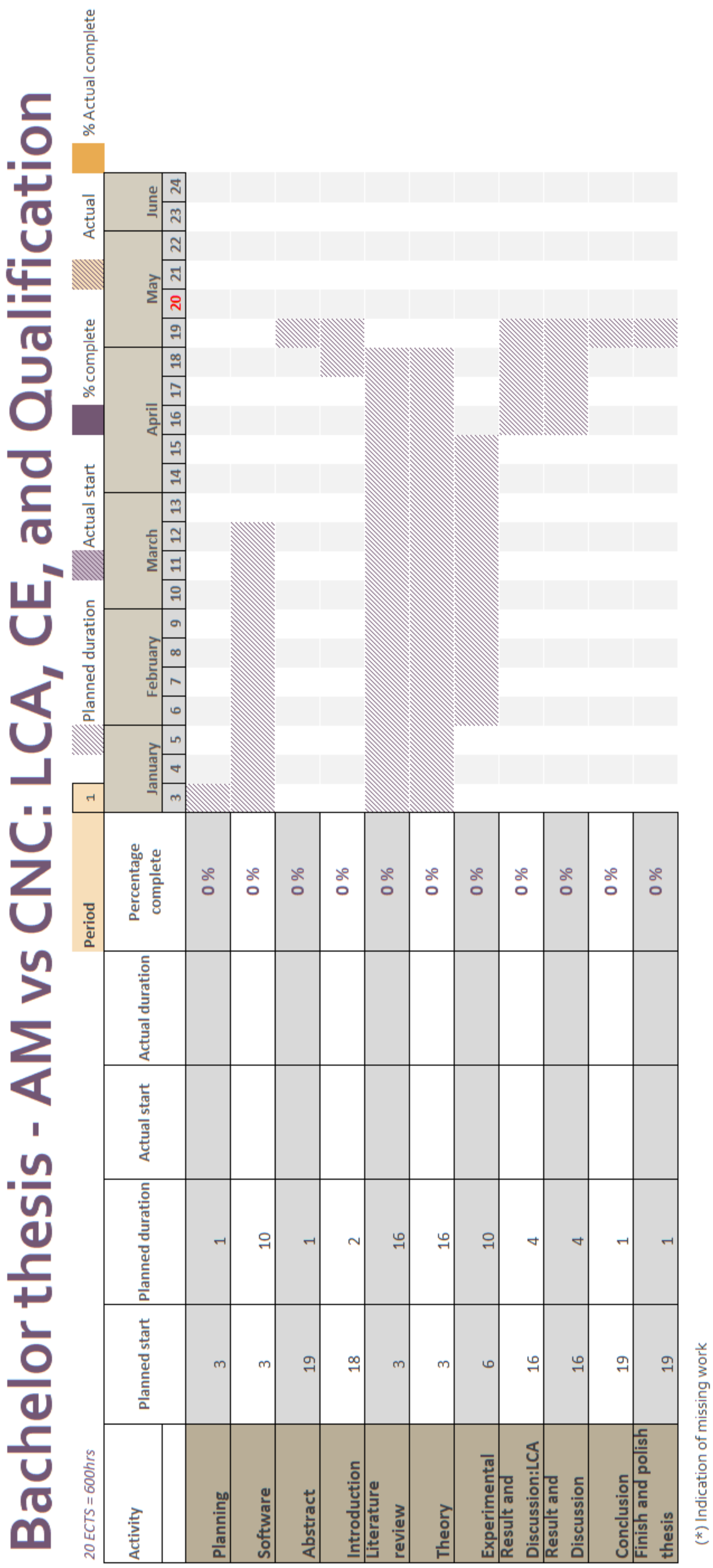


Figure 1-1 Gantt chart displaying project timeline

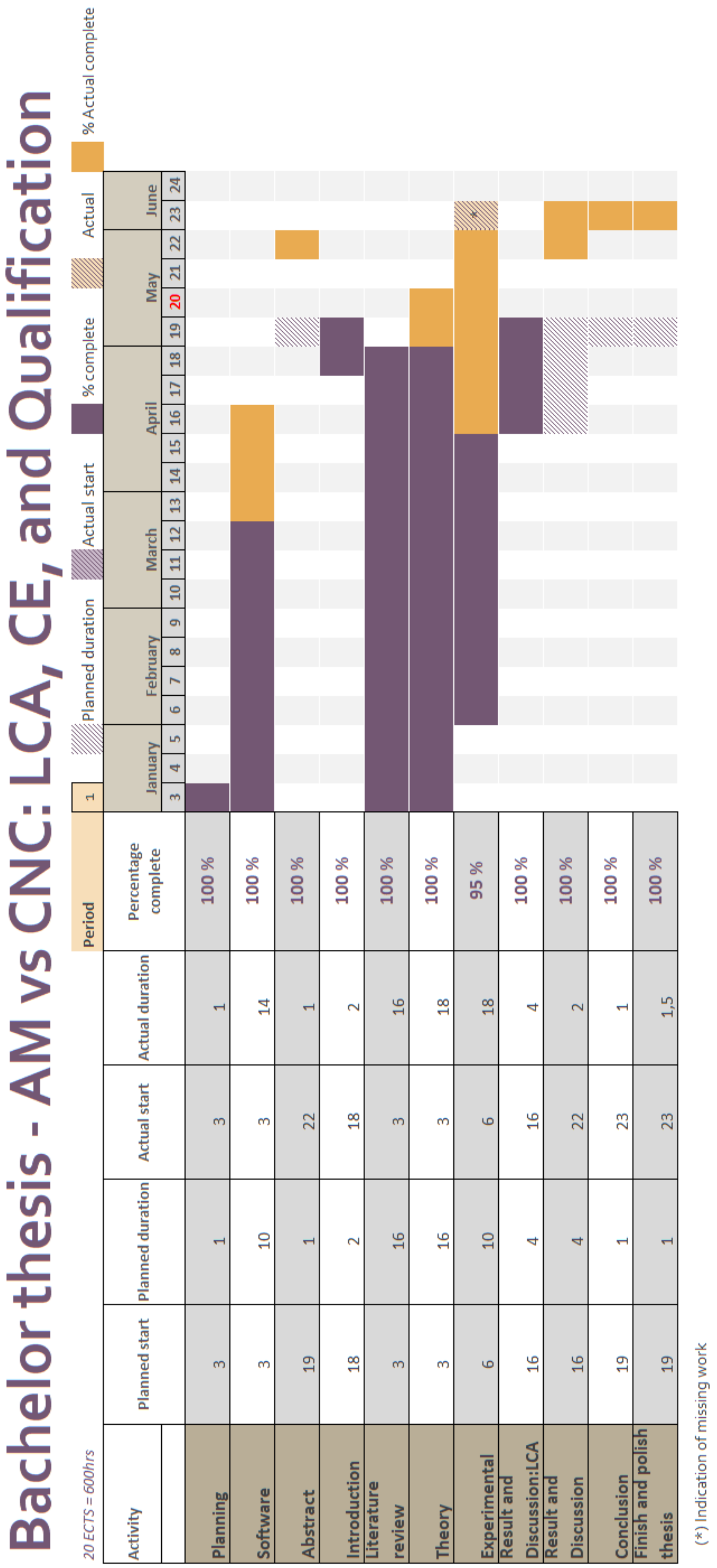


*Figure 1-2 Gantt chart displaying actual project timeline. *Did not get time to perform leak/ pressure test*

2 Literature Review

Literature reviewed are similar investigations of AM and SM. Furthermore, this chapter is meant to give some background to the thesis. In Table 2-1 below some excerpts are given to give some background to the LCA research that has been conducted over the last few years.

Table 2-1 LCA literature review of selected articles

Article	Citation	Excerpt
Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel	(Bekker and Verlinden, 2018)	‘‘*Results indicate that, in terms of total ReCiPe endpoints, the environmental impact of producing a kg of stainless steel 308 l product using WAAM is comparable to green sand casting. It equals CNC milling with a material utilization fraction of 0.75. Stainless steel is the main cause of environmental damage in all three techniques, emphasizing the importance of WAAM's mass reduction potential.*’’
How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies	(Saade, Yahia and Amor, 2020)	‘‘*LCA played a significant role in finding an optimum production approach and seems to be a valuable lens to assure 3D printing’s environmental competitiveness. […] 3D printing processes account for almost 80% of AM’s total GWP, while for CM that position is held by the material-related loads. For construction related AM processes, the material intensity is, however, still by far the largest contributor to building systems’ GWP, maintaining the impact distribution as in typical manufacturing processes.* ’’
Life Cycle Assessment of Metal Products Produced by Additive Manufacturing: A Metal Mold Case Study	(Stieberova *et al.*, 2022)	‘‘*The results of this study demonstrate that although the material used in 3D printing brings higher environmental impacts and is significantly more expensive, even in the production phase additive technology is associated with lower impacts in most categories evaluated by the chosen method of IMPACT 2002+. Even greater benefits are associated with the use phase. Similar results are achieved in the evaluation of levels of cumulative energy demand, greenhouse emissions, and lifecycle costs.* ’’

3 Theory

3.1 Industry 4.0

Industry 4.0 includes informatics, AI, automation, and decrease in human interactions. Industry 4.0 is a model that introduces and creates data exchange and automation internally in a production environment. This model communicates through its tools to give not only out data of production but also valuable information that will help operators do their daily tasks. Some of the main elements in industry 4.0 is to have open communication between machines, units, operators, and sensors via Internet of Things (IoT). Another element of industry 4.0 is to have big data analytics – yielding meaningful insights into data reflecting the physical production environment. Lastly, the elements of automation and smart technology are to introduce helping systems to solve problems, and decision-making, and furthermore eliminate fatigue and health problems for operators. Automation adds fewer manual steps in a production layout, and some use of robotics will aid in daily tasks and reducing the need for manual labor in dangerous environments. In today's demanding production needs the utilization of Industry 4.0 adds traceability, and a decrease the quality loss (*Manufacturing's next act | McKinsey*, n.d). To do all this information transfer, the use of digitalization has been implemented. Digitalization is an business transformation that demands that much of the production activities are communicated digitally – meaning that the productions digital infrastructure yields definite visions, planning, and status of the steps done, current, and future (Stensberg, n.d). In Figure 3-1 below a basic illustration of cloud digitalization and IoT is given.

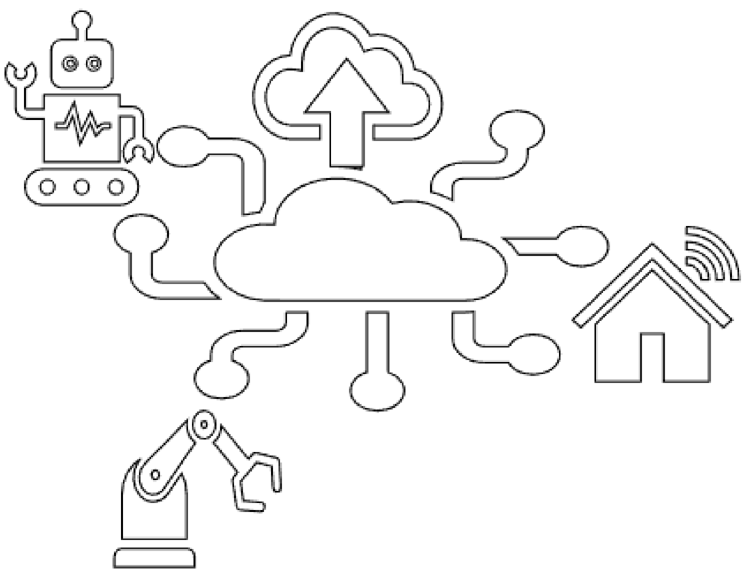


Figure 3-1 Basic Industry 4.0 and IoT illustration

3.2 *Life Cycle Assessment*

The idealization of LCA began in the 1960s. The motivation was due to environmental degradation and scarcity of resources started to be concerning, the first studies conducted were in packaging and focused on energy use. The main goal with the study was to check ‘‘is product A better than product B?’’ (Guinée *et al.*, 2011). An example of this scenario is:

Product A: Designed to be tough and have a longer lifespan.

Product B: Prone to wear and tear and have a shorter lifespan.

Furthermore, between the 1970s and 2000 LCA became conceptualized through issues about environment, some of which are resource scarcity, energy efficiency, pollution control, and solid waste (Guinée *et al.*, 2011).

In the 1980s LCA was conducted but there was no common framework to follow, although there were different methods of LCA that were used but no standardized method (Guinée *et al.*, 2011).

In the 1990s there was a remarkable growth in scientific discussion and coordinated work in the field of LCA. The Society of Environmental Toxicology and Chemistry (SETAC) played a leading role in standardizing LCA framework, terminology, and method through its North American and European branches and scientists, users, and practitioners from these branches (Guinée *et al.*, 2011). Due to this initiative, it followed two standards (International Organization for Standardization, 2006a, 2006b):

- ✓ ISO 14040:2006: ‘*Environmental management – Life cycle assessment – Principles and framework’*
- ✓ ISO 14044:2006: ‘*Environmental management – Life cycle assessment – Requirements and guidelines*’

In Figure 3-2 below there is shown an overview of the LCA method, and impact categories (*What is LCA? – LCA.no*, n.d).

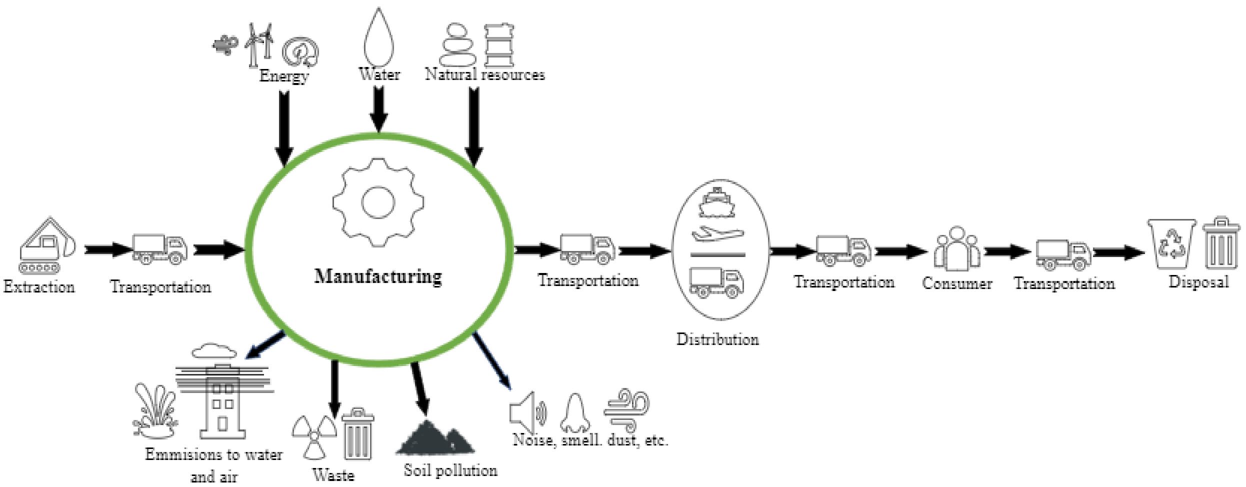


Figure 3-2 Production from a LCA standpoint

The first decade of 2000s illustrated an increasing interest in LCA, followed by United Nations Environment Program (UNEP) and SETAC launched the International Life cycle partnership known as life cycle initiative (Guinée *et al.*, 2011). Through this initiative the frequency of implementation in the various industries gave feedback and further development of the LCA Framework became efficient (in opposition to the start of LCA when this information was kept private by the companies). In the recent decade (2010s) the demand for LCA has increased significantly. Also, researchers and industry increasingly recognize the importance of understanding the product life cycle from raw materials and processes – to recycling and based on this information make informed decisions for sustainability and eco-conservation. Some research that has been conducted in the 2010s is focused on sustainability and environmental impact and benefits, some of which are circular economy initiatives, EV vehicles, renewables, fashion, food, agriculture, to name a few (Guinée *et al.*, 2011). Furthermore, in the recent years of LCA the interest does not lie within the boundaries of cost, but rather efficiency and environmental impact so to compare to the first given scenario – the scenario may look different:

Product A: Designed for easy deconstruction and recycling, with reusable components.

Product B: Holds hard to non-recyclable materials, which increases levels of waste and pollution.

LCA considers the entire life cycle of a product. This includes the raw material extraction to recycle/ reproduce/ disposal (cradle-to-cradle). While also addressing the environmental aspects and effects of a product. Further, LCA is an iterative process, this contributes to a sturdy approach which in return is consistent (International Organization for Standardization, 2006a).

Phases of LCA – According to ISO 14040-2006 LCA consists of four phases to achieve an transparent and comprehensive study, these phases are as follows (International Organization for Standardization, 2006a):

- ✓ The goal and scope definition.
- ✓ Inventory analysis (LCI).
- ✓ Impact assessment (LCIA).
- ✓ Interpretation.

The general framework for these phases according to ISO 14040-2006 are shown in Figure 3-3 below (International Organization for Standardization, 2006a).

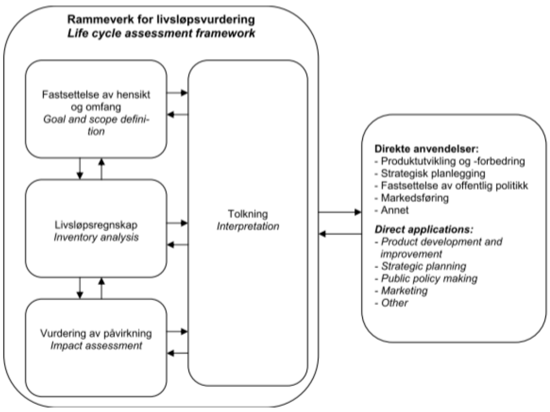


Figure 3-3 Life cycle assessment framework according to ISO 14040-2006

The goal and scope definition assess range of application ('for what?'), interest of realization ('why?'), target groups ('for whom?'), and relevance of LCA ('how?') this phase also aids in interpretation and understanding results (Klöpffer and Grahl, 2014). Furthermore, the product that should be assessed has to be comprehensively researched to understand the full function and build, therefore it is important to have a system boundary where the product specifications, manufacturing and use are assessed. Also, it is important to give a time estimate and goal predictions (Klöpffer and Grahl, 2014).

Inventory analysis is an energy and material analysis gathered by different simplified linear systems. Solving these systems yields information about what quantity of a product can form, energy consumption (minimum and maximum). The data saved from the inventory analysis will further be used in the impact assessment (Klöpffer and Grahl, 2014).

Impact assessment yields concrete numbers correlated to the potential environmental impact the product has (consumption). The data from the inventory analysis are used here to give clarity to actual emissions and can further be used to check data between an imaginary product A - to an imaginary product B. The data will describe the total environmental impact for the product through its life cycle (Klöpffer and Grahl, 2014).

Interpretation yields the conclusion and completeness of the total assessment. In this phase the results from the inventory analysis and impact assessment are interpreted and evaluated in relation to the goal and scope definition where recommendations are made that are reflecting the identification of significant issues (International Organization for Standardization, 2006a; Klöpffer and Grahl, 2014). Impact categories are the so-called categories of interest for the study. To give an example for AM impact analysis, the categories would be Energy use, greenhouse gas emissions, resource depletion, raw material consumption, water usage, ecotoxicity, occupational health and safety, waste generation, transportation, land use, end-of-life considerations, social impacts. But for efficiency the impact categories are chosen after needs, and for what the product makes sense of using (Luc Hillege, 2024).

3.2.1 Dassault Systèmes: 3DExperience (LCA software)

3DExperience is a comprehensive business platform that has integrated solutions for design, engineering, manufacturing, and collaboration. Engineered and developed by the French company Dassault Systèmes, an expert within design and product life cycle management (PLM) (Systèmes, 2022). PLM is a process and technological approach that allows organizations to manage all life cycle aspects of a product, from concept and design, to operations, and products end of life considerations. Furthermore, this software is designed to improve business processes and connect several departments within a company structure, stakeholders, and product development involvement, this enhances efficiency and reduces time to cradle-to-market. Although there has been several different software for decades yielding LCA data, there has been a lot of special made software by internal teams in corporations where LCA results has been difficult to interpret by other companies, because of confidentiality of the data that has been used to create the analysis (*Life Cycle Assessment: Do more than measure your environmental impact*, 2021). The 3DExperience software gives measurements within categories like **CO2 emissions**, **Land use**, **Fossil depletion**, **Minerals and metals depletion**, **water use**, **freshwater ecotoxicity**, **freshwater eutrophication**, **acidification**, **marine eutrophication**.

Where according to *Life Cycle Assessment: Do more than measure your environmental impact*, 2021 some of the following impact categories are:

CO2 emissions is the quantification of human emissions caused by greenhouse gases changing environmental and social impacts, measured in kg.

Land usage is the amount of damage done to soil, this includes erosion resistance, mechanical/ physic-chemical filtration, groundwater regeneration, and biotope, measured in Points. Points are a unit which is not normalized or weighted. But is given in a figure and unit for interpretation.

Fossil depletion depicts fossil fuel impact on resource depletion as energy carriers, measured in MJ.

Minerals and metals depletion representing abiotic resource depletion, measured in Sb kg/g extraction.

Water usage according to scarcity adjusted mass of water used, or water depletion, measured in m^3 world deprived.

Freshwater ecotoxicity measures the toxic effects on species living in freshwater, measured in CTUe.

Freshwater eutrophication measures the excessive growth of underwater plants or algal blooms, due to higher levels of nutrients, measured in PO4.

Acidification due to air emissions caused by NH3, NO3, and Sox, measured in mol H+.

Marine eutrophication caused by excessive availability of a scarce nutrient, measured in kg N.

(A more in-depth description of the units and categories are given in the appendix: APPENDIX C 4 and APPENDIX C 5).

Figure 3-4 below is an example given by Dassault systems and displays what data to expect when using the 3DExperience software and also the use of digital twin to alter design to check how the changes impacts the different LCA groups (*Life Cycle Assessment: Do more than measure your environmental impact*, 2021).

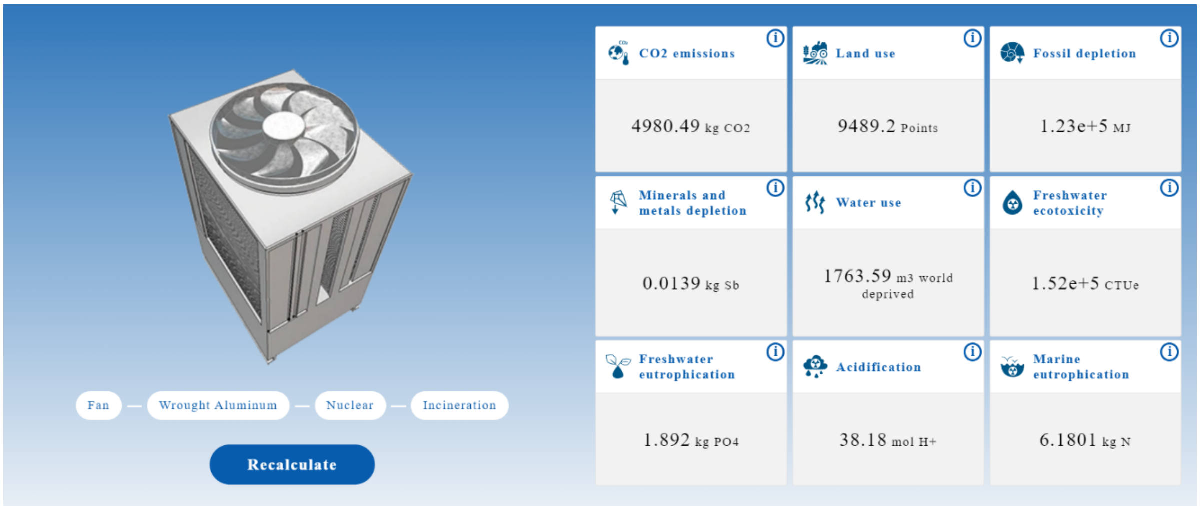


Figure 3-4 3DExperience LCA categories

Within the 3DExperience platform there are a lot of applications that can be used to create a super-efficient PLM ground for all products, and manufacturing within a company structure. Applications used in the thesis are **product explorer**, **business value definition**, **eco-design assessment**, and **life cycle collaboration**.

Product Explorer is the application where the respectable part is opened and viewed in and gives an overview of the model and model tree.

Business value definition is where the data for human activities are added all from ecoinvent library, in this application there can be added raw material extraction, packaging and transport, manufacturing, product as a service and end of life data. The data which is added to this application is extracted from ecoinvent which is a global resource for environmental data. This data is then used to create the matrix (eco design assessment (shown in Figure 3-4 above)) with given data and display it accordingly.

Eco-Design Assessment is the application where the actual life cycle data is displayed (as shown in Figure 3-4 above).

Life cycle collaboration is the application where assessment of multiple projects is used. By adding more part revisions to apply different manufacturing strategies to get the best overlook of the LCI of the analysis.

3.2.2 Life cycle Cost

The life cycle cost (LCC) is used to sum all costs that are accountable in the total life cycle of a product for a consumer or factory either producing or scrapping the product. The LCC can either be used as a standalone assessment, or to be supplemented in a comprehensive LCA study. The LCC framework indicates where in the supply/ or value chain cost efficiency can be improved. LCC in addition to LCA yields a comprehensive sustainability assessment that takes into account not only the environmental research but in addition the cost (Klöpffer and Grahl, 2014).

3.2.3 EF 3.0 – Impact Assessment Method

The Environmental footprint initiative is done by the European Commission which is used to assess the different categories within LCI. The EF method assesses 16 different metrics to showcase in the impact assessment (9 of the metrics given in Figure 3-4 above) (Sala *et al.*, 2022).

3.2.4 Ecoinvent – Life Cycle Inventory (LCI)

Ecoinvent states: *'ecoinvent is an internationally active, mission-driven organization devoted to supporting high-quality, science-based environmental assessments.'* (*Mission & History*, n.d). Ecoinvent is a comprehensive LCI that maintains the database of life cycle related data. Ecoinvent introduces robust data that researchers and companies can use to get coherent data in studies. Earlier challenges with LCA were that much of the life cycle data was created by different companies making the datasets for similar project lack in robustness – ecoinvent is a library that can be used to eliminate unsure data and introduce similarity in research done by companies. Figure 3-5 below shows ecoinvent data extracted to the 3DExperience software, yielding all LC relevant data.

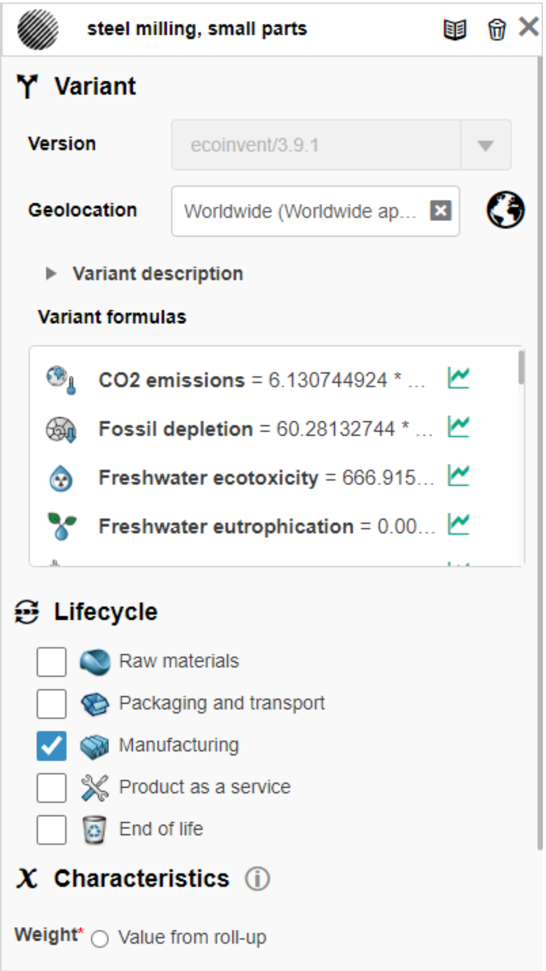


Figure 3-5 Showcase of Ecoinvent data in LCA software

3.2.5 *LCA Sensitivity and Error (Monte Carlo Simulation and Sensitivity Analysis)*

A sensitivity analysis (SA) is a valuable tool to distinguish the best data from the data set, the SA is further used to check robustness of the LCA result, and the sensitivity of the data. This sensitivity can be one of the uncertain factors in the LCA. SA utilizes the model parameters in the set of data to determine if the data is robust and enhance the interpretation of the set of data given in the LCA (Wei *et al.*, 2015). One method to do an SA is to use Monte Carlo simulation (MCS) where the MCS shows the analyst how uncertain the data is, and how much uncertainty the data carries. Furthermore, the tool can categorize within two placements: Deterministic and probabilistic, where the deterministic data placement is a model where the randomness of data is neglected, giving the same result for every iteration. Whilst the probabilistic model includes the randomness of data yielding different results for every iteration even with the exact same set of data (Cadence PCB Solutions, 2020).

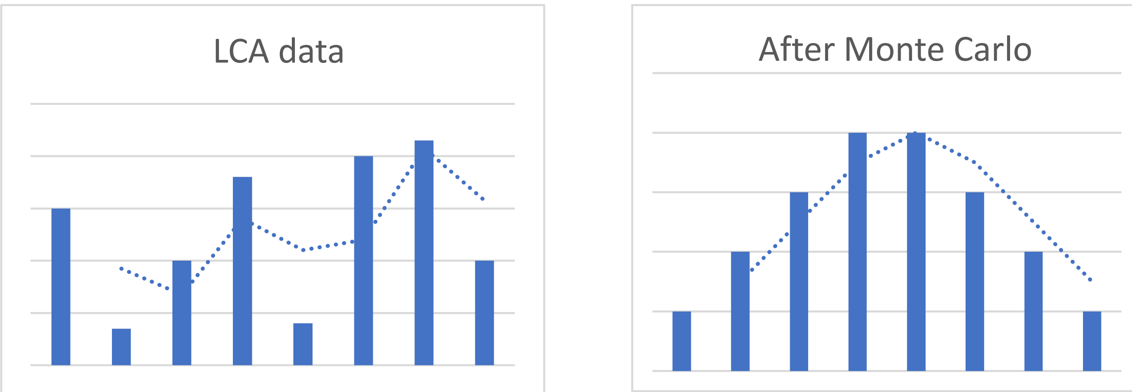
MCS utilizes a normal distribution typically, and the dataset is most wanted to be narrow (the wider the spread the bigger the uncertainty). MCS operates like this (Spherica Blog, 2023):

1) Assign random parameter values between MIN and MAX values
2) Software examines random parameter values and data compositions
3) Analysis is conducted, and examination of the graph is done, furthermore check how uncertain the curve is in terms of percentage and which combination is useful for the analysis.

The results are often given as a normal distribution.

To visualize the Monte Carlo principle in LCA the following basic illustration is given in Figure 3-6 below:

Before Monte Carlo: After Monte Carlo:



a) b)

Figure 3-6 Basic illustration of the Monte Carlo sensitivity analysis a) Before Monte Carlo application, b) After Monte Carlo application

3.3 *Circular Economy*

Before the conceptualization of the circular economy the basic use of the linear economy was used. The linear economy is a straight progression of a product, and the linear part of the economy means that there is no recycling step, only disposal. Therefore, the linear system is also referred to as a polluting system that is not good for the environment. This economy is cheaper for the manufacturer but expensive for the consumer meaning that raw material extraction is low cost and low labor cost, manufacturing is low cost and low labor cost, and the product is at an expensive price point for the consumer (Chris Knight, 2023). Figure 3-7 below shows a simplified model of the linear economy.

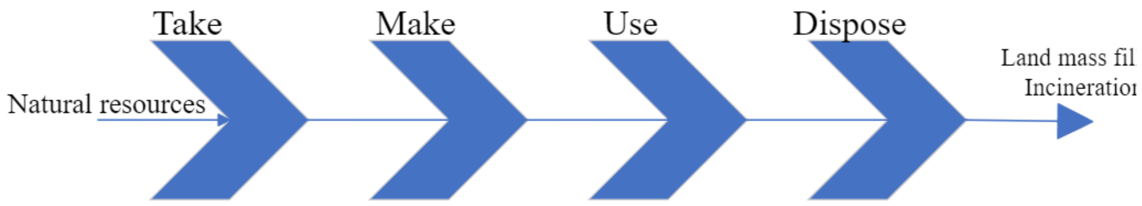


Figure 3-7 Linear economy basic illustration

CE is a new way to conform to sustainability and sustainable development. As mentioned, the products linear economy is based on material extraction, production of the product, use and disposal. For production facilities to meet the current and future needs, there is need for a circularity to add recycling steps to a products economy (if possible). Further, CE models production and consumption, which includes the latter mentioned steps from raw materials - to production and use - to recycling. Also, the life cycle of the product extends to this process to ensure that the measures taken are reasonable and right for the product. CE is a collective goal to overcome resource scarcity, climate complications, waste, and air pollution. CE also extends to resource management through its initiative to get more value out of less resources (International Organization for Standardization and Final Draft International Standard, 2023a, 2023b; *Circular economy: Technology - Economy - Environment*, 2023). A basic illustration of the CE is given in Figure 3-8 below.

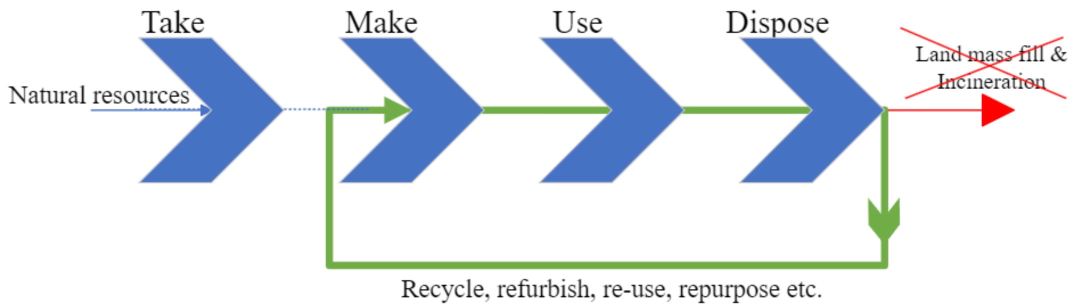


Figure 3-8 Circular Economy basic illustration

3.4 *Manufacturing Principles*

In history there are two subjects within manufacturing where the first one is invention and research of materials and processes, and secondly production development. Some of the first known manufacturing processes are casting, hammering, and grinding – dating back six thousand years or more. These manufacturing processes were not known as manufacturing as they are today but more as a trade, or craftmanship. The Romans used factories to mass produce weapons, pottery, scrolls, and glassware. It was not before the late 1800s – early 1900s that the manufacturing process as it is known today was developed. Mainly finding best methods in practice, rating system, time studies and extensive use of standards where used (Mikell P. Groover, 2010). Describing manufacturing – It is the application of processes to alter the geometry, properties and/ or appearance of a block or axle of metal or a spool of filament. The manufacturing process involves machining, tools, power, and labor as shown in Figure 3-9.

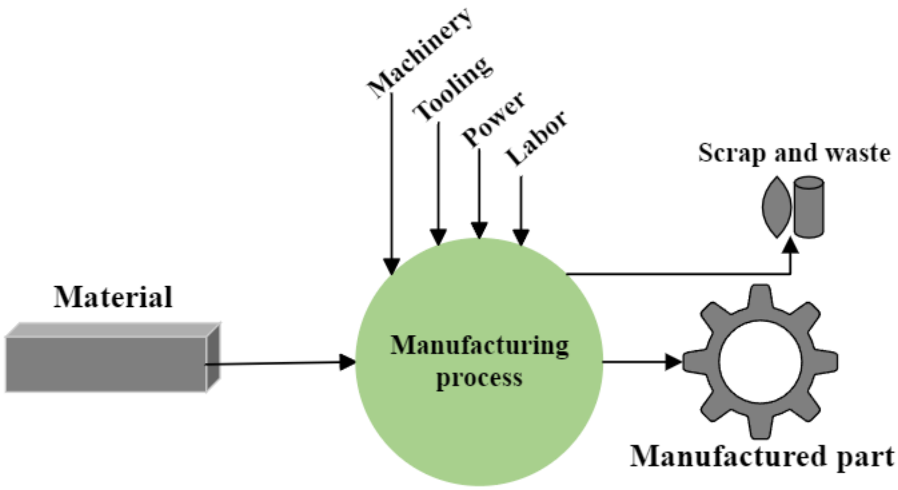


Figure 3-9 Manufacturing process

There are several manufacturing techniques and technologies in the various industries to aid with many different operations, where the most important are – namely subtractive, and additive manufacturing techniques. These techniques or technologies get their name after the manner of manufacturing – Subtractive manufacturing has its name from getting rid of material to form a product, whilst additive manufacturing adds material to form a product. Different methods of these technologies exist, for subtractive there are: CNC lathe-turning, CNC milling, and its traditional predecessor manual lathe-turning and milling machines, drilling, grinding, cutting, to name a few.

Additive manufacturing or 3D-printing has a collective term for a lot of different techniques such as FDM, FFF, PBF, DLD, DED, and SLA. Also included in these processes are assembly operations such as permanent joining (welding, bonding, etc.) and mechanical fastening (threaded fasteners, and permanent fastening methods) (Mikell P. Groover, 2010).

3.4.1 Improvement of Manufacturing Efficiency and Waste: Lean and Six Sigma

In more recent years there have been large investments in different industries to improve quality and efficiency in manufacturing, there have been two programs: Lean and Six Sigma. Lean implements fewer resources and higher productivity. Whilst Six Sigma is a quality based program that is utilizing teams within the company structure to accomplish improvements in its operational performance (Mikell P. Groover, 2010).

Lean – Efficiency Improvement

Lean is a type of control philosophy and implements different tools and methods to reduce waste. There are seven general types of waste which are: **Faulty Production** – Lean has a goal to reduce faulty production to zero, also first-time production of a product. Also to reduce **Over Production** - keeping waste to a minimum. **Unnecessary Transportation** of goods internally in the production environment. **Waiting** on other parts of the production. **Unnecessary Stockkeep** of materials, **Unnecessary Movement** i.e. keeping tools a different place than the general work area, and **Inappropriately Processes** – simplification of processes to meet the general needs of the customer (Kjell Gunnar Hoff and Morten Helbæk, 2021). A production facility implementing Lean philosophy is characterized by its established systems and a culture for continuous improvement. To implement Lean in a production demand that the production operators take some Lean courses and get more efficient and systematic, whilst the production lead facilitates correctly for the Lean implementation to take place (Kjell Gunnar Hoff and Morten Helbæk, 2021). Further, there are some downsides to this implementation, some of which are: the operators take less brakes and can get sick by work overload, even when the production rates get higher - the salary can stay the same as before Lean were introduced yielding dissatisfaction between operators. Figure 3-10 below illustrates the principles of Lean.

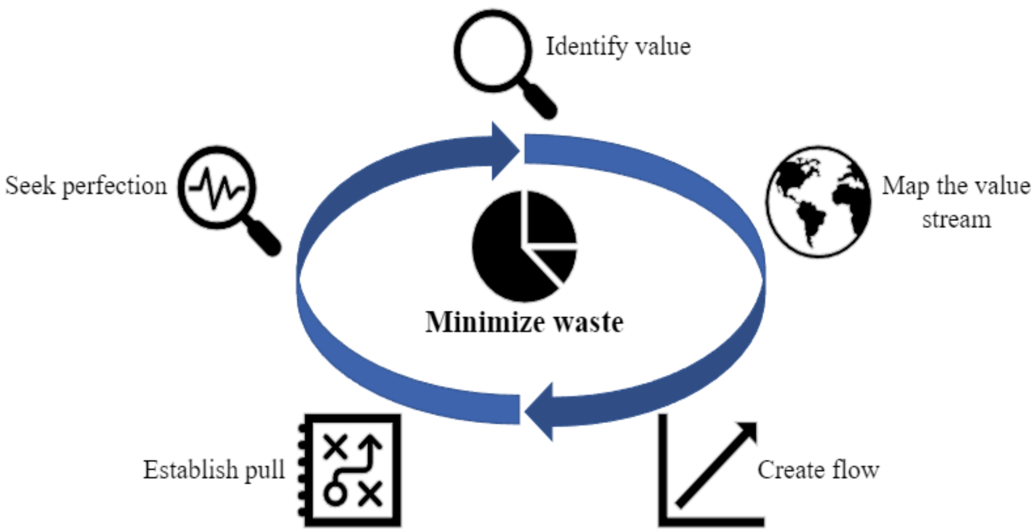


Figure 3-10 The basic Lean principle

Six Sigma – Manufacturing Waste Elimination

The **Six Sigma (6σ)** term is adopted from the manufacturing industry. The sigma (σ) assessment indicates the wellness of the performance, if the sigma value is high the performance is better. The main objective with Six Sigma is to reduce variation in processes and meet customers specific needs (*What is Six Sigma? Everything You Need to Know in 2024 | Simplilearn*, 2019). The Six Sigma model (Taguchi loss function) can be looked at as an American football field goal with a concave parabola signifying the nominal area of production (where all products within this area are within acceptance or nominal value for specifications), where the lowest point of the curve implies nominal production, as long as the production is within the Taguchi loss function it follows the Six Sigma procedure, if it is outside the variance Six Sigma is not followed and there will be loss in production and money as shown in Figure 3-11.

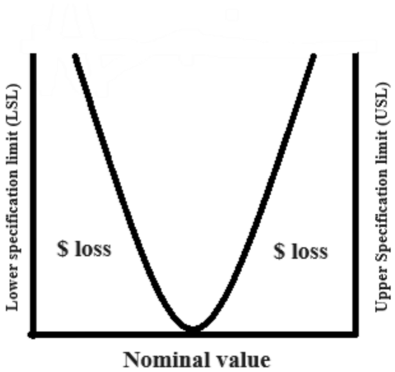


Figure 3-11 Taguchi Loss Function (Six Sigma)

Lean Six Sigma

Combining Lean and Six Sigma yields the **Lean Six Sigma (LSS)** model, where Lean contributes to eliminate waste, and Six Sigma reduces the variation of the production. While the two methods are different they still do share some common ways to efficiently improve manufacturing. According to Drohomeretski *et al.*, 2014 the companies introducing LSS to the manufacturing layout achieve superior performance in the respective competitive area in the range of quality, reliability and processing speed with the reliability being the predominant main objective. The combination of these two methods demands a lot of work for implementation, but improvement is continuous throughout the process as shown in Figure 3-12 below the cogwheels for the combination will reduce variation of manufacturing between the LSL and USL, waste of time, reliability, production, and waiting.

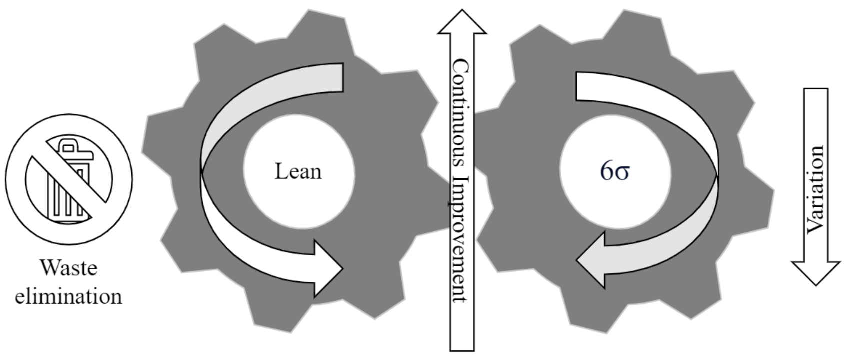


Figure 3-12 Lean Six Sigma model

3.4.2 *Just-In-Time Manufacturing*

Just-in-Time (JIT) philosophy is a manufacturing process that has a goal to **make the right products with the right quantity and quality at the right place and time**. The philosophy was introduced in the 1970s by Toyota Motors Company when they were developing new methods within material – and production control Toyota was trying to reduce waste (waste of material, labor, machines, equipment, and other activities connected to production and business processes). Just in Time describes a production system characterized by small series production, minimal stock, and shortchange time when receiving a new order and maintain a high quality of the production. The descriptive change that needs to be made is to change from a traditional fabrication system to a JIT fabrication system (Kjell Gunnar Hoff and Morten Helbæk, 2021).

Traditional Fabrication with No JIT Implementation – A Typical Illustration

In a **traditional fabrication layout** system where there is no implementation of JIT the use of a traditional fabrication layout is used. The traditional fabrication layout organization the manufacturer strives to keep a production flow steady according to the chosen process. With this layout there can be some consequences which are that there is no general system regarding where the machines are placed, nor a planned allocation for materials or types of job plans, but rather the jobs allocated are based on availability. Also, the sales and production planes departments will try to plan production ahead and not take into consideration any bottlenecks or other types of delay (Kjell Gunnar Hoff and Morten Helbæk, 2021). Following this will disturb the steady production flow and the production will instead move sideways, or backwards in production as shown in Figure 3-13 below.

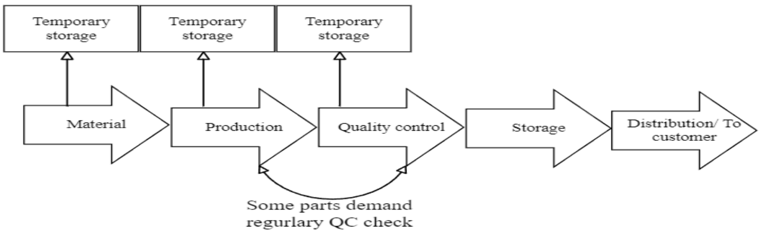


Figure 3-13 Traditional fabrication layout workflow

JIT Fabrication Layout and Introduction to the FMS Strategy

The **JIT fabrication layout** introduces a term called the suction-method, where the suction is introduced at the end of a production line and subsequently introduced to the preceding stations in the production line as shown in Figure 3-14 below. The suction method introduces taking orders from a customer directly to the sales department, and instead of contacting the sub-distribution lines directly the JIT order goes through every department. Where those departments order the wanted specifications directly from the sub-department and the JIT process makes it so that there is less work time on the manufacturing of the product, hence there is minimal time loss (Kjell Gunnar Hoff and Morten Helbæk, 2021).

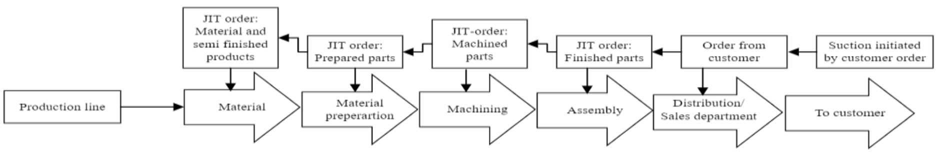


Figure 3-14 The JIT suction-method

The JIT fabrication layout depends on a flexible manufacturing facility that can withhold the introduced suction-system. A typical JIT order is often only one part, or a small series of parts, therefore it is important to have machines that can do a quick changeover and have stability to start production of a new part/ or series. The JIT layout uses so called production units where each unit is a kind of small factory that can make the part with most of the specifications. This kind of fabrication layout is mostly used in the CNC-fabrication, and now in the AM-scene as well. But the combination of these technologies (depending on the products) yields high versatility within JIT manufacturing. Furthermore, the use of flexible manufacturing systems (FMS) introduces automated transport, handling, and storage flexibility. The use of FMS is fully automated and there is no need for manual interaction, therefore no operators. The system is integrated into a computer integrated manufacturing (CIM) solution, where the fabrication is utilizing CAD, CAM, and FMS and can in principle be operated 24/7 unsupervised. The FMS method is currently only used in a one production unit, and not in full scale fabrication due to manual labor still being necessary to keep up to date with today's standard (Kjell Gunnar Hoff and Morten Helbæk, 2021).

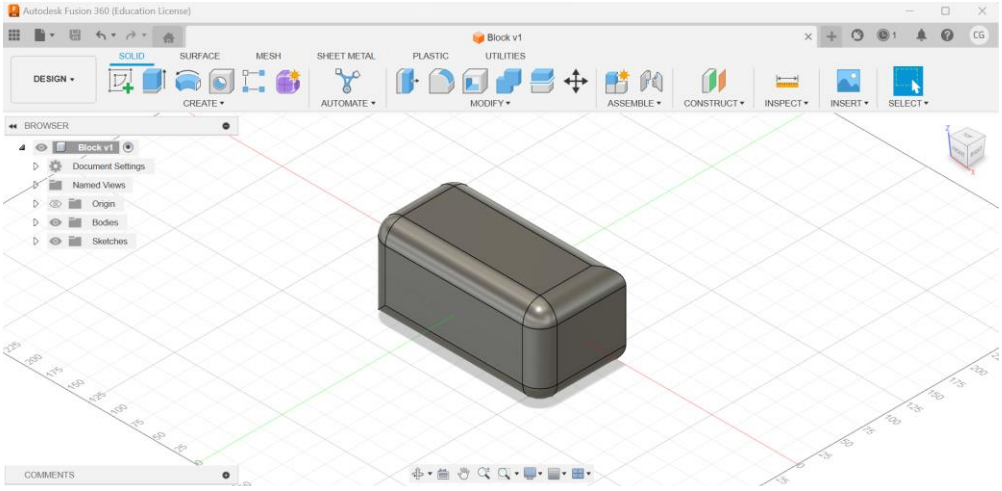
While JIT implements a wanted product right on time, the philosophy still carries some issues or more defined as a weakness. This weakness is typically production stall, when something in the production line stops - it can cause tremendous flaws in the JIT philosophy. Also, if the part is utterly important in i.e., offshore or health business the JIT philosophy is needed to work flawlessly therefore continuous quality improvements (*kaizen*) are important. Toyota motor company introduced the word kaizen-leadership to state its focus on preparation and progress. An equivalent to the kaizen-leadership is Total Quality Management (TQM) which are a leading group in an organization that mainly focuses on quality and takes in user inputs from operators and sub-departments to achieve long-term success and customer satisfaction (Kjell Gunnar Hoff and Morten Helbæk, 2021).

3.4.3 CAD/ CAM

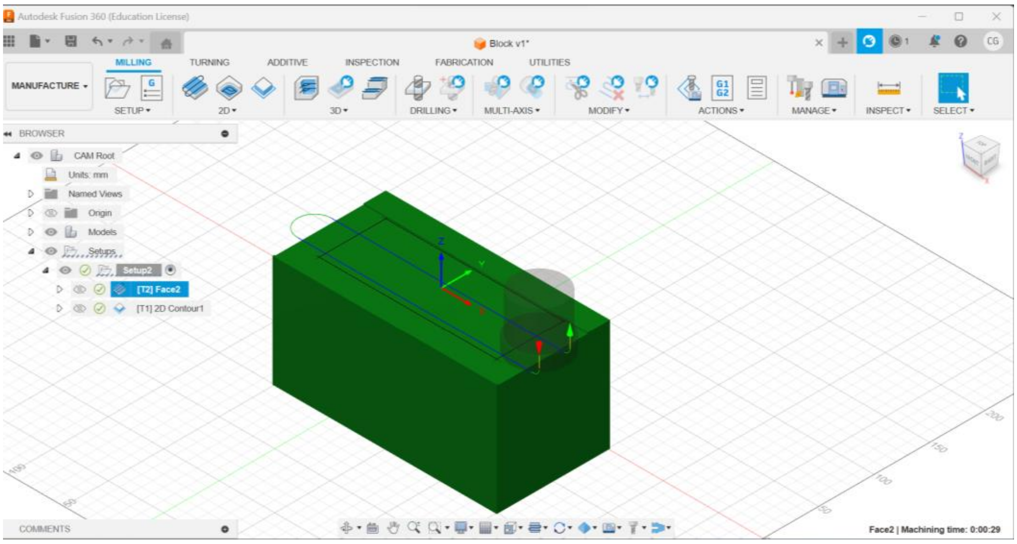
CAD is a process where the design of a product takes place, this is a geometrical assemble of the product that is going to be manufactured, further, the CAM software is where the actual manufacturing and automation processes are analyzed and assessed (which machine, what tools, and programming) (Zeid Ibrahim, 2005). A finished CAD drawing is a feature based model which means that the surfaces, edges and vortices are defined in a manner that the parts main attributes are recognized and interpretable by other software, by other words translated from CAD language to CAM language, therefore also important to have standardized file formats (Zeid Ibrahim, 2005). An example of a combined CAD/ CAM software is **Fusion 360** (some screenshots given in Figure 3-15 below), this software is an all-in-one package which delivers CAD, and CAM possibilities.

3.4.4 G-Code

G-codes or geometrical-codes are widely used within manufacturing. G-code is a language that can be written line by line, or automatically generated in an eligible CAM software. Lines of g-code consists of a letter and numbers, the letter corresponds to an action or axis, whilst the number either gives action or coordinates. The type of file that is created with G-code is also known as a .NC file (numerical control file). In Figure 3-15 below there are screenshots of Fusion 360's CAD and CAM software and a generated g-code (Zeid Ibrahim, 2005).



a)



b)

```
(T2  D=50. CR=0. - ZMIN=-1. - FACE MILL)
G21
G40
G49
G80
G90

(FACE2)
M5
T2 M6
S5000 M3
G54
G0 B0. C0.
G17
G0 X112.5 Y-24.375 Z15.
Z5.
G94 G1 Z4. F333.
G18 G3 X107.5 Z-1. R5. F1000.
G1 X105.01
X-105.01
G17 G2 X-120.148 Y-9.238 R15.138
X-105.01 Y5.9 R15.138
G1 X105.01
G18 G2 X110.01 Z4. R5.
G0 Z15.
G17
```

c)

Figure 3-15 Illustrations of a) CAD, b) CAM, and c) G-Code

3.4.5 *Technical/ Engineering Drawing*

Technical drawings are used to convey technical information from a designer to an operator. The drawing 'language' is standardized through a European or American standard. The European standards give clear information on the use of symbols, and numbering for a technical drawing (International Organization for Standardization, 2011). For all tolerances that are not stated a standard is used to define those measurements (International Organization for Standardization, 1993). The drawings should state the standard used for tolerancing, and symbols. The process of creating the technical drawing is rule based regarding execution (International Organization for Standardization, 2020). In Figure 3-16 below a simple technical drawing is shown.

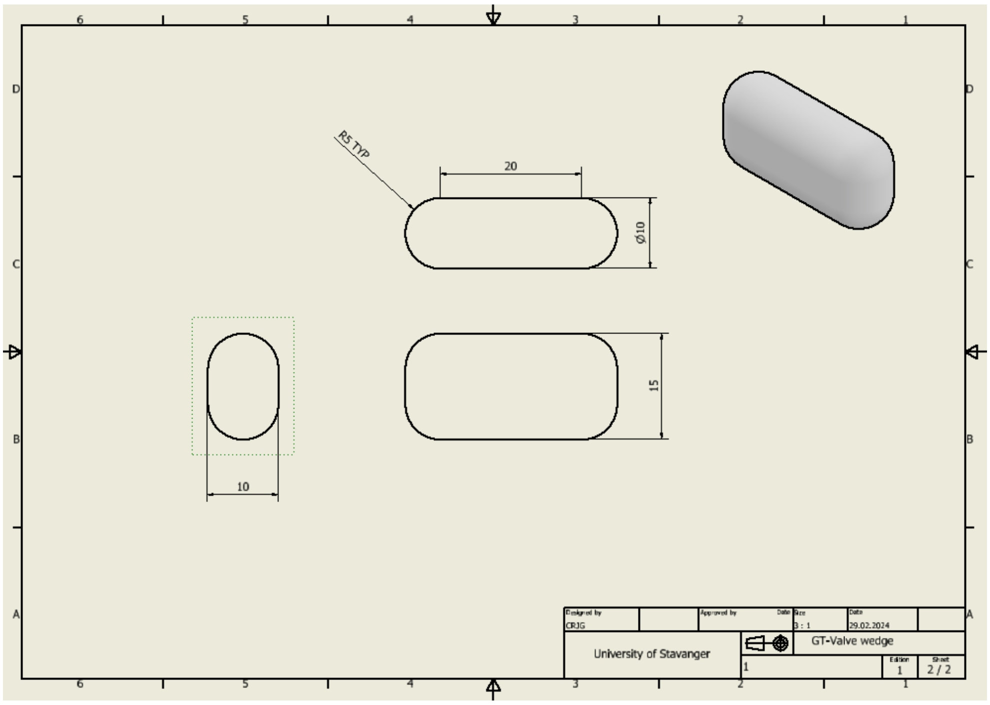


Figure 3-16 Basic drawing illustration

3.5 *Subtractive Manufacturing*

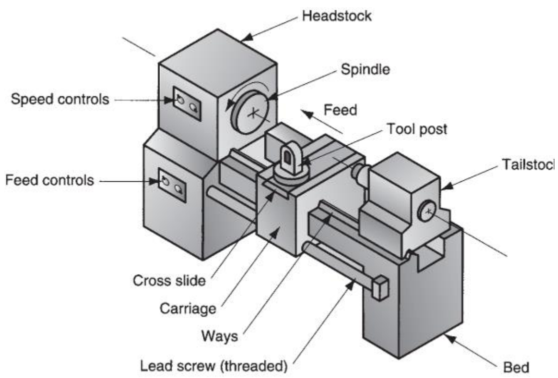
Subtractive – meaning 'the process of removal,' is most commonly referencing to the use of milling or turning machines to create a product by removing material piecewise using various machines such as CNC machines, or traditional machines. CNC machines use G-Codes to perform tasks to get the geometry wanted, whilst the traditional machines have calibrated number disks that the operator uses to define the wanted depth of removal to get the wanted geometry. In both cases the use of tolerance drawings is the basis of both programming G-code, and to get correct result in the traditional machines.

3.5.1 Traditional Machines

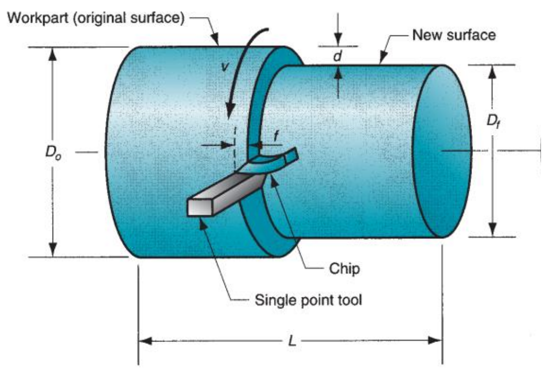
The traditional term for manufacturing from a mechanical perspective is *machining*, where the desired outcome is to produce in a subtractive fashion a workpart in such a way to get a desired geometry specified by a designer or an engineer to get a specific result. There are two types of machines that are most used, one is the lathe machine, and the other is a milling machine. Where the difference between these two types of machines is based on movement of the workpart and movement of the tool.

Lathe Machine

The **lathe machines** have been modernized throughout the years. The lathe is most used for manufacturing axle/ round workparts but has possibilities to attach different clamps to the spindle to adjust to the desired part. In the lathe machine the part is spinning whilst the tool is still. The lathe machine is characterized by the movement of tools and the workpart. By rotating the workpart by N rotations and feeding the tool along the axis with a depth d to perform the cutting and achieving the desired tolerance as shown in Figure 3-17 below (Mikell P. Groover, 2010).



a)



b)

Figure 3-17 Lathe illustrations a) Lathe machine,b) Lathe illustrative operation

Milling Machine

The **milling machine** is mostly used for square workparts but has a variety of different tools that can be used to get the desired geometry of the workpart. In the milling machine the workpart stays still whilst the tool is rotating at a desired rpm. Furthermore, the mill is an axis-controlled machine – this means that the workpart can be moved in x, y, and z axis, whilst the tool stays centered in relation to the column. To make a cut the tool is set to a desired rpm, and the axis is set to a cutting depth (depending on the tool) and then the workpart gets fed along the tool. An illustration of the mill and its process are shown in Figure 3-18 below (Mikell P. Groover, 2010).

a) b)

Figure 3-18 Milling illustrations a) Milling machine ,b) Mill illustrative operation

3.5.2 CNC-Machines

Widely used in the industry due to its efficiency and precision. The machines have an precision of ± 0.0025mm or 2.5 µm, which is important to address when tolerancing drawings and designing products to know ('Tolerances in CNC Machining', 2019). Further, CNC-machines improve production speed and have more credibility and trust in the industry compared to the traditional machines. There are three different CNC-machines, CNC-lathe, CNC-mill, and multi-CNC or 5-axis CNC machine which combines lathe and mill (and other technologies) to create a powerful machine with impressive workability. While the CNC lathe and milling machines have the general configuration of the traditional ones, the CNC machines have higher complexity (automated tool change, integrated life expectancy of tools to name a few), making these machines highly versatile for multi machining operations. A CNC-machine are shown in Figure 3-19 below.

Figure 3-19 CNC-Machine

CNC machines interpret the programming language G-code (.NC files) to understand tasks given by the operator. Various tasks such as drilling, typical lathe, and mill operations, sawing to name a few are pre-programmed in an NC file with the G-code language. CAM software is widely used within CNC-operations, in some software's toolpaths can be placed and the numerical control program gets generated automatically and other still needs the operator to manually program the toolpaths. Furthermore, there are also some operators that program directly in the NC on the machine.

3.5.3 Environmental Challenges and Impact: SM

Within subtractive manufacturing there are introduced four main environmental challenges and impacts:

- ✓ **Material waste** – when machining large objects or complex geometries there may be a need for a lot more material than the actual product specification.
- ✓ **Energy consumption** – Due to the large scale of a CNC machine, and the requirement of substantial energy (especially with denser or harder materials) to cut and shape workparts.
- ✓ **Coolant** – Although the coolant usually is re-used in a CNC cycle there still are some coolants that get carried with the shavings to the re-cycling stations and get into the drains and released in the nature.
- ✓ **Tool wear** – Wear and replacement of cutting tools generates additional waste and the environmental impact contribution.

3.6 Additive Manufacturing

The process of manufacturing an object by adding layers on top of each other by utilizing different methods of AM, such as FDM, FFF, PBF, DLD, DED, and SLA, where the several types of AM are solely represented by how the layers are created (bonding method) or build direction. Depending on what type of AM is used are also based on accuracy of the part, rapidness of production, mechanical properties, size, and the overall cost (Gibson *et al.*, 2010). The first main objective with AM technology was to rapidly prototype (RP) objects before commercialization (before AM, layer-by-layer manufacturing was called RP). Utilizing RP to create parts quickly can enhance the design stage in most of the product development processes, and furthermore, give the designer a feel for the product or what the product might need in terms of design. Although RP is an good interpretation of what AM is capable of, it undermines the actual capabilities of the technology, therefore the term AM was created as a collective term for layer-by-layer manufacturing (Gibson *et al.*, 2010).

3.6.1 The AM Processes

The basic AM process consist of 8 key steps according to (Gibson *et al.*, 2010):

1. Conceptualization and CAD - is based on the need, wishes of the product, and drawing of the concepts given or wanted.
2. Conversion to stl - is to take the drawn concept and convert it to a file format which is transferable between CAD and slicer software such as a .stl file.
3. Transfer and manipulation of STL file on software and AM machine - is to utilize the slicer software to manipulate internal structure, infill density and use other slicing software tools, and convert the .stl file to a g-code file which can be transferred to the AM machine.
4. Machine setup - is to do necessary pre-processing such as bed cleaning, priming nozzles, checking necessary equipment before manufacturing.
5. Build/ Manufacturing – which is the actual manufacturing.
6. Part removal and cleanup – the removal process and machine cleaning.
7. Post-processing of part – which is to do necessary cleaning of the part, such as support structure removal, chemical cleaning, surface cleaning to name a few.
8. Application - is the last step for the AM process which is application of the AM’ed part.

3.6.2 STL File Format

The STL file format is a term derived from stereolithography, the STL file format helps with interpretation of the CAD file in terms of geometry or surface description. The STL process removes construction data, modeling history and are approximating the models surface with a series of triangular facets (polygons) – where the size of these polygons is representative for the resolution of the part (the smaller the polygon the better the resolution). The triangular size is derived from the minimum distance between the represented plane and the triangle. The STL file conversion is available in most modern CAD software. STL file manipulation is also possible. When opening an STL file in an applicable software (Slicer) there are options to split, scale, emboss, etc. this is also referred to as STL manipulation (Gibson *et al.*, 2010). In Figure 3-20 below the triangular facets and STL model are shown.

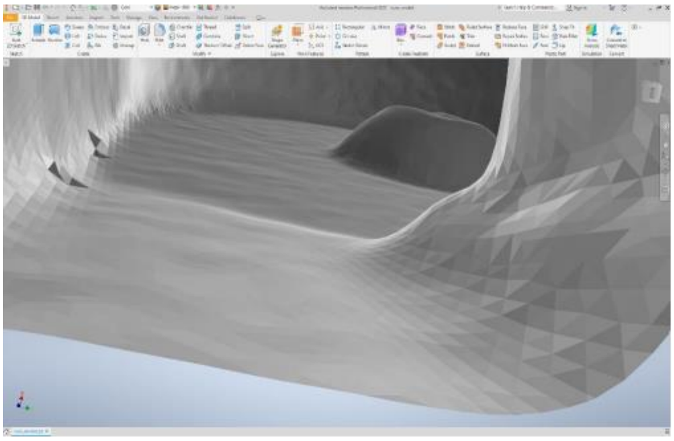


Figure 3-20 STL file and triangular facet representation (Autodesk Inventor)

3.6.3 Slicer Software

Slicer is a term used for CAM software applicable for AM. The slicer software takes an STL file and generates g-code that is applicable for AM machines. This software enables STL manipulation and other processing steps for AM. The slicer software segments the object in several flat layers and uses the linear movements of the pre-programmed printer in the software and generates toolpaths (g-code) to execute the commands needed to achieve the wanted geometry. Some of the features that can be added in this software includes brim/ raft/ skirt (which is a feature that adds an adhesive layer between the part and bed), infill (which is both density percentage and pattern) and supports (to support layers that would be printed in the air, or otherwise support layers with inclined structure). In Figure 3-21 a basic slicer software is shown.

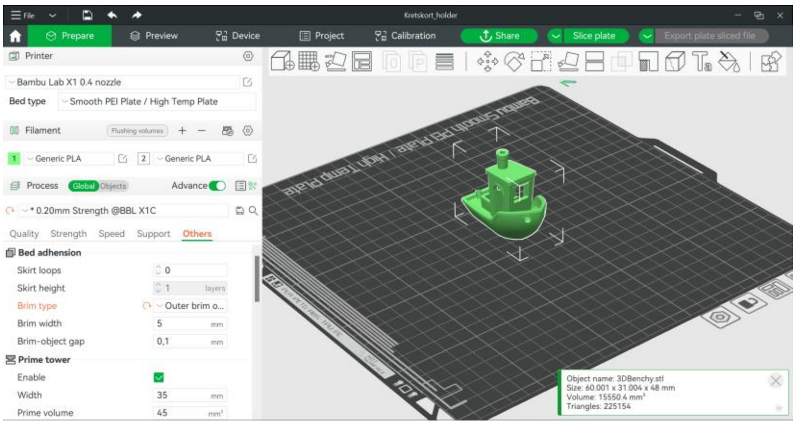
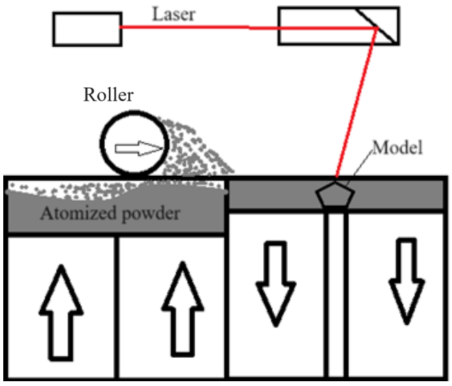


Figure 3-21 BambuStudio slicer software

3.6.4 SLM – Selective Laser Melting

SLM is an additive manufacturing technology that utilizes atomized powder and laser to create layer-based models. SLM is a part of PBF manufacturing method, also known as PBF-LB where a strong laser focused beam selectively goes in a pattern to fuse particles together through melting to build geometry models. The PBF method and machine as shown in Figure 3-22 a) below. There are two platforms moving along the z-axis (up and down), one platform with powder supply, and the other with the build volume. The roller collects powder at the powder supply and rolls it over the build volume, building a thin layer of atomized powder. The laser beam 'scans' the powder in a selective manner melting the powder in the 'scan' area. The 'scan' is given by the toolpath (g-code) generated by the slicer. The powder not selectively 'scanned' can be post-processed and re-used (Callister and Rethwisch, 2020).



a)

b)

Figure 3-22 a) SLM method and b) SLM machine

3.6.5 DNV-ST-B203 Standardization for AM of Metallic Parts

The objective for standardization of AM metallic parts is to provide an internationally acceptable framework for AM. Also, to insure consistency in quality of metal additive manufacturing (MAM). This standard aids in guidance of the qualifications necessary for part production, testing, and use in different MAM technologies. Furthermore, the business aspects of MAM parts are also covered in this standard (Det Norske Veritas AS, 2022).

Additive Manufacturing Category

The manufacturing and testing requirements are solely based on the categorization that is chosen in accordance with the standard – also known as **Additive Manufacturing Category (AMC)** which describes the intentions with the part, and results in both manufacturing method, and testing requirements. There are 3 main categories – AMC 1, 2 and 3, but also a simple category which is AMC 0 that is intended for low criticality parts and has no definite qualification or production scheme (Det Norske Veritas AS, 2022). The categorization chosen can introduce some extra steps in the manufacturing process such as build process qualification, and further non-destructive (NDT), and destructive testing (DT) of the parts printed.

The decision making process for AMC takes some considerable choices such as (Det Norske Veritas AS, 2022):

- Failure modes for health and safety
- Failure modes for failure
- Failure modes for environmental consequences
- Loss of reputation
- Regulatory requirements

BPQ – Build Process Qualification

BPQ is a qualification that requires the making of test specimens in the machine that is going to be used in production of the given part. The test specimens are built of a standardized set of geometries and parameters that are to be followed strictly. The reason for running a BPQ is to ensure that the build volume in the tested machine is satisfactory to produce mid-to-high risk parts and the required material properties for the qualifying part. The test specimens for PBF-LB are given in Figure 3-23 below.

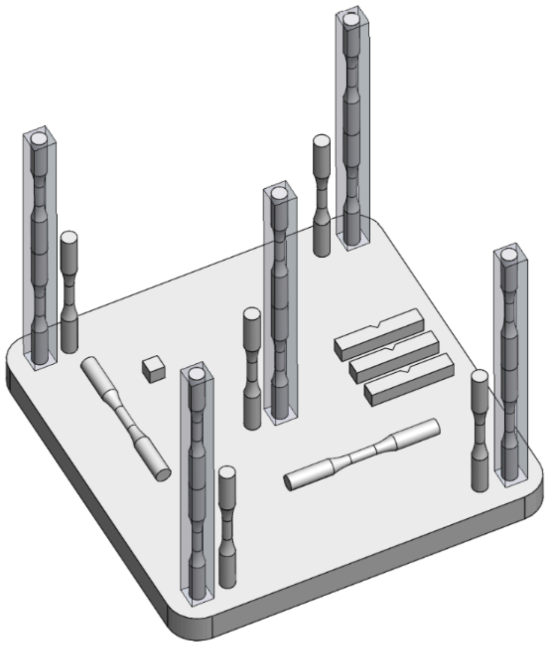


Figure 3-23 Illustration of the standard qualification build (SQB) for PBF-LB

The BPQ also introduces the need for both DT and NDT, for PBF-LB these tests are: Tensile test, Impact (Sharpy) test, Hardness (Vickers) test, macro-micro structural assessment, porosity assessment, and chemical analysis. All these tests are performed on the different specimens produced in the SQB.

3.6.6 Environmental Challenges and Impact: AM

Within AM there are introduced six main environmental challenges and impacts:

- ✓ **Material selection and emissions** – Some AM processes use plastic, metals or other materials that may be associated with environmental concerns towards production emissions or disposal.
- ✓ **Energy consumption –** Some AM processes are energy-intensive and therefore can cause some environmental challenges.
- ✓ **Limited material recycling –** Some AM processes and materials limits recycling options, and therefore increase waste.
- ✓ **Post processing –** In most AM processes there is a need for post processing and finishing to meet the desired product specification, some of these steps can contribute to increasing environmental impact.
- ✓ **Hazardous substances –** Some AM processes involve the use of chemicals such as binders, resins, and alcohols that may emit volatile organic compounds (VOCs) or other substances. Therefore, it is crucial to follow datasheet specifications for handling to mitigate environmental and health risks.
- ✓ **Build size –** Some projects may be too large for the AM-machines that are available now, therefore some products must be produced in several steps therefore impacting efficiency.

3.6.7 Common Environmental Challenges and Impacts Between AM and CNC

Lastly there are some familiar challenges between AM and CNC:

- ✓ **End-of-life considerations –** Products produced by these methods may face challenges toward end-of-life cycle. Therefore, LCA is critical to minimize environmental impact.
- ✓ **Supply chain impacts –** The sustainability of a product is influenced by raw material extraction, transportation, and supply chain considerations.
- ✓ **Regulatory Compliance –** To withhold compliance towards regulations and standards it is essential for both methods to ensure minimizing negative environmental impacts and ensure responsible manufacturing practice.

3.7 *Material Technology for BPQ and Part Qualification – VIGA 316L Stainless Steel*

316L stainless steel is within the 300 series of stainless steel which are classified as austenitic. The letter L designated in 316 indicates that there is low carbon rate in the material in comparison to the regular SS316. 316L is an austenitic chrome-nickel stainless steel where the increased corrosion resistance comes from approximately two-three percent molybdenum, this makes the material improve resistance to pitting and increases strength at elevated temperatures (Sandmeyer Steel Company, 2014).

3.7.1 Powder Atomization and Powder Morphology

Powder atomization is a process used to make filament for metal additive manufacturing. The process utilizes a hot melt of a desired material in a furnace where the melt is released highly pressurized through a nozzle. After the molten metal extraction nozzle there is a fluid (air, water, plasma, inert gas, or helium) that will rapidly cool down the melt and create powder. The powder morphology after rapidly cooling is characterized as spherical particles. The size of the particles and morphology is determined by the chosen fluid - by using water the morphology can be characterized as lumpy semi-spherical particles, whilst for the use of inert gas and vacuumized chamber (vacuum inert gas atomization (VIGA)) will yield near perfect spherical morphology and uniformity. The size of either method can range from ~10µm-300µm. The simplified gas atomization process is shown in Figure 3-24 below (*Vacuum induction melting Inert Gas Atomization (VIGA) | Additive manufacturing | Höganäs*, n.d).

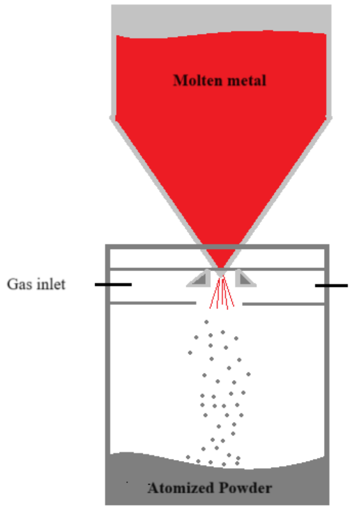


Figure 3-24 Gas atomization process simplified illustration

The powder morphology and uniformity have a high impact on the overall quality of the AM'ed part. Meaning, the more non-uniform and non-morphological particles in the powder chamber the higher the surface roughness, and possibilities for poor layer adhesiveness of the AM'ed part (*Our 3D printing metal powder portfolio | Höganäs*, n.d; *Stainless steel 3D printing powders | Höganäs*, n.d).

3.7.2 Destructive Testing (DT)

Hardness – Vickers

Hardness testing is used to determine the specimens resistance to plastic deformation. By indenting the specimen with a diamond pyramid with 136° squared based indenter, a force is indenting with a mass between 1g-1000g on the specimen. The hardness is determined by the indentation size – a large indentation indicates a softer material (Callister and Rethwisch, 2020). Figure 3-25 below illustrates the Vickers hardness test method ('Vickers Hardness Testing', n.d).

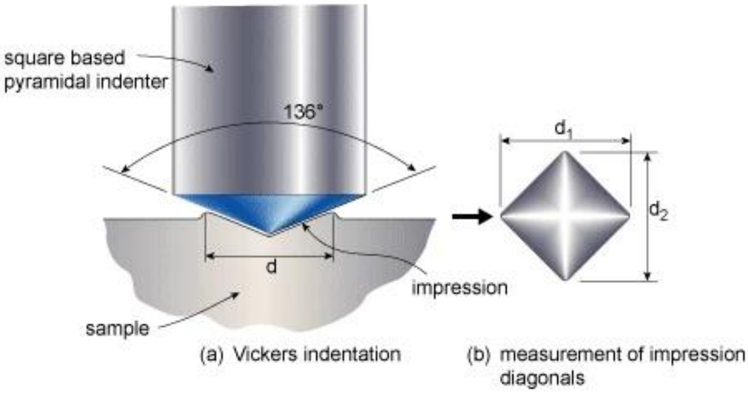
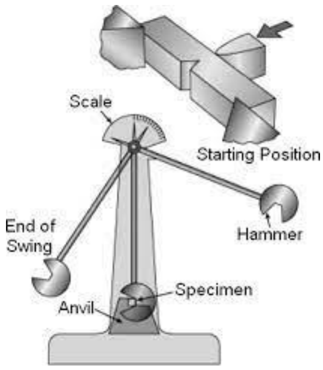
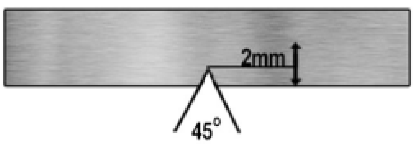


Figure 3-25 Vickers test method and indentation illustration

Impact – Charpy

A Charpy test is done to determine impact strength (relative toughness) by applying an instant load of force to the specimen. The test is performed by swinging a pendulum with a hammer utilizing potential energy (Potential Energy Formula) at a standardized height, and releasing this pendulum hitting the standardized Charpy specimen with kinetic energy (Kinetic Energy Formula) and the pendulum arm is measured at the top of the follow-through to measure the amount of Jules of kinetic energy the arm absorbed (Saba, Jawaid and Sultan, 2019). In Figure 3-26 below the machine and specimen is shown (Saba, Jawaid and Sultan, 2019).





a) b)

Figure 3-26 Illustration of a) Charpy machine and b) V-Notch specimen

Tensile Strength

Tensile strength testing is a test performed to validate a specimens reaction to withstand axially loaded (pulling) stress. A test like this will give data on material characterization such as ultimate tensile strength (UTS - the most important data), E-modulus (Young's modulus of elasticity), yield strength and strain. These data can be gathered through a stress/ strain curve shown in Figure 3-27 below (*Tensile Testing Machines | An Introduction*, n.d). The UTS is the maximum stress the specimen can withhold during a test. The modulus of elasticity is the measurement of material stiffness, the elasticity is measured in the linear part of the stress/ strain curve, when the line goes from linear to non-linear it will result in plastic change in the specimen this point of the curve is known as the yield strength (*Tensile Testing Machines | An Introduction*, n.d).

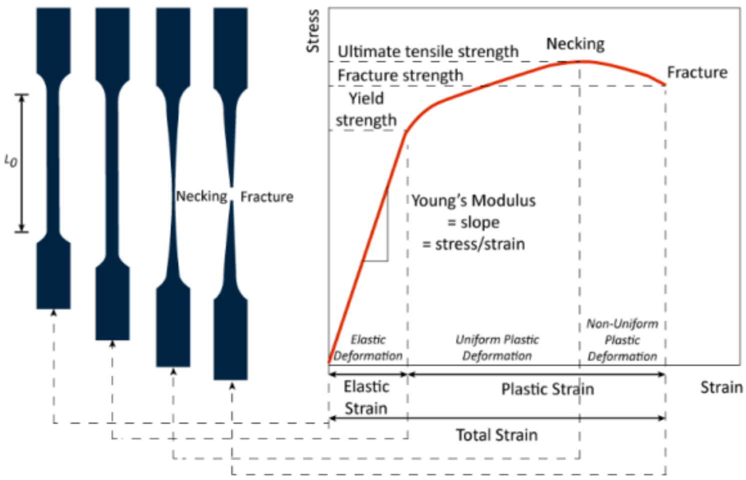


Figure 3-27 Tensile test specimens and illustrative stress/ strain curve with descriptions

3.7.3 *Micro and Macrostructural Assessment of PBF-LB Processed Material*

There are several different methods to achieve images to perform micro and macrostructural assessment. Some of these methods are light microscopy, SEM (and SEM with EBSD technique). The macrostructural analysis shows build direction, weld pools, and fusion lines. Whilst the microstructural analysis yields grains sizes, phases, nano-inclusions, and other perfections and imperfections. The optical microscopy uses a focused beam of photons usually light to gain information about the structure of the material, the SEM uses a focused beam of electrons to gain information on the structure and composition of the material. EBSD is a technique used within the SEM microscope to gain more in-depth information about the structure and orientations (*Electron microscope | Uses, Advantages & Limitations | Britannica*, 2024).

3.7.4 Non-Destructive Testing (NDT)

Surface Testing (PT)

Penetrant testing is a method used to check surface conditions regarding cracks, pores, or other surface defects in the specimen. The test is conducted by exposing the surface to a penetrating liquid in a colored or fluorescent medium. This medium has properties to penetrate defects. When the excess medium is removed the part will then be exposed to a developing medium which has the property to develop the surface defects by drawing forth the penetrating liquid in the defects. Defects with width 1µm and length 0.1mm can be found under optimal conditions (*NDT tjenester*, n.d).

Dimensional Check (CMM, Caliper and Gauges)

Dimensional check is a method to confirm the size and tolerance checking of a part. CMM is a machine used to find geometric deviations such as surface flatness, and right angles (the CMM method description is described in APPENDIX A 1 Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM (Grashei, 2023)) (*Coordinate Measuring Machine*, n.d). A caliper is a traditional measuring device that measures the distance between two opposite sides of a part by using two legs (*Caliper | accuracy, precision, range | Britannica*, n.d). Gauges are near perfect machined objects that are used as a reference to a geometric tolerance such as radius, holes, squares to name a few. These gauges will be used to fit in the part and the tolerance are within or rejected depending on the gauge fit (*Gauge | Types, Uses & Measurement | Britannica*, n.d).

Density/ Volumetric Testing (Archimedes Principle) and Computed Radiographic Inspection (CR)

Archimedes and buoyancy principles are a method to determine the density of an object. By measuring the weight of the part in air first, then by submerging the part in water and calculate the density of the sample my using Equation 1. Then by using the theoretical density of the material of the object and the density of the sample to calculate the relative density from Equation 2 to determine the percentage of density in the measured object (Sayyar *et al.*, 2023).

Equation 1 Density of sample

$$\rho_{sample} = \left(\frac{m_{air}}{(m_{air} - m_{water})}\right) \cdot \rho_{water}$$

Equation 2 Relative density

$$\rho(\%) = \left(\frac{\rho_{\text{sample}}}{\rho_{\text{theoretical}}}\right) \cdot 100\%$$

For volumetric NDT CR inspection was used. The methods principles are that the specimens are exposed to x-ray and gamma rays that penetrate through the specimen on one side, and a film placed on the other side are then exposed to the different energy levels that penetrates the specimen. If there is a defect in the specimen the dampening effect of the rays will be changed in this area and since a e.g. pore will not dampen the ray as good as a dense body the x-ray power will be greater in this area (*NDT tjenester*, n.d).

4 Experimental

4.1 Part Selection and Valve Information

Part selection is based on earlier work done in an earlier report (Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM (Grashei, 2023)). Where the selection was based on availability and accessibility. The part chosen was based on not being too complex due to restricted time of writing the latter mentioned report. A roadmap for part digitalization is shown in Figure 4-1. The part selection was done in as following steps:

1) Visit IKM Flux AS and review available valves,

2) Collect and assess valve,

3) Valve disassembly and assessment,

4) Choose part of interest,

5) Scan part,

6) CAD and reverse engineer part,

7) Print and process part.

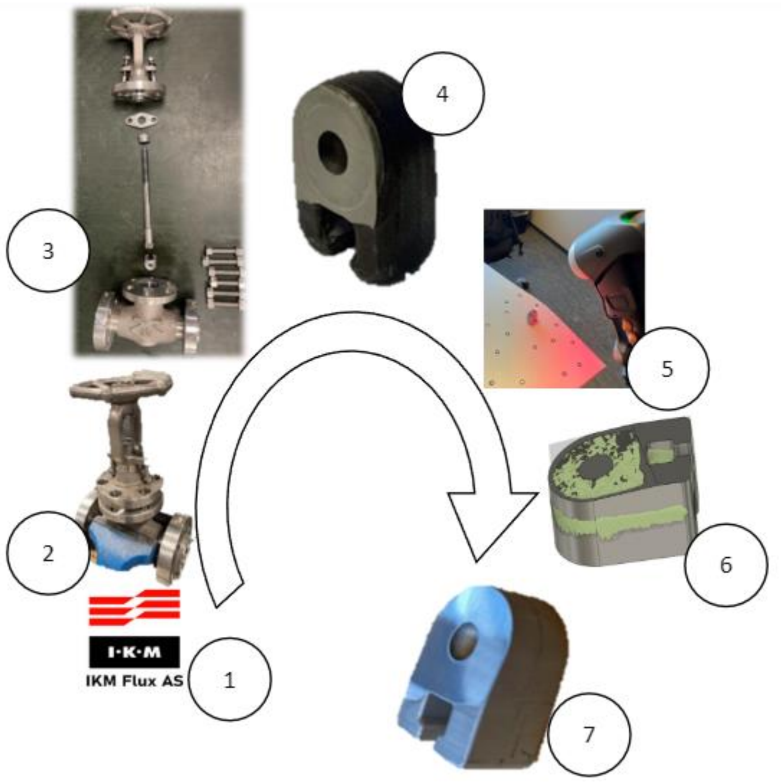


Figure 4-1 Part selection - Reverse engineering process

The valve assessed is an ¾'' gate valve acquired from IKM Flux AS. The valve has actively been used offshore and has been decommissioned and given to reverse engineering (Grashei, 2023).

4.2 Part Design Optimization

4.2.1 Measurement

The measurement technique used for the valve wedge is reverse engineering based, by using scanning technology and CAD software to design a printable fresh part, and CMM to validate the scanned and printed part towards the original part. The report given in APPENDIX A 1 Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM thoroughly explains the process for part geometry and validation steps in CMM.

4.2.2 Surface Roughness

Surface roughness testing of seal surface to acquire the desired seal surface. The test is done according to relevant standards such as NS-EN ISO 21920:2021/2022 (International Organization for Standardization, 2021, 2022a, 2022b). Where the measurement area is as shown in Figure 4-2 below.

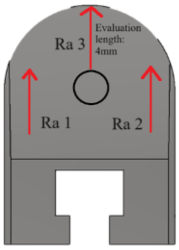


Figure 4-2 Surface roughness test mapping

Before starting the test, a reference test was done to see if the equipment was calibrated (see APPENDIX F - 1 Surface roughness calibration step for pictures and results). The measurement data is collected three times per measurement area (R1/R2/R3) and on both side A and side B (marked with pencil) as shown in Figure 4-3 below. The mean value is calculated and shown in Table 4-1 below.

Table 4-1 Surface roughness values

Side	Ra 1	Ra 2	Ra 3	Ra mean
A	0.48 µm	0.42 µm	0.46 µm	0.453 µm
B	0.62 µm	0.42 µm	0.50 µm	0.513 µm

Following the Ra values are added to the work drawing and relevant manufacturer is informed about the seal surface tolerance which is the mean value of both side A and B = 0.48µm. Therefore, reasonable to set Ra = 0.4µm to technical drawings.

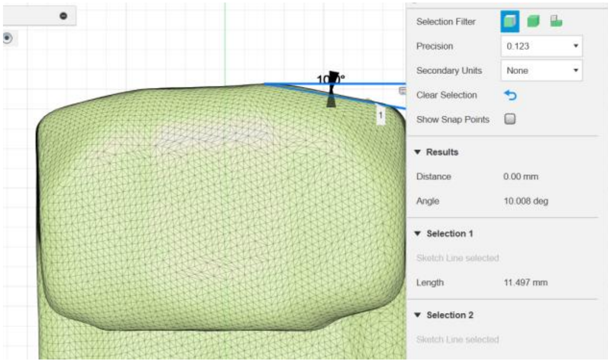
a)

b)

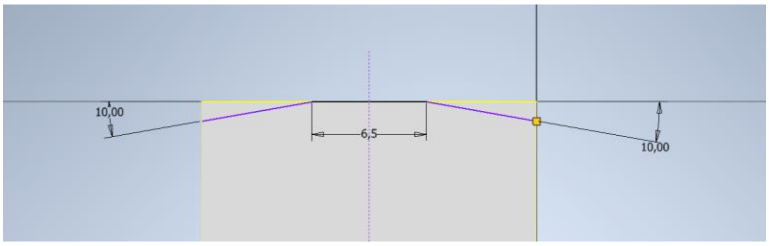
Figure 4-3 Surface roughness orientation

4.2.3 *Rapid Prototyping and Design*

In the earlier report written (Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM) (Grashei, 2023) there was printed a wedge for verification of scanning method, this part did not fit the valve due to the curvature of the side of the wedge, this has been fixed for this iteration of the wedge. Curvature was checked to be approximately 10 degrees. Curvature check and fix are shown in Figure 4-4 below.



(a)



(b)

Figure 4-4 a) Angle check for valve entry and b) adding change to CAD

To correctly fit the wedge in the valve – implementation of rapid prototyping aided in designing and adding features to the design accordingly. Slicing of the prototypes shown in Figure 4-5 below.

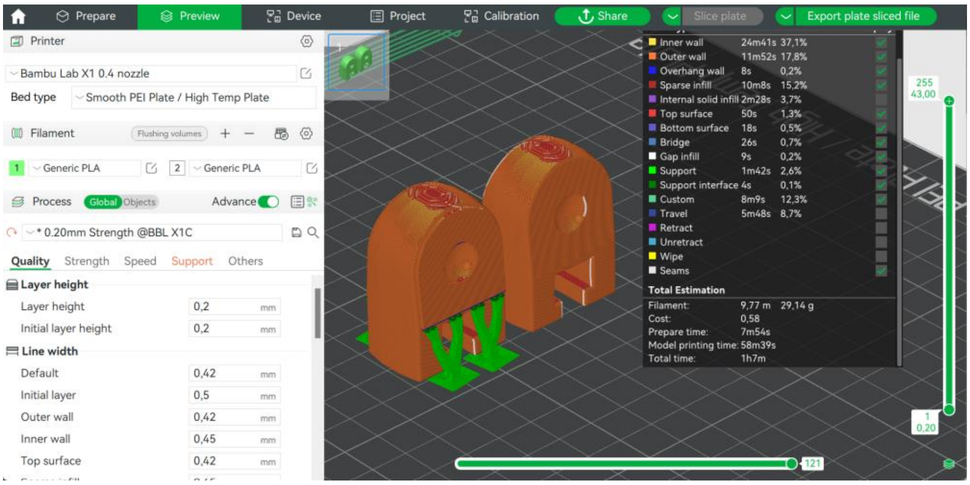
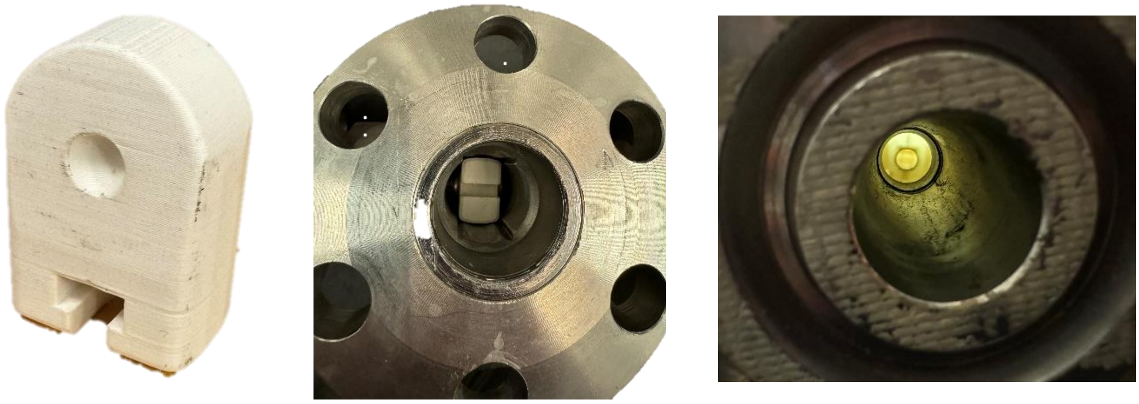


Figure 4-5 Slicing of STL formatted wedges for prototyping of AM and SM models in BambuStudio

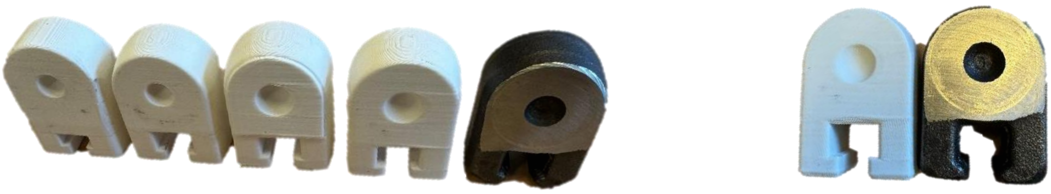
After altering the CAD file and prototyping with help from 3D-print technology the AM’ed model was fitted in the valve to check if it fitted neatly with the seat rings. The AM’ed wedge prototype and valve fitting are shown in Figure 4-6 below.



a) b) c)

Figure 4-6 Valve prototype valve fitting a) Wedge prototype, b) Top view, c) Side view with illumination

Furthermore, by use of AM technology and rapid prototyping there were some prototypes of the finished design. The prototypes were checked towards the original equipment and resulting in good coherence. All prototypes next to the original equipment as shown in Figure 4-7 a) and the original equipment and new design prototype shown in Figure 4-7 b).



a) b)

Figure 4-7 a) Prototypes and OE, b) Final design and OE

4.2.4 Technical Drawing and File Formatting to Send to Manufacturers

After checking the coherence of the original equipment towards the new design the go ahead for production was given. The subtractive manufacturer needs a technical drawing of the part, whilst the additive manufacturer requested files that were formatted as step files.

The technical drawings are given in APPENDIX C 2 Wedge drawing given to Stamas and APPENDIX C 3 Drawing for AM'ed wedge part given to Stamas for raised face removal.

4.3 Part Manufacturing

4.3.1 Subtractive Manufacturing

The part subtractive manufactured was produced at Stamas Solutions in Stavanger using CNC mill.

The part was manufactured using a 5-axis CNC machine.

The AM'ed raised face model was delivered to UiS CNC operator and the raised face was removed using a CNC lathe machine In Table 4-2 the chemical composition of the 316L material for SM is given.

Table 4-2 Chemical composition of E+AOD+LRF processed 316L steel

Elements	**Cr**	**Ni**	**Mo**	**C**	**Mn**	**P**	**S**	**Si**	**N**	**O**
Wt%	16.84	10.03	2.03	0.009	1.88	0.033	0.026	0.38	0.049	0.02

The fully subtractive manufactured part is given in Figure 4-8 below.

Figure 4-8 Subtractive manufactured wedge part

In figure below the AM'ed model is given after raised face removal in Figure 4-9 below.

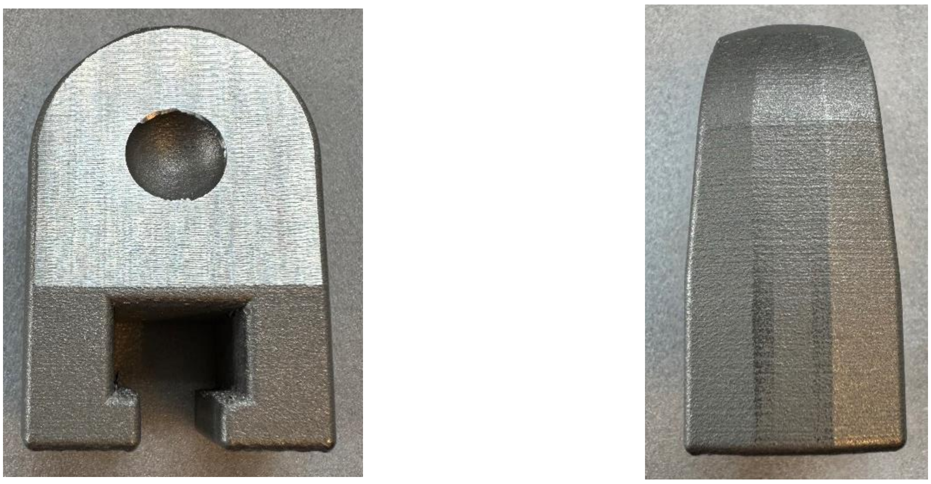


Figure 4-9 AM'ed and SM'ed part (Raised face removed)

4.3.2 Additive Manufacturing

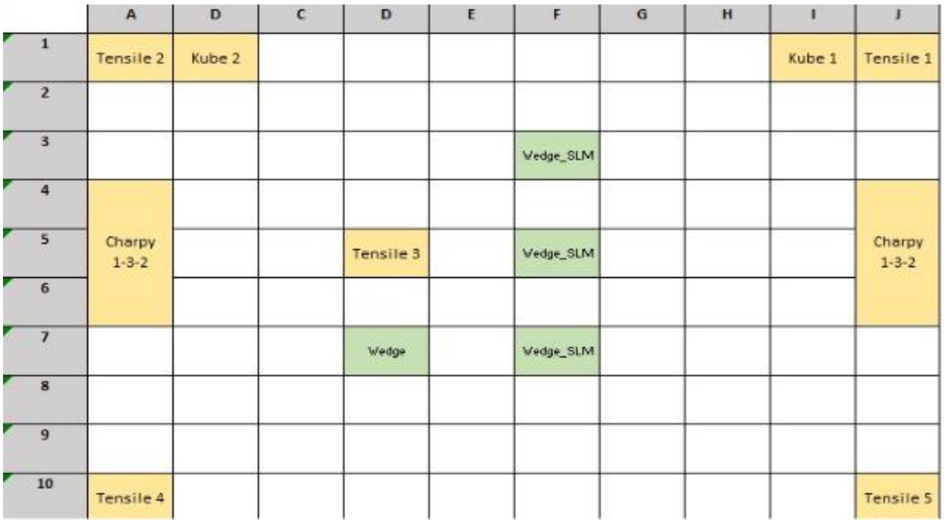
The part additively manufactured was produced at AM North in Hammerfest using the PBF-LB AM method. Given in Table 4-3 below is the chemical composition of the 316L vacuum inert gas atomized powder (VIGA) with Ar.

Table 4-3 Chemical composition of 316L powder

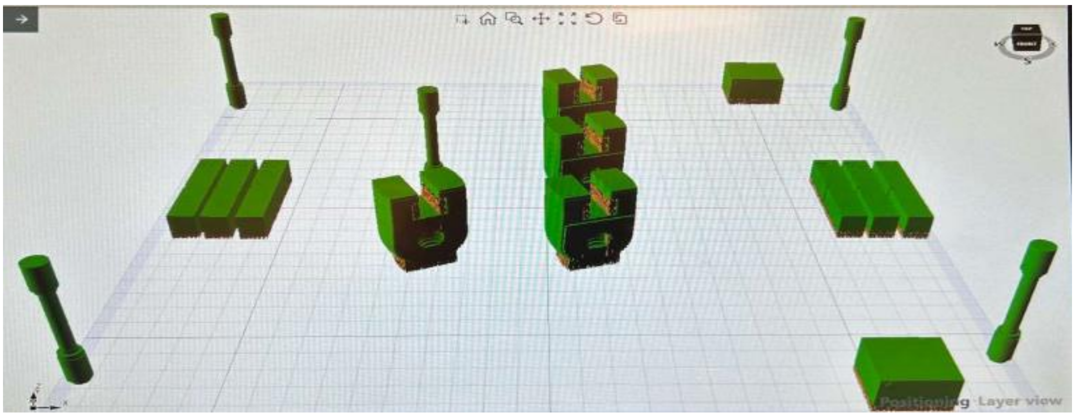
Elements	**Cr**	**Ni**	**Mo**	**C**	**Mn**	**P**	**S**	**Si**	**N**	**O**
Wt%	17.8	11.9	2.3	0.00	1.5	<0.001	0.003	0.2	0.01	0.02

SQB – Standard Qualification Build

An SQB was manufactured for the BPQ testing requirements, the SQB included 5 tensile specimens, 2 sets (2x3) Charpy specimens and 2 blocks for micro, macro, and hardness testing. SQB build plate orientation and sliced plate from AM North are given in Figure 4-10 below.



a)



b)

Figure 4-10 SQB a) build plate orientation, b) picture of build plate slice

Also, the finished printed SQB is given in Figure 4-11 below.

Figure 4-11 Finished printed SQB specimens

Additively Manufactured Part (Clean Model and Raised Face Model)

The printed parts are given in Figure 4-12 below.

a)

b)

Figure 4-12 a) Printed wedge, b) Printed wedge with raised face

The BPQ and part documentation requirements according to the standard (Det Norske Veritas AS, 2022) are given in the appendix:

APPENDIX D - 2 Traceability list: AMN-03-05-0007

APPENDIX D - 3 Build traceability: AMN-03-05-0009

APPENDIX D - 4 Test specimens traceability: AMN-03-06-0005

APPENDIX D - 5 MPS: AMN-03-01-0011

APPENDIX D - 6 ITP: AMN-03-03-0002

APPENDIX D - 7 PPS: AMN-03-08-0004

APPENDIX D - 8 PQR: AMN-03-08-0005

APPENDIX D - 9 BPQR: AMN-03-10-0001

4.4 Life Cycle Assessment

According to ISO14040/14044 the baseline for the LCA is to state and define the goal and scope. The 3DExperience software version is R2024x, ecoinvent 3.9.1 version, and EF 3.0 impact assessment method.

4.4.1 Definition of Goal and Scope

The goal of this study is to conduct a comparative LCA to determine whether the Additive manufacturing process or the conventional manufacturing process has the lowest environmental impact when producing a small valve part. The valve part was initially produced with stainless steel (316L) forging method in Italy, whilst for this project both parts is produced in Norway with CM in CNC machine, and with SLM AM method both with 316L material. The CM is based locally while the AM is based in northern Norway (Hammerfest). The functional unit of the study is defined as manufacturing of one valve part. Furthermore, the LCA analysis will be done using Dassault systems 3DExperience software and EF 3.0 impact assessment method.

4.4.2 System Boundaries

Cradle-Gate and EOL consideration. The LCA study will not include transport and packaging due to lack of national geolocation in the 3DExperience software, but it is worth noting that both parts are produced in Norway (AM in northern Norway, and SM locally in Stavanger). Furthermore, the part as a service will not be recorded in this report either. The LCA study will focus on manufacturing the part. The system boundaries are as follows:

- ✓ Raw materials
- ✓ Manufacturing
- ✓ End-of-life

Using the 3DExperience software directly will yield 16 impact categories using EF 3.0 Impact assessment given in Figure 4-13 below:

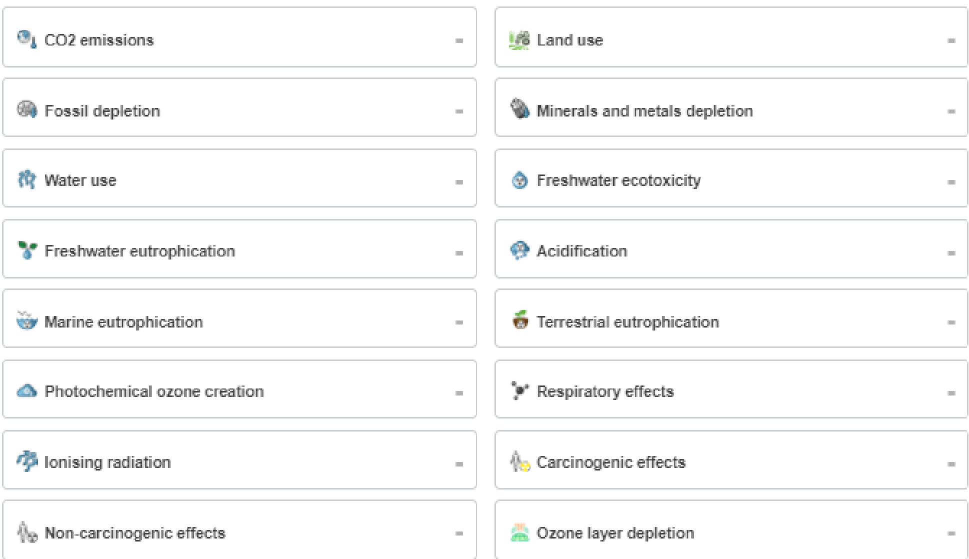


Figure 4-13 LCA Impact categories within the system boundaries

4.4.3 Life Cycle Inventory – Categorization

The LCI is chosen from the ecoinvent database within the 3DExperience software. In the human activities in the BVD software there are 5 categories which are applicable for inventory manipulation. The human activities are chosen regarding the methodology of the manufacturer in the aspect of material bought, used, and scrapped. Also, the EOL considerations are chosen for both methods. Furthermore, the inventories for each of the manufacturing methods are selected in further detail in this chapter.

LCI - Subtractive Manufacturing

Within the 3DExperience platform there are a lot of inventories to choose from for the SM method. In Table 4-4 below the categories with the respective inventory are shown with the weight of part and used as the formula variable.

Table 4-4 LCI for subtractive manufacturing

Category	**Inventory**	**Formula variable**
Raw material	Hot rolling, steel	0.900 kg
Transport and packaging	NA	
Manufacturing	Steel milling, small parts	0.700 kg
Product as a service	NA	
End-of-life	Market for scrap metal	0.900 kg

These inventories chosen are datasets from the ecoinvent database. Where the metric for the given inventory is set, and the variable to have the uniqueness of the analysis is the weight of the part (for the respective analysis). Given by Equation 3 below.

Equation 3 Variant Formula

$$LCA\ metric = Environmental\ category * formula\ variable$$

In Figure 4-14 below, the variant formulas for a small selection of the ecoinvent metrics are shown from the 3DExperience platform.

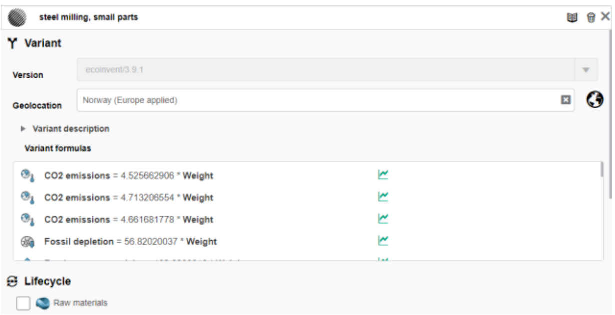


Figure 4-14 LCI and variant formulas shown for a small selection from the BVD

LCI - Additive Manufacturing

For the AM analysis – there were some issues regarding the inventory classification. The 3DExperience software does not have an inventory classification for AM, therefore closely related inventories were chosen in this analysis. In Table 4-5 below the inventories and formula variables are given in the respective categories.

Table 4-5 LCI for additive manufacturing

Category	**Inventory**	**Formula variable**
Raw material	Steel production, Electric, Chromium steel	0.200 kg
Transport and packaging	NA	
Manufacturing	Laser machining, metal, with YAG 200W power	0.700 kg
	Steel milling, small parts	0.010 kg
Product as a service	NA	
End-of-life	Market for scrap metal	0.200 kg

4.4.4 Software Setup

In the 3DExperience software it is possible to make a dashboard with the desired applications. The applications that will be used for LCA are:

- Product Explorer (3D-model navigation application)
- Business Value Definition (Ecoinvent database and LCA category specification)
- Collaborative Life Cycle (Used to compare the different manufacturing methods)
- Eco-Design Assessment (The results of the LCA are presented)

A thorough step-by-step guide on the setup and analysis is given in APPENDIX C 1 LCA setup and tutorial.

4.4.5 Business Value Definition (BVD) & Ecoinvent

All ecoinvent data were gathered through the Dassault systems 3DExperience software. The ecoinvent data is inbuilt in the business value definition (BVD) application in the software. Through the BVD the process is chosen regarding raw materials, packaging and transport, manufacturing, product as a service and lastly end of life considerations. Through these various activities the actions are chosen as closely as possible to real-life applications, furthermore, extracting the ecoinvent data to use in the metrics for LCA. In Figure 4-15 below the software and BVD is shown.

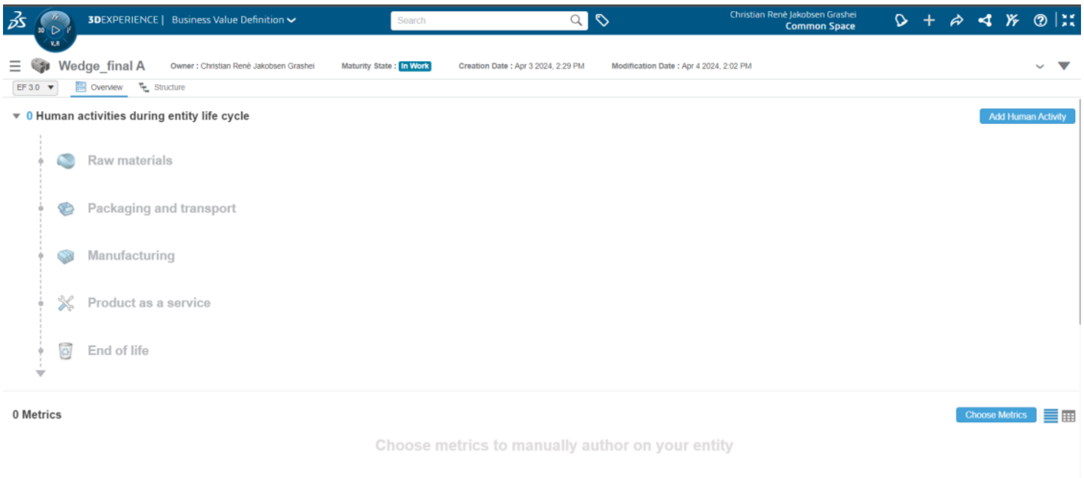


Figure 4-15 3DExperience and Business Value Definition application and ecoinvent data

The part is then split into different iterations to cover both SM and AM processes. In Figure 4-16 below the collaborative life cycle window is shown, here the different iterations of the part hold different information (LCI) regarding categorization, and process description.

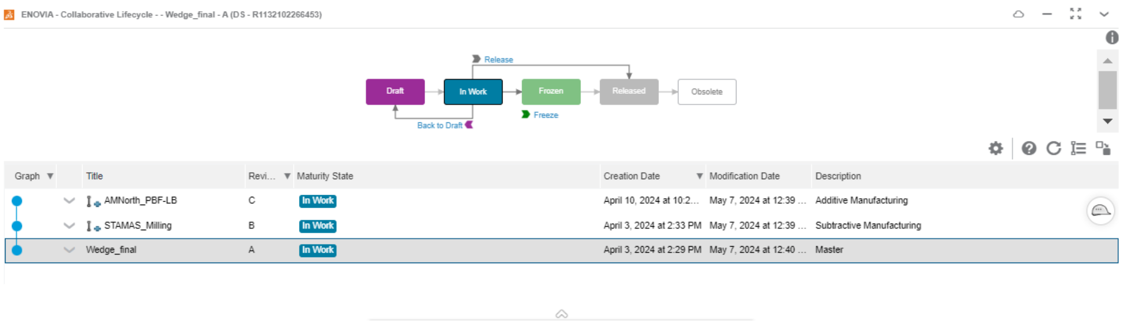


Figure 4-16 Collaborative Life cycle window and part iterations

4.4.6 *Software Application: SM*

The SM part (called STAMAS_Milling) is placed in the BVD window, and the respective categories are chosen from the ecoinvent library. In Figure 4-17 below the part is shown and the impacts are selected and placed in the respective categories. The categories chosen are given in Table 4-4 above.

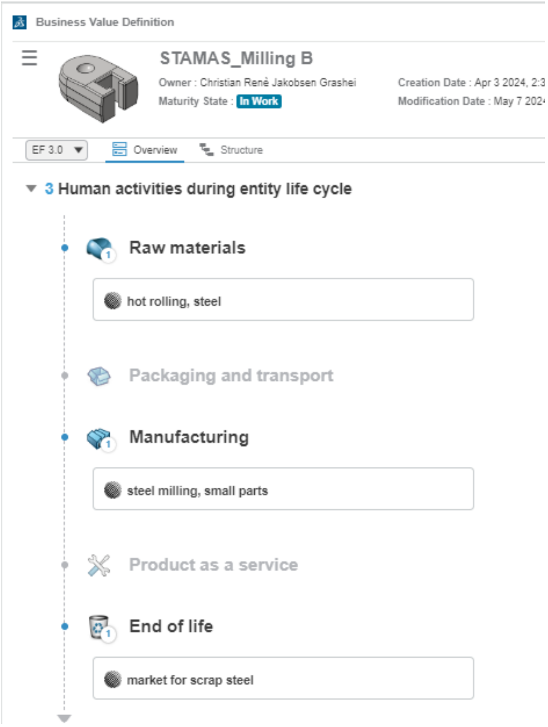


Figure 4-17 LCI Software application and applied processes for SM part

After the BVD step the actual simulation is done by placing the SM part in the Eco-Design assessment tab. The Eco-design assessment application then calculates the variants and gives the metrics for the LCA. Analysis result given in Figure 4-18 below.

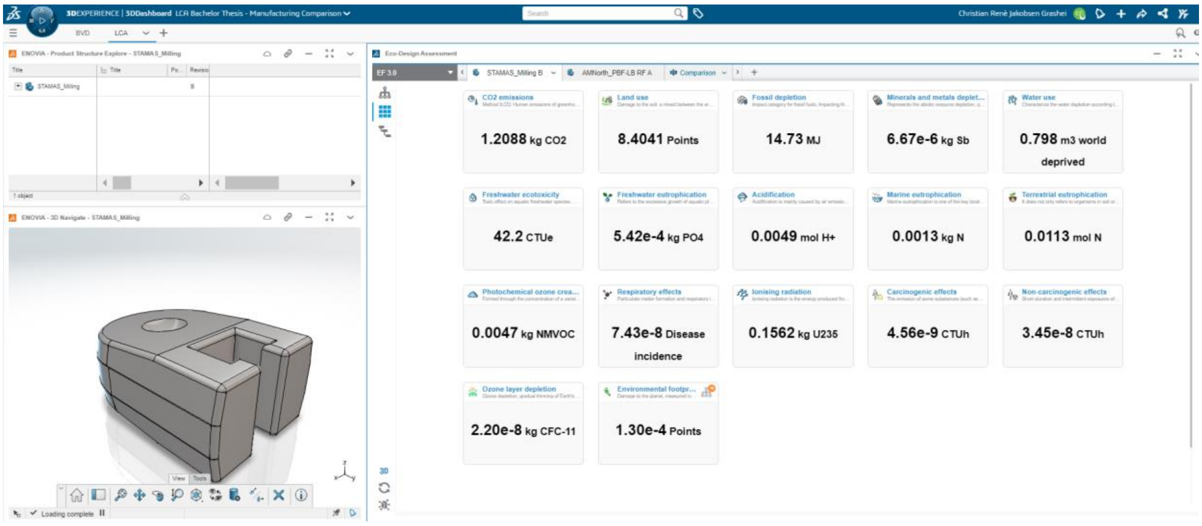


Figure 4-18 Eco-Design Assessment finished analysis for SM part

4.4.7 *Software Application: AM*

The AM part (called AMNorth_PBF-LB RF) is placed in the BVD av given processes in the respective categories from the ecoinvent library. The actions and processes are chosen in the ecoinvent library and allocated in the categories in the BVD as shown in Figure 4-19 below. Given in Table 4-5 in earlier chapter.

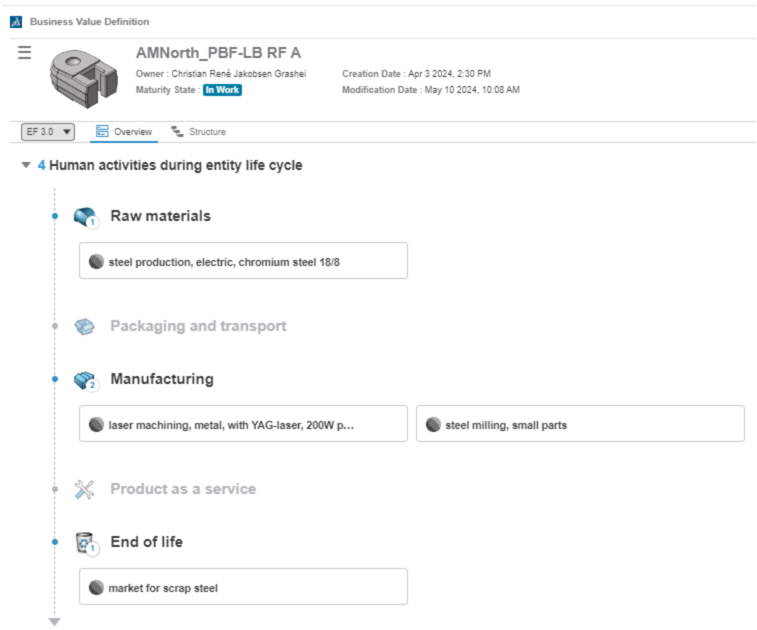


Figure 4-19 LCI Software application and applied processes for AM part

The simulation is then done in Eco-Design Assessment and the metrics of the LCA are given. Analysis results are given in Figure 4-20 below.

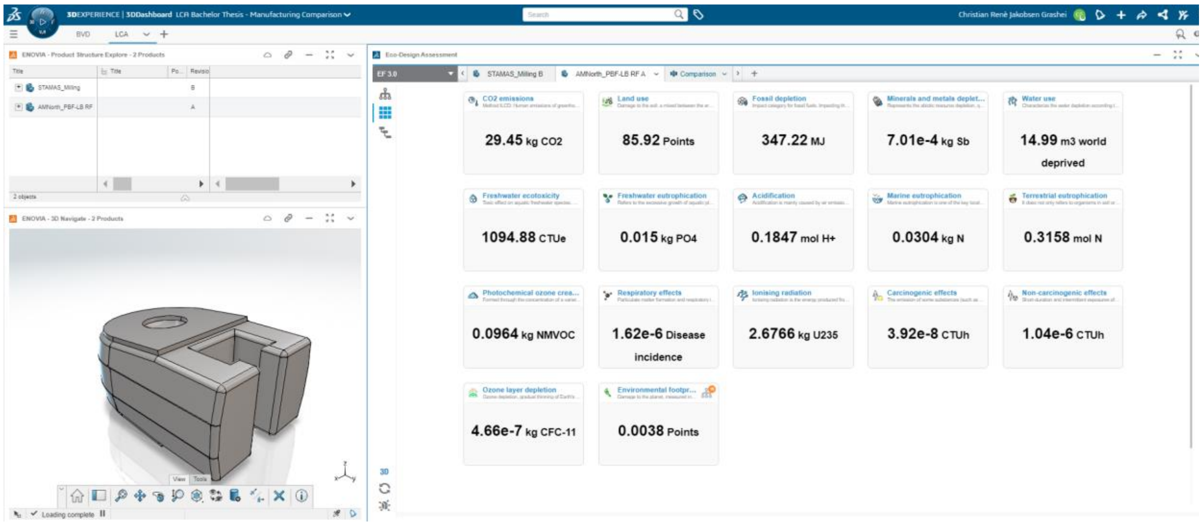


Figure 4-20 Eco-Design Assessment finished analysis for AM part

4.5 AMC Selection, Build and Part Qualification (AMC, BPQ, PT)

4.5.1 AMC Selection

To successfully choose an AM category there are some considerations to consider:

- ✓ Failure modes for health and safety
- ✓ Failure modes for failure
- ✓ Failure modes for environmental consequences
- ✓ Loss of reputation
- ✓ Regulatory requirements

As this valve is a legacy part with no further documentation other than valve data sheet (VDS): GTFS00J (valve information and theory are given in APPENDIX A 1.). The assessment will be assumptions that fit with most used valves. The VDS gave information about max working pressure (which is set to 248,2 barg at both -101℃-38℃) and max temperature 350℃ with operating pressure 152,1 barg. Assuming that the process medium is not gas it is easy to eliminate AMC-3 at this range of pressure. Also, the valve being manually managed and not actuated means that it serves either open or closed and does not serve a purpose as a regulating process object.

In Table 4-6 below a chart is made to evaluate the importance of each consideration of AMC selection, the grading will be done from 1-10 where 1 is low importance, and 10 is high importance. This scoring system will determine the extent of which AMC category shall be used. 1) Due to HSE is a paramount consideration on the Norwegian continental shelf, and there is a remotely possibility that there is a failure in the valve that could lead to injuries or fatalities it warrants a grade 9. 2) Directed towards valve functionality and the consequence for failure, however the use of the valve is not known, therefore a provisional grade 5 is given. 3) This is dependent on the fluid transport, given that the leak test is typically done with water, and is not going to be functionally used in real practice a grade 2 is given. 4) AM in general would be damaging for the technology, therefore a grade 6 is given. 5) Compliance with important regulations where failure to meet those regulations could lead to legal issues, and further reputational damage, therefore a grade 7 is given. After assessing the score, the AMC 2 level is chosen due to No.1, health and safety is particularly important, and ensuring high standards for the build this helps open some barriers and trust to the AM process.

Table 4-6 AMC Grading chart

No.	AMC considerations	Grade of importance
1	Failure modes for health and safety	9
2	Failure modes for failure	5
3	Failure modes for environmental consequences	2
4	Loss of reputation	6
5	Regulatory requirements	7

4.5.2 SQB Test Specimen Preparation

In Figure 4-21 below, all test specimens produced in the SQB for the BPQ are shown.

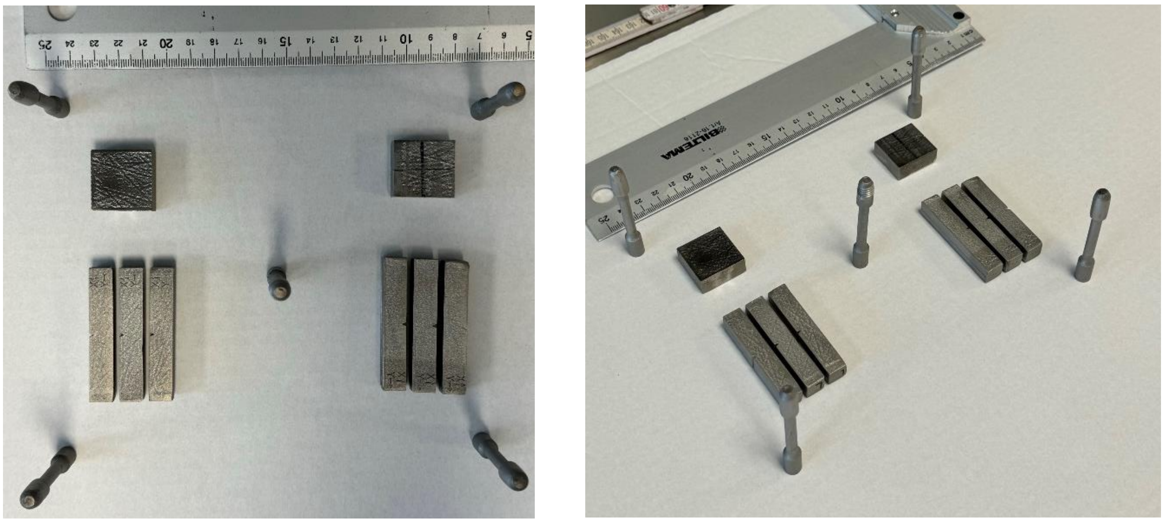
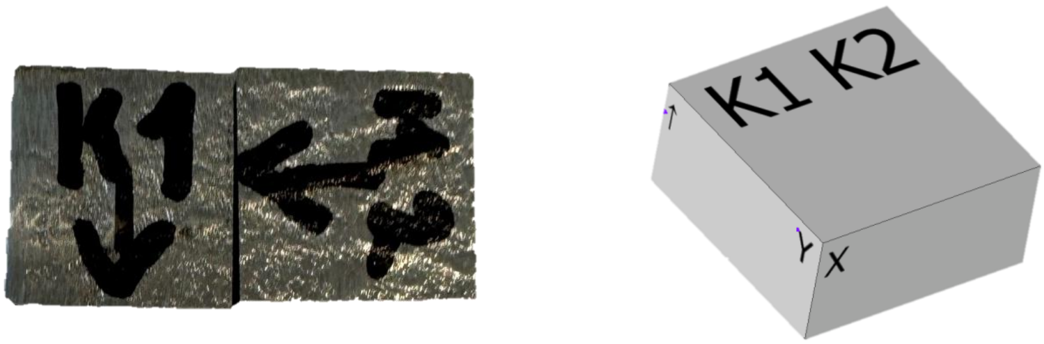


Figure 4-21 Test specimens printed in 316L

Preparation for Microscopy

To assess the macro and microstructure of the build the upper right block shown in Figure 4-21 above will be cut, polished, and prepared for assessment. First the specimen is cut in half to get a view of the XZ-plane of the part. The specimen after cut and visualization as shown in Figure 4-22 respectively. The cutting machine used was a Struers laboratory abrasive cutter.



a) b)

Figure 4-22 Micro, macro, and hardness specimen a) after cut, b) visualized with build direction and axis

Thereafter the specimens were molded in a resin mixture using Condufast and Clarofast and Struers Citropress-30. The finished molded specimens are shown in Figure 4-23.

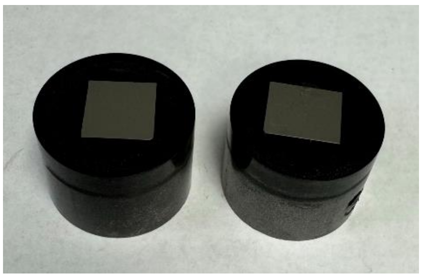


Figure 4-23 Specimens in mold, K1 on the left and K2 on the right (finished polished)

After molding the specimens, the polishing steps could begin as followed in Table 4-7. The machines used for polishing were Struers Pedemax-2 (for the first 3 steps) and Struers TegraForce-5 (for the last 4 steps).

Table 4-7 Grinding and polishing steps

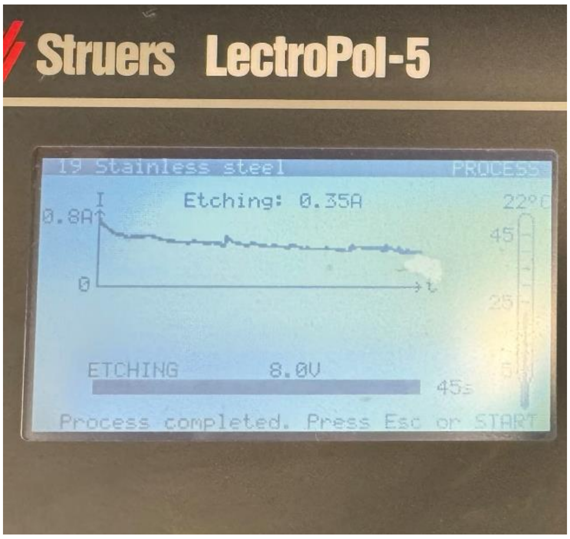
Surface	**Lubricant**	**Process time**	**Disc rotation RPM**
SIC-Paper #500	Water	3m00s	300
SIC-Paper #1200	Water	4m00s	300
SIC-Paper #2000	Water	4m00s	300
Allegro 9µm	All/Lar.	8m00s	150
MOL 3µm	MOL	5m00s	150
*NAP 1µm	NAP-B	10m00s	150
**Chem	OP-S	5m00s	150

*Last step for macrostructural analysis.

**Only done for microstructural analysis specimen.

After polishing the etchant was applied on both surfaces using Oxalic acid (10wt%). The Oxalic acid was applied in an electrolytic process with 8.0V and 22℃ applied to the specimens in 2x45 seconds intervals using Struers lectropol-5 and area etched was 5cm^3. Machines and process shown in Figure 4-24.

a)



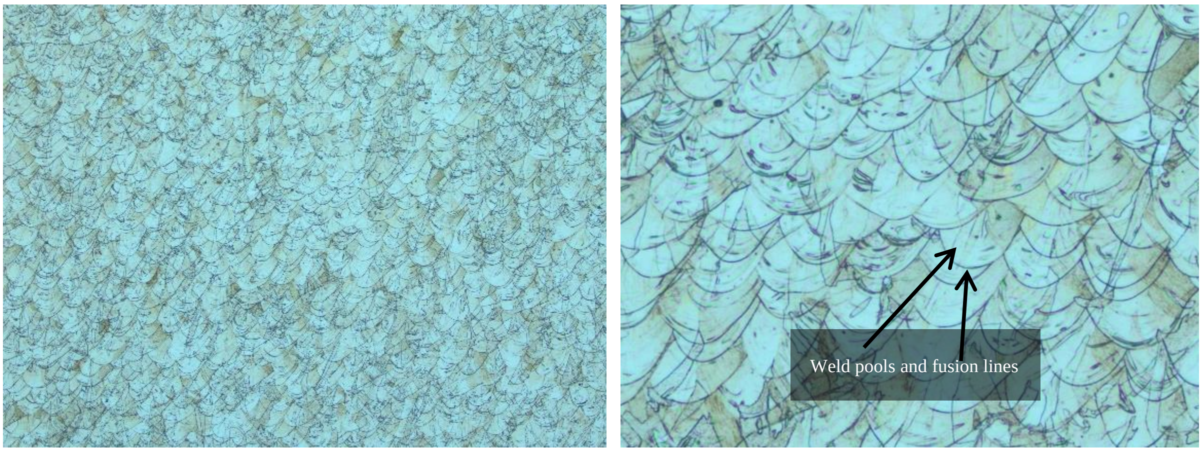
b)

Figure 4-24 Etching process a) Etchant applying machine b) Parameters used when etching

4.5.3 *DT & NDT-Testing of SQB*

Macro and Microstructural Assessment

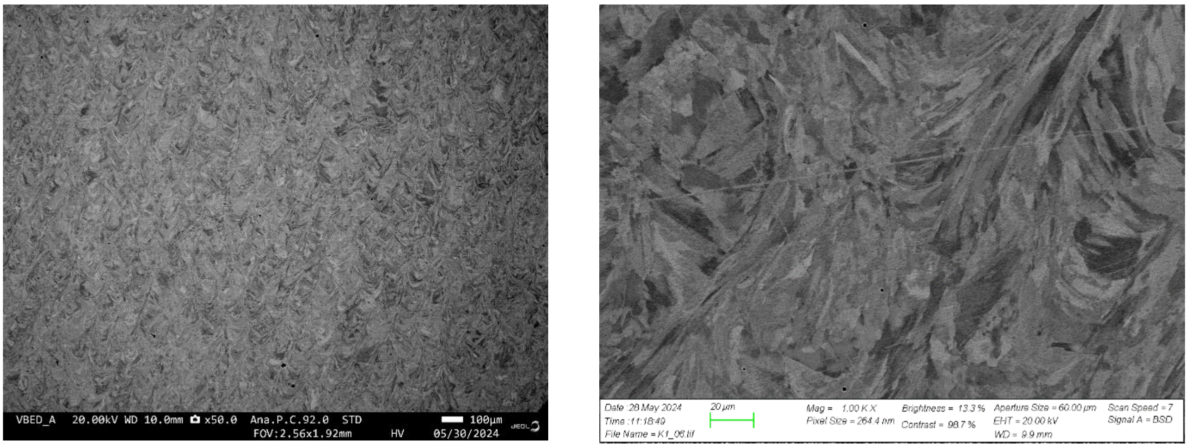
The Macro assessment was performed using an Olympus GX53 Light optical microscope. The DNV-ST-B203 standard gave instructions on the magnification that should be used in the assessment (between 3x and 5x). The magnification used was 5x. Also, the standard stated that the fusion lines or weld pools from the SLM-LB method should be visible in the process. By assessing the XZ-plane these lines are clearly visible as shown in Figure 4-25.



a) b)

Figure 4-25 Macrostructural assessment (5x) a) full view b) zoomed view and visible fusion lines

The Microstructural assessment was performed using ZEISS Supra 35VP and Jeol JSM-IT800 scanning electron microscope (SEM). The DNV-ST-B203 standard gave instructions on the magnification that should be used in the assessment (an overview image of 50x and an assessment image of minimum 100x). One image with 50x (shown in Figure 4-26 below) and several images from ranges 150x-1kx was taken given in APPENDIX F - 12 Microstructural images from SEM K1 and APPENDIX F - 13 Microstructural images from SEM K2.

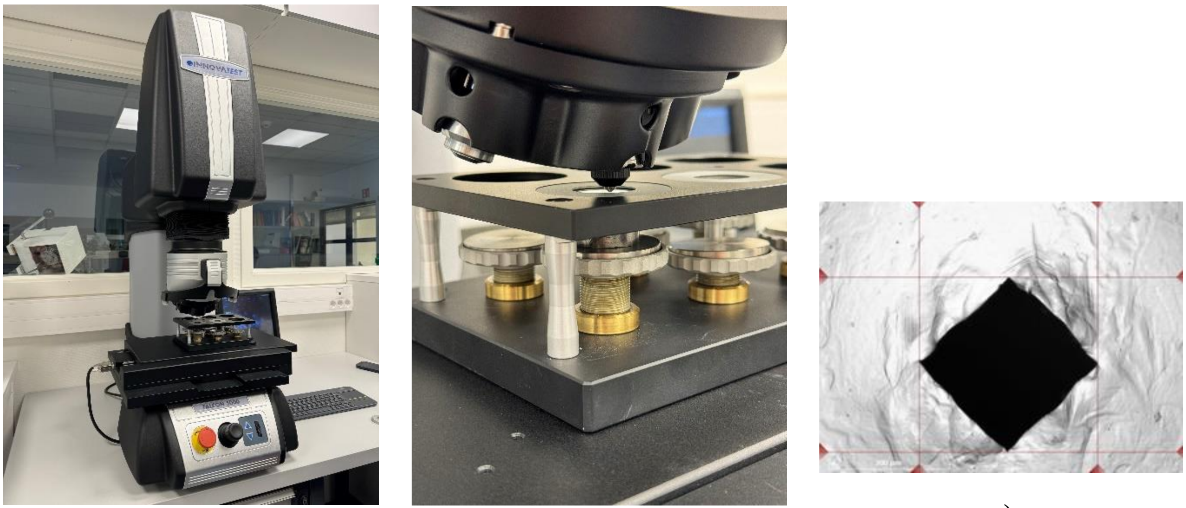


a) b)

Figure 4-26 Microstructural assessment in SEM a) 50x magnification (IT800), b) 1Kx magnification (Supra 35)

Hardness Vickers Testing

The hardness Vickers test was performed with an Innovatest Falcon 5001 hardness tester. Creating 10 indentations with 10 kg force spaced 1.25 mm apart along the cross-section. The machine and indentation process are shown in Figure 4-27 below. Test report is given in APPENDIX D - 20 Hardness test report from INNOVATEST FALCON 5001 tester.



a) b) c)

Figure 4-27 Vickers hardness testing a) machine, b) Stage and indentation overview, c) Indentation

Tensile Testing (Quality Lab)

The tensile test was done at Quality lab Stavanger. The specimens were threaded on both ends and inserted in the chucks of the tensile test machine. Two specimens (specimen 3 and 5) were tensioned until breakage. Machine with specimen, and specimen before and after breakage shown in Figure 4-28 below.

a) b) c)

Figure 4-28 Tensile testing a) machine during test, b) specimen before testing, c) specimen after testing

Impact Test (Charpy)

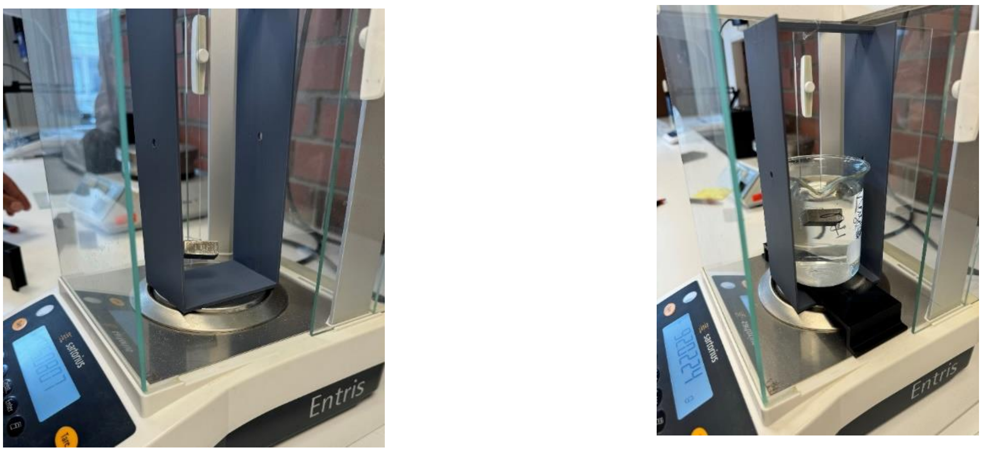
The Impact test was done at Quality lab Stavanger. The specimens were first sanded slightly on all sides except for the V-notch side to eliminate residual surface stresses. Furthermore, the specimens were inserted into the Charpy impact tester (shown in Figure 4-29 below) onto the dedicated area, the chamber was then enclosed, and the hammer was dropped. This process was done 3 times with specimens kept in room temperature. The specimens are shown in Figure 4-29 below. The specimens start from specimen 1 at the top and in a descending order down to specimen 3.

a) b) c)

Figure 4-29 Charpy Impact testing a) machine, b) Specimen 1-3 V-notch side, c) Specimen 1-3 breakage cross section

Volumetric Testing (Archimedes Principle)

The principle of Archimedes and buoyancy was used to determine the density of the printed part. By first measuring the specimen in air by using a scale with a stage and a small piece of string to perform the measurement yields a mass of specimen in air: $m_{air} = 24.2715\ g$ (measurement and stage shown in Figure 4-30) Secondly, measuring the specimen in water by using the same stage but adding a measuring glass of water and a bridge to keep the weight of water of the scale yields: $m_{water} = 21.2126\ g$.



a) b)

Figure 4-30 Archimedes density test a) mass in air, b) mass in water

4.5.4 NDT-Testing of Part According to AMC-2

The NDT-Testing such as volumetric and surface were done by Quality group Stavanger and reports are given in the appendix (links are given in the sub-chapters). Tests such as penetrant testing to unveil surface scratches were done, and x-ray to check the volumetric of the AM'ed part was outsourced to Quality NDT Stavanger.

Dimensional Check

The dimensional check was done with a coordinate measurement machine (CMM) (a) to verify the wedge seal face flatness, and face angle. All other dimensions were checked with a digital caliper (b), and radii's were checked with a radius gauge (c). Also, the surface roughness was checked using the same method as in 4.2.2.

(a)

(b)

(c)

Figure 4-31 Measurement devices a) CMM, b) Digital caliper 0.01-15.00mm , c) Radius gauge 1-7mm

Surface and Volumetric NDT

For the surface and volumetric NDT Quality Group Stavanger has performed these tests. The test reports are given in APPENDIX D - 23 Surface NDT - Penetrant testing report from Quality NDT Stavanger and APPENDIX D - 22 Volumetric NDT - Computed Radiography report from Quality NDT Stavanger.

5 Results and Discussion

5.1 LCA and Principles of the Circular Economy - Results and Discussion

5.1.1 Framework of LCA

Environmental Impact Comparison: CNC and AM

Full LCA analysis reports are given in APPENDIX C 4 LCA SM report and APPENDIX C 5 LCA AM report.

First the SM part LCA results are given in Table 5-1 below.

Table 5-1 SM part LCA results

SM-Part	CO2 Emissions	Land use	Fossil depletion	Minerals and metal depletion	Water use	Freshwater Ecotoxicity	Freshwater eutrophication	Acidification	Marine eutrophication
Result	1.2088	8.4041	14.73	6.67e-6	0.798	42.2	5.42e-4	0.0049	0.0013
Unit	kg CO2	Points	MJ	kg Sb	m3 world deprived	CTUe	kg PO4	Mol H+	Kg N

This yields a total environmental footprint of **1.30e-4 points**.

The AM part LCA results are given in Table 5-2 below.

Table 5-2 AM part LCA results

AM-Part	CO2 Emissions	Land use	Fossil depletion	Minerals and metal depletion	Water use	Freshwater Ecotoxicity	Freshwater eutrophication	Acidification	Marine eutrophication
Result	29.45	85.92	347.22	7.01e-4	14.99	1094.88	0.015	0.1847	0.0304
Unit	kg CO2	Points	MJ	kg Sb	m3 world deprived	CTUe	kg PO4	Mol H+	Kg N

This yields a total environmental footprint of **0.0038 points**

The EF 3.0 method yields information that the total environmental footprint between SM and AM differs with **~0.0037 points**.

To sum up some of the data from the above tables:

The AM process has a higher CO2 emission compared to SM indicating that AM utilizes intensive amounts of energy. AM process also has a superior amount of land use points suggesting larger resource extraction and manufacturing footprint than for SM. Fossil depletion indicates higher energy consumption for AM. Minerals and metals depletion suggest that AM has a more rigorous material usage. The AM process shows noteworthy environmental hotspots as mentioned, these hotspots or processes contribute most to the overall EF point system and have the best chances for targeted improvements.

The comparative results shown in Figure 5-1 below are generated using the LCA software. This shows the outer boundaries to be the most environmental (SM) whilst the green center (AM) shows the environmental footprint of the AM part. It is important to mention that the ecoinvent database did not have a PBF-LB process available to use in the analysis and therefore the best available option was chosen which was laser machining (YAG laser). Although the analysis still says AM there are some errors in the data regarding the process of manufacturing in the analysis.

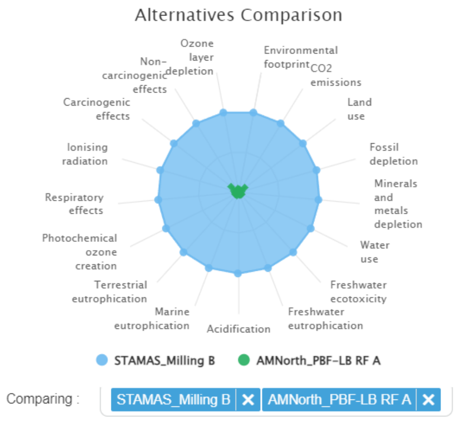


Figure 5-1 Comparison chart for LCA between AM and SM

Life Cycle Cost (LCC)

According to Outokumpu Stainless AB, 2013 the cost of stainless steel is higher than for carbon based steel, but this does not mean that cost during the product life cycle is higher for the stainless steel. The investment of production is one cost, but the total operating and maintenance costs, and scrap/ recycle costs gives the total LCC. Therefore, it is viable to interpret the higher investment costs of using 316L gives the lowest total cost.

Improvement of Sensitivity and Error of Data (Monte Carlo Sensitivity Analysis)

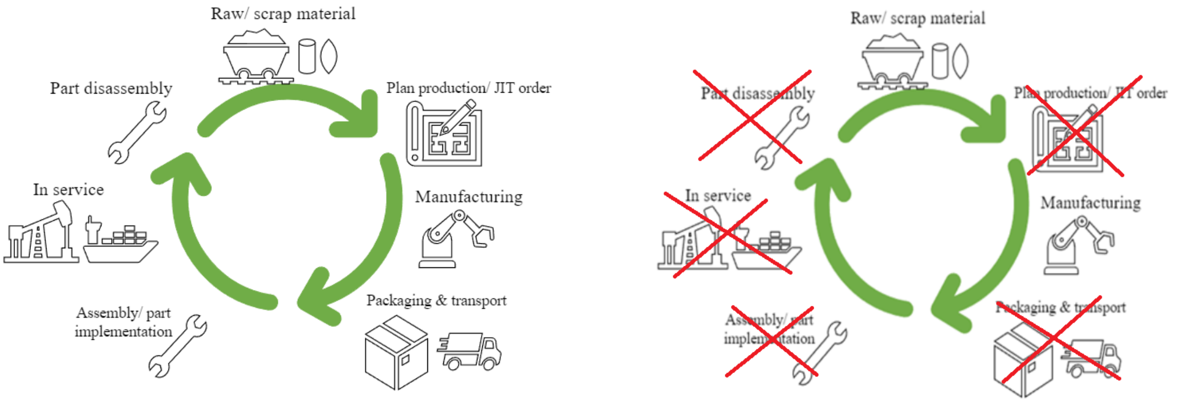
Implementation for Monte Carlo sensitivity and error analysis can be used to narrow down the parameters from the data collection. By normalizing the dataset from a widespread distribution to a normal distribution the max value for the different impact categories will be more precise than for the widespread data. This method will not be used but is shown for educational purposes.

Interpretation of the Analysis

The software gave a holistic view of the analysis and an overview of the total environmental footprint of both manufacturing methods. The analysis indicated that the total environmental footprint difference was 0.0037 points with AM being on the higher end of the scale – meaning that the SM process is environmentally preferable to the AM process in comparison of the categories. However, some of the trade-offs need to be determined to get the full view on choosing the manufacturing method, to mention potential material and time savings, and complex geometry production that AM offers are some of the trade-offs. These trade-offs are not fully captured in the impact categories which were analyzed. Also, the LCA research does not include comprehensive data collection, or any robust sensitivity or error analyses, or consider all life cycle steps. The best practice would be to incorporate these elements to give a full holistic LCA analysis.

5.1.2 *Circular Economy Principles*

Circular economy analysis is done at a micro-level, this means that circularity is assessed within a company. Some macro-level assessments will be drawn to conform with circularity questions regarding local waste management. Therefore, the boundaries are kept within production and material management for each of the methods. In Figure 5-2 below the circularity in a manufacturing system application for both a comprehensive study, and a basic CE material management analysis is shown.



a) b)

Figure 5-2 Applied Circularity illustration a) Comprehensive CE analysis, b) CE analysis in this study

In recent years manufacturers have conformed to invest in environmentally conscious technologies to produce carbon neutral machines and products.

Assessment of CE Principles in Subtractive Manufacturing

In subtractive manufacturing (or more generally CNC) circularity is a big part of this type of process, by being supported by sustainable manufacturing practices that reduce waste and encourage reusing of materials and cutting fluids. Files are sent digitally, most of the work is done digitally, and the machine only requires electricity to operate meaning that the production has full green operational potential. Also, the cutting fluids can be bought as environmentally friendly, and implementation of Lean manufacturing to cut waste and use just-in-time manufacturing to utilize resources at every step of the process. Furthermore, the use of energy efficient machines and recyclable materials to conform to sustainable production. The best way to aid circularity is to use fewer resources by using recyclable materials.

Assessment of CE Principles in Additive Manufacturing

In metal additive manufacturing circularity principles are embedded in this technology by reduction of material waste by manufacture only the required amount of material needed. And, conforming to driving resource and efficiency conservation. The most significant advantage is the optimization possibilities connected to part design. This precision aids in waste management of materials and the excess powder not used can be reused in a subsequent process. Furthermore, circularity within AM can aid in substantial environmental and economic benefits. Furthermore, life cycle extension of old parts by using AM technology to repair old, worn, or damaged parts can be restored using AM technology.

5.2 BPQ/ AMC 2 Qualification – Results and Discussion

All test reports are given in AM DOCUMENTATION. The visual inspection was done by AM North (ref. APPENDIX D - 6 ITP: AMN-03-03-0002). Furthermore, the BPQ test results give a basis for the material properties of the AM'ed part, the same way a material certificate for SM material is given such tests are done as well. Furthermore, the part NDT is done to verify that the surface has no cracks, and the volumetric NDT is done to check for internal pores or other unwanted structures within the part.

5.2.1 Dimensional Check

All measurements were within tolerances. Table 5-3 below gives an overview of the measurements, and the numbering (x) can be interpreted through the drawing in the measurement report in APPENDIX D - 17 Measurement assessment report and APPENDIX D - 25 Surface Roughness Measurement. All dimensions of the part are within tolerance.

Table 5-3 Measurements of PBF-LB manufactured valve wedge.

Measurement:	**Methods:**	**Result:**
Seal surface	CMM & Surface roughness	(1) = *9.8° between planes (1) = *Flatness deviation = 0.012 and 0.060 (2) = 0.47µm OK!
Outer dimensions	Digital Caliper	(3) = 43.06 (4) = 30.05 (5) = 19.00 Fits in valve: OK!
Detail dimensions	Digital Caliper	(6) = 5.03 (7) = 7.98 (8) = 6.98 (9) = 11.98 (10) = 11.50
Radiis	Radius gauge	OK (Within tolerance)

*Source of error: Tried to get ahold of OEM of valve seal to validate tolerances of valve part but did not get reply. Therefore, the design of the new valve seal was done using scanning method and CMM validation of legacy part to get the tolerances of the new part as close as possible.

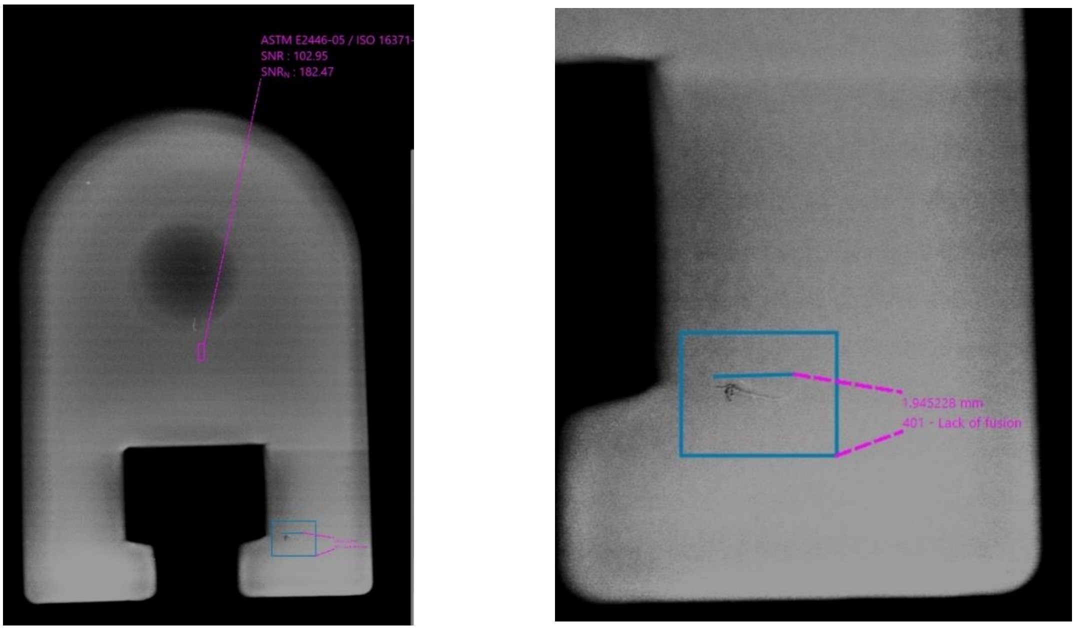
5.2.2 Volumetric Analysis and NDT (CR)

Using the Archimedes principle yielded:

$$\rho_{sample} = \left(\frac{24.2715}{24.2715-21.2159)}\right) \cdot 1 \ = \ 7.8098655 \ \mathrm{kg}/m^3 \ , \ \rho(\%) = \left(\frac{7.8098655}{7.85}\right) \cdot 100\% = 99.488\% \ dense$$

*This measurement includes the string in the total mass of part in water and air. This can cause some errors in the calculation.

The volumetric NDT gave results on some print defects shown in Figure 5-3 below. The overall report (given in APPENDIX D - 22 Volumetric NDT - Computed Radiography report from Quality NDT Stavanger) for the volumetric NDT indicates that the part is rejected due to lack of fusion shown in Figure 5-3 b).



a) b)

Figure 5-3 Computed radiographic inspection (Volumetric NDT) images a) overall look of part, b) lack of fusion detected in the printed part

5.2.3 Surface NDT (PT)

Done at Quality lab Stavanger. Report given in APPENDIX D - 23 Surface NDT - Penetrant testing report from Quality NDT Stavanger.

The surface was accepted after inspection.

5.2.4 Impact Testing (Charpy)

The impact test indicated that the mean value was 113.36J. This value is much lower than for the reported impact test done in the material certificate given by Sandvik for the material used in the SM. The average value for the SM material was 283-289J (for two different Lot numbers). The oxidation discovered in the microstructural assessment can have an impact on the result of the impact test done on the AM'ed specimen (Morozova *et al.*, 2023). The impact test report is given in APPENDIX D - 21 Charpy impact testing report from Quality Lab Stavanger.

5.2.5 *Tensile Testing*

In the tensile testing the DNV-ST-B203 standard has interest in the following parameters given in Table 5-4 below. The total result is given in the report from Quality lab Stavanger. The report from Quality Lab Stavanger is given in APPENDIX D - 24 Tensile test report of specimen no.2 from Quality Lab Stavanger.

Table 5-4 Tensile test results (only highlighted results in interest from the DNV-ST-B203 standard)

Parameter	**Yield Strength**	**UTS**	**Elongation**	**Reduction of area**
Result	464.252 MPa	590.000 MPa	42.983%	60.469%

The elongation has been reported to increase and strength decrease if heat treatment were to be done (Morozova *et al.*, 2023)

5.2.6 *Hardness Testing*

The Vickers hardness test yielded the results given in Table 5-5 below. The test and assessment report are given in APPENDIX D - 19 Hardnes test report and APPENDIX D - 20 Hardness test report from INNOVATEST FALCON 5001 tester .All the Vickers measurements were within range according to the ISO 6507-1 standard.

Table 5-5 Vickers hardness test results

Indentation number:	**Result:**
1	222.50 HV10
2	220.61 HV10
3	219.84 HV10
4	222.10 HV10
5	220.90 HV10
6	222.09 HV10
7	221.73 HV10
8	215.41 HV10
9	222.11 HV10
10	222.12 HV10
Mean:	220.94 HV10 with SD=2.01

5.2.7 Macrostructural Analysis

Done at UiS. Report given in APPENDIX D - 15 Macrostructural assessment report.

The macrostructural assessment criteria from the DNV-ST-B203 standard stated that the cross section viewed must show visible fusion lines and weld pools, this was achieved using the light microscope and shown in the macrostructural report. A picture of the macrostructural mapping and visible fusion lines and weld pools are given in Figure 4-25 b).

5.2.8 Microstructural Analysis

Done at UiS laboratory. Report given in APPENDIX D - 14 Microstructural assessment report.

Assessment of the microstructures gave no clear indication on the material property initially, but on closer inspection it can be located indicators of oxides traces in the specimen (given by several small black indicators in the specimen on 1kx magnification shown in Figure 5-4 below). The oxides could be a plausible problem regarding low energy absorption in the Charpy impact testing (Morozova *et al.*, 2023).

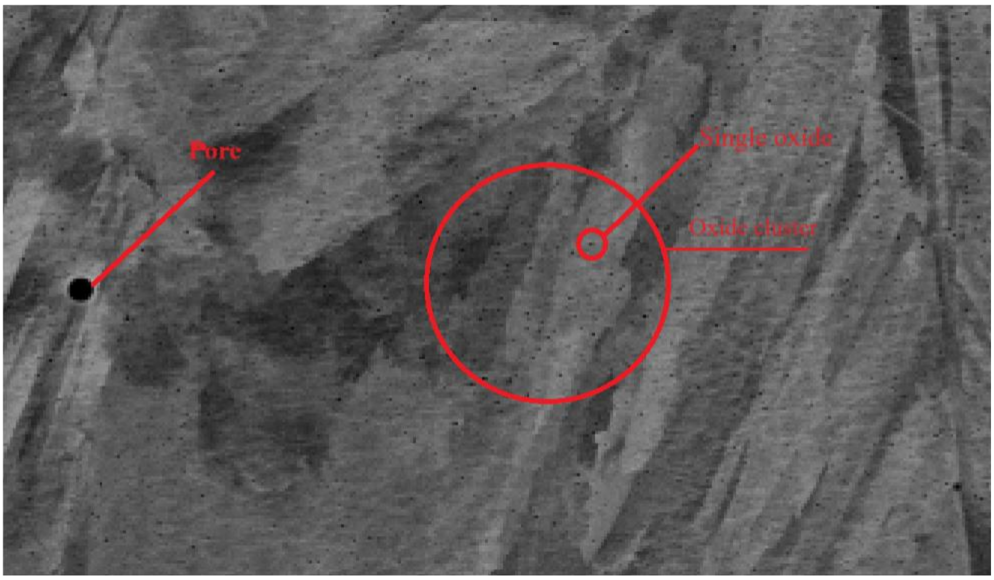
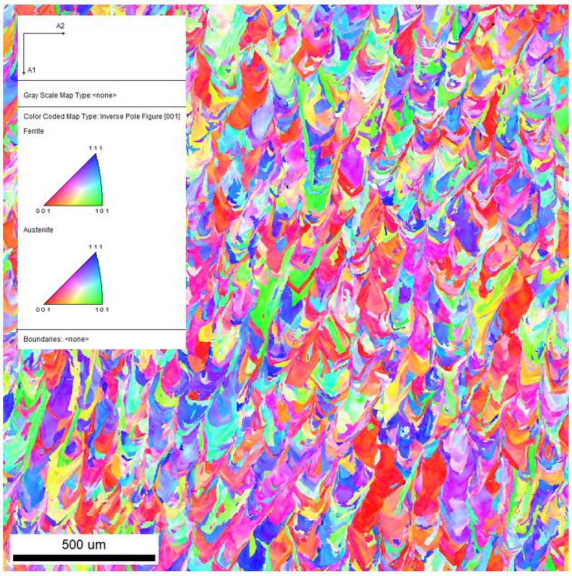
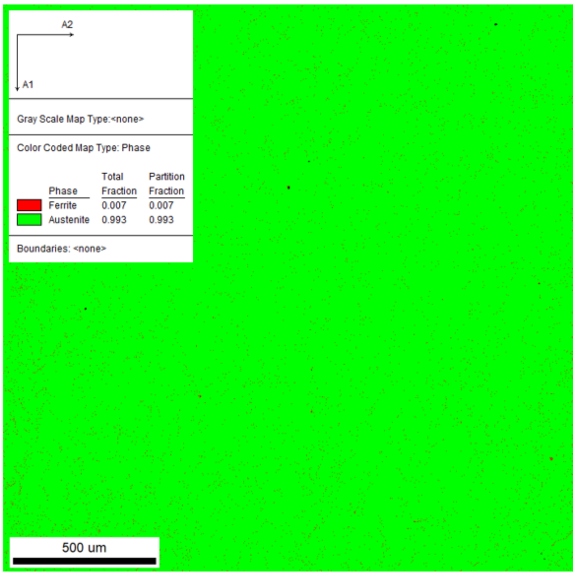


Figure 5-4 Oxide indicators in the 1kx magnification microstructural assessment

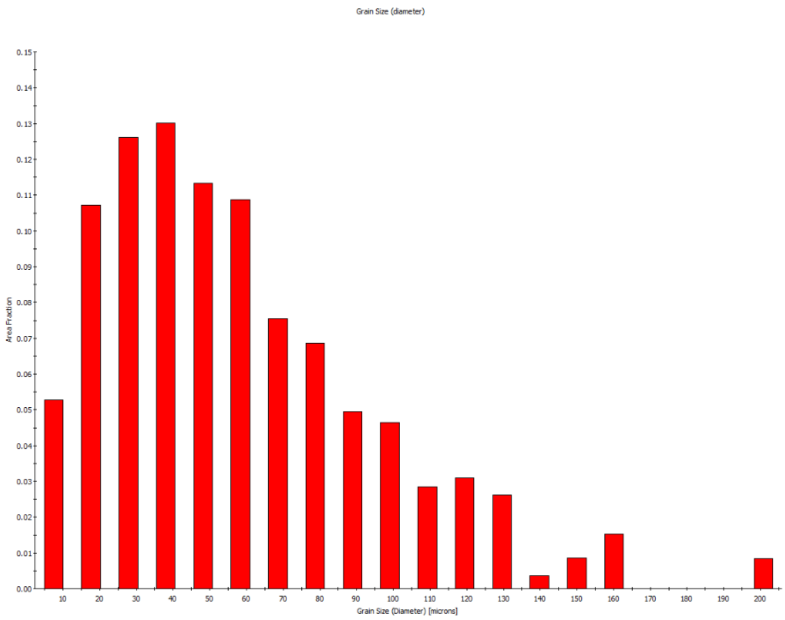
Furthermore, EBSD was used to determine the Austenite count in the specimen, and furthermore the grain size. The figures given below are both given in 45x magnification. The inverse pole figure (IPF) given in Figure 5-5 a) below shows the grains and orientation in the legend. The phase map given in Figure 5-5 b) shows the phase in the specimen and yields a total austenitic count of 99.3% given by the green colorization where the last 0.7% is ferrite or badly indexed patterns given by the red colorization. Followed by the grain size given in Figure 5-5 c) which is calculated to be 13,84μm average. In APPENDIX F - 14 Phase map in 500x magnification (99.8% Austenite, 0.2% other phase) and APPENDIX F - 15 IPF in 500x magnification the 500x magnification EBSD are given.



a)



b)



c)

Figure 5-5 Microstructural Assessment using EBSD a) IPF, b) Phase map, c) Grain size

5.2.9 Comparative Discussion on SM vs AM

In comparison to the material certificate of SM vs the BPQ test results there are some big differences in material quality given by Table 5-6 below. As mentioned earlier in the result and discussion of the BPQ test results; heat treatment of the material would have an impact on the different mechanical properties of the AM'ed material.

Table 5-6 Comparison table between SM material properties vs AM BPQ test results

	SM Material Certificate	**AM BPQ test results**
UTS (MPa)	554-557	590
Yield (MPa)	224-226	464
Elongation (%)	60	43
Red. of Area (%)	77-78	60
Hardness	Min. 126-133 HB /Max. 131-135 HB	221 HV10
Grain size (μ)	5 to 7	14
Impact (J)	283 - 289 Average	113

*The SM material certificate carries two different lot numbers, therefore there is an interval for the test results for the SM certificate.

6 Conclusion

By implementing LCA in a CNC+AM structure the manufacturer can make greener and more informed decisions to minimize emissions and impact about the manufacturing process, while further promote sustainability, produce eco-friendly products, and meet the growing demands for a greener manufacturing practice.

In the given data from the software, it became clear that the greenest production method is SM, although AM has a higher environmental impact than SM does not necessarily mean that it is not worthwhile working with this technology. However, the importance of doing thorough research and evaluation of time and aspects is important to consider when choosing the production method and can therefore be sufficient to not consider the production method on the environmental impact assessment alone. AM has a big potential towards complex design manufacturing and is therefore more versatile in comparison to the conventional methods. It was earlier in the result section mentioned about the trade-offs for manufacturing with AM instead or together with SM on the question of green production. The trade-offs can also include the time and price savings on utilizing the AM method.

In discussion with the different manufacturers the quantity produced has a large influence on price and the scoring system in the LCA and in larger quantities. After getting a quotation from AM North where it was asked on quantities 1-5-10-20-50pcs the price range was approximately 4 500 NOK for one wedge, 1 500 NOK pr wedge if five wedges were bought, 1 100 NOK pr wedge if ten wedges were bought, 900 NOK pr wedge if twenty wedges were bought, and 800 NOK pr wedge if fifty wedges were bought. The reasoning for the money decline for bigger quantities purchased is due to filling the build volume of the machine to manufacture parts is cheaper rather than printing only one part in the total build volume. Adding one part will not double the manufacturing time due to the speed of the laser. Whilst for the SM'ed part the time to make one part is the same for the next, having a serial production where the same part will be manufactured over a longer period will be cheaper, but for a JIT part it will be more expensive. Also, the initial production of one part will include the programming process whilst for the second piece the programming process will be excluded in the time estimates and the price for piece nr 2 and so forth will be lower an equal. Furthermore, ordering a serial production where it is guaranteed machine time for the manufacturer a lower price could be offered.

Regarding a clear statement on which manufacturer method works best. In this case the SM method is the best working method due to material testing requirements which only applies to the material certificate delivered with the 316L bar material given to Stamas. Whilst for the AM method the SBQ and BPQ of the material was produced with the wedge yielding little to no knowledge about the ordered parts until after production. It should be mentioned that normally a BPQ is produced before manufacturing of AMC level parts are initiated, but for this thesis the BPQ and documentation was done parallel due to time limitation. The DNV-ST-B203 standard has an extensive procedure on the qualification requirements that are within the AMC levels. After doing all the required tests it came clear that the AM'ed material lacks some mechanical properties in comparison to the SM material properties. However, the material testing in the BPQ is to supplement as a material certification for the AM part and is documented to give the customer an overview of the mechanical properties of the given part.

6.1 Future Research Suggestions

In-depth research into the LCA software and utilize it fully, and have a more in-depth analysis, and further use Monte Carlo principles for sensitivity and error analysis.

Use the digital twin in 3DS to alter the design of the valve wedge to create a material efficient design and use LCA to compare differences.

Look at the printability of the whole valve system and try to execute manufacturing of the valve with less parts, and check LCA and CE principles.

Heat treatment of 316L and check microstructures in heat treated vs as printed.

If it were not a time limitation, in-depth research on the material properties would have been done including TEM research to further investigate martensitic properties and the oxide inclusions found in the 1kx magnification images.

Check the remainder of the wedges printed in computed radiography about the lack of fusion defect detected in the printed part.

References

‘1984_Surf_Roughness_PG.pdf’ (no date). Available at: https://www.mitutoyo.com/webfoo/wp-content/uploads/1984_Surf_Roughness_PG.pdf (Accessed: 11 May 2024).

Alexander, A., Pascucci, S. and Charnley, F. (eds) (2023) *Handbook of the circular economy: transitions and transformation*. Berlin ; Boston: De Gruyter.

Bekker, A.C.M. and Verlinden, J.C. (2018) ‘Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel’, *Journal of Cleaner Production*, 177, pp. 438–447. Available at: https://doi.org/10.1016/j.jclepro.2017.12.148.

Cadence PCB Solutions (2020) ‘The Use of the Monte Carlo Method in Sensitivity Analysis and Its Advantages’. Available at: https://resources.pcb.cadence.com/blog/2020-the-use-of-the-monte-carlo-method-in-sensitivity-analysis-and-its-advantages.

Caliper | accuracy, precision, range | Britannica (n.d). Available at: https://www.britannica.com/technology/caliper-measurement-instrument (Accessed: 3 June 2024).

Callister, W.D. and Rethwisch, D.G. (2020) *Materials science and engineering: an introduction: SI Version*. 10th edition, global edition. Hoboken, NJ: Wiley.

Chris Knight (2023) *What is the linear economy?*, *European Investment Bank*. Available at: https://www.eib.org/en/stories/linear-economy-recycling (Accessed: 5 February 2024).

Circular economy: Technology - Economy - Environment (2023) *SINTEF*. Available at: https://www.sintef.no/en/sintef-research-areas/circular-economy/ (Accessed: 1 February 2024).

Coordinate Measuring Machine (n.d). Available at: https://www.zeiss.com/metrology/products/systems/cmm.html (Accessed: 3 June 2024).

Det Norske Veritas AS (2022) *DNV-ST-B203: Additive manufacturing of metallic parts*.

Drohomeretski, E. *et al.* (2014) ‘Lean, Six Sigma and Lean Six Sigma: an analysis based on operations strategy’, *International Journal of Production Research*, 52(3), pp. 804–824. Available at: https://doi.org/10.1080/00207543.2013.842015.

Electron microscope | Uses, Advantages & Limitations | Britannica (2024). Available at: https://www.britannica.com/technology/electron-microscope (Accessed: 3 June 2024).

Gauge | Types, Uses & Measurement | Britannica (n.d). Available at: https://www.britannica.com/technology/gauge-instrument (Accessed: 3 June 2024).

Gibson, I. *et al.* (2010) *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York, NY: Springer.

Grashei, C.R.J. (2023) *Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM*. Methodology report. Stavanger: University of Stavanger.

Guinée, J.B. *et al.* (2011) ‘Life Cycle Assessment: Past, Present, and Future’, *Environmental Science & Technology*, 45(1), pp. 90–96. Available at: https://doi.org/10.1021/es101316v.

International Organization for Standardization (1993) *NS-EN 22768-1:1993: General tolerances — Part 1: Tolerances for linear and angular dimensions without individual tolerance indications (ISO 2768-1:1989).*

International Organization for Standardization (2006a) *ISO 14040:2006: Environmental management, Life cycle assessment, Principles and framework*.

International Organization for Standardization (2006b) *ISO 14044:2006: Environmental management, Life cycle assessment, Requirements and guidelines*.

International Organization for Standardization (2011) *NS-EN ISO 8015:2011: Geometrical product specifications (GPS) — Fundamentals — Concepts, principles and rules*.

International Organization for Standardization (2020) *NS-EN ISO 128-1:2020: Technical product documentation (TPD) - General principles of representation*.

International Organization for Standardization (2021) *ISO 21920-1:2021: Geometrical product specifications (GPS) — Surface texture: Profile — Part 1: Indication of surface texture*.

International Organization for Standardization (2022a) *ISO 21920-2:2021: Geometrical product specifications (GPS) — Surface texture: Profile — Part 2: Terms, definitions and surface texture parameters*.

International Organization for Standardization (2022b) *ISO 21920-3:2021: Geometrical product specifications (GPS) — Surface texture: Profile — Part 3: Specification operators*.

International Organization for Standardization and Final Draft International Standard (2023a) *ISO/FDIS 59004 - Circular economy - Vocabulary, principles and guidance for implementation*.

International Organization for Standardization and Final Draft International Standard (2023b) *ISO/FDIS 59020 - Circular economy - Measuring and assessing circularity performance*.

Kjell Gunnar Hoff and Morten Helbæk (2021) *Bedriftens Økonomi*. 9th edn. Oslo: Universitetsforlaget AS.

Klöpffer, W. and Grahl, B. (2014) *Life Cycle Assessment (LCA): a guide to best practice*. Weinheim: Wiley-VCHVerlag GmbH & Co. KGaA.

Life Cycle Assessment: Do more than measure your environmental impact (2021) *Dassault Systèmes*. Available at: https://www.3ds.com/sustainability/life-cycle-assessment (Accessed: 22 February 2024).

Luc Hillege (2024) 'Impact Categories (LCA) - Overview', *Ecochain*. Available at: https://ecochain.com/blog/impact-categories-lca/ (Accessed: 23 January 2024).

Manufacturing's next act | McKinsey (n.d). Available at: https://www.mckinsey.com/capabilities/operations/our-insights/manufacturings-next-act (Accessed: 3 April 2024).

Mikell P. Groover (2010) *Fundamentals of Modern Manufacturing*. Lehigh University: John Wiley & Sons, Inc.

Mission & History (n.d) *ecoinvent*. Available at: https://ecoinvent.org/mission-history/ (Accessed: 20 March 2024).

Morozova, I. *et al.* (2023) 'On the Heat Treatment of Selective-Laser-Melted 316L', *Journal of Materials Engineering and Performance*, 32(10), pp. 4295–4305. Available at: https://doi.org/10.1007/s11665-022-07404-0.

NDT tjenester (n.d). Available at: https://www.qgroup.no/ndt-tjenester (Accessed: 3 June 2024).

Our 3D printing metal powder portfolio | Höganäs (n.d). Available at: https://www.hoganas.com/en/powder-technologies/additive-manufacturing-metal-powders/3d-printing-metal-powders/?gad_source=1&gclid=Cj0KCQjw6uWyBhD1ARIsAIMcADrvmkAR_7EENERW6QHIQDD_gKDddJ9wG0ZyVbeqGeD-Mpa75RkJea0aAmZLEALw_wcB (Accessed: 31 May 2024).

Outokumpu Stainless AB (2013) *Handbook of Stainless Steel*. Outokumpu Oyj.

Saade, M.R.M., Yahia, A. and Amor, B. (2020) ‘How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies’, *Journal of Cleaner Production*, 244, p. 118803. Available at: https://doi.org/10.1016/j.jclepro.2019.118803.

Saba, N., Jawaid, M. and Sultan, M.T.H. (2019) ‘An overview of mechanical and physical testing of composite materials’, in *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*. Elsevier, pp. 1–12. Available at: https://doi.org/10.1016/B978-0-08-102292-4.00001-1.

Sala, S. *et al.* (2022) ‘Toxicity impacts in the environmental footprint method: calculation principles’, *The International Journal of Life Cycle Assessment*, 27(4), pp. 587–602. Available at: https://doi.org/10.1007/s11367-022-02033-0.

Sandmeyer Steel Company (2014) ‘Specification Sheet: Alloy 316/316L (UNS S31600, S31603) W. Nr. 1.4401, 1.4404’.

Sayyar, N. *et al.* (2023) ‘Directed laser deposition of super duplex stainless steel: Microstructure, texture evolution, and mechanical properties’, *Heliyon*, 9(4), p. e15144. Available at: https://doi.org/10.1016/j.heliyon.2023.e15144.

Spherica Blog (2023) ‘Monte-Carlo Simulation, Uncertainty Analysis, and Sensitivity Analysis in Life Cycle Assessment’, January. Available at: https://dei.so/monte-carlo-simulation-uncertainty-analysis-and-sensitivity-analysis-in-life-cycle-assessment/.

Stainless steel 3D printing powders | Höganäs (n.d). Available at: https://www.hoganas.com/en/powder-technologies/additive-manufacturing-metal-powders/3d-printing-metal-powders/stainless-steel-3d-printing-metal-powders/ (Accessed: 31 May 2024).

Stensberg, T.-R. (n.d) *6 tips for å lykkes med digital transformasjon*. Available at: https://blogg.triple-s.no/6-tips-for-å-lykkes-med-digital-transformasjon (Accessed: 3 April 2024).

Stieberova, B. *et al.* (2022) ‘Life Cycle Assessment of Metal Products Produced by Additive Manufacturing: A Metal Mold Case Study’, *ACS Sustainable Chemistry & Engineering*, 10(16), pp. 5163–5174. Available at: https://doi.org/10.1021/acssuschemeng.1c08445.

Systèmes, D. (2022) *Learn more about the 3DEXPERIENCE Cloud platform*, *Dassault Systèmes*. Available at: https://discover.3ds.com/learn-more-about-the-3dexperience-cloud-platform (Accessed: 25 January 2024).

Tensile Testing Machines | An Introduction (n.d). Available at: https://www.instron.com/en/resources/test-types/tensile-test (Accessed: 14 May 2024).

‘Tolerances in CNC Machining’ (2019) *Xometry Europe*, 19 June. Available at: https://xometry.eu/en/tolerances-in-cnc-machining/ (Accessed: 30 January 2024).

Vacuum induction melting Inert Gas Atomization (VIGA) | Additive manufacturing | Höganäs (n.d). Available at: https://www.hoganas.com/en/powder-technologies/additive-manufacturing-metal-powders/vacuum-induction-melting-inert-gas-atomization-viga/ (Accessed: 31 May 2024).

‘Vickers Hardness Testing’ (n.d) *Hardness Tester*. Available at: https://www.hardnessgauge.com/testing-types/vickers-hardness-testing/ (Accessed: 15 May 2024).

Wei, W. *et al.* (2015) ‘How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model’, *Environmental Science & Technology*, 49(1), pp. 377–385. Available at: https://doi.org/10.1021/es502128k.

What is LCA? – LCA.no (n.d). Available at: https://lca.no/en/what-is-lca/ (Accessed: 23 January 2024).

What is Six Sigma? Everything You Need to Know in 2024 | Simplilearn (2019) *Simplilearn.com*. Available at: https://www.simplilearn.com/what-is-six-sigma-a-complete-overview-article (Accessed: 3 June 2024).

Zeid Ibrahim (2005) *Mastering CAD/CAM*. Boston: McGraw-Hill Higher Education.

APPENDIX A - METHODOLOGY REPORT REVERSE ENGINEERING

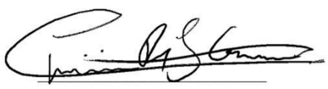
Here the summer project report at Vår Energi leading up to the thesis is presented, the appendix is removed due to irrelevance. If you want a copy of the full report please message me on LinkedIn.

Methodology Study:

Reverse engineering and validation of scan vs. actual part with CMM

Summer Intern R&D - Christian René Jakobsen Grashei

Specialization: *Research & Development*



Christian René Jakobsen Grashei

Pages: 41 + ~~57 appendix~~

APPENDIX A 1 Methodology Study: Reverse engineering and validation of scan vs. actual part with CMM

Intentionally left blank.

Foreword

The work done for this report is a part of my task for Vår Energi's summer internship program and more generally for the ''Additive manufacturing pilot and scrap'' project. The task was to research feasibilities within reuse of material, and how to implement them to digital warehouse. Therefore, the first study within this subject is how to reverse engineer legacy parts (obsolete parts or parts without documentation). This includes scanning, meshing, and re-modelling the part chosen.

This report is to give the reader basic knowledge within reverse engineering. The steps needed to take, and an overall guide to understand the process.

Further, this report is to be used towards my bachelor's degree where the work with qualifications and further research of scrap recycling for AM powder will continue.

I want to express my sincere gratitude towards Trine Boyer who took a chance on me and gave me the opportunity to work within R&D as a summer intern at Vår Energi AS and for using her connections and network to help me and introducing me to wonderful people.

I want to thank Moreld Flux w/ Rolf Lohne and Oddvar Lindanger for supplying with valves, tours at storage and workshop facilities and for always answering my peculiar questions regarding valves.

I want to thank Pål Svanes at Stamas for cooperation and wisdom shared regarding AM and conventional manufacturing methods. Further, for his input regarding sustainability of conventional production methods vs AM.

I want to thank UiS AM laboratory w/ Andras Skaare, and Jan-Tore Jakobsen for help and letting me use equipment, and materials for this study. Also, for wisdom and always answering any questions regarding AM and reverse engineering.

I want to thank Prof. RM Chandima Ratnayake for participating in future endeavours regarding this interesting topic and for answering my questions whatever they may be.

Lastly – working at Vår Energi with the best co-workers and co-interns has been a blast. The variety of different expertise at the office has been motivational for me to learn more about different subjects.

For all lunches, coffee breaks, excursions, and conversations I thank you all!

Abstract

Additive manufacturing (AM) lessens time spent waiting for new part, as well as getting on demand access within reasonable time, therefore it is important to research possibilities implementing additive manufacturing of recycled parts and adding parts to digital inventory. This study will focus on understanding scanned part versus actual part for implementation to digital warehouse and confirmation about reverse engineering as a tool for legacy part re-production. Implementing AM together with conventional manufacturing will reduce waste and be excellent regarding circular economy for scrap-to-powder and end-to-end manufacturing.

Literature study gave feedback within degradation of powder after recycling multiple times. Degradation takes place but in a slow manner. This means that powder can be reused several times without noticeable mechanical or chemical behaviour in the AM'ed parts.

Stamas provided information regarding cost of conventional production – in this case CNC manufacturing. This also included reverse engineering step done with conventional measurement equipment. Cost of one part is estimated to around 25 000 NOK for just-in-time production. This means rapid production – end to end manufacturing.

Valve part is scanned, meshed, and then implemented to CAD software, after this it will be sliced and printed for prototyping and hand-outs purposes. After the process of manufacturing, it will be conducted measurements with CMM to check deviations between scanned part and actual part. Here it will be checked flatness of seal surfaces as this is the surface easiest to check – and the most important.

Results gave answers whether there actually is big deviations or not. For this study results yielded max 0.02 mm deviation on the planes, and 0.3º deviation on angle between the plane (with nominal angle of 5º) or more precisely 9.691º with the nominal plane set to 5º.

Keywords: Valves, additive manufacturing, atomization, powder bed fusion, AM methods, reverse engineering, recycling materials.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Scrap metal and faulty process equipment are a big part of the oil and gas (O&G) industry, and most of the time the material used to manufacture, or produce this type of equipment is expensive, thus the parts are also expensive. By implementing AM technologies there is a lot of possibilities about reducing cost, such as:

- Looking into possibilities to reduce the number of parts i.e., combining several parts if possible.
- Use scrap metal to produce feedstock powder for AM.
- Relieve companies from 3rd party suppliers, and be self-sufficient about spare parts, and storage (digital inventory).

Being able to have an on-demand supply chain of spare parts enables large scale operators to be productive and efficient. In present years replacing parts consists of ordering from a vendor that may or may not have the part in storage and need to be transported offshore – this process can be extensive with a lead time much longer then with AM technology. There are also a lot of storage space belonging to the large operators within oil and gas, keeping spare parts back ordered from a century ago, as well as old scrap kept for research.

Hence it is important to study this topic and look at what parts are printable, which parts are most exposed to failure - and therefore the most interesting to study and get in the digital inventory ecosystem.

Furthermore, reverse engineering is also an important topic about the future of AM technology because of legacy parts that are no longer in stock, or missing drawings. On the Norwegian Continental Shelf (NCS) many of the oil rigs are from the 70s, 80s and 90s and some documentation of manufacturing, design, and material of specific components may be missing, and therefore reverse engineering can be a helpful tool on achieving the design at least. Reproducing legacy parts without specifications gives some advantages about design, and material – for the design aspects there are a lot of possibilities for topological optimization. For the material selection – material selected can be chosen in regards of sustainability, placement, and strength.

It is also important not to neglect the breakeven point both about cost and sustainability.

1.2 Problem formulation

Can there be a digital inventory with on demand production in the future? Is it possible to achieve a sustainable supply chain using recycled feedstock? How to reproduce obsolete parts?

In the oil and gas companies there is a large variety of parts such as valves, pump, pipe fittings, and so on, these parts are underlying strict regime regarding service and maintenance, and in some cases replacing. Therefore, there are large storage spaces for these spare parts, and even more storage of scrap material such as valves, shavings, and pipe fittings in all kinds of material. These scrap materials are often kept in storage to mend, or for further research and are often neglected.

The research done in this report will be a feasible study to find if there is possible to print valve parts and how qualification process work, reverse engineer existing legacy part and hopefully in the future print on demand just-in-time parts when needed. But first and foremost; reverse engineering of legacy part in this research.

1.3 Limitations

Not having access to certain software used within this research at Vår Energi's office.

Lack of articles and research within this field.

1.4 Report structure

In chapter 2 it will be conducted a literature study, where the relevant literature will be listed and a brief description of the contents important for this study.

In chapter 3 there is given the theory needed to conclude the study, such as valve theory and additive manufacturing theory, and methods of design and testing.

In chapter 4 the experimental section gives an overview of data collection and work done.

In chapter 5 the findings/ results are given.

In chapter 6 the discussion and conclusion will give insight into possibilities, and further studies.

In the appendices section is presentations that belong to this research and all the documentation, and other material some used and some not used in the above chapters.

1.5 Goals

Analyse valve parts and find printability within selected valve. Use reverse engineering to produce printable part files and check geometry deviations between scan and real part in CMM.

1.5.1 Sub-goal

Use the findings from this study further in academic research/ theses.

Produce PowerPoint presentation for end of summer presentation.

2 Literature study

The objective for the study is to determine printability of valve parts with recycled material and do necessary research to understand processes related to this study. Further find research related to reverse engineering regarding legacy parts.

2.1 Valves

Valve theory gives the reader preliminary knowledge going further in the study. This information is important from a design perspective so that small adjustments made in the modelling phase are in accordance with standards and basic valve, and fluid theory. As well as distinguishing critical parts from non-critical parts.

2.1.1 Standards

The NORSOK standard for pipes and valves [1] gives the researcher understanding for abbreviations used within various valves, design criteria regarding importance of fluid mechanics and pressure class. This standard also introduces other important standards bridging between ASME, ASTM, and ISO standards.

2.1.2 Theory

Prosess-kjemi [2] and the valve technology handbook [3] yields knowledge necessary to understand basic valve technology, as well as fluid movement and pressure influence on the valve.

2.2 Additive manufacturing (AM)

Metal additive manufacturing is an up-and-coming technology that will help reduce CO2 emissions and help the green transition in the oil & gas sector.

2.2.1 Standards

The DNV GL standard for additive manufacturing of metallic parts [4] is the most important document when implementing AM technology for metallic parts.

The standard yields the selection process for what parts are printable or not by additive manufacturing category (AMC), this table tells the reader what kind of test that are needed for the qualification of use (but are also type specific by AM method (WAAM, LBPBF)), some information about the AMC's:

- AMC-1 are feasible for a valve hand wheel. Testing of AMC-1 parts according to manufacturer's procedure and only build process control.
- AMC-2 are feasible for parts that are needed for higher safety measures; hence production testing shall be performed and might be required with qualification process (mechanical testing, production testing and build process).
- AMC-3 are the highest category, and are feasible for parts such as valve housing, and pressurized entities, hence the testing - and qualification processes that shall be performed are more demanding than for AMC-1 and 2, this includes part qualification, production qualification and build qualification. Also, excess powder used in this category cannot be reused, once it has been through the printer machine, whilst for AMC-1 and 2 excess powders can be reused.

2.2.2 Articles

There has been conducted a lot of research in this field, but not all articles are coherent in regards of test results, therefore it is vital to list a table of relevant findings and compare these against each other and find the most similar group of results – this will be done in the following sub-chapter respectively.

2.2.3 Degradation of powder

To reduce waste and implement AM as a financially viable alternative to conventional methods, it is important to research longevity of powders. Articles shows great promise in multiple recycle – production cycles of AM powder with laser powder bed fusion method. Further, mechanical properties seem to increase under the upcycling process of an recycled powder in comparison to virgin powder [[5] [6] [7]] .

3 Theory

3.1 Some preliminary theory

This section is to give the reader some preliminary knowledge about later chapters.

3.1.1 G-codes

Geometric-code (G-code) is a programming language that uses coordinates as a basis to move in a generated 3D-space. The generated 3D-space is predetermined by the logic board in the respectable machine. G-codes have been mostly used within CNC-machining but are also the foundation for AM/ MAM's logic. This means that code generated for AM/ MAM gives the machine tasks, on whether to go left or right, up, or down, speed, extrusion, and when to do what. Example of g-code: G01 X100 Z1 Y0. This translates to:

G01 – Go in straight line.

X100 – 100mm in X-axis direction.

Z1 – 1mm in Z-axis direction.

Y0 – 0mm in Y-axis direction.

G-code does not always need a G in the start of any string to determine the basis of the task given. So, another start of a string could be M – the M is for machine control. For instance, within AM - M220 code translates to ''set feedrate percentage''.

3.1.2 Geometry

Geometry regarding vector-spaces in 3D-modelling is needed to define working area and features of the 3D-model. Planes are used to define working space within CAD, CAM and CMM measurement software, a plane is defined by three points on a surface and yields possibilities to work in XYZ-coordinates. Features of parts is the information about the part, given by edges, vertices, and faces – it is needed to give software recognition about certain features to create base alignment and understand the part geometry.

3.2 Additive manufacturing

Additive Manufacturing (AM) is simply the process of manufacturing layer by layer. The foundation for AM happened after a researcher (Dr. Hideo Kodama) from Nagoya Municipal Industrial Research institute filed the first patent application regarding AM, the method filed for was photopolymer material exposed to light to create prototypes. In 1986 Chuck Hull invented stereolithography (SLA), this is the process of hardening resin with help of patterned laser exposure. This method was known as the first rapid prototyping system. Following Chuck Hull's invention came Carl Deckard of the University of Texas with selective laser melting (SLM) method which is the process of fusing small particles of plastic, metal, or ceramics to create 3D parts. To conclude, in the 80's Scott Crump, who is the founder of Stratasys company, invented fused deposition modelling (FDM). This process is done by filament extrusion of melted plastic material that solidifies after extrusion and makes a 3D object [8].

Metal Additive Manufacturing (MAM) is the same process as regular AM, but with metal. One distinctive difference is that MAM material is powder-based, this means that either the filament is in powder form, or in a combination with other mediums to make spool type filaments. For now, there are only a few types of readily applicable powders to MAM technologies such as ferrous, titanium, aluminium, nickel and cobalt chromium alloys, the reason behind the small selection is that most materials are optimized for conventional manufacturing [9]. Hence material research and study are a highly active field to research more and enabling applicable material types.

The industries motivation to research MAM are several main factors, but three of them are [9]:

- On-demand low-cost rapid prototyping [9]

  Manufacture functional prototypes at a fraction of the cost of the conventional way. Accelerates the design cycle. Reduces lead time by about 50%.

- Easier manufacture complex geometric parts [9]

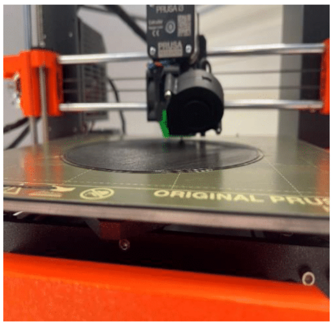
  Because of the unconventional way the MAM technologies work – production of intricate parts is possible. This also means that on an older part (legacy part) that is built up by several small parts can perhaps be manufactured in one part (also called parts consolidation).

- Topological optimization (requires finite element analysis (FEA) for critical parts)

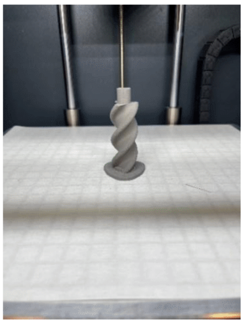
  Can manufacture in regards of emissions, and net weight (weight reduction). Giving a more both cost, and green efficient parts.

In more recent years AM/MAM has been mostly used in healthcare, automotive, and consumer goods. Technology has evolved a great deal in the last few years and is now increasingly implemented in the NCS. Especially with its ability to print recycled material the oil and gas sector can be highly beneficial regarding green change, and CO2 emissions goals. Also, to reduce storage spaces it can be highly beneficial to convert storage spaces to digital inventories and print on demand parts when needed. This can reduce waste regarding spare parts corroding in storage, and waste from manufacturing processes [9].

In Figure 1 is both AM and MAM shown, the AM method is done by Prusa MK3+ FDM with PLA. The MAM method is also done by Markforged Metal X FDM (Metal FFF) and in 17-4PH material.



a)



b)

Figure 1 a) AM, b) MAM

Qualification using MAM for manufacturers – for qualification of a new manufacturing process several aspects are important to qualify manufacturers. Which are: Facility, utilities (i.e., for pre – and post-processing), equipment (machines), personnel (getting qualified and up-schooled to understand the methods and procedures), end-to-end manufacturing (design to delivery), and control protocols and monitoring software. Further the qualifying for facility includes questions such as: Type of product, manufacturing method, range of applicable product sizes, applicable material types and grades, delivery conditions, reference to DNV material chemistry characteristics. Also, each material type for manufacturing, applications and AM equipment with OEM for the equipment, type of feedstock and feedstock manufacturer, max dimension, max section/ wall thickness, heat-treatment/ post-processing [10].

Metal powder atomization is the process of manufacturing powder, this process can be initiated with either ingots from raw material, or even scrap metal.

There are separate ways to achieve atomized powder, the most common methods are by gas or water both methods are shown in Figure 2. Depending on material property atomization process is chosen. Atomization by water is the cheapest of the two methods, yielding semi spherical powder particles and particle size of ~50µm-100µm [11]. Atomization by gas (air, nitrogen, argon, or helium) is much more expensive, but yields particle size of ~10µm-300µm [12]. The particle size is important for which method of AM is chosen, also the morphology of the particles is also important to achieve the best resolution of the print [13] Particle size and morphology is shown in Figure 3.

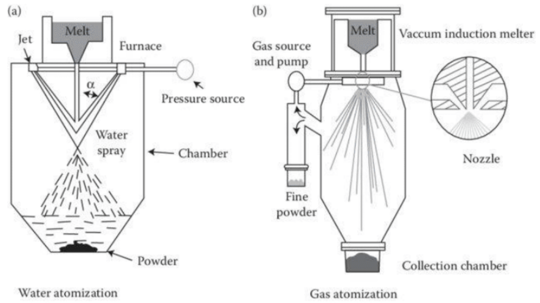
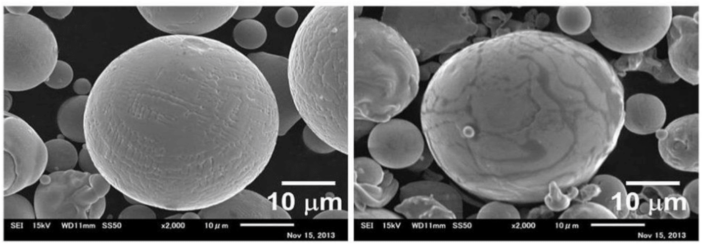
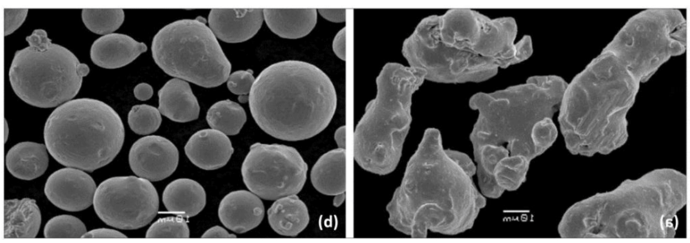


Figure 2 Atomization processes schematic [14]



a) b)



a) b)

Figure 3 Particle morphology - a) gas, b) water, pictures below are atomized 316L [15]

The reason for the irregular morphology in the water atomized particles is due to cooling rates being 10 to 100 times higher than for the gas atomized particles. For the gas atomized particles, the melting and atomizing happens in a protective atmosphere or in a vacuum yielding an environment that reduces oxidation, and nitrogen picks up in the particles [15] also known as vacuum inert gas atomization (VIGA).

Further, the gas atomization process can be used for more types of materials than qualified materials, this means that there will be ready-to-go feedstock whenever the respectable material is qualified.

Noticeable mention: Plasma atomization yields even better morphology than for the aforementioned.

Recycled AM material – is important for the future, but also research regarding quality of the powder. Using scarp materials such as old valves, steel shavings from production, or even already AM'ed parts. Advantages with using this type of powder are several, some which are future oriented:

- Minimizing mineral extraction from mining, and therefore minimizing global warming potential regarding metal production [16].
- Many companies can be self-sufficient when recycling scraps and can make their own powder or get a 3rd-party to atomize.
- Several recycling cycles yields better mechanical properties than for virgin atomized materials [7].

F3nice – is a company that specializes in the field of atomization of recycled material. The F3nice unique process is to directly atomize scrap metal and produce a sustainable feedstock for AM.

3.2.1 Methods

FDM – Fused Deposition Modelling

The most popular 3D-print method. Its main components are heated build platform, heated nozzle, and extruder shown in Figure 4. Either the build plate, or the extruder acts as the Z-axis (moves up and down). The principles of FDM printing are: Thermoplastic filament gets heated in the nozzle and gets pushed out the nozzle, and either the build plate or the extruder moves according to the G-code program. This method is most used for prototyping and making small figurines, but also functional products in exotic materials such as Onyx, Nylon, Ultem, PEEK and so on.

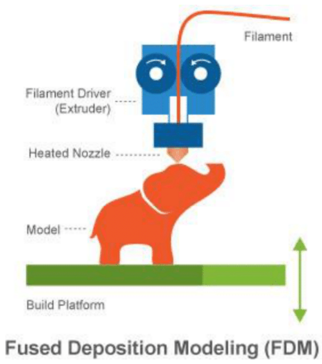


Figure 4 FDM Print method illustration [17].

SLA - Stereolithography

Its principles are submerging the printers build platform in the tank with resin, and selectively with a precision laser patterns according to the g-code given on to the build platform – its components are shown in Figure 5. This produces one layer, after that the built plate rises from the tank, the relocator blade accommodates the next layer of resin and the process repeats. Post processing requires washing with alcohol, and UV-chamber curing. Material utilized is photopolymer resin [18].

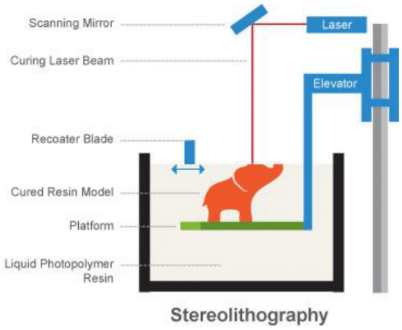


Figure 5 SLA method illustration [17].

SLS (Selective Laser Sintering) – Selective Laser Sintering (Powder Bed Fusion))

A versatile process using high power laser to sinter small particles of polymer powder to a solid part. Mostly used for rapid prototyping because of the low cost per part and use of exotic materials such as high-grade polymers like nylon, and TPU.

The principles for this type of method are to layer by layer put polymer on to the bed, them use the high-power laser to sinter in the pattern given by the g-code, after one layer is sintered a roller recoats on top of the initial layer and the process repeats – its components are shown in Figure 6. Post-processing requires cleaning of excess powder, and then use media blasting or tumbling to get a better finish [19].

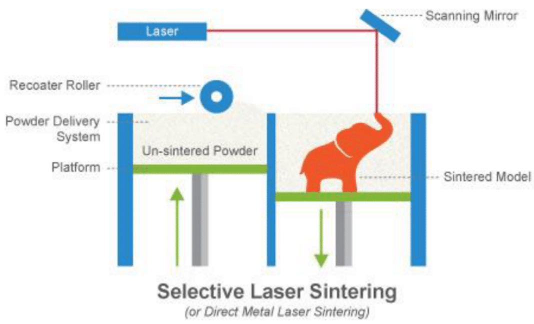


Figure 6 SLM method illustration [17].

SLM – Selective Laser Melting (Powder Bed Fusion (PBF))

While the method of SLS and SLM are quite similar in regards of methodology, the biggest difference is the morphology of the powder structure after laser passes. This means that with SLS the powder gets sintered together, while with the SLM method the powder melts together. Hence, SLM printing is more suitable for metal printing, and is also the most used method for MAM. Further, the process is like SLS. The post-processing steps for SLM are to remove excess powder, and for blasting and tumbling it is possible to use the same powder as the powder used in the manufacturing process.

WAAM – Wire Arc Additive Manufacturing (Direct Energy Deposition (DED))

The oldest and most cost-effective MAM method. Builds upon the known method of welding to produce layers, and therefore the most versatile regarding material selection because every weldable material is eligible for use with WAAM technology. Furthermore, the post-processing for this type of method is more extensive than the others because there is always a need for machining after printing. Some parts may not need machining but are dependent on use. Its principles are shown in Figure 7.

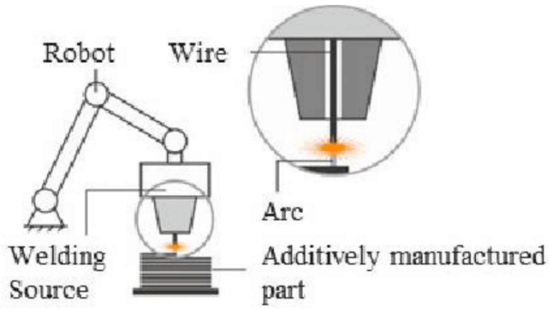


Figure 7 WAAM method illustration [20]

3.3 Computer aided design, Computer aided manufacturing and other software

Computer Aided Design (CAD) is the process of using software to create 3D-models. How this works is by help from global and local coordinates. Global coordinates are the programs 3D-space, whilst local coordinates are the models coordinates. Behind the coordinates are a lot of vector and geometry mathematics that forms curves, lines, and other features for the program. Some other quarks with these types of software are the possibilities to use analysis to strengthen parts, and even simulate dynamic loading.

File format in CAD software are parts files, these files contain information about features in the part i.e., faces, holes, edges, and corners, or only the geometry of the part. After the part files are saved, then the stereolithography (.stl) file can be generated through the CAD software.

Autodesk Inventor is a powerful computer-aided design (CAD) software developed by Autodesk Inc. Recognized as one of the leading tools within mechanical engineering and design.

First introduced in 1999 and has since then evolved into versatile CAD software used by engineers in various industries. The primary purpose of Inventor is to create, simulate, and visualize 3D-models. It forms an integral part of the digital prototyping process and allows engineers to validate and optimize ideas before physical production [21].

Autodesk Fusion 360 is also a powerful CAD software more used by hobbyists and AM enthusiasts around the world. This software has more options regarding optimization, and meshing scan files - with its own tools to do so. Further, software modelled in this software also works within other Autodesk applications making the software versatile and a safe choice for modelling work. Also, Fusion 360 has implemented CAM software within the user interface where g-code generation are possible for either AM or CNC-manufacturing.

Computer Aided Manufacturing (CAM) is the software used to generate g-code. This program uses logic to generate paths for the manufacturing machine (i.e., 3D-printer), paths generated are in the form of g-codes. Further, CAM can also be used to alter the code with speed inputs, colour change and so on. These programs are often referred to as slicer software in the AM community.

File format for CAM software within AM are g-code files (.gcode) these files contain information about toolpaths, speed and more. This is the coded representation of the .stl file and is used for generating 3D-parts.

CAM software within AM is referred to as **slicer** software. Slicer software is a software used to generate g-code files after inputting a .stl file. Slicing means to cut the part layer by layer to generate toolpaths for filament extrusion. When slicing file many options are available, some important options are:

Infill patterns – choice for what structure to be in the print part, can choose regarding forces applied to the part (axially, radially), for weight reduction (tree generation for only supporting structure, not applicable for parts exposed to force). Different infill patterns as shown in Figure 8.

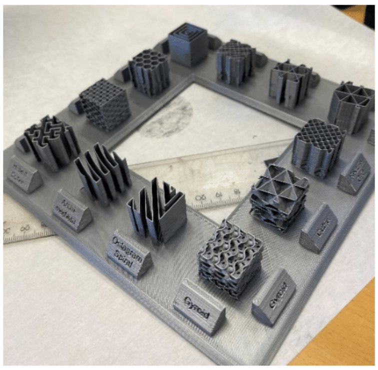


Figure 8 Infill patterns

Optimized part placement – Places the part in the most optimized placement to withstand force. One example would be printing a bolt. Placing a bolt vertically would print the layers vertically meaning when bolt is exposed to force it will loosen in the layer. Placing the bolt on an angle (45º) would make the layers longer and not in a direction exposed to force. Shown in Figure 9 the parts are place optimally in regards of optimal printing.

PreForm is an example of slicer software (used in this research). This software is used within SLA print method and is developed by **Formlabs**. Formlabs is a company founded by three MIT students. This company develops 3D printers and related software [22]. Preform print plate in user interface shown in Figure 9.

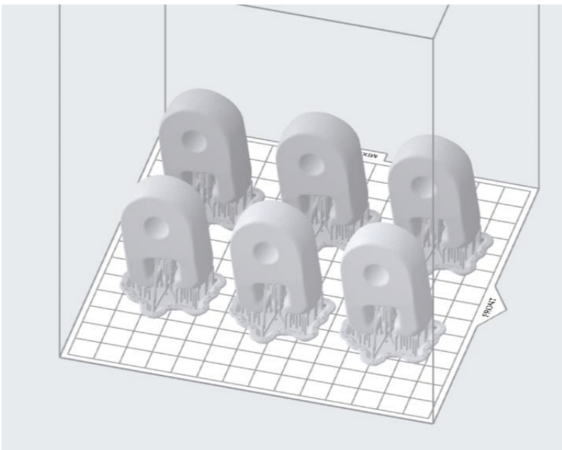


Figure 9 Optimal print placement in PreForm

3.4 Reverse engineering

Reverse engineering is the process of designing a part in a reversed manner, this often involves 3D-scanning, measuring, and drawing something already produces, or in more professional term – deconstruct software, machines, or structure to extract design information about them. Reverse engineering is often used to optimize or duplicate an existing object, or to repurpose legacy parts.

Creaform HandyScan Silver series 307 – delivers between 0.030-0.040mm precision and makes this tool a powerful and dependable regarding development, and cost when re-engineering parts. Using laser infrared technology to capture millions of discrete datapoints (point cloud) to produce detailed parts in scanning environment, measuring 480 000 measurements/s with a resolution of 0.100mm.

Creaform VXelements (VXmodel) – a scanning software used with the scanner to produce the 3D-space where the point cloud is generated, also used as a post-processing, and finalizing application where meshing, and cleaning takes place. The program also delivers mesh optimization for 3D-printing, and plug-in options for **Autodesk Inventor** that makes the software much more applicable for simulation and CAD operations.

3.5 Digital inventory

Digital inventory (DI) implements a better future for storage and up to date spare parts for on-demand supply chain, and just in time parts. DI is a sustainable option to lower cost of storage keeping and reducing lead time from manufacturer to end user. Typical DI should include inventory levels, order quantity, lead-time and help reduce part obsolescence (legacy parts).

Fieldnode delivers eco system for digital storage. Fieldnode keeps a part repository company can upload and manage intellectual property (IP), share, and collaborate on assorted designs efficiently. Thus, ensure consistency in the supply chain. Further, companies can order parts through Fieldnode from IP holders and OEM's, obtain quotes and lead times. Fieldnode is a network where operators and global suppliers collaborate through Fieldnode, to minimize lead time, and reduce supply chain complexity [23].

3.6 Coordinate Measuring Machine (CMM)

In production environments where part with tolerance-based geometries is made, it is important to assess the parts for uniformity and deviations. Hence the CMM is used. Using XYZ-axis movement and probes (styli) to measure deviations vs .step files, it is one of the most precise workshop tools in the industry. Axis encoding shown in Figure 10. The probe (styli) touches the surface of the respectable part until enough force is applied, and then runs according to the uploaded file, then measures along the surface until end of part – and the process repeats.

The CMM can measure geometric deviations, some examples are right angles, circularity and straightness. Using CMM instead of conventional measurement techniques reduces 80% time spent when measuring parts [24].

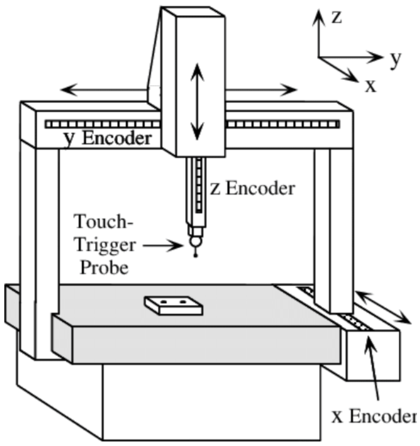


Figure 10 CMM illustration [25].

3.7 Valves

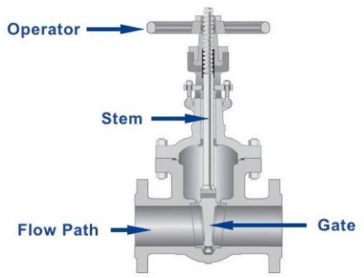
Valves are mostly used for opening and closing pipelines, but also for regulating flow, and controlling process environments onshore – and offshore. The types, material selection, and requirements are stated in standards regarding valve selection [1]. These examples are also mentioned later in the experimental section:

Ball valve and **Gate valve** are open/ close valves. When in open position the valve is supposed to yield no resistance in flow, this means that the flow has the whole pipe cross section in the valve to move past. The gate valve is also bi-directional meaning the flow can go either direction in the valve. The valves components are shown in Figure 11.

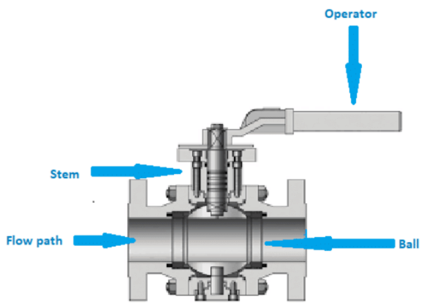
The surface roughness of the closing members of the valves is important due to the sealing function it needs. For the wedge in the gate valve - the faces used to block flow through the valve are called seal surface, this surface is used to properly seal between the pipe opening, and this surface, if the surface is to rough it would not properly seal. And the same for the ball valve, so therefore surface roughness is important.

For the wedge in the gate valve there are some criteria regarding design, some of which are:

- Angle on the wedge sealing surface (usually 5º)
- Surface roughness of the sealing surface (self-sealing surface). Mediums are also important to assess when choosing seal surface roughness. This is important for sealing properties between the wedge and pipes within the valve. Sufficient sealing prevents leakage.



a)



b)

Figure 11 Gate valve a) and Ball valve b) schematics

4 Experimental

4.1 Valve selection

For choosing a valve, it is important to do some feasible research so that the valve type chosen is eligible for assessment and further research. The focus was to find some valve types that are easy to assess in brief time notice, because of limitation with time. Also, in compliance with Moreld Flux regarding valve types in storage, and what is known to the cataloguing provided.

The valve types chosen were two ball valve types, and one gate valve type, shown in Figure 12.

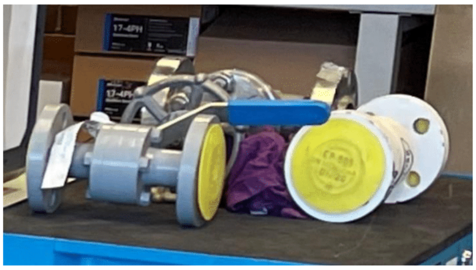


Figure 12 Collection of valves selected

4.2 Literature study; valves

The first stage of assessment is to find literature regarding the respectable valves. In researching literature, it is important to not neglect the main topic of the research. Therefore, literature used is mostly the NORSOK standard [1] regarding piping and valves. One book [2] is used for this part of the review that is used for processing technology. The handbook called valve technology [3] is also used a lot. An introduction to valve technology presentation and manuscript is made for the reader to get a better understanding of this technology (provided in the appendix). Findings from the literature provided excellent help regarding valve technology and gave the researcher the preliminary knowledge needed to research this topic.

4.3 Valve disassembly and selection process

When doing any type of mechanical work, it is important to use correct personal protective equipment (PPE), this is often informed at the workshop entrance. To assess the valves, it is important to disassemble and look at the individual parts of the valve. Going into the selection process with both a technical and engineering mindset is important for choosing a compatible part for the research. In Figure 13 below the gate valve is partly dismantled, and assessment started.

Figure 13 Semi dismantled gate valve

Gate valve – A larger and heavier object then for the ball valve, and far more intricate parts made this valve more suitable for the study. After further investigation the wedge is suitable for AM research, or more generally for scanning and deviation studies. The body, stem, disc and trim are all F316 material, meaning that the whole body could be suitable for print in one entity – reducing from 4 parts to 1 part (further research would be necessary before concluding possibilities on this matter). In Figure 14 the valve is dismantled, and the wedge is shown.

a)

b)

Figure 14 a) Gate valve exploded view, b) Gate valve wedge

Several parts in this build are suitable for optimization. The wheel could even be printed in a stronger polymer (would be cheaper than MAM). Furthermore, the body is very heavy and therefor weight reduction is a possibility with infill types and material choice. Under in Table 1 a printability chart shows optimization and what category of tests are required for qualification.

Table 1 Gate valve printability chart

Part	Printable	Optimizable	AMC
Body	Y	Y	3
Wedge	Y	Y	3
Handle	Y	Y	1
Small parts	Y	Y	1

Ball valve - Assessing the ball valve where there are few parts in general gave insights in possibilities with AM and reverse engineering. The body consists of general carbon steel (LF2) and trim consists of F316. Size: ¾.

In Figure 15 internals of the ball valve are shown, also a close up of the ball with connector.

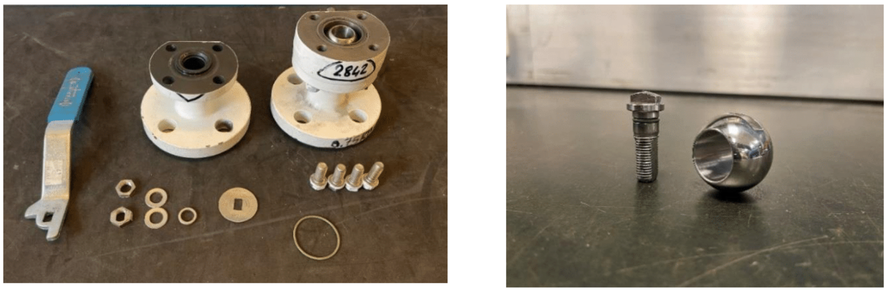


Figure 15 Ball valve dismantled.

The body is printable and optimizable – but important to check pressure class to understand working pressure. For this ball valve – the pressure class is 600 meaning that working pressure is approximately 100 bar. Further, the body is an AMC-2 category that means qualification process is not as critical as for AMC-3.

The ball in the ball valve is AM-able but complex in regards of post-processing, using machines to obtain a surface finish of at least 3,2 µm (machining surface roughness) is hard for a spherical object.

Further, the handle of the ball valve is printable and optimizable. Several of the small parts are also printable. Threaded parts are cheaper to produce the conventional way, but printing the entirety of the valve in less parts will reduce bolts, or even obsolete them. Optimizations possible are:

Body – weight reducing optimization.

Ball – there are some studies that show possibilities to change the ball visual structure – then weight can be reduced and less risk (turbulent flow) when open and closing the valve.

Handle – ergonomically optimization, use polymers.

Washers – just printable, but breakeven between conventional and AM is more in favour for the conventional method. Table 2 gives an overview of printable and optimizable parts in the ball valve, and qualification category.

Table 2 Ball valve printability chart

Part	Printable	Optimizable	AMC
Body	Y	Y	2
Ball	Y	Y	2
Handle	Y	Y	1
Small parts	Y	N	1

4.4 Gate valve wedge

Part chosen is used to stop flow through the valve. In Figure 16 the stem rod and wedge are shown but the rod will not be reverse engineered.

Figure 16 Valve wedge attached to stem rod

4.5 Digitalization of part

Digitalization is an important part to acquire a printable file - using laser scan method to digitalize the part is and ingenious way to do it. The scanner needs a software to visualize the point cloud made with the scanner, using VXelements and VXmodel further in the research.

When scanning it is important to move the scanner according to the user manual – this means not to pivot the scanner to far down (it will not record points) and keep a distance where the scanner still can track points. Before scanning it is necessary to spray any shiny surfaces with a scanner spray (makes a matte finish detectable by the scanner). To create the scanning environment - marker dots are placed, these dots also get detected in the software these marker dots are shown in both Figure 17 and Figure 18.

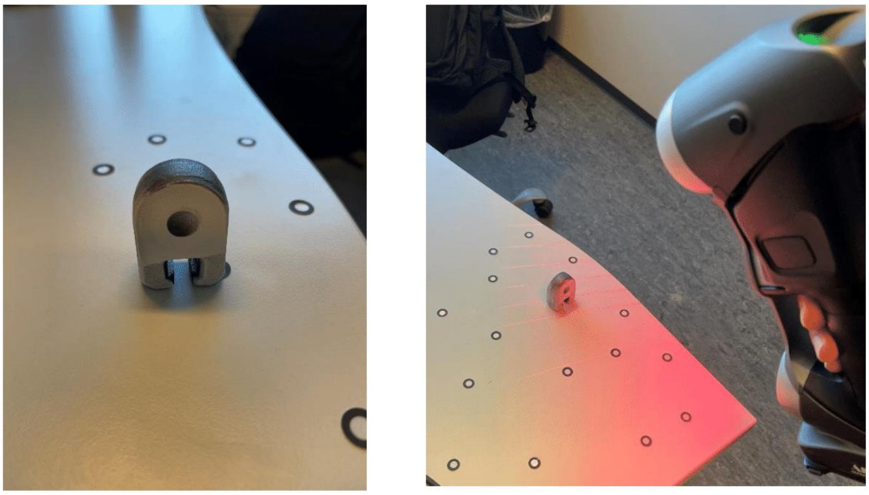


Figure 17 Scanning in progress

When meshing in VXelements several scans are needed to get every side of the scan part. In this instance seven (7) scans were made and merged to get all angles needed to get a uniform part. Also, when scanning - noise usually gets recorded, this need to be deleted before the merging stage, but are usually done when removing scanning environment (table and marker dots).

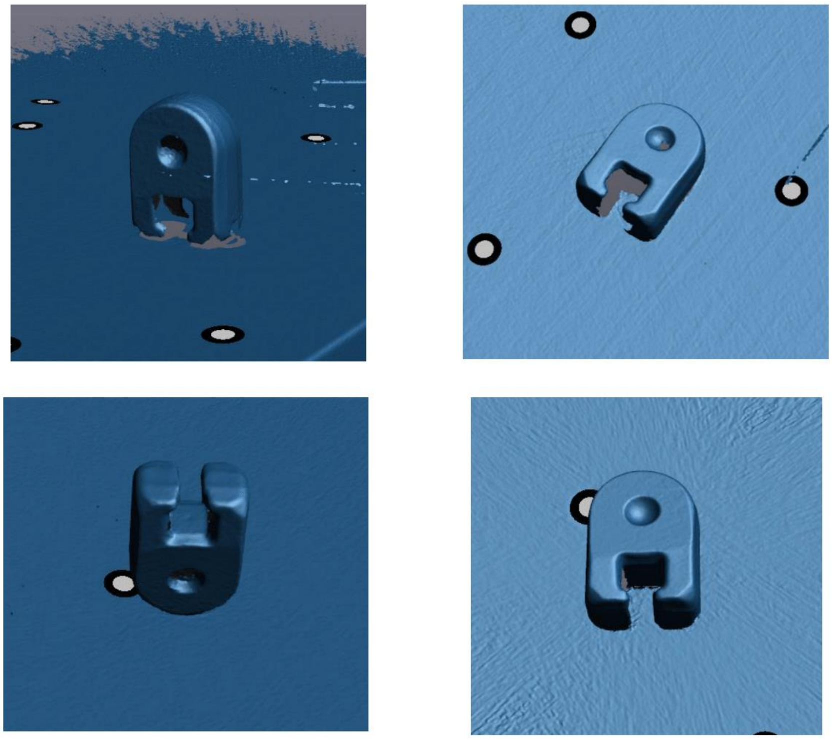


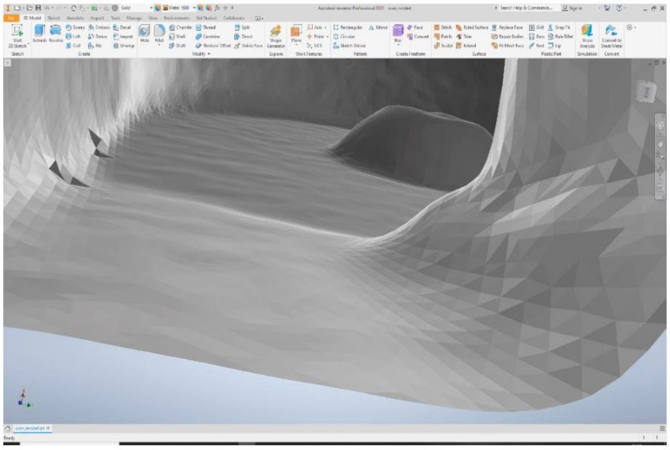
Figure 18 Snapshots from VXelements

When finished with merging and meshing, file format can be chosen, and part converted. For this research two file formats are used: .stl, and .step. .stl file format is used for 3D-print, and .step for CMM. In Figure 19 the finished scan is shown.

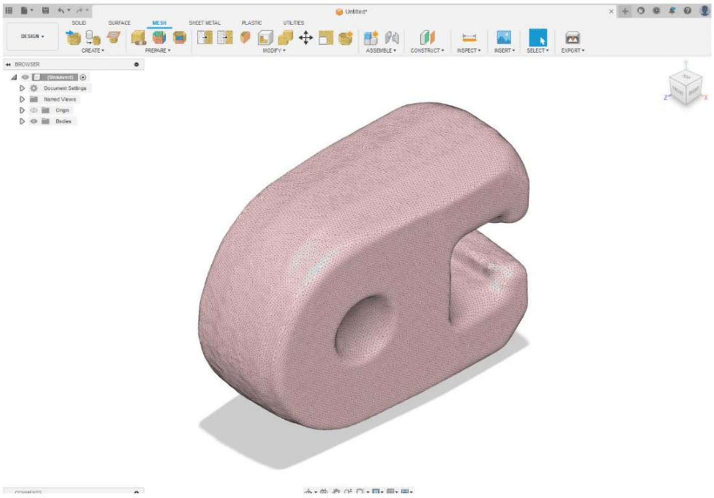
Figure 19 Finished scan and meshed part

4.6 File conversion

From the scan software a .stl file can be formatted directly in VXelements, simply by selecting the upload to be this format. For conversion to .step file – the .stl file is uploaded to inventor, then all facets need to be converted to solid so that the body of the scan is not thousands of polygons but rather a 3D-model with only features such as edges, vertices and faces. In Figure 20 a) the mesh is .stl. In Figure 20 b) the format for the mesh is converted to .step.



a)



b)

Figure 20 File conversion a) .stl, b) .step

Further post-processing of the wedge to get the correct file format, therefore mesh-fitting was implemented.

This process is more commonly used when total reverse engineering or topological optimization procedure is done. Mesh-fitting remakes the scan to a fully functional new model, it must be done when assessment in the CMM machine is next-step in the procedure. This is to get features added in the model so that the CMM software recognizes surfaces, edges, circles and cylinders. When scanning these features are not present but rather a model based on thousands or even millions of faces (polygons).

First the scan file is imported to Autodesk fusion to be used as a reference when fitting new ‘’shell’’ to the outside perimeters. In Figure 20 b) is the imported scan file in Fusion 360 global coordinates.

Secondly, there is made several planes on the most important asset of the wedge, respectively the seal surfaces. This surface is chosen as a point of interest (POI) going further with CMM. In Figure 21 the plane lays on top of the chosen POI surface, the yellow specks show good merge between plane and scan surface yielding information about whereabout the new surface will align with the original part. This is repeated for the surface on the other side of the wedge as well.

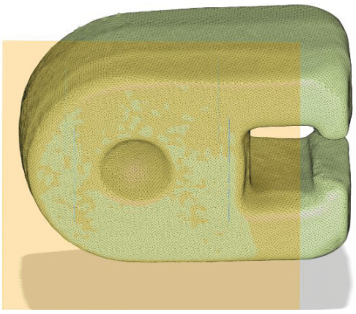


Figure 21 Step 2; plane of chosen POI

Thirdly, designing a new model on top of the scan mesh and use the planes to cut excess material to form around the scan. In Figure 22 the new model is taking shape within the scan’s perimeters. Since the wedge is originally forged there is a lot of impurities at the perimeter of the scan, this is now cleaned in the mesh-fit part.

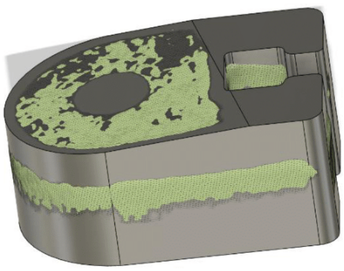


Figure 22 Step 3; shaping the new model

The user interface is shown in Figure 23.

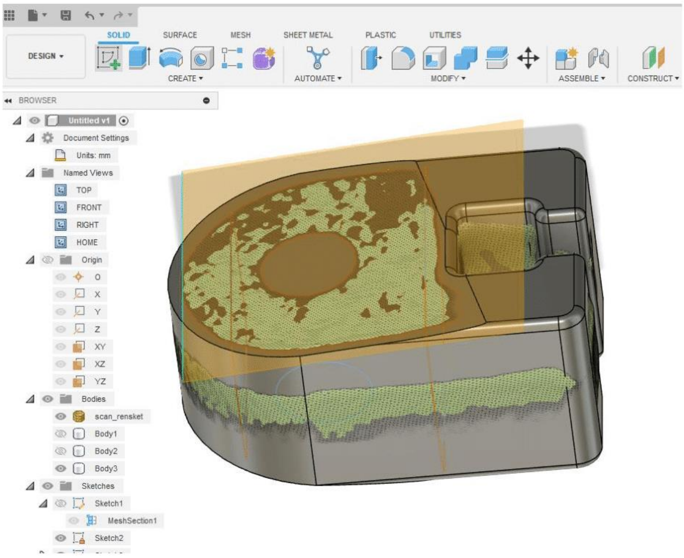


Figure 23 User interface Autodesk Fusion 360

Finished part is created and features of the model are now available for the CMM software to recognize the part. In Figure 24 the finished mesh-fitted part is rendered and presentable.

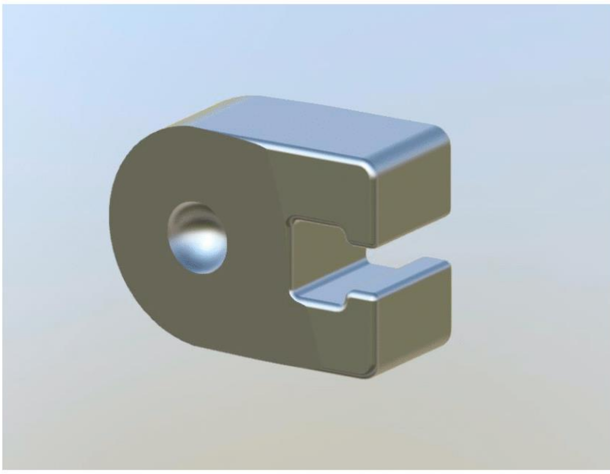
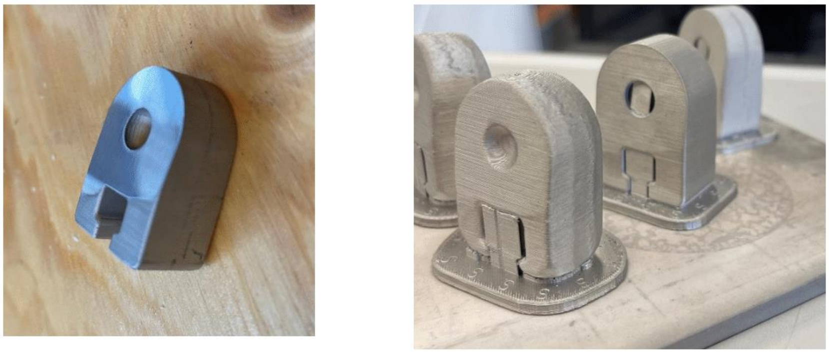


Figure 24 Finished mesh-fitted model ready for CMM software

4.7 Metal printed part and polishing

Using Markforged Metal X to visualize metal printed part, to compare with conventional manufacturing method (APPENDIX D – STAMAS QUOTE AND DOCUMENTATION). In Figure 25 the polished and unpolished part are shown. The polishing finish is achieved by hand.



a) b)

Figure 25 3D-printet metal part a) polished, b) unpolished

In Figure 26 the printed part is fitted to the stem rod.

Figure 26 Printed part fitted on stem rod

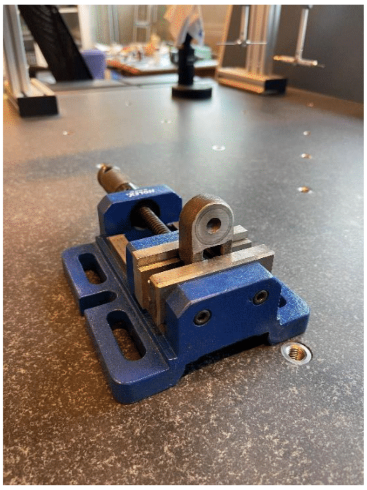
In Figure 27 Markforged Metal X system is shown.

Figure 27 Markforged Metal X, WASH-1, and SINTER-1

4.8 CMM

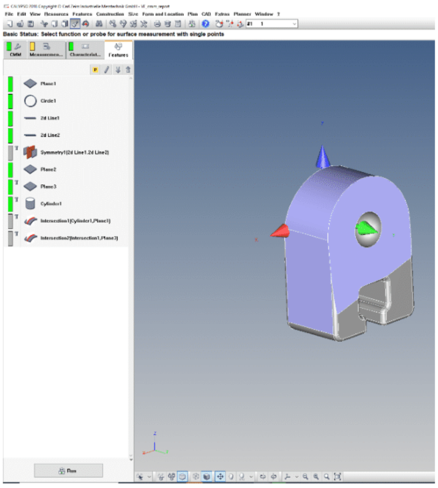
First uploading the .step file to the CMM software (Calypso 2018), in the software features is defined so that the machine recognizes the motion it needs to do – to execute the measurement asked for. After defining features and characteristics shown in Figure 29, the styli can be brought to the part where it need to define planes and surfaces. In Figure 28 the machine and wedge orientation are shown.

a)

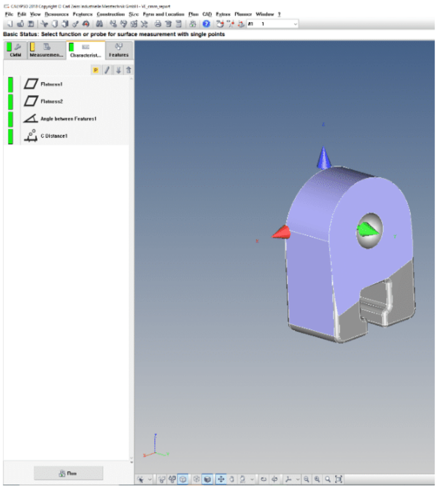


b)

Figure 28 a) CMM, b) Wedge fitted in vise



a)



b)

Figure 29 Calypso 2018 user interface a) Base alignment and feature definitions, b) measurement characteristics

When recording the surfaces in the CMM, vectors are generated on the part in the software. These vectors are used for the machine to calculate the characteristics asked for, in Figure 30 the vectors on the surfaces are shown. In the GUI on the left side of each figure are information about orientation but also note points recorded for each part.

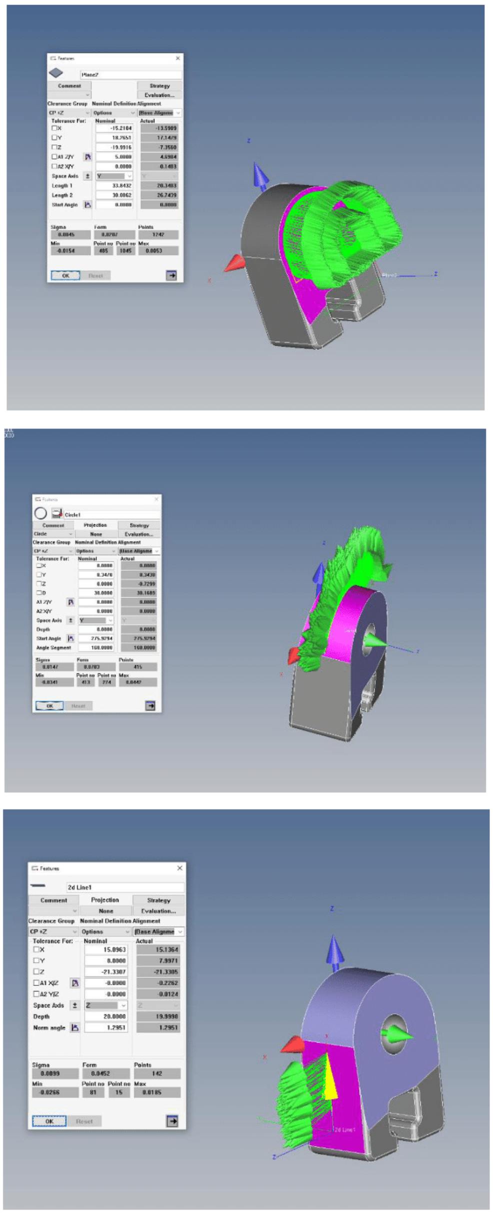


Figure 30 Vector recordings of base alignment in Calypso 2018

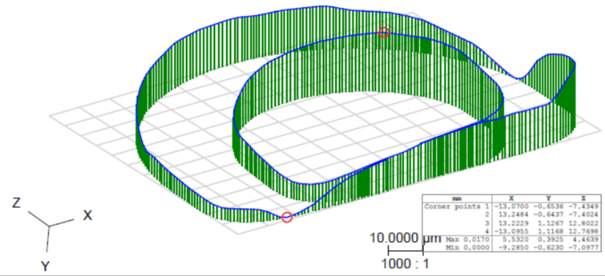
5 Results

5.1 CMM results scan vs real part

In Figure 31 deviations of the seal surfaces are shown, the results show only a deviation of less than or equal to 0.020 mm. This measurement is measured between the CAD model shown in Figure 24 and the wedge shown in Figure 28 b).

Name	Measured value	Nominal value	+Tol	-Tol	Deviation +/-
Flatness1	0.017	0.000	0.100	0.000	0.017

Points	1248
Filter type	Low-pass Spline
Lc	2.5
upr	
Vmess[mm/sec]	10.00
Probe radius	2.500
Evaluation method	Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation +/-
Flatness2	0.020	0.000	0.100	0.000	0.020

Points	1242
Filter type	Low-pass Spline
Lc	2.5
upr	
Vmess[mm/sec]	10.00
Probe radius	2.500
Evaluation method	Minimum Feature

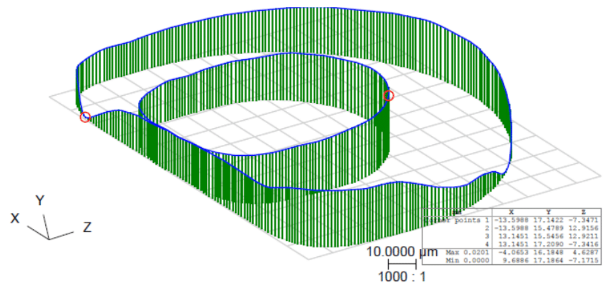


Figure 31 CMM deviations of seal surfaces; scan vs real part

Further the angle between the seal surfaces was measured. Result shown in Figure 32. The angle on the nominal plane was set to 5º and measured between both planes.

Angle between Features1	9.691	10.000	1.000	-1.000	-0.309

Figure 32 Angle check with CMM; scan vs real part

5.2 CMM CAD vs printed part

In addition to checking scan vs real part – as a part of research of manufacturing methods and information given by Stamas it was necessary to give a result from scan vs printed metal part. In Figure 33 the report from CMM shows very small deviations in contrast to the CAD file.

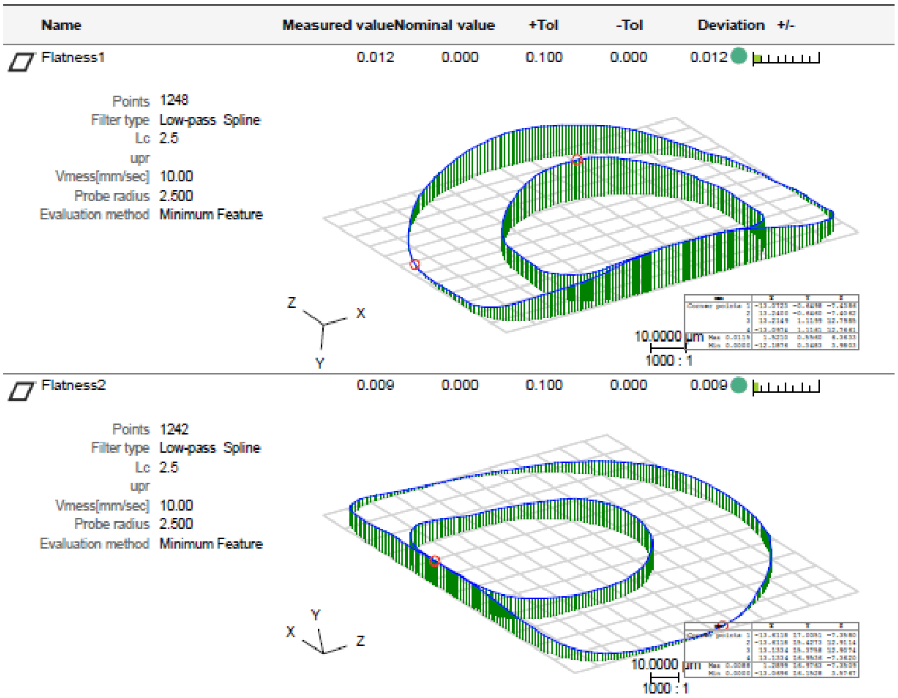


Figure 33 CMM deviations of seal surfaces; CAD vs real part

In Figure 34 the angle between the planes is shown, with nominal angle of one of the planes is set to 5º.

Angle between Features1	9.458	10.000	1.000	-1.000	-0.542

Figure 34 Angle check with CMM; CAD vs print

6 Discussion and conclusion

If the deviations were too big i.e., 0.1 mm - the CMM would crash into the part because the program and wedge fitted in the CMM would have to large deviations for the CMM to recognize that the scan model and actual part to be the same. Furthermore, all deviations found with CMM can be implemented in the scan/CAD file to reduce deviations so that the scan/ CAD file is more like to the original real part.

Furter post-processing is required to get polished seal surfaces.

With more time the CAD model could be further altered after the given CMM result. Then there would be very small deviations.

The wedge is both printable and optimizable regarding less material used (topological optimization), but flow simulation, finite element analysis (FEA) and numerical modelling would be necessary to do correct re-design in regard of forces.

Conventional storage means having thousands of square meters of storage spaces with spare parts, these spare parts may be old, corroded, or even unusable while being stored. Furthermore, the lead-time of getting spare parts from OEM's is often long and can complicated keeping up-time on the respective equipment. Digital inventory can help reduce storage spaces and lead-time with its on-demand philosophy – meaning less down time, and money saved.

Further, implementation of life cycle assessment (LCA) in the digital warehouse (DW) to give on-demand data for environmental impact per print, or even impact saved when choosing the greener option could be a future possibility for the DI [26]. Also, implementing Manufacturing Execution Systems (MES) to digitize manufacturing processes, this includes managing, monitoring, and tracking transformation of raw material into finished products in real-time. Also, see how to improve performance, lower cost and increase efficiency [27].

When scanning and mesh-fitting full replication of the legacy part – it is easy to make errors. When inspecting the scanned and mesh-fitted model vs real model the planes on the faces have a small deviation from right to left of the plane (please look at Figure 24), this translates to the skewed angle on the plane. These planes were made to exact specification in Fusion 360 (4.6) and in terms of CMM the deviations yielded only a maximum of 0.02 mm, therefore conclusion of this error is that it is not a mesh error, but rather a part error (Long time of use, or as-built errors). Further, using the CMM data, these errors can be fixed so that the part is as-new instead of as-built (used). In short terms use the new mesh-fitted CAD model and calculate the angle on the plane in terms of the deviations found – from there add changes and the part should have zero deviations.

In terms of work done and applying both technical and engineering knowledge made laboratory a stress-free experience. Further, writing the report was more a knowledge distribution from a research point of view rather than learning by reading or learning by doing then writing a report (more commonly done in bachelor's degree). Experience gained towards writing report and research methods is invaluable towards further research and work application.

7 Bibliography

[1] NORSOK L-001, *Piping and valves,* 2017.

[2] E. Ignatowitz, Prosesskjemi, Yrkesopplæring, 1999.

[3] Norwegian Oil and Gas, Valve technology handbook, 2020.

[4] DNVGL-ST-B203, *Additive manufacturing of metallic parts*, 2020.

[5] D. Powell, A. E. Rennie, L. Geekie and N. Burns, "Understanding powder degradation in metal additive manufacturing to allow upcycling of recycled powders".

[6] A. T. Sutton, C. S. Kriewall, S. Karnati, M. C. Leu and J. W. Newkirk, "Characterization of AISI 304L stainless steel powder recycled in the laser powder-bed fusion process," *Additive manufacturing 32,* 2020.

[7] S. Cacace, V. Furlan, R. Sorci, Q. Semeraro and M. Boccadoro, "Using recycled material to produce gas-atomized metal powders for additive manufactuing processes," 20 May 2020. [Online]. Available: https://doi.org/10.1016/j.jclepro.2020.122218. [Accessed 07 August 2023].

[8] V. May, "Portal UK," 07 October 2022. [Online]. Available: https://prototaluk.com/blog/history-of-additive-manufacturing/. [Accessed 14 July 2023].

[9] E. Toyserkani, D. Sarker, O. O. Ibhadode, F. Liravi, P. Russo and K. Taherkhani, Metal additive manufacturing, Waterloo, Ontario: John Wiley & Sons Ltd, 2022.

[10] DNV-CP-0267, "*Approval of manufacturers,*" DNV, 2022.

[11] Total Materia, "The water-atomizing process: Part one," [Online]. Available: https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=309.

[12] O. D. Neikov, Handbook of Non-Ferrous Metal Powders, Kiev, Ukraine: Elsevier Science, 2009.

[13] T. Fedina, J. Sundqvist, J. Powell and K. F. Alexander, "A comparative study of water and gas atomized low alloy steel powders for AM," 16 October 2020. [Online]. Available: https://pdf.sciencedirectassets.com/306190/1-s2.0-S2214860420X00054/1-s2.0-S2214860420310472/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEB4aCXVzLWVhc3QtMSJHMEUCIQCFAEd%2F6BJ251VJd3Br8jVV00dBg1DXJ94FeYaXoMzyZQIgeb%2BUoq0BTmeg8vDAdrSMX9FmTRpoOd5mAqKaGchO. [Accessed 31 July 2023].

[14] R. M. German, Powder Metallurgy Science, Princeton, NJ: Metal powder industries federation, 1994.

[15] D. D. Whittaker, "Additive Manufacturing at World PM2016: Opportunities for the use of water atomised metal powders," Metal AM, 2017. [Online]. Available: https://www.metal-am.com/articles/additive-manufacturing-3d-printing-water-atomised-metal-powders/. [Accessed 31 July 2023].

[16] F3nice, "F3nice - Sustainablity," [Online]. Available: https://f3nice.com/sustainability/. [Accessed 2023 August 2023].

[17] PRINTSPACE3D, "The Main 3 Additive Manufacturing Methods," PRINTSPACE3D, [Online]. Available: https://www.printspace3d.com/what-is-3d-printing/3d-printing-processes/. [Accessed 31 July 2023].

[18] Formlabs, "Ultimate guide to stereolithography 3D-printing," [Online]. Available: https://formlabs.com/blog/ultimate-guide-to-stereolithography-sla-3d-printing/. [Accessed 28 July 2023].

[19] Formlabs, “What is SLA,” [Online]. Available: https://formlabs.com/blog/what-is-selective-laser-sintering/. [Accessed 28 July 2023].

[20] A. Sviridov and M. Bambach, “Material Properties of Features Produced from EN AW 6106 by Wire-Arc additive manufacturing,” January 2020. [Online]. Available: https://www.researchgate.net/publication/340937165_Material_Properties_of_Features_Produced_from_EN_AW_6016_by_Wire-Arc_Additive_Manufacturing. [Accessed 31 July 2023].

[21] T. English, “A Look at the History of Inventor Through the Eyes of Jay Tedeschi,” Autodesk, 20 January 2017. [Online]. Available: https://blogs.autodesk.com/inventor/look-history-inventor-eyes-jay-tedeschi/. [Accessed 28 July 2023].

[22] Formlabs, “Company,” Formlabs, [Online]. Available: https://formlabs.com/company/. [Accessed 28 July 2023].

[23] Fieldnode, “Everything you need to rund you Digital inventory,” [Online]. Available: https://fieldnode.com/. [Accessed 31 July 2023].

[24] Zeiss, “Coordinate Measuring Machines (CMM) Reliable and high-quality coordinate metrology,” [Online]. Available: https://www.zeiss.com/metrology/products/systems/coordinate-measuring-machines.html. [Accessed 03 August 2023].

[25] W. Singhose, “Sketch of a typical CMM,” March 1996. [Online]. Available: https://www.researchgate.net/figure/Sketch-of-a-Typical-CMM_fig1_2584285. [Accessed 07 August 2023].

[26] Environmental Management, “Life Cycle assessment,” 2017. [Online]. Available: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment. [Accessed 31 July 2023].

[27] Autodesk Prodsmart, “Production planning the way that it should be - Digital,” Autodesk, [Online]. Available: https://www.autodesk.com/campaigns/prodsmart/production-planning?mktvar002=5398186|SEM|18533362756|150663210148|kwd-296293481010&utm_source=GGL&utm_medium=SEM&utm_campaign=GGL_D-M_Prodsmart_AMER_US_Visits_SEM_NBR_New_BRO_0000_5398186&utm_id=5398186&utm_te. [Accessed 2023 July 2023].

[28] “Fused Filamet Fabrication - Simly Explained,” All3DP, 4 January 2020. [Online]. Available: https://all3dp.com/2/fused-filament-fabrication-fff-3d-printing-simply-explained/. [Accessed 31 July 2023].

[29] “Stereolithography,” Printspace3D, [Online]. Available: https://www.printspace3d.com/what-is-3d-printing/3d-printing-processes/stereolithography_illustration-2/. [Accessed 31 July 2023].

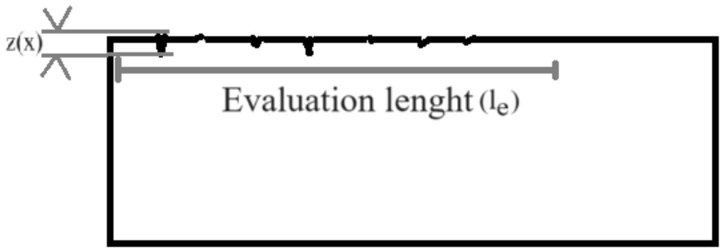
APPENDIX B - OTHER RELEVANT THEORY AND EQUATIONS

In this chapter relevant theories towards practices done in the report are given.

Surface roughness – Arithmetic mean value Ra

Surface roughness is a definition used to describe the finish of a surface. By finding the arithmetic mean height value Ra to determine the surface deviations to find the surface roughness number in µm. By dividing the evaluation length and takin the integral of the absolute value of the heights (z(x) in the length interval yields the equation below with the given illustration below the equation (‘1984_Surf_Roughness_PG.pdf’, no date)

$$Ra = \frac{1}{l_e}\int_0^{l_e} |z(x)|dx$$



APPENDIX B 1 Surface Roughness

$$\sigma = \frac{F}{A}$$

F= Force, A= Area, unit= MPa

APPENDIX B 2 Tensile stress Formula

$$E = \frac{\sigma}{\varepsilon}$$

σ=Tensile stress, ε= Strain, unit=MPa

APPENDIX B 3 Young's modulus of elasticity formula

$$KE = \frac{1}{2}mv^2$$

m= Mass, v= Velocity, unit= Joules

APPENDIX B 4 Kinetic Energy Formula

$$PE = mgh$$

m= Mass, g= Gravity(9.81), h= height, unit= Joules

APPENDIX B 5 Potential Energy Formula

APPENDIX C - LCA, DRAWINGS AND OTHER TECHNICAL INFORMATION

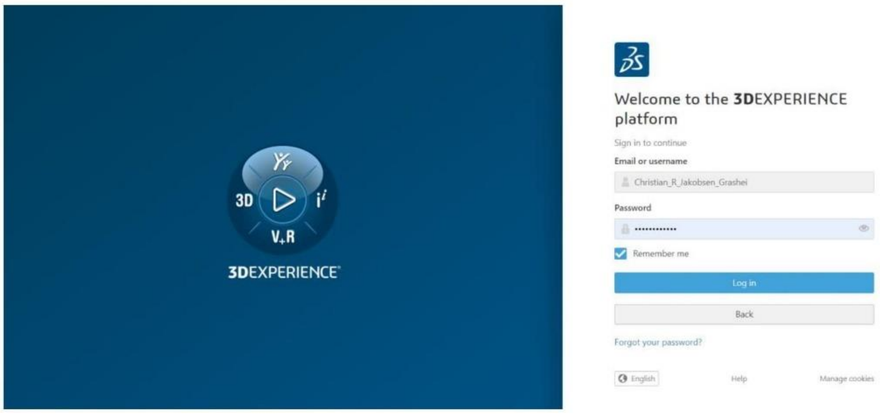
How to perform LCA with 3DExperience

By Christian René Jakobsen Grashei

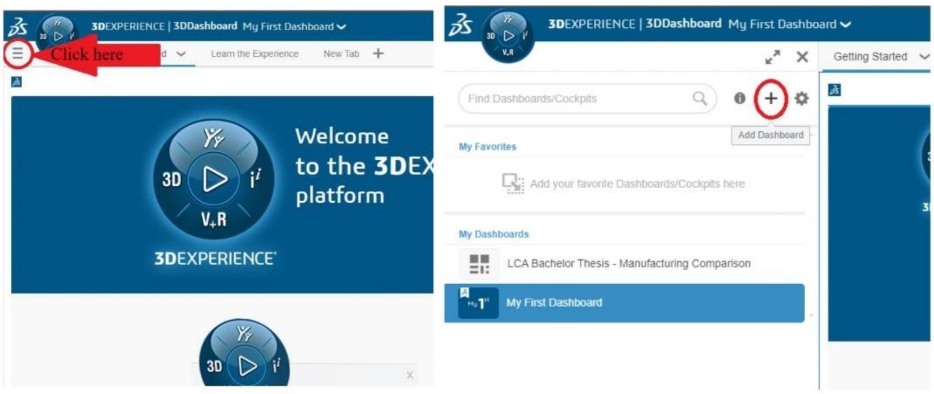
APPENDIX C 1 LCA setup and tutorial

Contents

- ✓ **Log onto software**

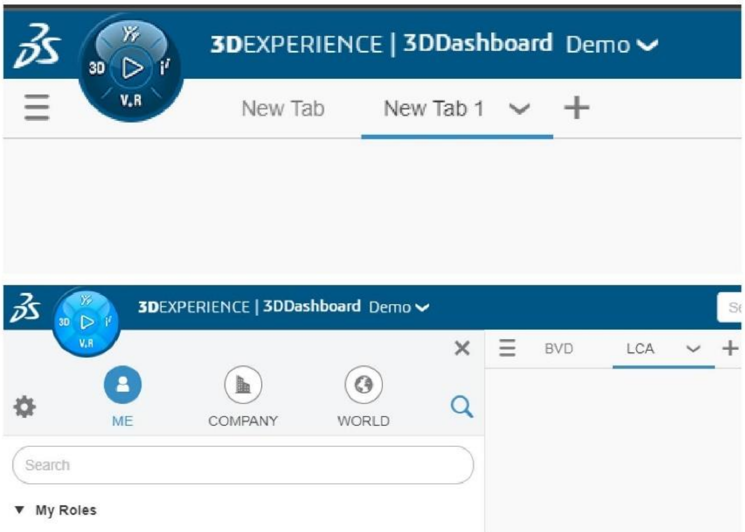


- ✓ **Open a new dashboard**



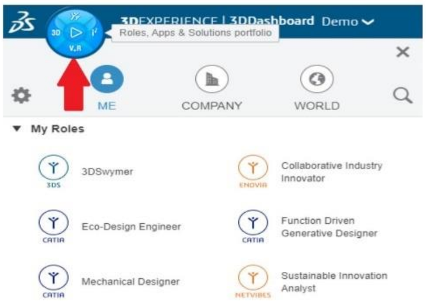
Click the '+' sign then name the dashboard and click "Create".

✓ **Create and name the tabs**



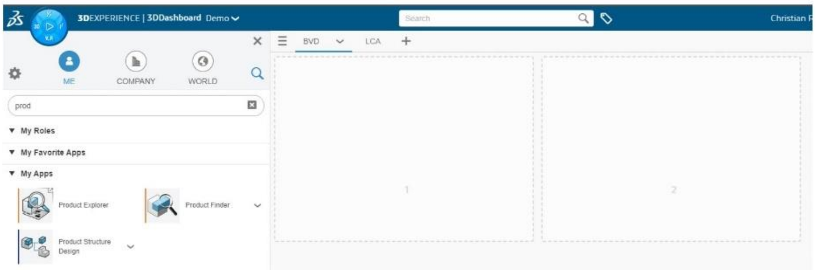
Click the ‘New Tab’ and ‘New Tab 1’ tabs and rename according to picture above.

✓ **Open application portfolio**



Click on the ‘play’ button to access the applications.

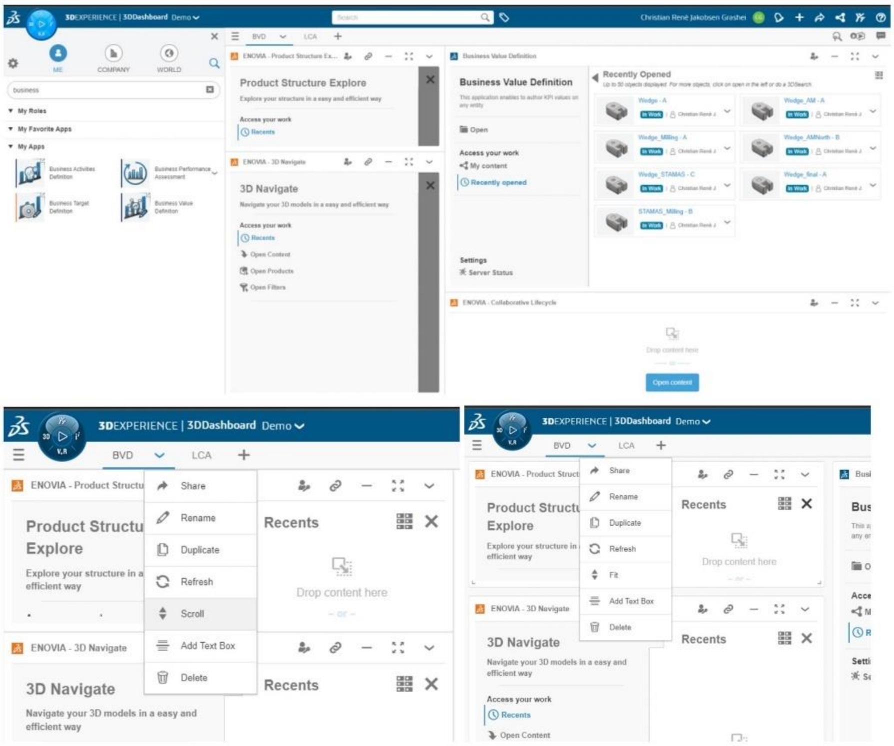
✓ **Add applications to your BVD dashboard**



Click the search icon and search for these applications (when the wanted application is found, drag and place in the dashboard):

- Product Explorer (Two boxes should show up when dragged).
- Business Value Definition (One box should show when dragged).
- Collaborative Lifecycle

Layout the applications like shown below and use ‘Scroll’ (to adjust the windows freely) and ‘Fit’ (to adjust the windows while connected) to do so.

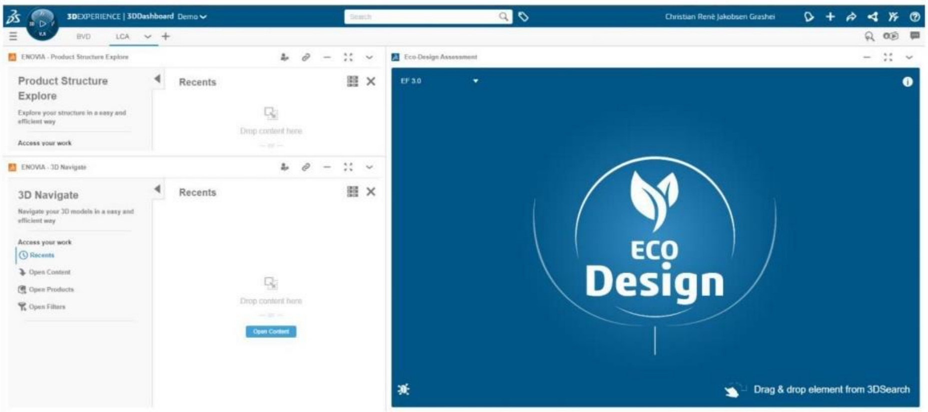


✓ Add applications to your LCA dashboard

Doing so the same way as previous step.

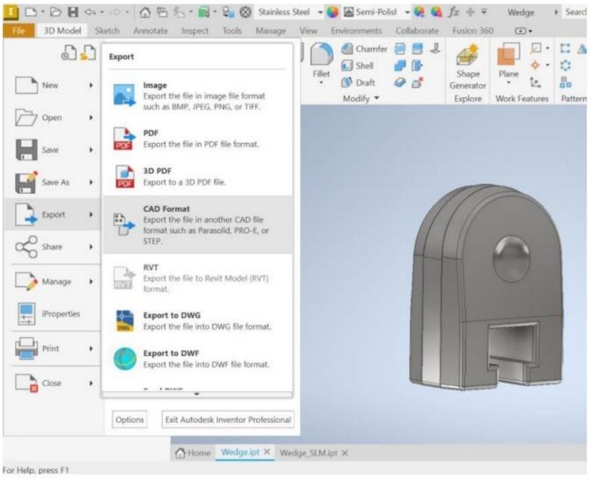
Adding applications: Product Explorer and Eco-Design Assessment.

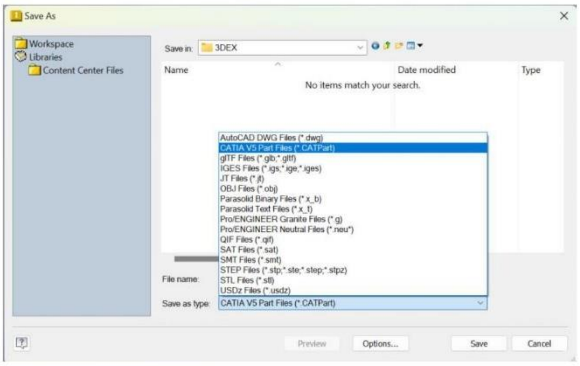
Layout like this:

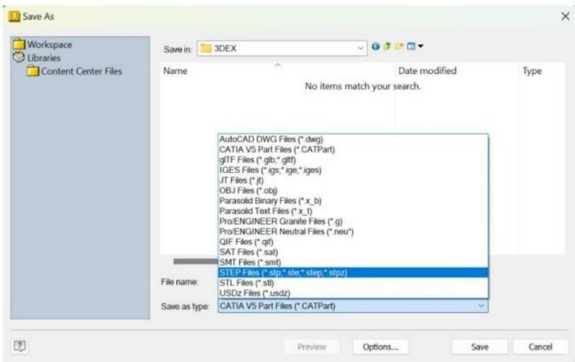


✓ **Adding the part to the 3DExperince platform from Autodesk Inventor**

After finishing part drawing go to file – Export – CAD Format, select either Step or CATIAv5 file (these file formats are applicable for use on 3DExperience).

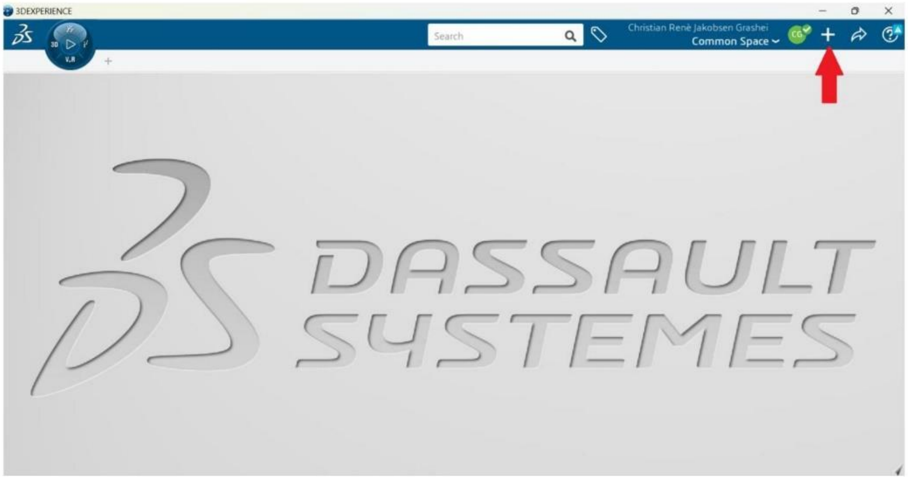




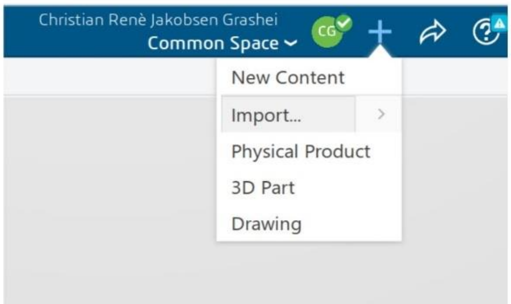


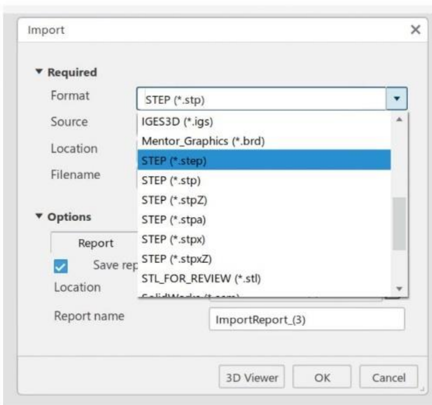
After saving the correct file format go to 3DExperience software. Open the application portfolio and search for 'Part Design' and open this (this will execute the data application, so wait until this has loaded).

When the software is finished initializing press the + icon on the top right side of the window.

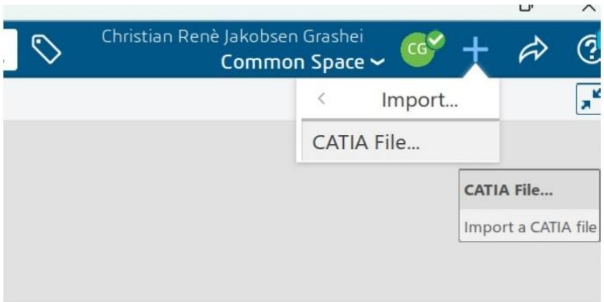


Next press the 'Import' button and choose format .step. From there choose the desired file you want to import.

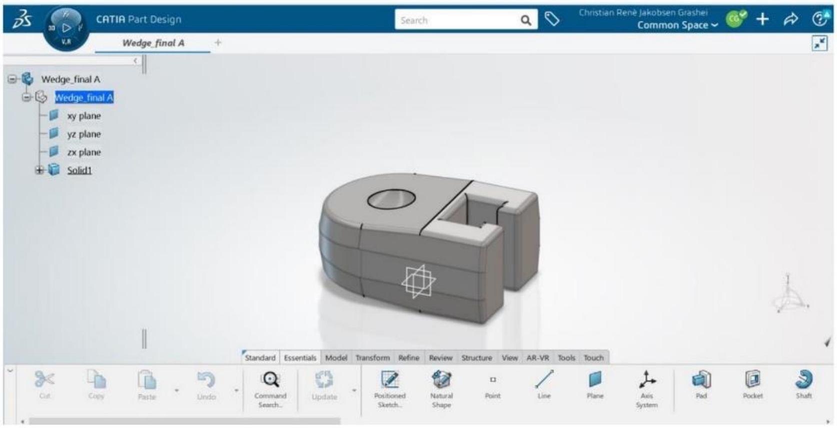




For Catia files press the arrow next to import and choose 'CATIA file…'. This will lead you directly to your computers folder system. From there choose the file you want to add to the 3DExperience software. Some prompts will pop up. To the first pop-up press 'Import', and the last one press 'Ok'.

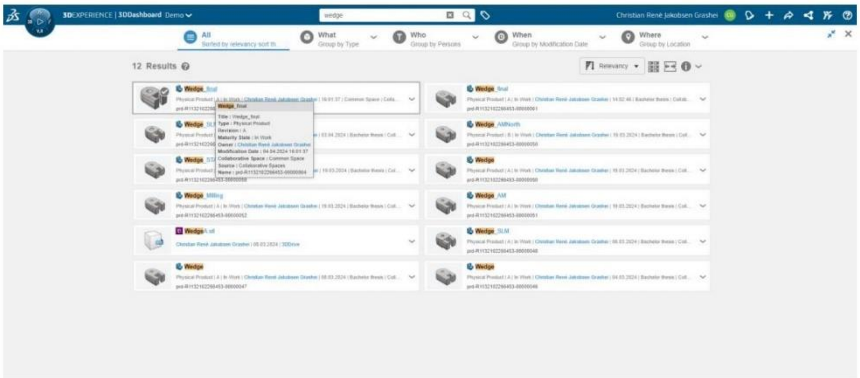


When successfully imported the file, it will be placed in a 3D-environment, from there save the file and exit the software and resume at the browser application.

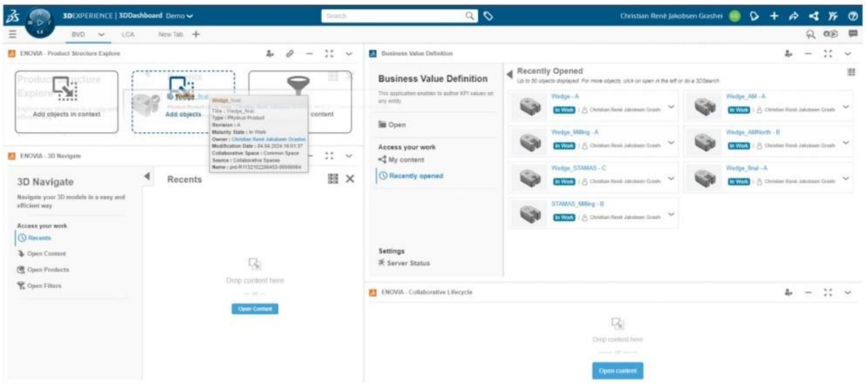


✓ Add the part to the BVD and LCA tabs in the browser application

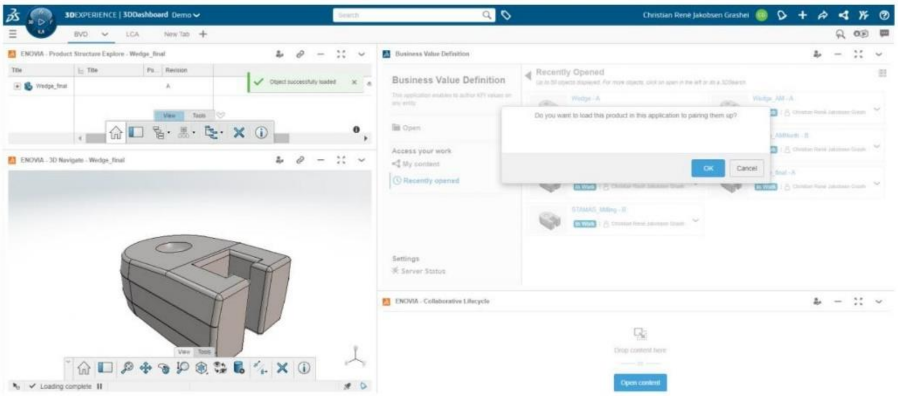
First, go to the search bar at the top middle of the screen and type in the name of the part you just saved.



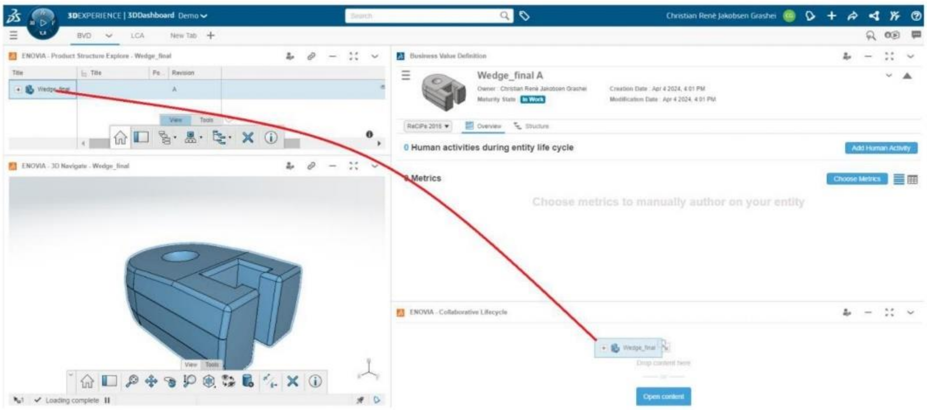
Click and drag this onto the BVD tab in the Product Explorer application.



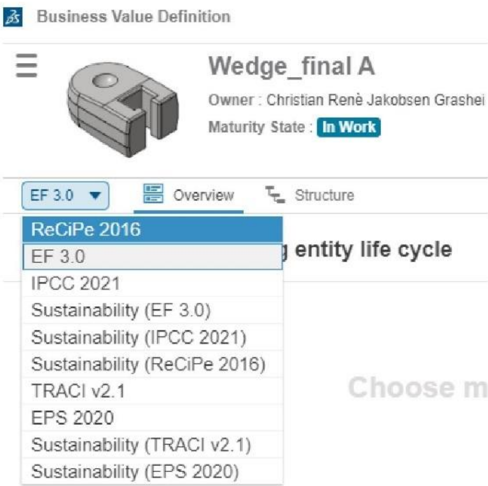
Press OK in the pop-up on the Business Value Definition window.



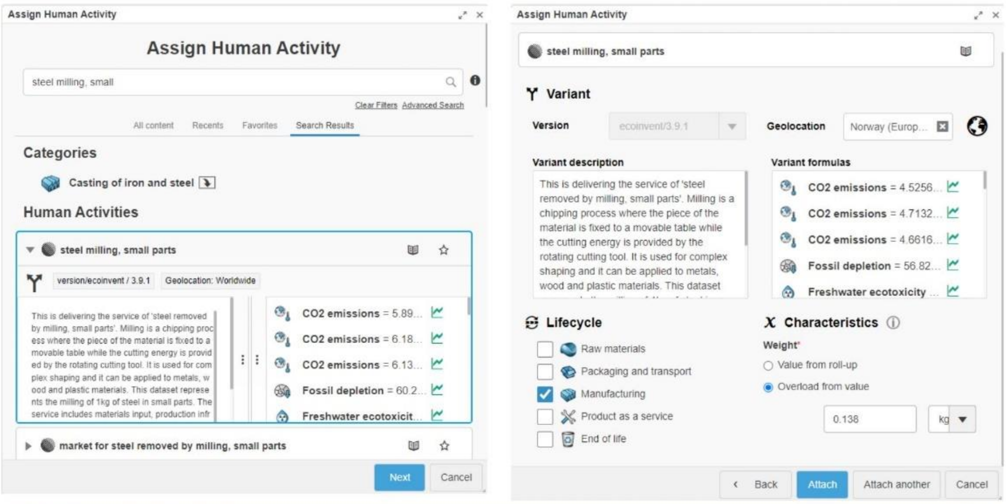
After clicking OK in the pop-up window there will be a possibility to add human activities to the different impact categorization, before this add the part to the collaborative lifecycle application by dragging from the product explorer to Collaborative lifecycle application.

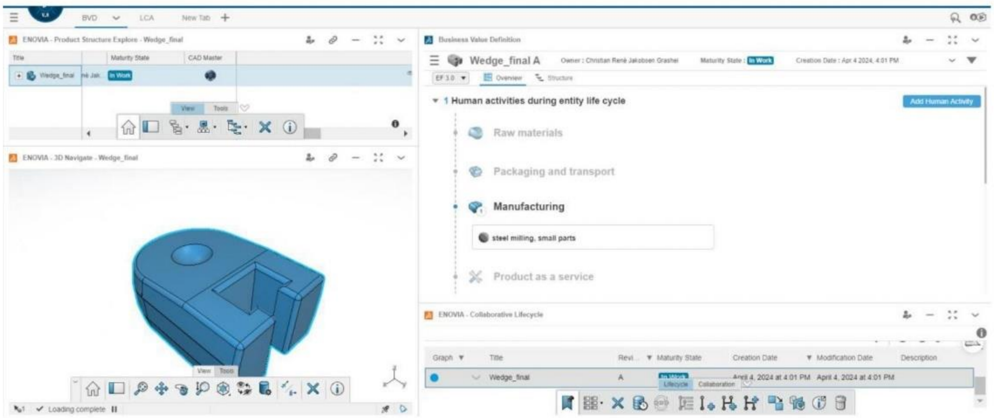


In this software it is possible to alter the impact assessment used. Choose this after your need. EF 3.0 will be used here.

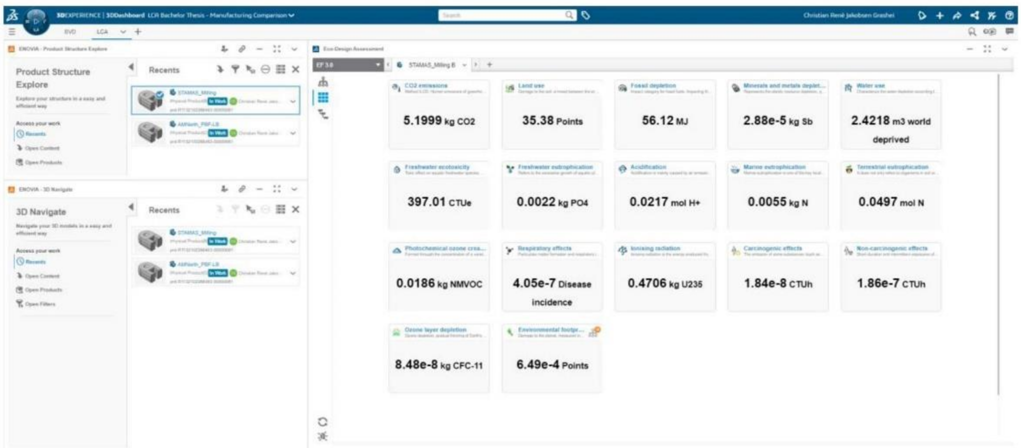


After choosing the Impact assessment method, choose which human activities are applicable for your simulation. For this example, 'Steel milling, small parts' will be used as a manufacturing method. When clicking next, in the new window choose geolocation applicable for the analysis, which Lifecycle impact category fits within the analysis and if needed the weight value of the product. After this click Attach.



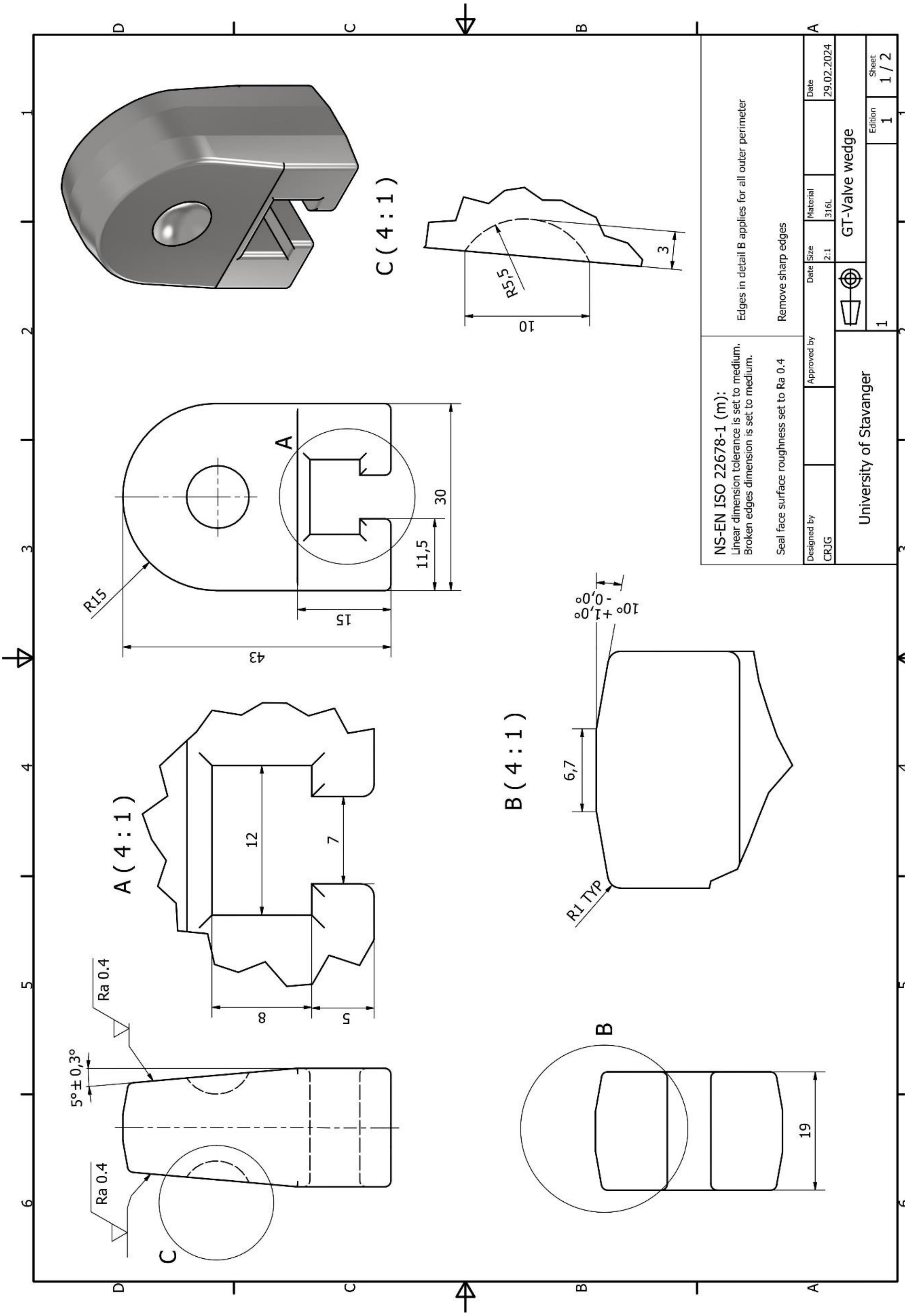


Now drag the object from the product explorer onto the LCA tab and release the object in the product explorer application within the LCA tab. Press OK on the pop-up message in the Eco-Design assessment application. Now the LCA metrics should be shown, and the analysis has been finished.

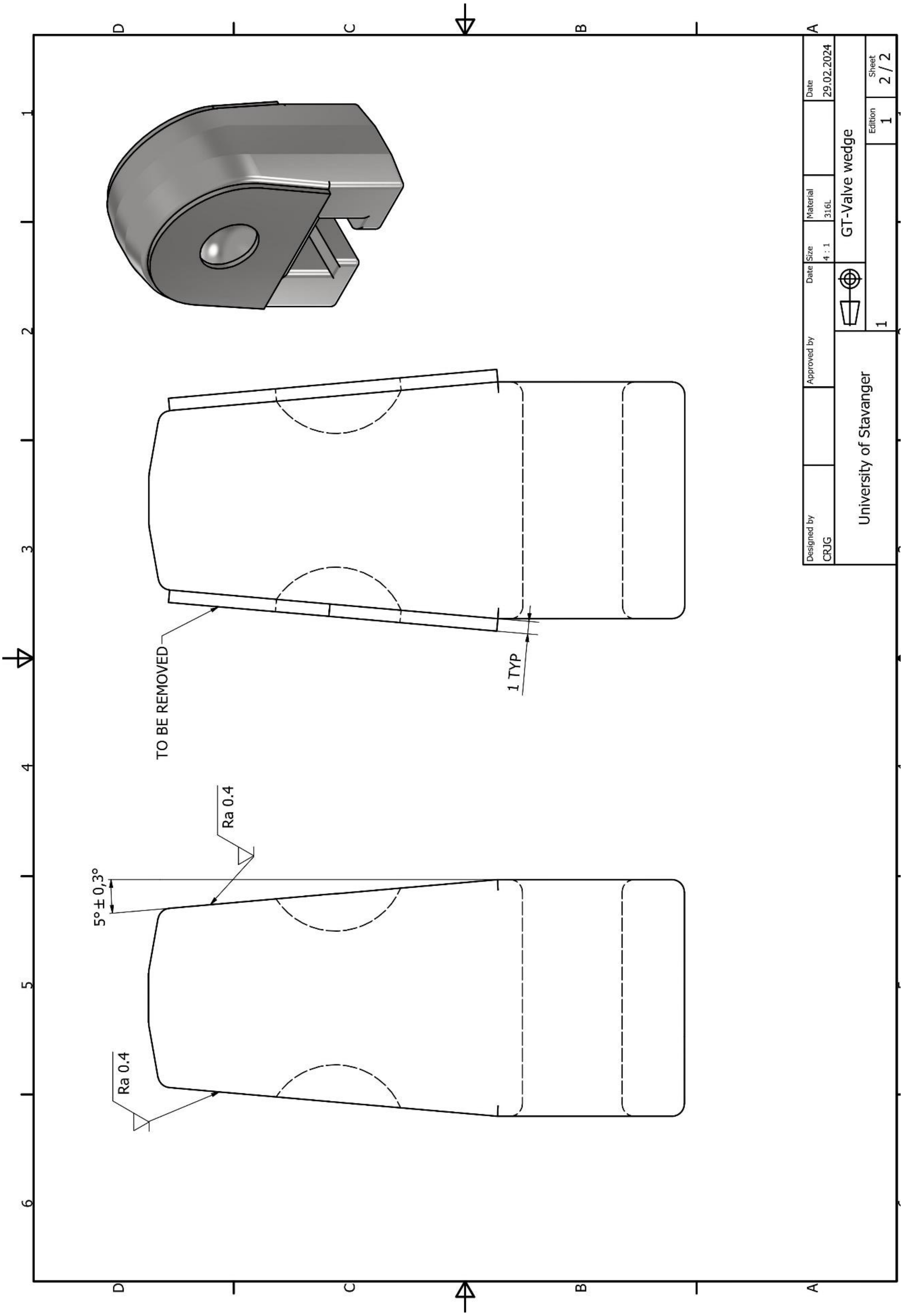


✓ **Troubleshooting and known issues**

EF 3.0 analysis is not showing up in Eco-design assessment window.	Open software in incognito and retry (copy and paste link in incognito mode).
Part design application not opening.	Check for updates, update and retry.
Changes in BVD does not change in LCA	Wait for the software to apply settings by itself (3-5 minutes)



APPENDIX C 2 Wedge drawing given to Stamas



APPENDIX C 3 Drawing for AM'ed wedge part given to Stamas for raised face removal

1/ Context of the study

Name	Revison	Report author	Publish Date
STAMAS_Milling	B	Christian Renè Jakobsen Grashei	2024-5-10

EF 3.0 :

- **Environmental footprint (Points) :**
  Damage to the planet, measured in Points.
- **CO_2 emissions (kg CO_2) :**
  Method ILCD: Human emissions of greenhouse gases that cause environmental and social changes.
- **Land use (Points) :**
  Damage to the soil: a mixed between the erosion resistance, the mechanical filtration, the physico-chemical filtration, the groundwater regeneration and the biotic production.
- **Fossil depletion (MJ) :**
  Impact category for fossil fuels. Impacting the resource depletion as energy carriers.
- **Minerals and metals depletion (kg Sb) :**
  Represents the abiotic resource depletion, quantified in kg of antimony-equivalent (Sb-eq) per kg extraction.
- **Water use (m3 world deprived) :**
  Characterize the water depletion according to scarcity adjusted mass of water used.
- **Freshwater ecotoxicity (CTUe) :**
  Toxic effect on aquatic freshwater species. Measured in Comparative Toxic Unit for ecosystems.
- **Freshwater eutrophication (kg PO_4) :**
  Refers to the excessive growth of aquatic plants or algal blooms, due to high levels of nutrients in freshwater.
- **Acidification (mol H^+) :**
  Acidification is mainly caused by air emissions of NH_3, NO_2 and SOX.
- **Marine eutrophication (kg N) :**
  Marine eutrophication is one of the key local stressors for coastal marine ecosystems, particularly in those locations with many estuaries.
- **Terrestrial eutrophication (mol N) :**
  It does not only refers to organisms in soil or on plants but also to the inhabitants of aquatic sediments.
- **Photochemical ozone creation (kg NMVOC) :**
  Formed through the concentration of a variety of highly reactive gases in the atmosphere and are often implicated in problems of smog, crop damage and the degradation of works of art.
- **Respiratory effects (Disease incidence) :**
  Particulate matter formation and respiratory inorganics. Human health effects associated with exposure to PM2.5.

- **Ionising radiation (kg U235) :**
  Ionising radiation is the energy produced from natural or artificial sources. It has more energy than non-ionising radiation, enough to cause chemical changes by breaking chemical bonds. This effect can cause damage to living tissue.
- **Carcinogenic effects (CTUh) :**
  The emission of some substances (such as heavy metals) have impacts on human health (carcinogenic effects).
- **Non-carcinogenic effects (CTUh) :**
  Short-duration and intermittent exposures of humans to chemicals. Result in non-carcinogenic effects. Measured in Comparative Toxic Unit for human (CTUh).
- **Ozone layer depletion (kg CFC-11) :**
  Ozone depletion, gradual thinning of Earth's ozone layer in the upper atmosphere caused by the release of chemical compounds containing gaseous chlorine or bromine from industry and other human activities.

Life-cycle phases :

- Raw Material
- Manufacturing
- Packaging and Transport
- Product In Use
- End Of Life

2/ Overview: EF 3.0

Metric name	Unit	Value	Target	Comparison
Environmental footprint	Points	**1.30e-4**		
CO2 emissions	kg CO2	**1.21**		
Land use	Points	**8.40**		
Fossil depletion	MJ	**14.73**		
Minerals and metals depletion	kg Sb	**6.67e-6**		
Water use	m3 world deprived	**0.80**		
Freshwater ecotoxicity	CTUe	**42.20**		
Freshwater eutrophication	kg PO4	**5.42e-4**		
Acidification	mol H+	**4.92e-3**		
Marine eutrophication	kg N	**1.29e-3**		
Terrestrial eutrophication	mol N	**1.13e-2**		
Photochemical ozone creation	kg NMVOC	**4.68e-3**		
Respiratory effects	Disease incidence	**7.43e-8**		
Ionising radiation	kg U235	**0.16**		
Carcinogenic effects	CTUh	**4.56e-9**		
Non-carcinogenic effects	CTUh	**3.45e-8**		
Ozone layer depletion	kg CFC-11	**2.20e-8**		

3/ Structural Distribution

Breakdown Structure
Total

4/ Analytics

Life-cycle phases

Indicator	Unit	Total
Environmental footprint	Points	1.30e-4
CO2 emissions	kg CO2	1.21
Land use	Points	8.40
Fossil depletion	MJ	14.73
Minerals and metals depletion	kg Sb	6.67e-6
Water use	m3 world deprived	0.80
Freshwater ecotoxicity	CTUe	42.20
Freshwater eutrophication	kg PO4	5.42e-4
Acidification	mol H+	4.92e-3
Marine eutrophication	kg N	1.29e-3
Terrestrial eutrophication	mol N	1.13e-2
Photochemical ozone creation	kg NMVOC	4.68e-3
Respiratory effects	Disease incidence	7.43e-8
Ionising radiation	kg U235	0.16
Carcinogenic effects	CTUh	4.56e-9
Non-carcinogenic effects	CTUh	3.45e-8
Ozone layer depletion	kg CFC-11	2.20e-8

Breakdown

Environmental footprint

Indicator	Value (Points)	Contribution (%)
CO2 emissions	3.14e-5	24.13 %
Freshwater ecotoxicity	1.90e-5	14.57 %
Fossil depletion	1.88e-5	14.46 %
Respiratory effects	1.12e-5	8.58 %
Freshwater eutrophication	9.45e-6	7.25 %
Minerals and metals depletion	7.92e-6	6.07 %
Water use	5.92e-6	4.54 %
Carcinogenic effects	5.75e-6	4.41 %
Photochemical ozone creation	5.51e-6	4.23 %
Acidification	5.49e-6	4.21 %
Non-carcinogenic effects	2.76e-6	2.12 %
Terrestrial eutrophication	2.37e-6	1.82 %
Marine eutrophication	1.95e-6	1.50 %
Ionising radiation	1.85e-6	1.42 %
Land use	8.40e-7	0.64 %
Ozone layer depletion	2.58e-8	1.98e-2 %
Total	1.30e-4	100 %

1/ Context of the study

Name	Revison	Report author	Publish Date
AMNorth_PBF-LB RF	A	Christian Renè Jakobsen Grashei	2024-5-10

EF 3.0 :

- **Environmental footprint (Points) :**
  Damage to the planet, measured in Points.
- **CO2 emissions (kg CO2) :**
  Method ILCD: Human emissions of greenhouse gases that cause environmental and social changes.
- **Land use (Points) :**
  Damage to the soil: a mixed between the erosion resistance, the mechanical filtration, the physico-chemical filtration, the groundwater regeneration and the biotic production.
- **Fossil depletion (MJ) :**
  Impact category for fossil fuels. Impacting the resource depletion as energy carriers.
- **Minerals and metals depletion (kg Sb) :**
  Represents the abiotic resource depletion, quantified in kg of antimony-equivalent (Sb-eq) per kg extraction.
- **Water use (m3 world deprived) :**
  Characterize the water depletion according to scarcity adjusted mass of water used.
- **Freshwater ecotoxicity (CTUe) :**
  Toxic effect on aquatic freshwater species. Measured in Comparative Toxic Unit for ecosystems.
- **Freshwater eutrophication (kg PO4) :**
  Refers to the excessive growth of aquatic plants or algal blooms, due to high levels of nutrients in freshwater.
- **Acidification (mol H+) :**
  Acidification is mainly caused by air emissions of NH3, NO2 and SOX.
- **Marine eutrophication (kg N) :**
  Marine eutrophication is one of the key local stressors for coastal marine ecosystems, particularly in those locations with many estuaries.
- **Terrestrial eutrophication (mol N) :**
  It does not only refers to organisms in soil or on plants but also to the inhabitants of aquatic sediments.
- **Photochemical ozone creation (kg NMVOC) :**
  Formed through the concentration of a variety of highly reactive gases in the atmosphere and are often implicated in problems of smog, crop damage and the degradation of works of art.
- **Respiratory effects (Disease incidence) :**
  Particulate matter formation and respiratory inorganics. Human health effects associated with exposure to PM2.5.

- **Ionising radiation (kg U235) :**
  Ionising radiation is the energy produced from natural or artificial sources. It has more energy than non-ionising radiation, enough to cause chemical changes by breaking chemical bonds. This effect can cause damage to living tissue.
- **Carcinogenic effects (CTUh) :**
  The emission of some substances (such as heavy metals) have impacts on human health (carcinogenic effects).
- **Non-carcinogenic effects (CTUh) :**
  Short-duration and intermittent exposures of humans to chemicals. Result in non-carcinogenic effects. Measured in Comparative Toxic Unit for human (CTUh).
- **Ozone layer depletion (kg CFC-11) :**
  Ozone depletion, gradual thinning of Earth's ozone layer in the upper atmosphere caused by the release of chemical compounds containing gaseous chlorine or bromine from industry and other human activities.

Life-cycle phases :

- Raw Material
- Manufacturing
- Packaging and Transport
- Product In Use
- End Of Life

2/ Overview: EF 3.0

Metric name	Unit	Value	Target	Comparison
Environmental footprint	Points	**3.76e-3**		
CO2 emissions	kg CO2	**29.45**		
Land use	Points	**85.92**		
Fossil depletion	MJ	**347.22**		
Minerals and metals depletion	kg Sb	**7.01e-4**		
Water use	m3 world deprived	**14.99**		
Freshwater ecotoxicity	CTUe	**1.09e+3**		
Freshwater eutrophication	kg PO4	**1.50e-2**		
Acidification	mol H+	**0.18**		
Marine eutrophication	kg N	**3.04e-2**		
Terrestrial eutrophication	mol N	**0.32**		
Photochemical ozone creation	kg NMVOC	**9.64e-2**		
Respiratory effects	Disease incidence	**1.62e-6**		
Ionising radiation	kg U235	**2.68**		
Carcinogenic effects	CTUh	**3.92e-8**		
Non-carcinogenic effects	CTUh	**1.04e-6**		
Ozone layer depletion	kg CFC-11	**4.66e-7**		

3/ Structural Distribution

Breakdown Structure
Total

4/ Analytics

Life-cycle phases

Indicator	Unit	Total
Environmental footprint	Points	3.76e-3
CO2 emissions	kg CO2	29.45
Land use	Points	85.92
Fossil depletion	MJ	347.22
Minerals and metals depletion	kg Sb	7.01e-4
Water use	m3 world deprived	14.99
Freshwater ecotoxicity	CTUe	1.09e+3
Freshwater eutrophication	kg PO4	1.50e-2
Acidification	mol H+	0.18
Marine eutrophication	kg N	3.04e-2
Terrestrial eutrophication	mol N	0.32
Photochemical ozone creation	kg NMVOC	9.64e-2
Respiratory effects	Disease incidence	1.62e-6
Ionising radiation	kg U235	2.68
Carcinogenic effects	CTUh	3.92e-8
Non-carcinogenic effects	CTUh	1.04e-6
Ozone layer depletion	kg CFC-11	4.66e-7

Breakdown

Environmental footprint

Indicator	Value (Points)	Contribution (%)
Minerals and metals depletion	8.32e-4	22.14 %
CO2 emissions	7.66e-4	20.39 %
Freshwater ecotoxicity	4.93e-4	13.11 %
Fossil depletion	4.44e-4	11.83 %
Freshwater eutrophication	2.62e-4	6.97 %
Respiratory effects	2.43e-4	6.48 %
Acidification	2.06e-4	5.49 %
Photochemical ozone creation	1.14e-4	3.02 %
Water use	1.11e-4	2.96 %
Non-carcinogenic effects	8.31e-5	2.21 %
Terrestrial eutrophication	6.63e-5	1.76 %
Carcinogenic effects	4.94e-5	1.32 %
Marine eutrophication	4.60e-5	1.22 %
Ionising radiation	3.18e-5	0.85 %
Land use	8.59e-6	0.23 %
Ozone layer depletion	5.48e-7	1.46e-2 %
Total	3.76e-3	100 %

APPENDIX D - AM DOCUMENTATION

Höganäs

CERTIFICATE OF ANALYSIS

Page: 1(1)

Lot number	Date	
3825851	2023-10-13	
OrdernumberH	Delivery	Shipment
0010695363	2867518	0

Item name
0717.074/5036 316L 45/15 ST

Item number
161755

CustomerH 73714
AM North AS
Havneveien 50,

NO-9610 Rypefjord
Norway

Quantity	YourRefH	ProddateH
160.000 Kg	001012	2023-07-17

forAM®
316L 15-45 VG
Multiple specification code
0717.074
0717.5036 - AM 4404 REV.1.7
VIGA Ar

Comments

Fe = balance

Multi specification code: Tightest limits of all specifications

	Test Result.	Unit.	Specification. MIN	MAX		ISSUE Date 202
CHEMICAL PROPERTIES						
Cr	17.8	%	17.0	18.5	%	
Ni	11.9	%	11.0	13.0	%	
Mo	2.3	%	2.0	2.5	%	
C	0.00	%		0.03	%	
Mn	1.5	%		2.0	%	
P	< 0.010	%		0.045	%	
S	0.003	%		0.015	%	
Si	0.2	%		1.0	%	
N	0.01	%		0.03	%	
O	0.02	%		0.05	%	
PHYSICAL PROPERTIES						
MICROTR.X100 vol.distri. 10 %	20	µm	16	20	µm	
MICROTR.X100 vol.distri. 50 %	30	µm	25	31	µm	
MICROTR.X100 vol.distri. 90 %	46	µm	40	47	µm	
MICROTR.X100 <= 15.00 µm	2	%		5	%	
Camsizer X2 MW SPHT3	0.9092					
Hall Flow 0.1 inch	13	sec/50g	12	25	sec/50g	
Apparent density, Hall	4.27	g/cm3	3.50		g/cm3	
SIEVE ANALYSIS						
ROTAP > 45 µm	5	%		5	%	

12:56:51 2023-10-13 DE2 COAMMS480AH-A4

For determination of conformance with applied specifications an observed value or calculated value is rounded to the nearest unit in the last right-hand significant digit used in expressing the limiting value. The described rounding method is in accordance with ASTM E 29 and DIN 1333."
Inspection certificate
EN 10 204 3.1

Approved by

J. Müller

Jörg Müller
Authorized Inspection Representative

APPENDIX D - 1 Certificate of Analysis for AM Powder

AM NORTH	Traceability List		
Made By:	Jan-Inge Kongsbak	**Revision** 1	**Revision date:** 08.01.2024
Doc.no:	AMN-03-05-0007	**Document according:**	DNV-ST-B203
Project Name:	**Part for gate valve**	**Client Name:**	**Vår Energi / UIS**
Project No:	300034	**Client reference:**	Part for gave valve
Project Leader:	Jan-Inge Kongsbak	**Client PO no:**	4900000174
		Client POC:	Trine Boyer
Item 1:			
Part Name:	**GT-Valve wedge**	**Client Part Name:**	GT-Valve wedge
Part no:	AMN-10000-300034-03-01-01	**Client Part no:**	1
DWG no:	AMN-10000-300034-03-02-01	**Client DWG no:**	1
DWG Rev:	1	**DWG Rev:**	1
Build file no:	AMN-10000-300034-03-03-240429	**Build ID:**	AMN-10000-300034-00940-11109
BPQ ID:	AMN-03-10-0001	**PQR no:**	AMN-03-08-0005
PPS no:	AMN-10000-300034-09-03		
Serial No:	AMN-10000-300034-03-01-01-01		
Item 2:			
Part Name:	**GT-Valve wedge_SLM**	**Client Part Name:**	GT-Valve wedge_SLM
Part no:	AMN-10000-300034-03-01-02	**Client Part no:**	2
DWG no:	NA	**Client DWG no:**	1
DWG Rev:	NA	**DWG Rev:**	1
Build file no:	AMN-10000-300034-03-03-240429	**Build ID:**	AMN-10000-300034-00940-11109
BPQ ID:	AMN-03-10-0001	**PQR no:**	AMN-03-08-0005
PPS no:	AMN-10000-300034-09-03		
Serial No:	AMN-10000-300034-03-01-02-01		
	AMN-10000-300034-03-01-02-02		
	AMN-10000-300034-03-01-02-03		
AM North AS Date: 26.05.2024 Sign:			

APPENDIX D - 2 Traceability list: AMN-03-05-0007

AM NORTH				Build Traceability		
Made By:	Jan-Inge Kongsbak	**Revision**	1	**Revision date:**	09.01.2024	
Doc.no:	AMN-03-05-0009	**Document according:**		DNV-ST-B203		
Project Name:	Part for gate valve	**Client Name:**		Vår Energi / UIS		
Project No:	300034	**Client reference:**		Part for gate valve		
Project Leader:	Jan-Inge Kongsbak	**Client PO no:**		4900000174		
		Client POC:		Trine Boyer		
Build plate SN:	AMN-BP-304-0001	**Build start date:**		08.05.2024		
Build Material:	316L	**Build end date:**		11.05.2024		

Build plate setup:

	A	D	C	D	E	F	G	H	I	J
1	Tensile 2	Kube 2							Kube 1	Tensile 1
2										
3						Wedge_SLM				
4	Charpy 1-3-2									Charpy 1-3-2
5				Tensile 3		Wedge_SLM				
6										
7				Wedge		Wedge_SLM				
8										
9										
10	Tensile 4									Tensile 5

X direction: from 10 to 1, Y direction: from A to J, Z direction: Up
Row 1: Gas flow inlet to build chamber
Row 10: Gas flow outled from build chamber
Column J: Recoater rest positions. Recoater moved from J to A, and in same sequence from A to J, before rest in between layers.

Part no:	SN:	BP Location:	Comment:
AMN-10000-300034-03-01-01	AMN-10000-300034-03-01-01-01	D7	
AMN-10000-300034-03-01-02	AMN-10000-300034-03-01-02-01	F3	Parts not marked, traceability lost
AMN-10000-300034-03-01-02	AMN-10000-300034-03-01-02-02	F5	Parts not marked, traceability lost
AMN-10000-300034-03-01-02	AMN-10000-300034-03-01-02-03	F7	Parts not marked, traceability lost

Sample no:	Sample DWG:	Method:	BP Location:	Comment:
T1	AMN-GEN-03-06-01-03-01	Tensiel	J1	
T2	AMN-GEN-03-06-01-03-01	Tensiel	A1	
T3	AMN-GEN-03-06-01-03-01	Tensiel	D5	
T4	AMN-GEN-03-06-01-03-01	Tensiel	A10	

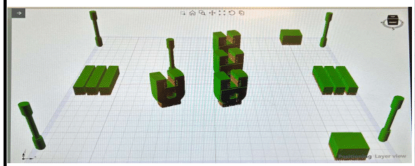
T5	AMN-GEN-03-06-01-03-01	Tensiel	J10	
C1	AMN-GEN-03-06-01-01-01	Charpy	J4-6	Flip X and Y direction
C2	AMN-GEN-03-06-01-01-01	Charpy	J4-6	Flip X and Y direction
C3	AMN-GEN-03-06-01-01-01	Charpy	J4-6	Flip X and Y direction
C4	AMN-GEN-03-06-01-01-01	Charpy	A4-6	Flip X and Y direction
C5	AMN-GEN-03-06-01-01-01	Charpy	A4-6	Flip X and Y direction
C6	AMN-GEN-03-06-01-01-01	Charpy	A4-6	Flip X and Y direction
K1	AMN-GEN-03-06-01-02-01	ANY	I1	
K2	AMN-GEN-03-06-01-02-01	ANY	A1	

AM North AS
Date: 26.05.2024
Sign:

APPENDIX D - 3 Build traceability: AMN-03-05-0009

AM NORTH		Test Speciments Traceability			
Made By:	Jan-Inge Kongsbak	**Revision**	1	**Revision date:**	09.01.2024
Doc.no:	AMN-03-06-0005	**Document according:**	DNV-ST-B203		
Project Name:	**Part for gate valve**	**Client Name:**	**Vår Energi / UIS**		
Project No:	300034	**Client reference:**	Part for gate valve		
Project Leader:	Jan-Inge Kongsbak	**Client PO no:**	4900000174		
PPS ref:	AMN-10000-300034-09-03	**Client POC:**	Trine Boyer		
ITP ref:	AMN-10000-300034-09-02				
ITP Item:	4.6 to 4.9				
Testing Provider	QLAB AS	**Testing order no:**	TBC		
Adress:	Strandsvingen 3, 4032 Stavanger	**Contact Info:**	TBC		

Build plate setup:



	A	D	C	D	E	F	G	H	I	J
1	Tensile 2	Kube 2							Kube 1	Tensile 1
2										
3						Vedge_SLM				
4										
5	Charpy 1-3-2			Tensile 3		Vedge_SLM				Charpy 1-3-2
6										
7				Vedge		Vedge_SLM				
8										
9										
10	Tensile 4									Tensile 5

Sample no:	Sample DWG:	Method:	BP Location:	Build direction	Comment:
T1	AMN-GEN-03-06-01-03-01	Tensiel	J1	P-BD	P-BD (pararell to build direction)
T2	AMN-GEN-03-06-01-03-01	Tensiel	A1	P-BD	
T3	AMN-GEN-03-06-01-03-01	Tensiel	D5	P-BD	
T4	AMN-GEN-03-06-01-03-01	Tensiel	A10	P-BD	
T5	AMN-GEN-03-06-01-03-01	Tensiel	J10	P-BD	
C1	AMN-GEN-03-06-01-01-01	Charpy	J4-6	P-BD	Flip X and Y direction
C2	AMN-GEN-03-06-01-01-01	Charpy	J4-6	P-BD	Flip X and Y direction
C3	AMN-GEN-03-06-01-01-01	Charpy	J4-6	P-BD	Flip X and Y direction
C4	AMN-GEN-03-06-01-01-01	Charpy	A4-6	P-BD	Flip X and Y direction
C5	AMN-GEN-03-06-01-01-01	Charpy	A4-6	P-BD	Flip X and Y direction
C6	AMN-GEN-03-06-01-01-01	Charpy	A4-6	P-BD	Flip X and Y direction
K1	AMN-GEN-03-06-01-02-01	Material	I1	P-BD	
K2	AMN-GEN-03-06-01-02-01	Material	A1	P-BD	

APPENDIX D - 4 Test specimens traceability: AMN-03-06-0005

MANUFACTURING PROCEDURE SPECIFICATION

DOCUMENT ACCODRING TO:
DNV-ST-B203

Project Title:	**Part for gate valve**	**Client Name:**	**Vår Energi / UIS**
Project No:	**300034**	**Client Ref:**	**Part for gate valve**
Project Leader:	**Jan-Inge Kongsbak**	**Client PO no:**	**4900000174**
MPS no:	**AMN-MPS-300034-01-01**	**Client POC:**	**Trine Boyer**

AM NORTH Doc No: AMN-03-01-0011
30. OKTOBER 2023
AM NORTH AS

APPENDIX D - 5 MPS: AMN-03-01-0011

REVISION HISTORY

REVISION	PREPARED BY	DATE:	CLIENT: APPROVED BY	CLIENT: APPROVED DATE
1.0	JAN-INGE KONGSBAK	19.04.2024	Christian Renè Jakobsen Grashei	
1.1	JAN-INGE KONGSBAK	26.05.2024	Christian Renè Jakobsen Grashei	

REVISIONDETAILS

REVISION	CHANGE DETAIL
1.0	Issued for review
1.1	Heat treatment skipped and removed with comment, and “part no” changed.

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

Innhold

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

1. SCOPE

1.1. Purpose

Purpose of this document is to provide an overall plan and description of the manufacturing and post-processing of the ordered part(s).

A defined manufacturing procedure specification (MPS) shall be established by AM North, outlining the plan to produce a part or parts. The MPS shall address all factors that affect the quality, repeatability, and reliability of manufacturing, including subcontracted processes. Every principal production step within the scope of the manufacturer shall be addressed.

When this MPS is agreed upon and signed by the purchaser, AM North will initiate production.

1.2. Part(s) description

In this project there has been quoted to produce 4 parts:

3ea – GT-Valve Wedge AM North part no: AMN-10000-300034-03-01-01
Material: 316L

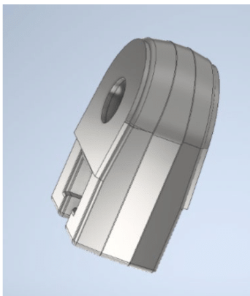


Figure 1: GT-Valve Wedge_SLM model

1ea – GT-Valve Wedge_SLM AM North Part no: AMN-10000-300034-03-01-02
Material: 316L

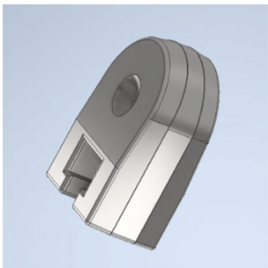


Figure 2: GT-Valve Wedge Model

Manufactured according to DNV-ST-B203 AMC2

Parts are manufactured by 3D-Printing with technology: Powder bed fusion – laser beam (PBF-LB)

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

Parts are for a student writing his bachelor's degree on AM Manufacturing. These parts will be manufactured and tested according to AMC2 for research only and will not be installed in any valve for any industrial purposes.

2. MATERIAL

2.1. Raw material properties

Powder feedstock for PBF-LB: 316L 15-45µm

For feedstock material properties, see attached material certificate with LOT: 3825851

AM North will also send a powder sample to Christian (UIS) with the parts manufactured.

2.2. Properties after printing

Mechanical and metallurgical properties shall be in accordance with the relevant design or material acceptance criteria from standard:

See also acceptance criteria for non-destructive testing in DNV-ST-B203 chapter 8.3.

3. MANUFACTURING PROCEDURES

3.1. Manufacturing factory and site

Manufacturer: AM North AS – Org: 930 841 560
Factory site: Polarbase, Havneveien 50 Bygg 23, 9610 Rypefjord
Established: 2023
MD: Jan-Inge Kongsbak, Phone: 97981973, Mail: jan.inge@amnorth.no

Machine used in manufacturing of parts: DMG Mori Lasertec 30 SLM – 2nd generation. ID: 91530000940
Feedstock: Metal powder alloy from Hoganas
Build Plate material: SS 304 – 1.4301
Gas shielding: Argon 4.8
Max build dimensions: 300x300x300 mm

Certifications: NA

3.2. The process sequence and steps of manufacturing

1. Models of the parts to be manufactured are developed and provided to AM North by purchaser. AM North do a feasibility inspection on the model for AM Manufacturing.
2. Pre-Print data preparation: Model are placed on build plate, elevated 4mm form build plate, oriented, supported, and sliced through software AM-Studio and which generate a build file. Build file is not hatched and is sliced by 50µm layer height settings.
3. Build file are transferred by USB stick from office computer to the Lasertec 30 SLM (ID:91530000940)
4. Test sample build is also loaded to the machine with the agreed upon dimensions and quantities.
5. Machine-turnaround are always done after the print prior. Build plate is loaded and machine is prepared for next print. This is checked and cleared by AM North at this point.
6. Parts are hatched and with hatching parameter:
7. Laser parameter name:

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

8. AM North go through the prestart check list. (Powder amount, gas, filter status..ect..) And do the prestart operations.
9. The machine and laser are turned on. The process from here to build finished is done without the operator, but it is monitored and checked up on occasionally.
10. Build plate with parts are extracted from the machine.
11. Build plate is heat treated.
12. Parts are brought to a 3rd party (Oss-Nord) where the parts and build plate are separated by band saw.
13. Support removal by hand pliers and, hammer and chisel.
14. Part surface smoothened with straight grinder.
15. Parts are glass blasted for better surface finish.
16. Pars and test samples is packed and shipped.

3.3. Data preparation

3.3.1. 3D Model

Part model is provided by the purchaser. No changes are made by AM North.

Model is checked by AM North operator to determine feasibility for print.

AM North has given the model its own name for traceability purposes.

Model is converted to STL to be able to import in slicing software.

3.3.2. Orientating & supporting

Parts are turned 180deg, upside down as shown in figure 3.

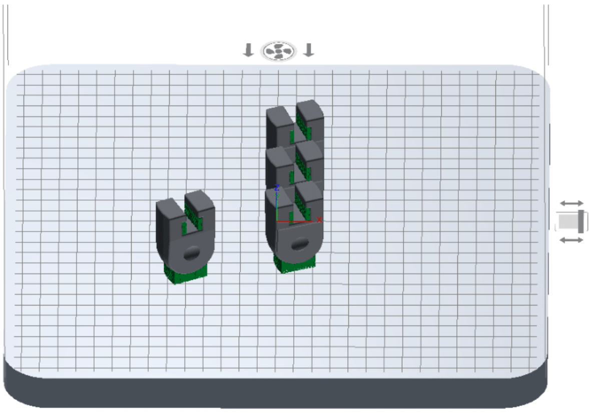


Figure 3: Part orientation and supporting

Parts are placed In position F3, F5, F7 & D7.

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

	A	B	C	D	E	F	G	H	I	J
1										
2										
3						Wedge_SLM				
4										
5						Wedge_SLM				
6										
7				Wedge		Wedge_SLM				
8										
9										
10										

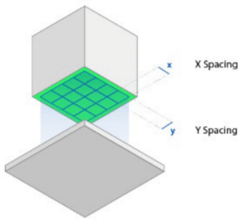


Figure 4: Block spacing

Supported to build plate with block support. 1.0mm block spacing

Supported in overhang with block support to mesh. 1.5mm block spacing

3.3.3. Slicing

Slicing is done with AM Studio software. 50µm layer height and 4mm elevation from build plate to be able to use band saw without cutting in parts.

Hatching is done in machine with hatching parameters:

Parts are 47mm high, giving 940 layers.

GT-Valve Wedge_SLM Bonding box: 43x28,6x32,33mm
GT-Valve Wedge Bonding box: 43x28,58x32,89mm

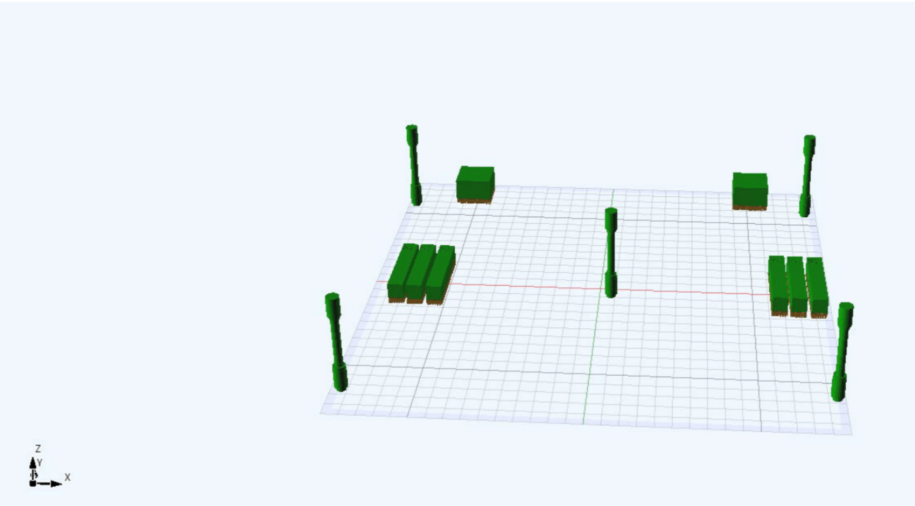
3.3.4. Printing job preparation

After slicing, the build file is transferred to the machine using a UBS Stick.

Hatching and sorting of supports are done on machine.

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

Test samples are added to the build plate:
5x Tensile bars
2set = 6x Impact samples
2x block samples



3.4. Printing

3.4.1. Machine preparation

Machine is usually made ready from the previous job. At this stage, the operator does the preprint check list.

1. Pre-purge check list

-Build plate is inserter. Note the build plate serial number.

-Powder trash bins are checked.

-Powder feedstock level is checked.

-Gas level on rack is checked.

-Recoater lip is changed or non-damaged.

-Lence is cleaned

2. During gas purging

-Filter capacity is checked.

-No leakage on machine

-Machine is reaching oxygen levels.

-Build plate leveled

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

-Build chamber pressure limit reached.

If any of the mentioned checkpoint fail its acceptance criteria, actions are taken do adjust.

Before print starts, the operator notes the build name and the operator name.

3.4.2. Printing

Printing starting and the operator scans the print QR-Code to log the print start.

Print is monitored occasionally during print.

Laser parameter:

3.4.3. Ends printing

When the print is finished, the operator scans the QR-Code again to log ending information of the print and any error, problems or similar.

Operators empties the powder leftover and extract the build plate with parts from build chamber.

Parts are inspected for any damage or anomalies. Photos are taken.

3.5. Post-processing

3.5.1. Powder cleaning

Any left over powder on build plate and parts are removed using vacuum cleaner.

3.5.2. Heat-Treatment

~~Build plate with parts are moved to furnace for heat treatment.~~

~~Prior heat treatment, one of the block samples are removed from build plate to be sent to UIS without being heat treated.~~

~~Heat treatment is done as below:~~

1. ~~Heating to 650 ºC~~
2. ~~Hold 2 hours at 650 ºC~~
3. ~~Heating to 820 ºC~~
4. ~~Hold 1 hour at 820 ºC~~
5. ~~Cooling in the furnace to ambient temperature~~

Heat treatment skipped due to manufacturer issues. Accepted by customer.

3.5.3. Removing supports

Supports are removed using clippers, pliers, hammer and chisel, and straight grinder.

Part surface is smoothened after support are removed with fine tools on straight grinder.

3.5.4. Sandblasting

Glass blasting is done.

3.6. Inspection

3.6.1. Visual inspection

Visual inspection is done on part.

Report issued to purchaser.

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

3.6.2. Dimension inspection

Dimensional control is done and report is issued to purchaser prior shipping of parts.

3.6.3. Mechanical properties testing

NA – Done by purchaser

3.6.4. NDT

NA – Done by purchaser

3.6.5. Final inspection

NA – Done by purchaser

3.6.6. Manufacturer Compliance Record

Delivered with the pars manufactured, AM North will issue a Manufacturer Compliance Record containing all documentation throughout the manufacturing of agreed upon items.

To be delivered latest 7 days after final inspection is completed.

Org.Nr: 930 841 560
Adresse: Havneveien 50, 9610 Rypefjord
Mail: jan.inge@amnorth.no
Tlf: +47 97 98 19 73

AM NORTH

INSPECTION & TEST PLAN (ITP)

Made By:	Jan-Inge Kongsbak	Date:	08.01.2024	Revision:	1
Doc.no	AMN-03-03-0002		Acc.Standard:	DNV-ST-B203	

Customer Name:	Vår Energy / UIS	Document #:	AMN-ITP-300034-01-01
Contract/PO #:	4900000174	Rev #:	1
QA Agreement #:		Prepared By:	Jan-Inge Kongsbak
Part/Drawing #:	1	Approved By:	
Discription:	Parts to be shipped to service provider when post processing is done by AM North. Testing and similar done by client Reports to be provided AM North for final MCR to be made.		

Item #	Activity	Frequency	Records	Acceptance Criteria	Inspection Preformed by:	Inspection: What/who Employee	Service provider	Client	Notes
1 Data Preparation									
1.1	3D Model Inspection	The 3D Model first generated/Changed	NA	NA	Client			H	Done prior AM North involement
1.2	Support design Inspection	Supports first generated/changed	MPS	Client approval	Client	H		W	
1.3	Slicing file inspection	Slicing file implemented/changed			Employee	S			
1.4	Printing job file inspection	Printing task file first generated/changed			Employee	S			
2 Printing									
2.1	Machine preparation	Printer prepared prior print	Pre-Print Check list		Employee	S			
2.2	Print		Print record/Photos		Employee	S			
2.3	Post print inspection	Print end	Photos	Client approval	Client	H		W	
3 Post-processing									
3.1	Heat treatment	End of HT	HT Log	AMN Procedure	Employee	H			HT skipped, accepted by client
3.2	Post prosessing inspection	Every part	Visual control / Photos	Client approval	Client	H			
3.3	Machining						H		Parts shipped to STAMAS
4 Inspection									
4.1	Visual inspection		Visual inspection report	No visible damages	Service Provider		H		
4.2	Dimentional Control		Dimentional control report	All dim. Within tolerances	Service Provider		H		
4.3	NDT - VT				Client			H	
4.4	NDT - PT				Client			H	
4.5	NDT - RT				Client			H	
4.6	Tensile Testing				Client			H	
4.7	Impact testing				Client			H	
4.8	Hardness measurements				Client			H	
4.9	Microstructial assesment				Client			H	
4.10	Macrostructual assesment				Client			H	
4.11	Porosity assesnebt				Client			H	
4.12	Chemical analysis				Client			H	

Key

W= Witness point — A witness point provides a party (such as the customer, service provider and regulatory authority) with the opportunity to witness the inspection or test or aspect of the work at their discretion.

H= Hold point — A hold point defines a point beyond which work may not proceed without the authorisaton of a designated service provider or authority. Ex. 3.party testing.

S= Surveilance or monitoring by supervisor

X= Self inspection by employee performing the work

AM North AS
Date: 26.05.2024
Sign:

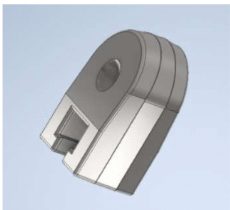
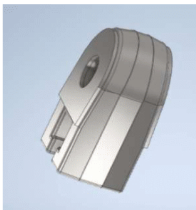
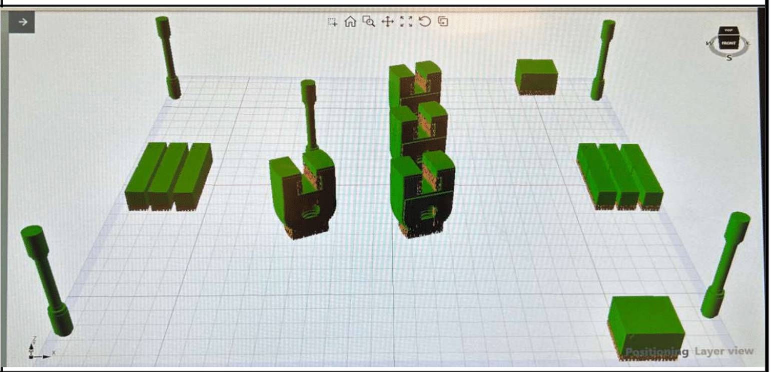
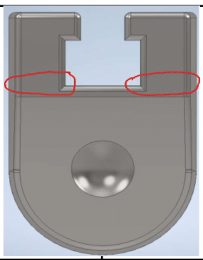
APPENDIX D - 6 ITP: AMN-03-03-0002

AM NORTH		Part Production Spesification (PPS)			
Made By:	Jan-Inge Kongsbak	Date:	02.01.2024	Revision:	1
Doc.no:	AMN-03-08-0004	Doc acc:	DNV-ST-B203		

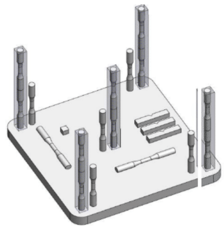
Project Name:	Part for gate valve	Client Name:	Vår Energy / UIS
Project No:	300034	Client reference:	Part for gate valve
Project Leader:	Jan-Inge Kongsbak	Client PO no:	4900000174
		Client POC:	Christian Renè Jakobsen Grashei
PPS no.:	AMN-10000-300034-09-03	Revision no:	1
Supporting BPQR ID no.:	AMN-03-10-0001	Date:	28.04.2024
Manufacturer/comany:	AM North AS	Approved by:	DNV (liksom)
Site:	Polarbase Rypefjord	Approver name:	TBC
Part no:	AMN-10000-300034-03-01-01 AMN-10000-300034-03-01-02	PQR ID no.:	AMN-03-08-0005
Build file ID:	AMN-10000-300034-03-03-240429	Build file version:	01
AM Process:	PBF-LB. Powder bed fusion with laser beam melting. Hatching 254 watt on 0.07mm focus point.		
Welding process:	PBF-LB	Feedstock feed mechanism:	Recoater
Power Source:	Laser beam	Positioner:	NA
Computer control system:	CELOS 1.10.0	Build preparation software:	AM Studio & CELOS
Atmosphere control, temperature:	NA	Atmosphere control, shielding:	Inert gas chamber. 0.1-0.15% Oxygen
Consumable classification or trade name:	Hoganas - 316L 15-45 VG	Wire diameter:	NA
Laser Parameter	LT30SLM_1.4404_50µm_1947_2_03		
Laser defenition:	50µm	Layer Structuring:	Stripes 10mm, 31deg layer rotation
Build parameter	LT30SLM_1.4404_50µm_1947_1Lip2Way-Copy		
Build plate heater:	200 deg	Gas flow	850 l/min
Scans of first layer	3	Mimimum layre duration	30sec
Dynamic temperature adjustments	Off		

AM North AS
Date: 26.05.2024
Sign:

APPENDIX D - 7 PPS: AMN-03-08-0004

AM NORTH	Part Qualification Record (PQR)				
Made By:	Jan-Inge Kongsbak	Date:	02.01.2024	Revision:	1
Doc.no:	AMN-03-08-0005	Doc acc:	DNV-ST-B203		
PQR ID no.:	AMN-03-08-0005	Date:	19.04.2024		
Manufacturer/comany:	AM North AS	Approved by:	DNV (liksom)		
Operator name:	Jan-Inge Kongsbak	Approver name:	TBC		
AM Process:	PBF-LB	Reference to BPQR ID no.:	AMN-03-10-0001		
Part Description:	High critical part form a valve - Massive 316L, boinding box 30x21x43				
Part 3D-Model no.:	AMN-10000-300034-03-01-01 AMN-10000-300034-03-01-02	Build file ID no.:	AMN-10000-300034-03-03-240429		
Image of part: (insert image of part taken from CAD viewer or build preparation software)	 				
Image of build platform: (insert image of build platform taken from build preparation software. The image shall clearly show the orientation, placement and number of part(s) and test specimens.)					
Specimens:	Tensile	5 x P-BD (pararell to build direction)			
	Impact	2 set (3) P-BD			
	Material sample	2 x P-BD			
Definition of critical area(s): insert description of critical area, preferably including image.	Critical area shown in picture, critical area due to transition between thick and thin geometry, and sharp corner. Potentially break area is also is also perpandicular to layers Z direction.				

Date of test specimen production:		11.05.24	
Image of test specimen extraction:			
Log of voltage during build:	NA	Log of current during build:	NA
Log of wire feed rate during build:	NA	Log of gas flow rate during build:	See excel file "gas flow log from wedge print"
Log of oxygen content in atmosphere during build 1):	See excel file "oxygen log from wedge print"	Log of temperature during build 2):	NA
1) Relevant for oxygen sensitive materials, such as duplex or titanium alloys. 2) If built in a closed chamber.			
AM North AS Date: 26.05.2024 Sign:			
AM North AS Date: 26.05.2024 Sign:			

AM NORTH		**Build process qualification record (BPQR)**			
Made By:	Jan-Inge Kongsbak	Date:	02.01.2024	Revision:	1
Doc.no:	AMN-03-10-0001	Doc acc:	DNV-ST-B203		
BQR ID no.:	AMN-03-10-0001		Date:	17.04.2024	
Manufacturer/comany:	AM North AS		Approved by:	DNV (liksom)	
Operator name:	Jan-Inge Kongsbak		Approver name:	TBC	
AM Process:	PBF-LB				
Part 3D-model no.:	AMN-10000-300034-03-01-01 AMN-10000-300034-03-01-02		Buildfile ID no.:	AMN-10000-300034-03-03-240429	
Build process qualification test setup according to DNV-ST-B203: 					
Deposition strategy:		10mm Stripes, 31deg per layer			
Tensile specimens, thick coupon: 3 x P-BD direction (T1, T2, T3) 3 x P-DP direction (T4, T5, T6). Tensile specimens, thin coupon: 3 x P-BD direction (T7, T8, T9) 3 x P-DP direction (T10, T11, T12)		ISO 6892-1 Round tensile specimens Ø 6 mm			
Impact specimens, thick coupon: 3 x notch in P-BD direction (C1, C2, C3)		ISO 148-1 Charpy V-notch 10 mm x 10 mm			
2 x cube for macrostructure, microstructure, porosity and hardness, from the thick and thin coupon (M1 and M2)		20 mm x 20 mm x 20 mm			
Chemical analysis sample from remaining material		ASTM A751			
Log of voltage during build:	NA		Log of current during build:	NA	
Log of wire feed rate during build:	NA		Log of gas flow rate during build:	l file "gas flow log from wed	
Log of oxygen content in atmosphere 1:	e excel file "oxygen log from wedge prin		Log of temperature in atmosphere 2:	NA	

AM North AS
Date: 26.05.2024
Sign:

APPENDIX D - 9 BPQR: AMN-03-10-0001

AM NORTH

AM North AS
Havneveien 50
Rypefjord Finnmark 9610 Norway
+4797981973
jan.inge@amnorth.no

Packing Slip
SH-700040

SHIPMENT DETAILS

Ship Date
5/19/2024

Carrier
Tracking Number
Invoice Ref. Number

SHIP TO

Company
Vår Energi

Shipping Address
Hammaren 9A
Stavanger 4056 Norway

Contact
Trine Boyer
trine.boyer@varenergi.no
+4797758690

Items in Shipment

AO:300034 **UIS Bachelor del** **Order Date: 5/19/2024**

#	Item	Shipment Qty
1	GT-Valve wedge	4ea

Powered by StartProto

Last edit was made Sun May 19 20243:45:35 PM by Jan-Inge Kongsbak

1/1

APPENDIX D - 10 Packing slip

AM NORTH

AM North AS
Havneveien 50
Rypefjord Finnmark 9610 Norway
+4797981973
jan.inge@amnorth.no

Quote
RFQ:001002

CUSTOMER INFO

Company
Vår Energi
Billing Address
Shipping Address
Contact
Trine Boyer
trine.boyer@varenergi.no
+4797758690

QUOTE DETAILS

RFQ Reference
UIS Bachelor part
RFQ Date
7/30/2023
Customer Reference
Expiration Date
5/30/2024

Items in Quote

#	Item	SKU	Qty	Lead Time	Unit Price	Subtotal
1	GT-Valve wedge		4	3 day(s)	NOK 1,663.961	NOK 6,655.844
				6 Price Opts available for this item		
		Price Break Opts: This option is not included in the Subtotal	1ea	3 days	NOK 4,501.854	NOK 4,501.854
			4ea	3 days	NOK 1,663.961	NOK 6,655.844
			5ea	3 days	NOK 1,496.222	NOK 7,481.11
			10ea	3 days	NOK 1,116.0625	NOK 11,160.625
			20ea	3 days	NOK 916.572	NOK 18,331.44
			50ea	3 days	NOK 823.656	NOK 41,182.80
2	Frakt		1 ea	3 day(s)	NOK 550.00	NOK 550.00
				Subtotal	**NOK 7,205.844**	
				Total	**NOK 7,205.844**	

Notes

Pris eks MVA
Frakt kommer i tillegg

Terms and Conditions

ACCEPTING A QUOTE FOR THE MANUFACTURING OF A PART CONSTITUTES THE ACCEPTANCE OF THE MANUFACTURING AGREEMENT BY THE PURCHASER WITH THE FABRICATOR.

The following terms are the "Manufacturing Agreement" and apply between AM North and a Purchaser/customer with respect to any Order in the absence of Custom Manufacturing Terms.

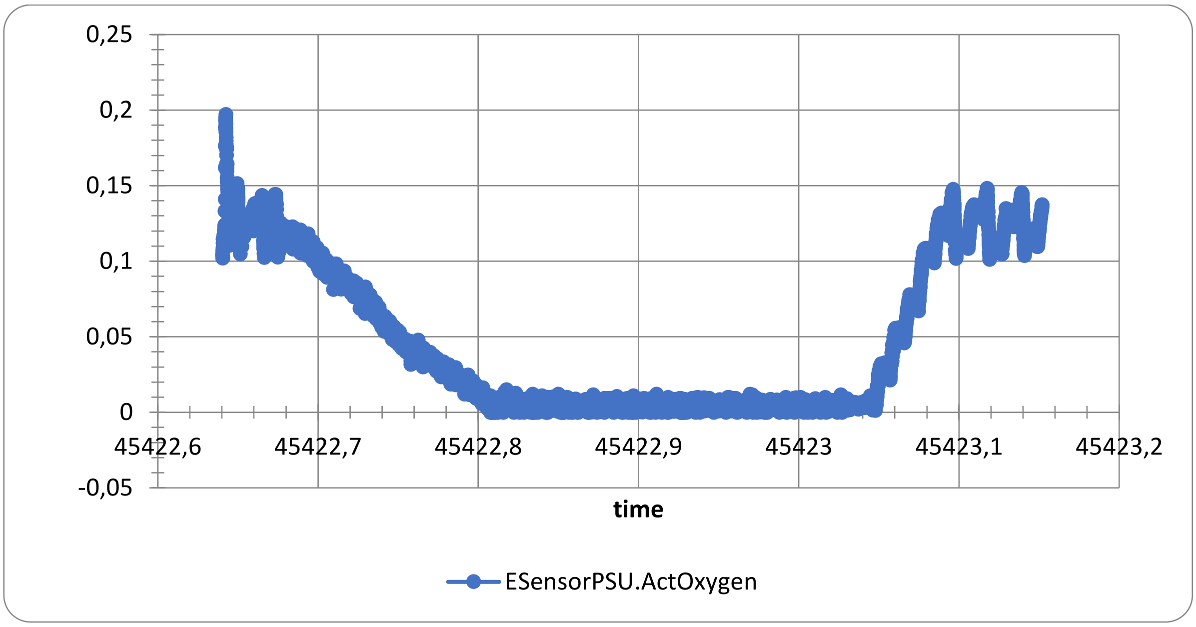
A. Consequential Damages
AM North AS Disclaim responsibility for economic or non-economic loss that our products cause, unless it can be demonstrated that AM North AS has been guilty of gross negligence or intent. Liability for the indirect losses is waived in any case. All cases of reduced or discontinued production, turnover, loss of profit or other consequences of our product not being able to be used as intended are considered indirect losses. Indirect loss is also considered damage to something other than our product, including processes/things our product is used for in production of, or which has a close and direct connection with the use of our product. AM North AS' liability for damages is in all cases limited to 10.000 NOK per product, regardless of the number of cases of the damage each product causes.

B. Delivery disclaimers
The delivery lead time is counted from the day AM North receives signed PO from customer/purchaser.
The delivery date and the quoted price are based on the following assumption(s):
- That there are no delays or increased time spent due to conditions that AM North is not to blame.
- That there are no delays or increased time spent due to machine breakdown.
- After the agreement is done, no revision or process changes are made to the
current product. Any changes in product or manufacturing will be charged, documented through change order requests (COR)

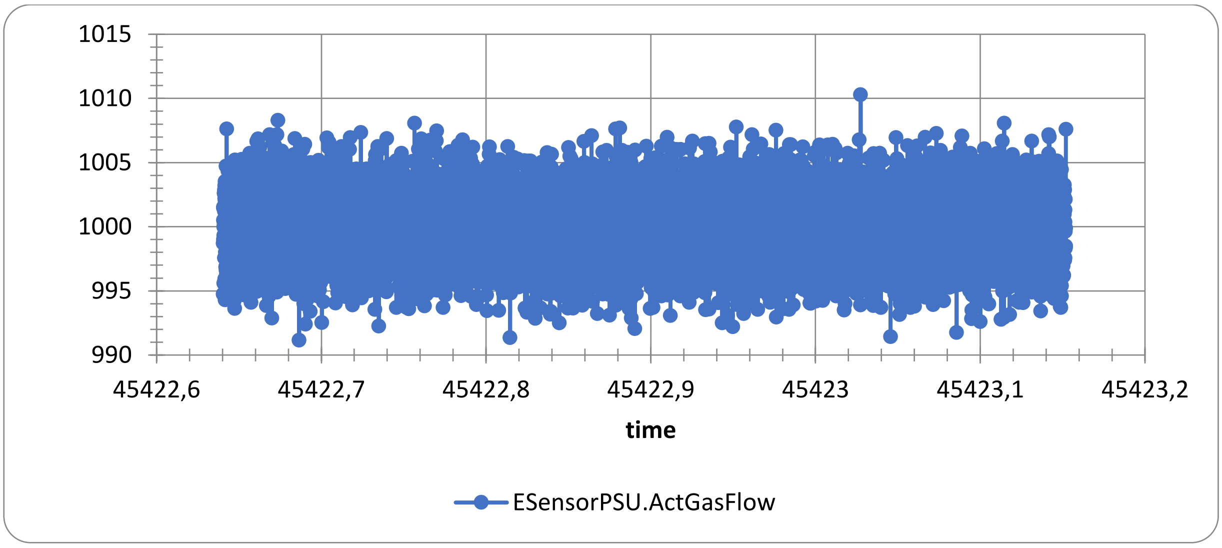
C. IP responsibility
-The customer warrants and bears the responsibility that the submitted drawing / file as 3D-printed does not infringe any existing IP rights, including patent, design and / or copyright. If the Customer uses a drawing / file that the Customer is aware of infringes on the rights of third parties, this is considered a breach of the agreement.
-If a third party holds the Institute liable for infringement of its IP rights, including but not limited to patents, design, and / or copyright or other rights to a product caused by work performed by the Institute for the Customer, the Customer is obliged to hold the xxx indemnified for any claim that may be brought against the xxx. The xxx may request the customer to defend such a claim on behalf of the xxx.

D. Product tolerances and/or limitations on SLM (Metal printing)
-SLM tolerance ±0.2 mm +0,2% of dimension. If tolerances on given surfaces are required to be tighter than the mentioned limitations, Customer is obligated to inform AM North.
-Max build volume available: 300x300x300 mm.
-Large parts can be split on agreement with purchaser before printing, and then mechanically assembled before delivery. This can affect tolerances.
-Split and assembly can also be done to smaller parts to optimize orientation and/or geometry.
-Dialog for critical measurements is preferred.
-Geometry of large parts can affect tolerances.
-In additive manufacturing processes there is always a risk for deviation in Z-axis of ± 2 layers (reaching 30-100µm each).

APPENDIX D - 11 AM North Quote 1PC-50PC

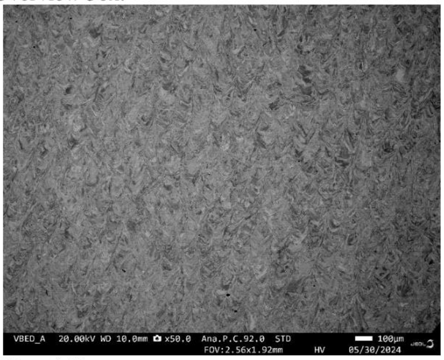
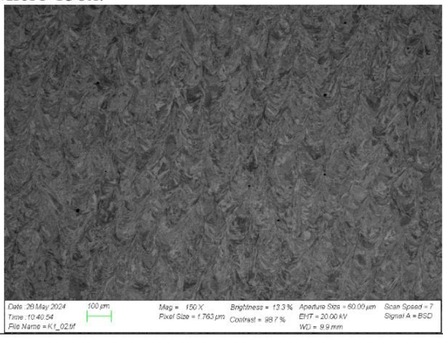


APPENDIX D - 12 Oxygen flow log from print



APPENDIX D - 13 Gas flow log from print

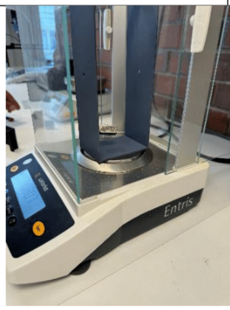
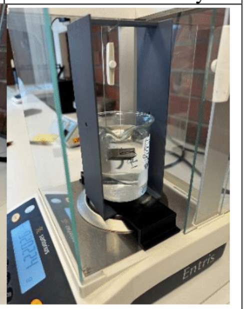
Microstructural Assessment

Test procedure:		- Cross sections cut and polished. Final step: Chem - Cross section etched with OP-S - Image gained by SEM.	
Reference to standard:		DNV-ST-B203	
Specimen type:		Cube, K1	
Specimen dimensions		12.5 mm x 12.5 mm x 12.5 mm	
Acceptance criteria:		N/A	
Testing performed by:		Christian René Jakobsen Grashei/ Espen Undheim	
Date of testing:		29.05.24	
Acceptance Criteria:		N/A	
Description/ image of area(s) analyzed:	XZ-cross section of cube	Magnification:	Overview: 50x Micro: 150x
Part thickness at sectioning plane:	12.5	Orientation:	XZ-plane visible
Image of microstructure :		Overview 50x:  Micro 150x: 	

Macrostructural assessment

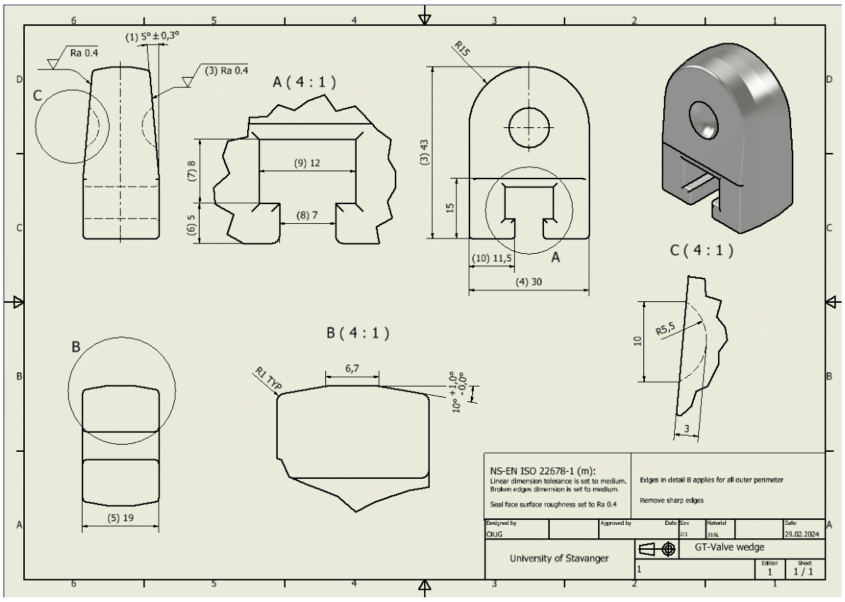
Test procedure:		- Cross sections cut and polished. Final step: 1µm NAP - Cross section etched with electrolyte Oxalic acid 10wt%, 8V, 2x 45s - Image gained by light microscope	
Reference to standard:		DNV-ST-B203	
Specimen type:		K1 Cube	
Specimen dimensions		12.5 mm x 12.5 mm x 12.5 mm	
Acceptance criteria:		N/A	
Testing performed by:		Christian René Jakobsen Grashei	
Date of testing:		24.05.2024	
Acceptance Criteria:		N/A	
Description/ image of area(s) analyzed:	XZ-cross section of cube	Magnification:	5x
Part thickness at sectioning plane:	25 mm	Orientation:	XZ-plane
Image of microstructure :			

Porosity assessment

<table>
<tr><td>Test procedure:</td><td colspan="3">Cross sections cut.
Archimedes method: Weigh part in air, and weigh part in water and use density formula.
Check result towards actual density and calculate percentage difference.</td></tr>
<tr><td>Reference to standard:</td><td colspan="3"></td></tr>
<tr><td>Specimen type:</td><td colspan="3">Half of test block</td></tr>
<tr><td>Specimen dimensions</td><td colspan="3">12.5 mm x 25 mm x 11.9 mm</td></tr>
<tr><td>Acceptance criteria:</td><td colspan="3">Max 0.5%</td></tr>
<tr><td>Testing performed by:</td><td colspan="3">Christian René Jakobsen Grashei</td></tr>
<tr><td>Date of testing:</td><td colspan="3">23.05.2024</td></tr>
<tr><td>Density of 316L</td><td colspan="3">Min: 7.85, Max: 8.05</td></tr>
<tr><td>Description/ image of area(s) analyzed:</td><td>XZ-cross section of cube</td><td>Magnification:</td><td>N/A</td></tr>
<tr><td>Masses:</td><td>$m_{air} =$ 24.2715
$m_{water} =$ 21.2159</td><td>$\rho_{sample} = \frac{w_{air}}{w_{air} - w_{water}}$</td><td>= 7.8098655
→ 0.511% porosity (including thread) using Min. value of density.</td></tr>
<tr><td>Images:</td><td colspan="3"></td></tr>
</table>

Measurement report

Image of part:			
Measured item nr. Ref to dwg below		Measurements given in mm.	
Measurement:	Methods:	Result:	Ref drawing
Seal surface:	CMM & Surface roughness	*(1) = *9.8° between planes *(1) = *Flatness deviation = 0.012 and 0.060 *(2) = 0.47µm *External report given	1,2
Outer dimensions	Digital Caliper	(3) = 43.06 (4) = 30.05 (5) = 19.00	3,4,5
Detail dimensions	Digital Caliper	(6) = 5.03 (7) = 7.98 (8) = 6.98 (9) = 11.98 (10) = 11.50	6,7,8,9,10
Radiis	Radii measuring device	OK (Within tolerance)	R's
Measurements performed by:		Christian René Jakobsen Grashei	



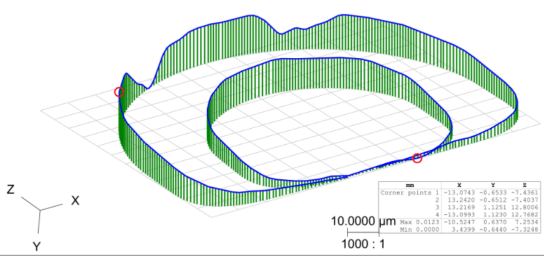
APPENDIX D - 17 Measurement assessment report

ZEISS CALYPSO
6.6.1606

Part name	**VE_cmm_report**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company	UIS	Part ident	9
Department	Measuring room	Time/Date	5/27/2024 3:34 PM
CMM Type	CON_2014_G2	Run	All Characteristics
CMM No.	532083	No. measured values	4
Operator	Master	No. values: red	0
Text		Measurement Duration	00:04:06.0

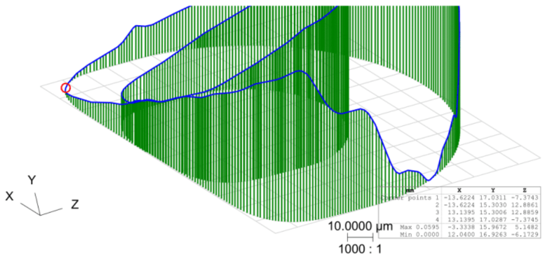
Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Flatness1	0.012	0.000	0.100	0.000	0.012	

Points 1248
Filter type Low-pass Spline
Lc 2.5
upr
Vmess[mm/sec] 10.00
Probe radius 2.500
Evaluation method Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Flatness2	0.060	0.000	0.100	0.000	0.060	

Points 1242
Filter type Low-pass Spline
Lc 2.5
upr
Vmess[mm/sec] 10.00
Probe radius 2.500
Evaluation method Minimum Feature

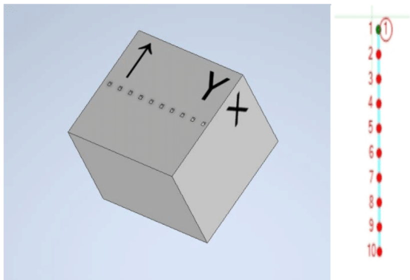


Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Angle between Features1	9.830	10.000	1.000	-1.000	-0.170	
C Distance1_Y	14.208	14.500	0.500	-0.500	-0.292	

(6.6_15) StandardProtocol

APPENDIX D - 18 CMM report

Hardness test report

Test procedure:	- Specimen K2 used - Use Innovatest FALCON 5001 With HV10, 10sec dwell time
Reference to standard:	ISO 6507-1
Specimen type:	K2
Specimen dimensions	12.5 mm x 12.5 mm x 11.9 mm
Acceptance criteria:	Given in MPS: AMN-MPS-300034-01-01
Testing performed by:	Espen Undheim/ Christian René Jakobsen Grashei
Date of testing:	29.05.2024
Illustration of pattern:	Min. 5 indentations: 10 were taken 
Description/ image of area(s) analyzed:	YZ-cross section of cube
Result:	See Vickers report. Mean value: 220.94 HV10 Min value: 215.41 HV10 Max value: 222.50 SD: 2.01

INNOVATEST
Advanced Hardness Testing Solutions

Universitetet i Stavanger

www.uis.no

General Information

Date	May 29, 2024
Operator	Espen
Hardness tester type	FALCON 5001

Program Description

Name	HV10 - indent, measure last

Enter Comments

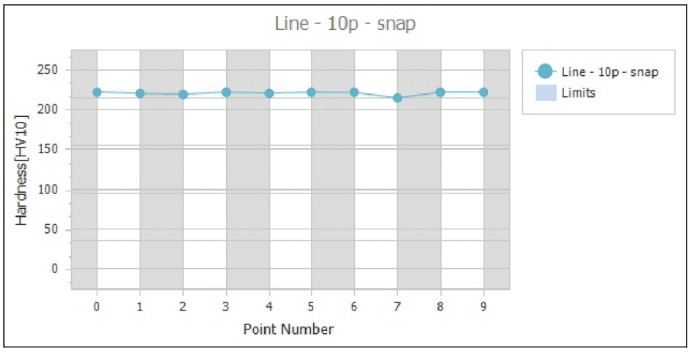
Hardness Test Information

Method	VICKERS
Hardness scale	HV10
Dwell time	10 sec.

Test Pattern

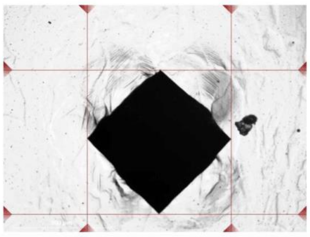
Diagrams

1/5

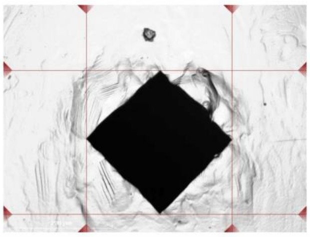

Line - 10p - snap
250
200
150
100
50
0
Hardness[HV10]
0
1
2
3
4
5
6
7
8
9
Point Number
Line - 10p - snap
Limits

2/5

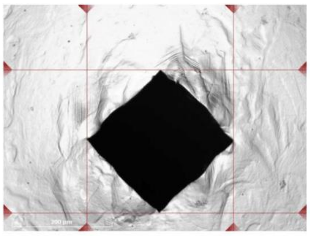
ID	**1 (1/1)**
Hardness	222.50 HV10
d1	0.2877 mm
d2	0.2897 mm
position	x: 104.11 mm y: 36.36 mm
Conversions	
Time	9:59:21 AM



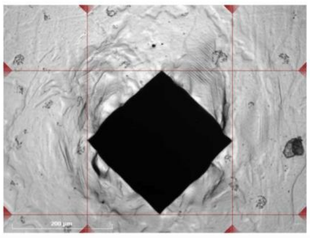
ID	**2 (1/1)**
Hardness	220.61 HV10
d1	0.2917 mm
d2	0.2882 mm
position	x: 104.12 mm y: 35.36 mm
Conversions	
Time	9:59:38 AM



ID	**3 (1/1)**
Hardness	219.84 HV10
d1	0.2932 mm
d2	0.2877 mm
position	x: 104.13 mm y: 34.36 mm
Conversions	
Time	9:59:55 AM

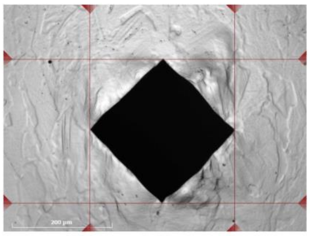


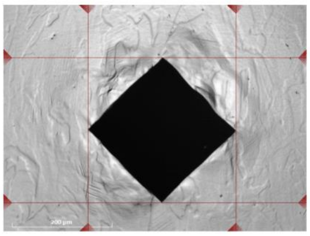
ID	**4 (1/1)**
Hardness	222.10 HV10
d1	0.2902 mm
d2	0.2877 mm
position	x: 104.14 mm y: 33.36 mm
Conversions	
Time	10:00:13 AM



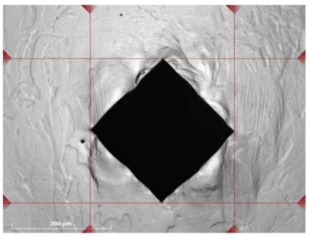
ID	**5 (1/1)**	
Hardness	220.90 HV10	
d1	0.2942 mm	
d2	0.2852 mm	
position	x: 104.15 mm y: 32.36 mm	
Conversions		
Time	10:00:30 AM	

ID	**6 (1/1)**	
Hardness	222.09 HV10	
d1	0.2892 mm	
d2	0.2887 mm	
position	x: 104.15 mm y: 31.36 mm	
Conversions		
Time	10:00:47 AM	

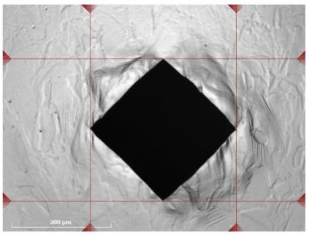
ID	**7 (1/1)**	
Hardness	221.73 HV10	
d1	0.2892 mm	
d2	0.2892 mm	
position	x: 104.16 mm y: 30.36 mm	
Conversions		
Time	10:01:04 AM	

ID	**8 (1/1)**	
Hardness	215.41 HV10	
d1	0.2956 mm	
d2	0.2912 mm	
position	x: 104.17 mm y: 29.36 mm	
Conversions		
Time	10:04:28 AM	

ID	9 (1/1)
Hardness	222.11 HV10
d1	0.2892 mm
d2	0.2887 mm
position	x: 104.18 mm y: 28.36 mm
Conversions	
Time	10:01:38 AM



ID	10 (1/1)
Hardness	222.12 HV10
d1	0.2927 mm
d2	0.2852 mm
position	x: 104.18 mm y: 27.36 mm
Conversions	
Time	10:01:54 AM



Measurement Tables

Line - 10p - snap

Measurement Index	Result
1 (1/1)	222.50 HV10
2 (1/1)	220.61 HV10
3 (1/1)	219.84 HV10
4 (1/1)	222.10 HV10
5 (1/1)	220.90 HV10
6 (1/1)	222.09 HV10
7 (1/1)	221.73 HV10
8 (1/1)	215.41 HV10
9 (1/1)	222.11 HV10
10 (1/1)	222.12 HV10

Statistics

Pattern	Mean	Min	Max	SD	Range	USL	LSL	Cp	Cpk
Line - 10p - snap	220.94	215.41	222.50	2.01	7.08	0.00	0.00	0.00	-36.68

QUALITY LAB

Quality lab AS
Strandsvingen 3
4032 Stavanger

Serie: UIS Prosjekt Vår energi

Test	Position	KV (J)	Date	Flat Width (b) (mm)	Flat Thickness (a) (mm)	Temp (°C)	Operator
1	BM	112.7	5/28/2024	10.00	8.00		
2	BM	109.0	5/28/2024	10.00	8.00		
3	BM	118.4	5/28/2024	10.00	8.00		

28/05/2024 09:33

Page 1 / 1

APPENDIX D - 21 Charpy impact testing report from Quality Lab Stavanger

QUALITY NDT
Part of Quality Group

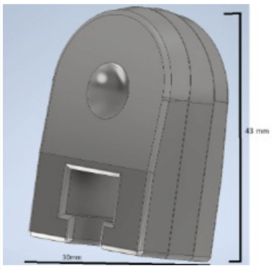
COMPUTED RADIOGRAPHIC INSPECTION

Doc.Status	Approved
Report	CR-24-192
Purchase Order	TBA
Date	May 29, 2024
Revision	A

Customer	Quality Lab AS	Q-NDT Project	SP-30857
Location	Quality NDT AS	Material Quality	316L
Subject	Test Piece	Drawing No	N/A
Procedure	DNV-CG-0051	NDT Technician	Siv Byberg
Acceptance Standard	N/A	Sch/Thickness	20mm
Serial Number	See listed below	Heat Treatment	N/A
Part Number	Not Quoted	Technique	SWSI
Inspection Extent	100%	Radiation Source	BALTO 300kv
Detector	Flex XL Blue	IQI Location	N/A
Detector Serial	NA	IQI	N/A
Scanner	HD-CR35 NDT Plus 440936007	Source Size	3,54mm
FFD/SDD	600mm	Exposure Data	230Kv, 5mA, 1:00min
SNRn	168+	Ug	0.1
SRB	50μ	Joint Type	3DP m SLM

Weld No.	Film No	Spool No.	Welder	WPS	Defect Type	Defect Area	Technician	Result
Test Piece	1	3DP m/SLM	N/A	N/A	401	1	SB	REJECT

RT carried out of item mentioned above.



Signed By:	Document Approved By:	
Siv Byberg Radiographic Testing Level 2 12158-N2-R / ISO 9712	Petter Hagland	

APPENDIX D - 22 Volumetric NDT - Computed Radiography report from Quality NDT Stavanger

QUALITY NDT
Part of Quality Group

DYE PENETRANT INSPECTION

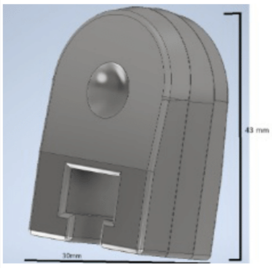
Doc.Status	Approved
Report	PT-24-1596
Purchase Order	TBA
Date	May 29, 2024
Revision	A

Customer	Quality Lab AS	**Customer Address**	Strandsvingen 3
Manufacturer	N/A	**Q-NDT Project**	SP-30857
Drawing	N/A	**Procedure**	PT 104 Rev 8
Acceptance Standard	N/A	**Material Quality**	316L
Inspection Extent	100%	**Location**	Quality NDT AS
Part Number	Not Quoted	**Subject**	Test Piece
Serial Number	See listed below		

Joint Type	Machined	**Thickness**	20mm
Surface	Machined	**Light Intensity**	1076 LUX | 2024-05-29
Weld Process	N/A	**Welder ID**	N/A
WPS	N/A	**Penetrant Type**	Elite K71B2p
Surface Temperature	According To Procedure	**Remover Type**	Elite BC1 / Water
Developer Type	Elite D112A	**Penetration Time**	20 Minutes
Developer Time	20 Minutes		

Weld / Part ID	Status	Comments
Test Piece	ACCEPT	Note: Edge after machining (600)

PT carried out of all accessible areas on item mentioned above.



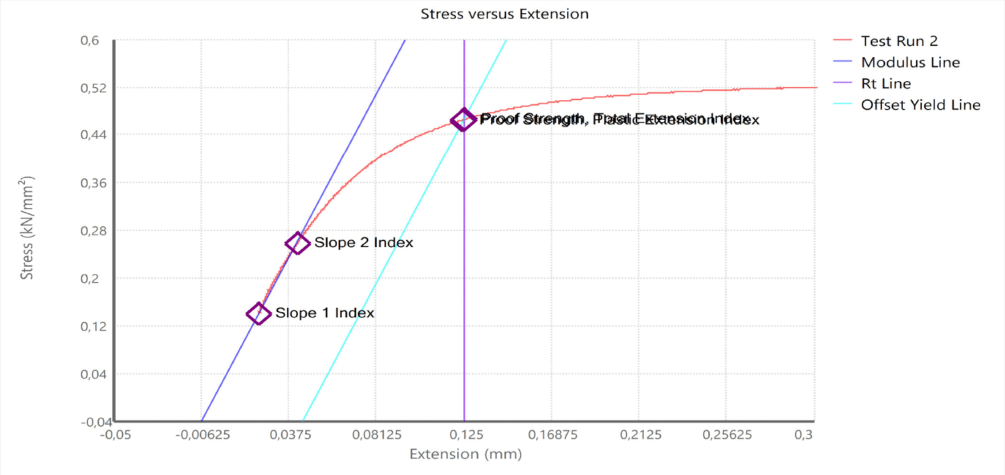
Signed By:	Document Approved By:	
Siv Byberg Radiographic Testing Level 2 12158-N2-R / ISO 9712	Petter Hagland	

APPENDIX D - 23 Surface NDT - Penetrant testing report from Quality NDT Stavanger

Default Test Run Report

Test Name	**UIS VÅR ENERGI**
Test Run Name	**Test Run 2**
Test Run Date	**28.05.2024 09:58:17**

Test Run Review Graph



Test Run Results:

Display Name	Value	Unit
Test ID	UIS VÅR ENERGI	
Original Gage Length (Lo)	25,010	mm
Operator	KAS	
Test ID	UIS VÅR ENERGI	
Original Gage Length (Lo)	25,010	mm
Operator	KAS	
Area	19,7136	mm²
Tensile Strength (Rm)	598,0	MPa
% Elongation after Fracture (A)	42,983	%
Modulus (E)	158,265	GPa
Proof Strength, Total Extension (Rt0.5)	465,466	MPa
Proof Strength, Plastic Extension (Rp0.2)	464,252	MPa
% Reduction of Area (Z)	60,468	%
Final Diameter (Round Specimen)	3,150	mm
Final Gage Length (Lu)	35,760	mm
Sample No.	NO2	
Diameter	5,010	mm

APPENDIX D - 24 Tensile test report of specimen no.2 from Quality Lab Stavanger

Mitutoyo Surftest SJ-301

DATE	01-01-2000
TIME	00:04:45

STAND	JIS2001
PROFILE	R
FILTER	GAUSS
EVA-L	4.0mm
N	5
λc	0.8mm
λs	2.5μm
TILT-COMP.	ALL
M-SPEED	0.5mm/s
RANGE	AUTO
	ESC
PRE/POST	ON
DRIVE	STAND

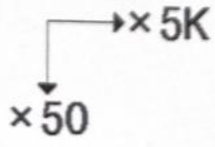
R-PROFILE

EVA-L	4.0mm
λc	0.8mmX5

Ra	0.47μm
Rz	2.79μm
Rq	0.59μm

R-PROFILE

EVA-L 4.0mm
λc=0.8mmX5



Ver.	2.0μm/cm
Hor.	200.0μm/cm

APPENDIX D - 25 Surface Roughness Measurement

APPENDIX E - DOCUMENTATION FROM STAMAS

Hammaren 9a
4056 Tananger
+47 51 64 88 90
post@stamas.no

CERTIFICATE OF COMPLIANCE

Customer Name:	**University of Stavanger (UIS)**		Page 1/1
Customer P.O. No:	**XX**	W.O. No.:	**103087**
AO:		Date:	**22.05.2024**
Description:	**GT-Valve wedge**	Rev:	**1**

Drawing no.	**Component Description**	**SN / PN**	**Heat No:**	**Mat. Quality**	**Qty Issued**
-	GT-Valve wedge	SS103087-1	551769	316/316L	1

This certificate compliance states that the above mentioned detail material / equipment has been manufactured, inspected and tested in accordance with the purchase order.

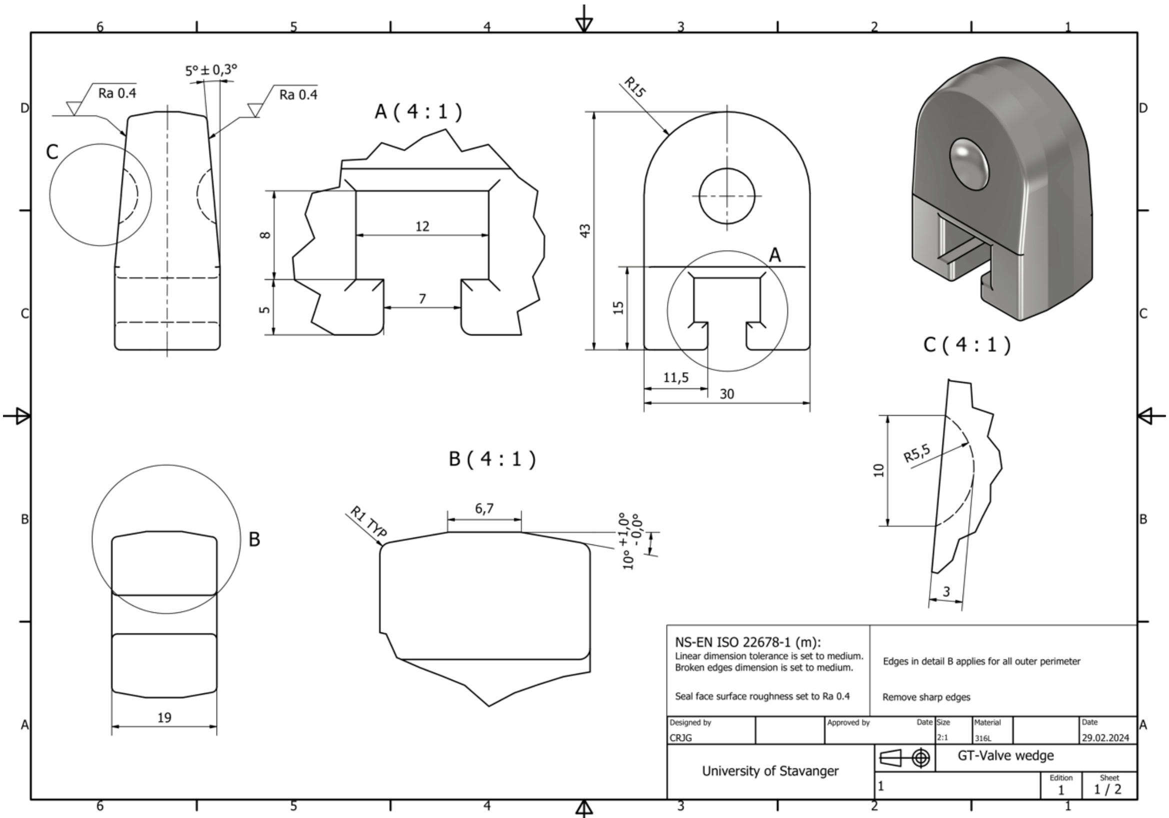
Name:

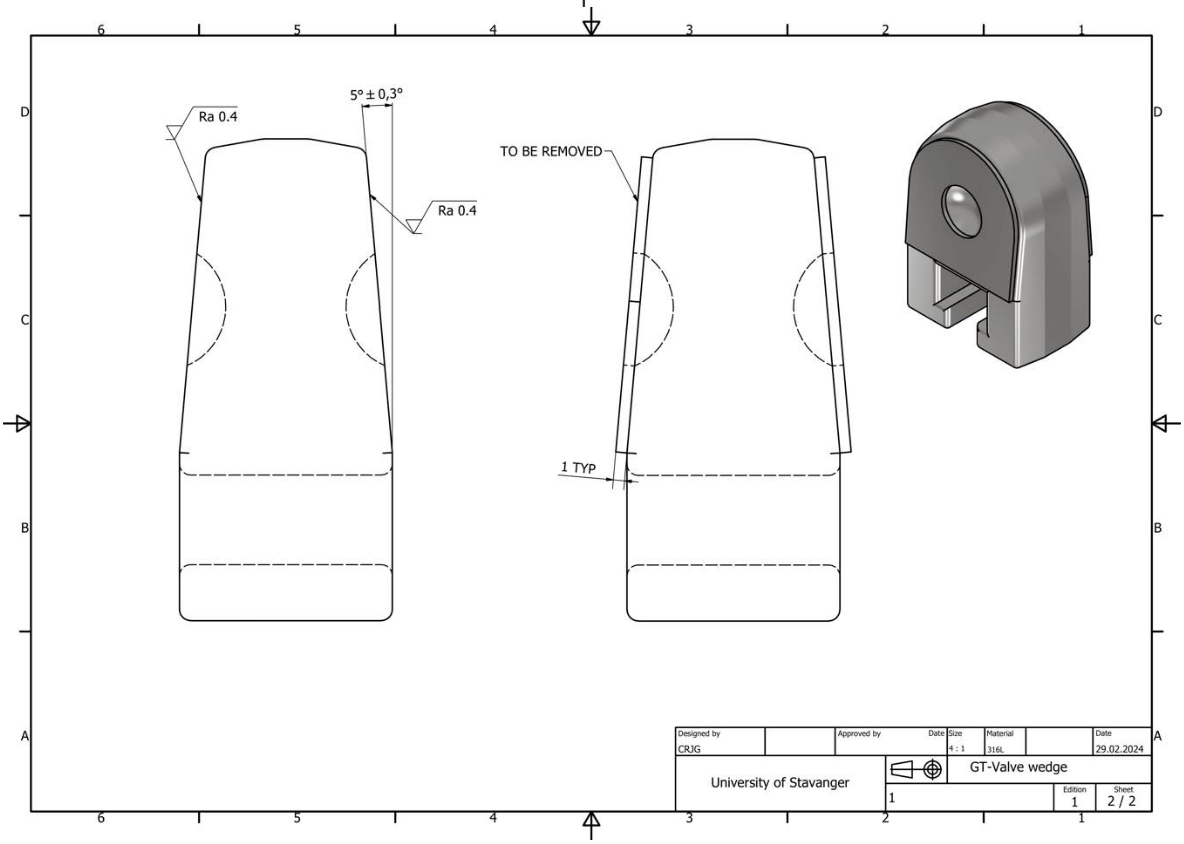
APPROVED BY
Sign.
STAMAS AS

Signature and company stamp

Form 013 CERT OF COMPL

APPENDIX E - 1 Stamas COC


Ra 0.4
5° ± 0,3°
Ra 0.4
C
A (4 : 1)
12
8
5
7
R15
43
15
A
11,5
30
C (4 : 1)
R5,5
10
3
B (4 : 1)
R1 TYP
6,7
10° +1,0° -0,0°
B
19
NS-EN ISO 22678-1 (m):
Linear dimension tolerance is set to medium.
Broken edges dimension is set to medium.
Seal face surface roughness set to Ra 0.4
Edges in detail B applies for all outer perimeter
Remove sharp edges
Designed by
CRJG
Approved by
Date
Size
2:1
Material
316L
Date
29.02.2024
University of Stavanger
GT-Valve wedge
1
Edition
1
Sheet
1 / 2


Ra 0.4
5° ± 0,3°
Ra 0.4
TO BE REMOVED
1 TYP
Designed by
CRJG
Approved by
Date
Size
4 : 1
Material
316L
Date
29.02.2024
University of Stavanger
GT-Valve wedge
1
Edition
1
Sheet
2 / 2

INSPECTION CERTIFICATE acc to
EN 10204 3.1

Sverdrup Steel AS
Strandsvingen 2
4032 STAVANGER
NORWAY

Customer References

829952 Customer order 2018-03-26

125-06911 SVERDRUP S

Sandvik References

Order No.	Subs No.	ABSMT Dispatch note
509470	648587	48162/53

ABSMT No.	C.Code
284-55489	87

Material description
HOT WORKED STAINLESS BAR STEEL
ROLLED
ANNEALED & STRAIGHTENED
PEEL TURNED AND POLISHED

Steel making process E+AOD+LRF
Origin Sweden

Steel/material Designations
Sandvik
SANMAC 316/SANMAC 316L

AISI	UNS
316/316L	S31600/S31603

W.nr	EN no
1.4401/1.4404	1.4401/1.4404

Technical requirements
EN 10088-3:-2014, EN10272:-2016*, EN10060:2003, EN 10221:1996
EN10222-5:-1999*, PED 2014/68/EU,
NACE MR0175/ISO 15156-3:2015, NACE MR0103/ISO 17945:2015, QQ-S-763 F,
ASTM A-276-17, ASME SA-276-ED-17 SECT II PART A,
ASTM A-479-18, ASME SA-479-ED-17 SECT II PART A,
ASTM A-484-18, ASTM A-182-16A*, ASTM A-965-14*, ASTM A-314-15*,
NORSOK M-630 ED-6, NORSOK MDS S01 REV. 5,
*For detailed information, please see the appendix

EXTENT OF DELIVERY

It	Product designation	Heat	Lot	Pieces	Kg
02	MBR-SANMAC316L-130	551769	87251	1	463.0
		551769	87252	2	948.0
			Total	3	1411.0

TEST RESULTS

Reduction ratio (times)

Lot	
87251	6.8
87252	6.8

Chemical composition (weight%) acc. to ASTM A-751

Heat	C	Si	Mn	P	S	Cr	Ni	Mo
551769	0.009	0.38	1.88	0.033	0.026	16.84	10.03	2.03

Heat	N
551769	0.049

Quality assurance - Erik Jansson/QA-manager Primary Products
MTC Service / Certificates

AB SANDVIK MATERIALS TECHNOLOGY Reg No. 556234-6832 VAT No. SE663000-060901
SE-81181 SANDVIKEN SWEDEN www.smt.sandvik.com mtc_service.smt@sandvik.com

Tensile test at room temperature acc. to ASTM A370/ISO 6892-1
Longitudinal
Location half radius

	Yield strength		Tensile strength	Elongation	
	Mpa	MPa	Mpa	%	%
Lot	**Rp0.2**	**Rp1.0**	**Rm**	**A**	**2"**
87251	226	263	557	60	60
87252	224	265	554	60	60

	Red.of Area
	%
	Z
87251	77
87252	78

Hardness test acc.to ASTM A-370/ISO 6506-1
Location half radius

	Min	Max
Lot	**HB**	**HB**
87251	126	131
87252	133	135

	Min	Max
Lot	**HRB**	**HRB**
87251	72	74
87252	71	74

Grain size acc to ASTM E-112.
Location half radius

Lot		
87251	7.0	7.0
87252	5.0	5.0

Impact test, J, 20°C, Longitudinal acc. to ISO 148-1
Location half radius

	Single values			Average
Lot	**Joule**			**Joule**
87251	269	303	294	289
87252	302	273	273	283

Following controls/tests have been satisfactorily performed:
- Intergranular corrosion test acc to ASTM A-262 PR.E and EN ISO 3651-2A
- Material Identification.
- Ultrasonic test acc to EN 10228-4 Scan coverage 1, Quality Class 3 Tab 4, AD 2000 - A4-2003 6.3.1 F., ASTM A-388 API 6A PSL3/3G
- Visual inspection and dimensional control.

HEAT TREATMENT:
20-30mm: Material soaking 1050°C, min. 20 minutes. Quenched in water. Water temp pre-quench max 40°C, after quench max 50°C.

35-150mm: In process annealed according to ASTM A484 above the minimum hot rolling temperature of 1010°C and rapidly cooled.

155-350mm: Material soaking 1065°C, min. 30 minutes. Quenched in water. Water temp pre-quench max 40°C, after quench max 50°C.

355-370mm: Material soaking 1050°C, min. 60 minutes. Quenched in water. Water temp pre-quench max 40°C, after quench max 50°C.

375-450mm: Material soaking 1050°C, min. 120 minutes. Quenched in water. Water temp pre-quench max 40°C, after quench max 50°C.

The raw material is free from radioactive contamination.

Material free from mercury contamination.

No welding or weld repair.

This is to certify that the contents of this certified material test report are correct and accurate and that all test results and operations are in compliance with the material specification.

Approved acc. AD 2000-Merkblatt W0 and certified acc. to Pressure Equipment Directive (2014/68/EU) (PMA 1326W113330-1) by TUEV NORD GmbH; notified body, reg.no. 0045.

The delivered products comply with the specifications and requirements of the order.

The material is manufactured according to a Quality system, approved and registered to ISO 9001:2008.

No unauthorized alterations. The contents of this Inspection Certificate may not be modified or revised in any way without the prior written approval of AB Sandvik Materials Technology. Unauthorized alterations to the Inspection Certificate, including introduction of false, fictitious or fraudulent statements or entries, may be punishable by fines, imprisonment, or both. This Inspection Certificate may be copied only in the manner and for the purposes specified in Section 6 of EN 10204:2004. Contravention of this notice will be prosecuted to the fullest extent of applicable law.

The certificate is produced with EDP and valid without signature.

APPENDIX

Lab accreditation
Our lab is accredited under SWEDAC Accreditation number 1636 for testing as per ISO/IEC 17025

Applicable only to specific dimensions
20mm - 250mm: EN 10088-5 EN (Only valid for CE marked products together with Sandvik Declaration of Performance certificate).
20mm - 400mm: PED 2014/68/EU *EN 10272 (Stainless steel bars for pressure purposes)
20mm - 375mm: *AD-2000-W2/W10
20mm - 450mm: NORSOK M-630 Ed. 6 - NORSOK MDS S01 Rev. 5
180mm- 450mm: PED 2014/68/EU *EN 10222-5
70mm - 450mm: AMS 5648 Rev. L, AMS 5653 Rev. H
Suitable for manufacturing of components in acc. with *ASTM A-182, ASTM A-965, ASTM A-314.

Test location
Mechanical, ferrite, corrosion testing:
Bar dim <=50mm - Longitudinal test pieces in center of the bar.

Bar dim > 50mm - 450 mm - Longitudinal test pieces, 1/4 T and minimum 100 mm from any second surface.
Bar dim > 160mm- 450 mm - Transversal test pieces, 1/4 T and minimum 100 mm from any second surface.

One set of test samples per heat treatment lot.
Maximum lot size 15 ton.

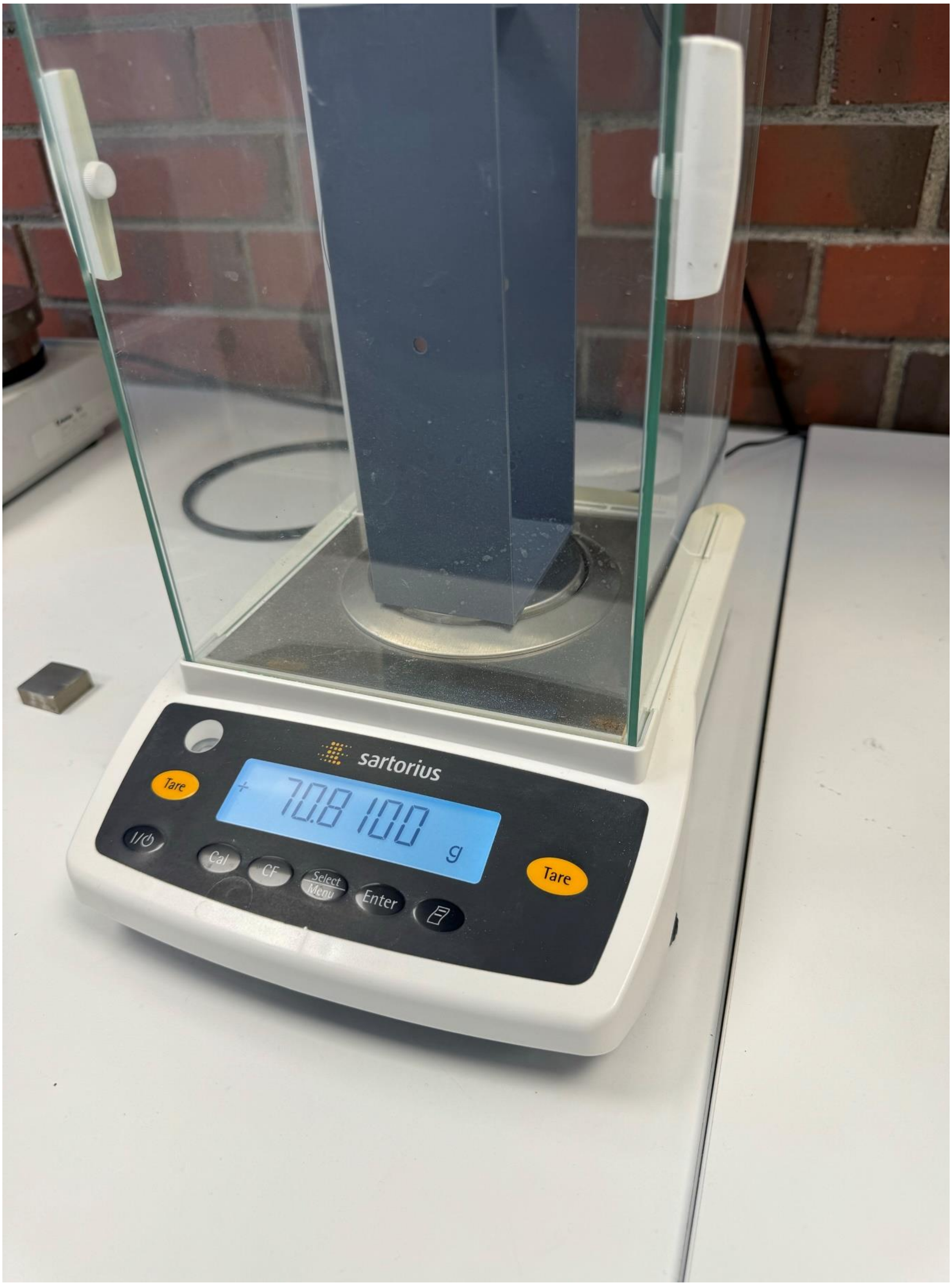
Furnace calibration every third month according to API 6A
Thermocouples of S-type (+/- 5°C tolerance) are used to monitor the furnace temperature.

APPENDIX F - PICTURES

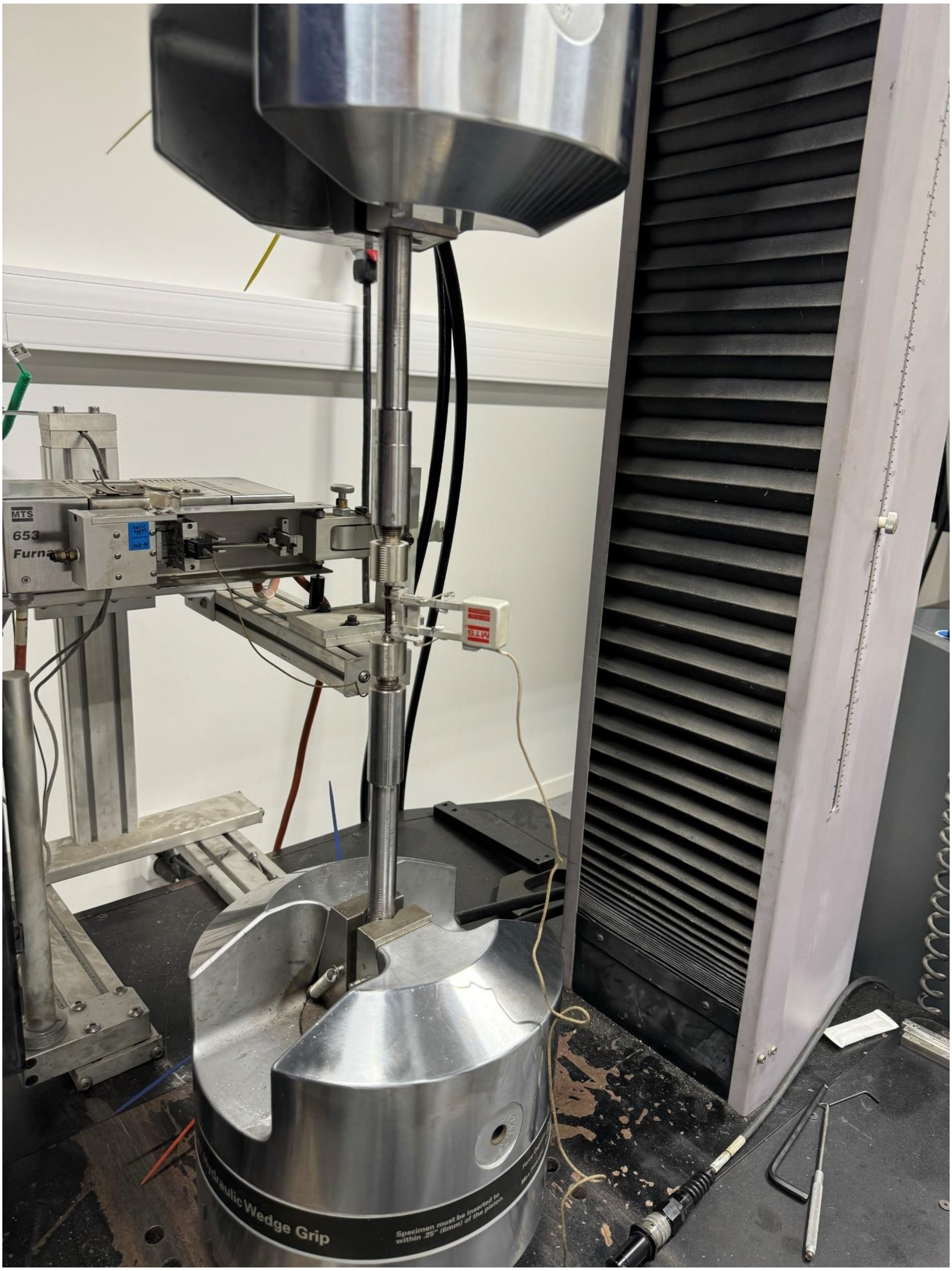
APPENDIX F - 1 Surface roughness calibration step

APPENDIX F - 2 Parameters from surface roughness

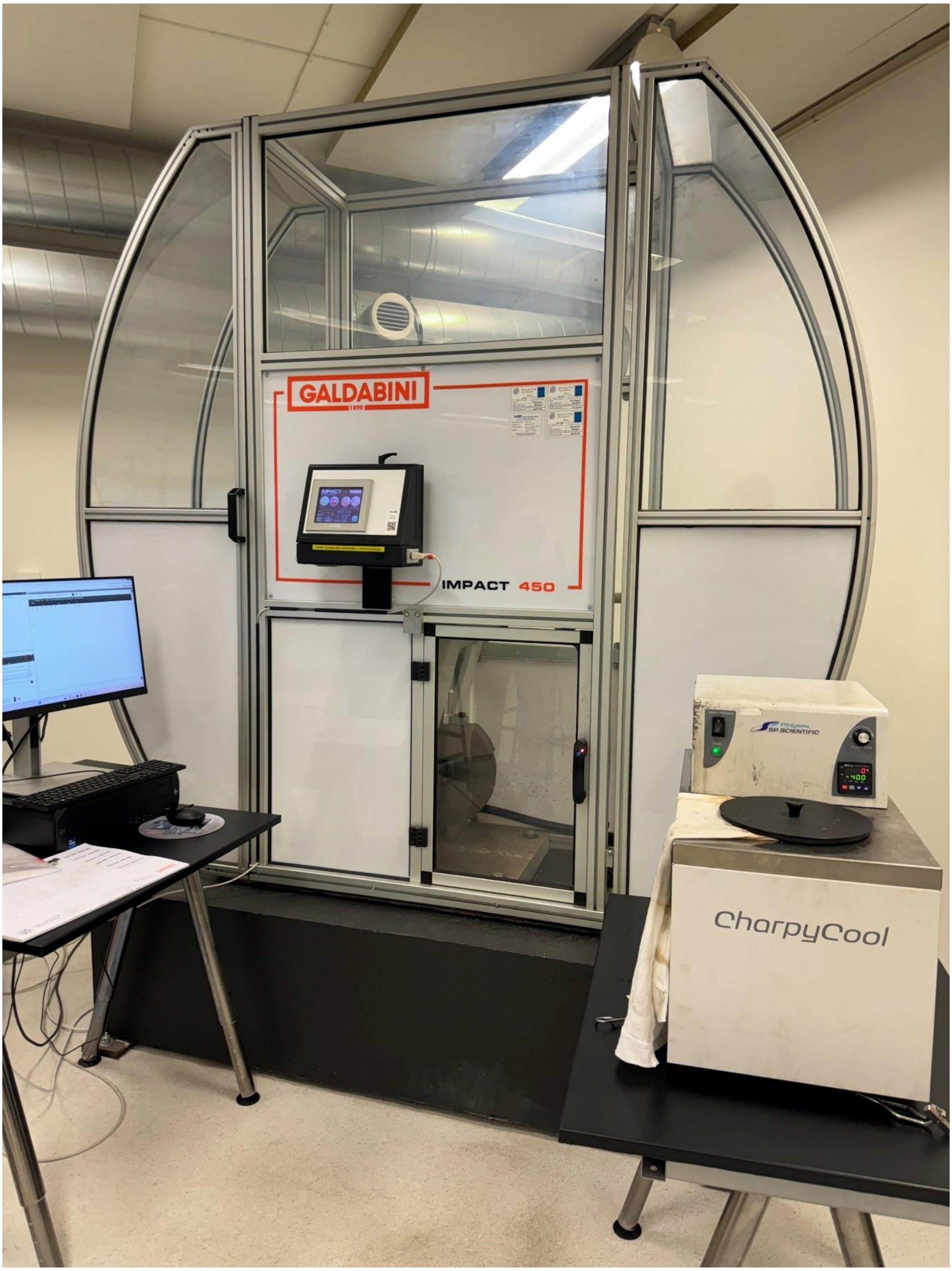
APPENDIX F - 3 Mitutoyo gauge blocks



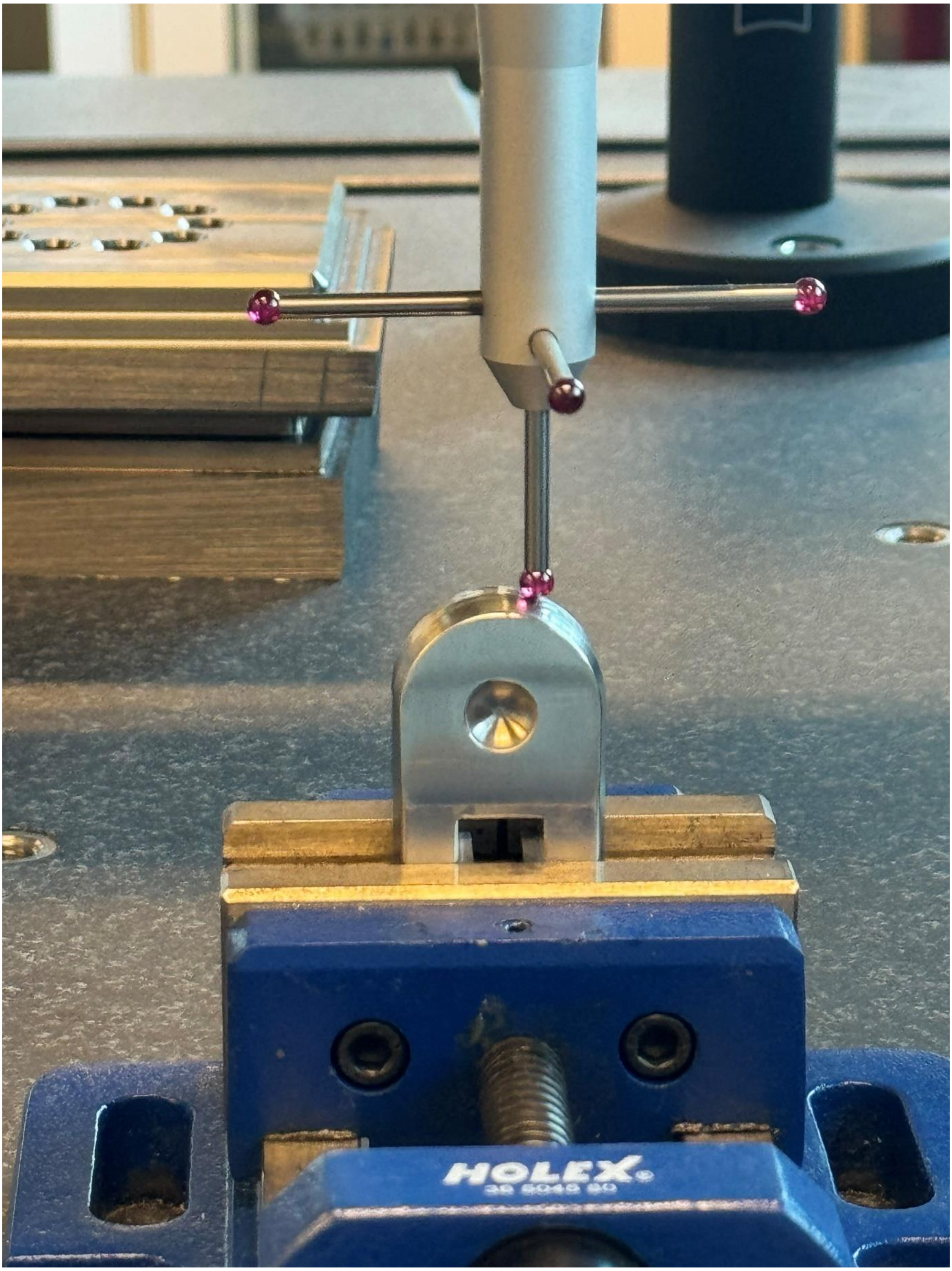
APPENDIX F - 4 Scale and stage used for Archimedes measurement



APPENDIX F - 5 Tensile test on specimen at Quality group Stavanger



APPENDIX F - 6 Charpy machine used for Charpy tests at Quality group Stavanger

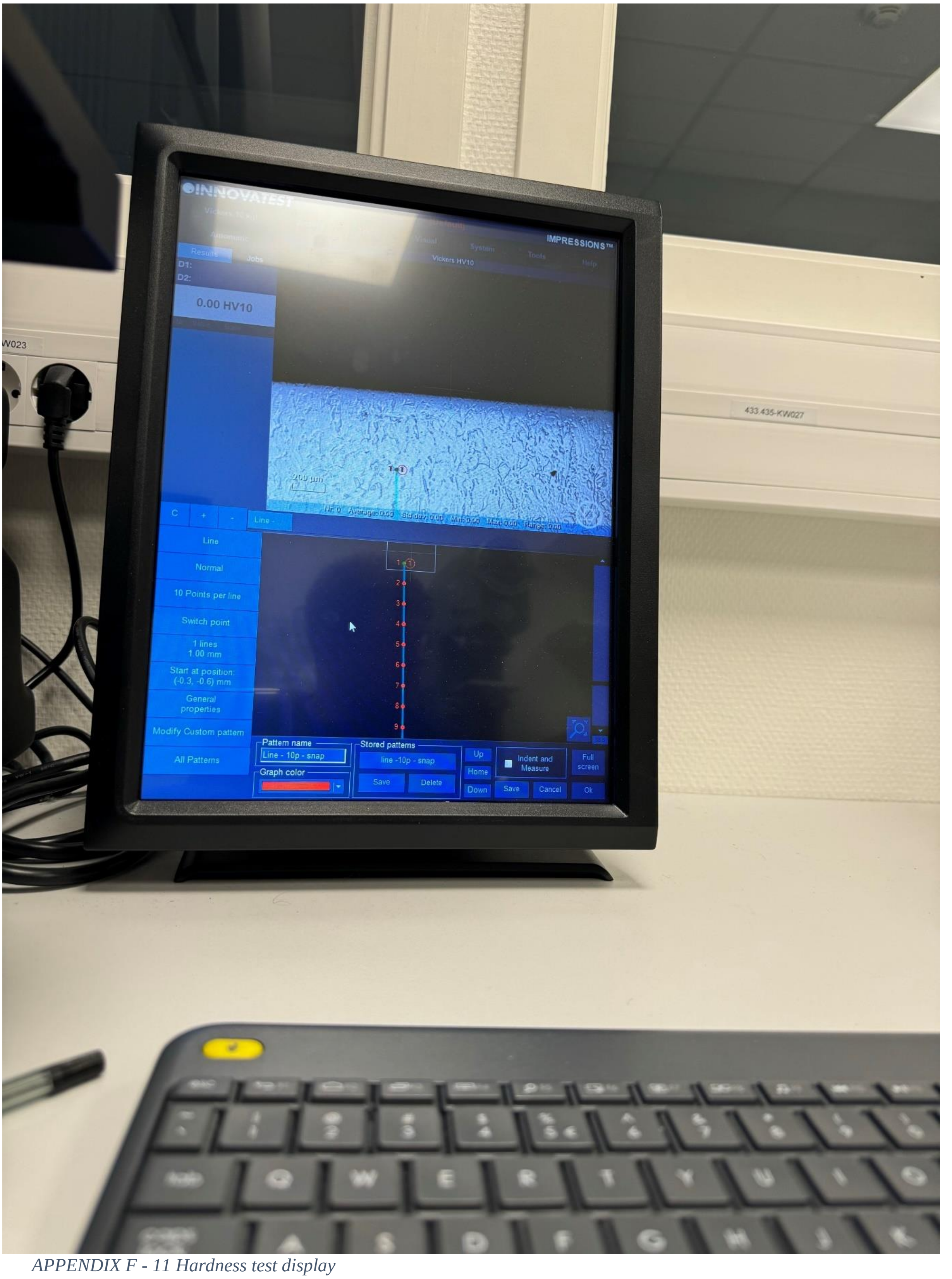


APPENDIX F - 7 CMM Measurement of SM part

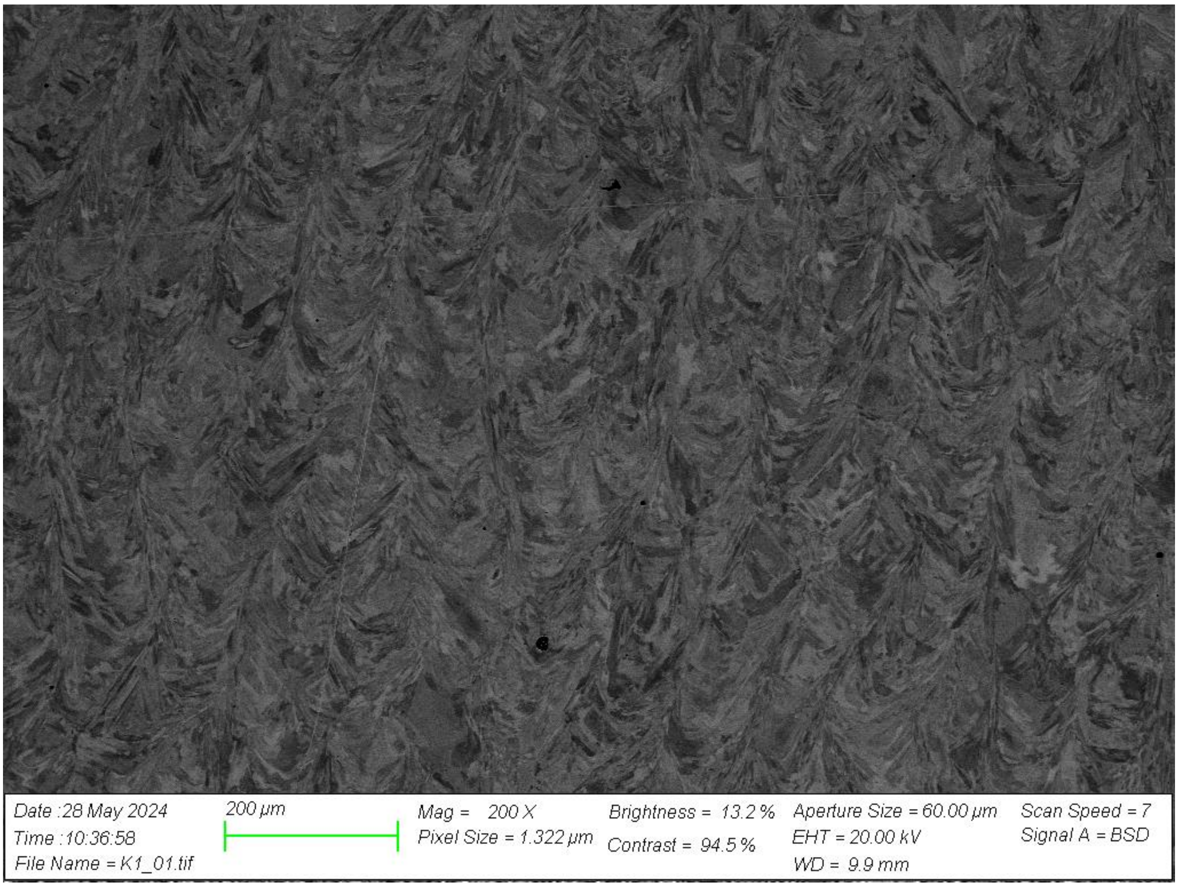
APPENDIX F - 8 Disk and lubricant parameters for polishing and op-s

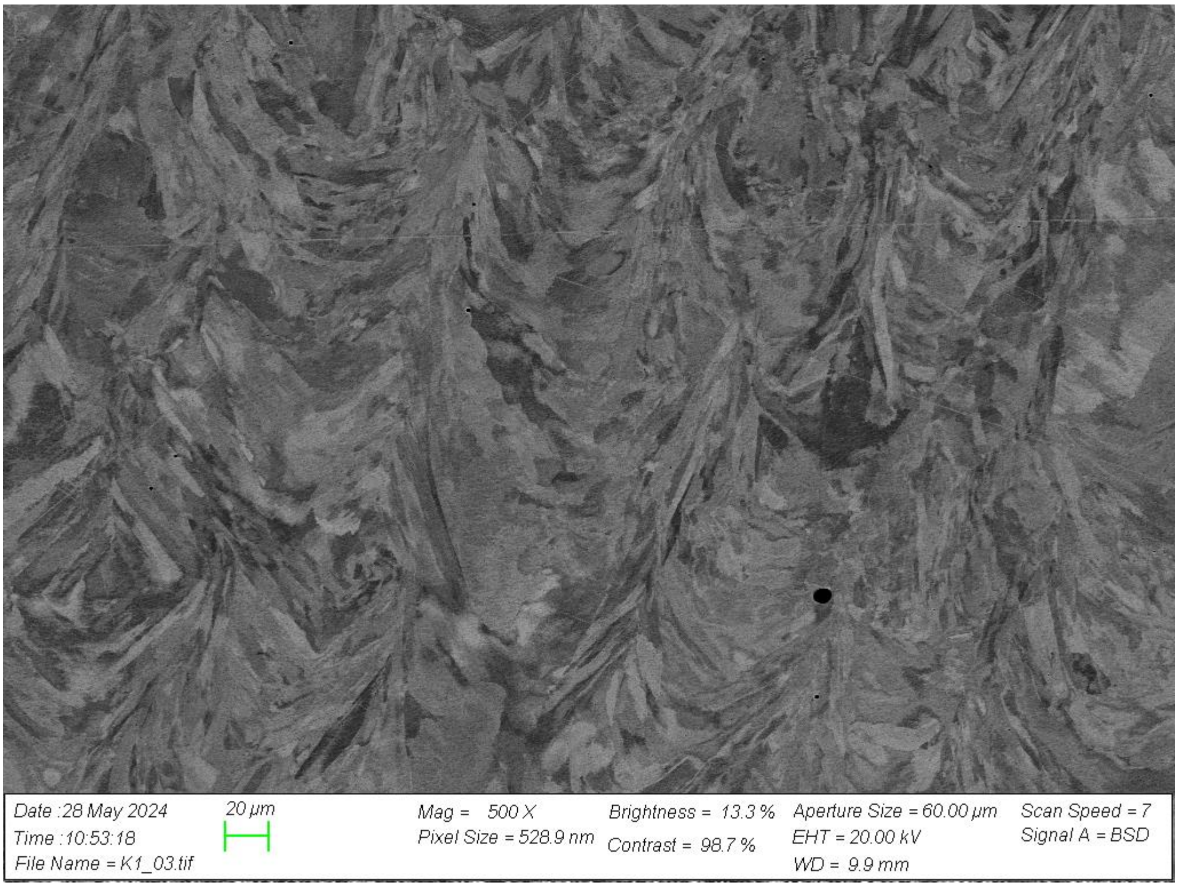
APPENDIX F - 9 Chemicals for polishing

APPENDIX F - 10 Struers tegraforce-5 polishing machine

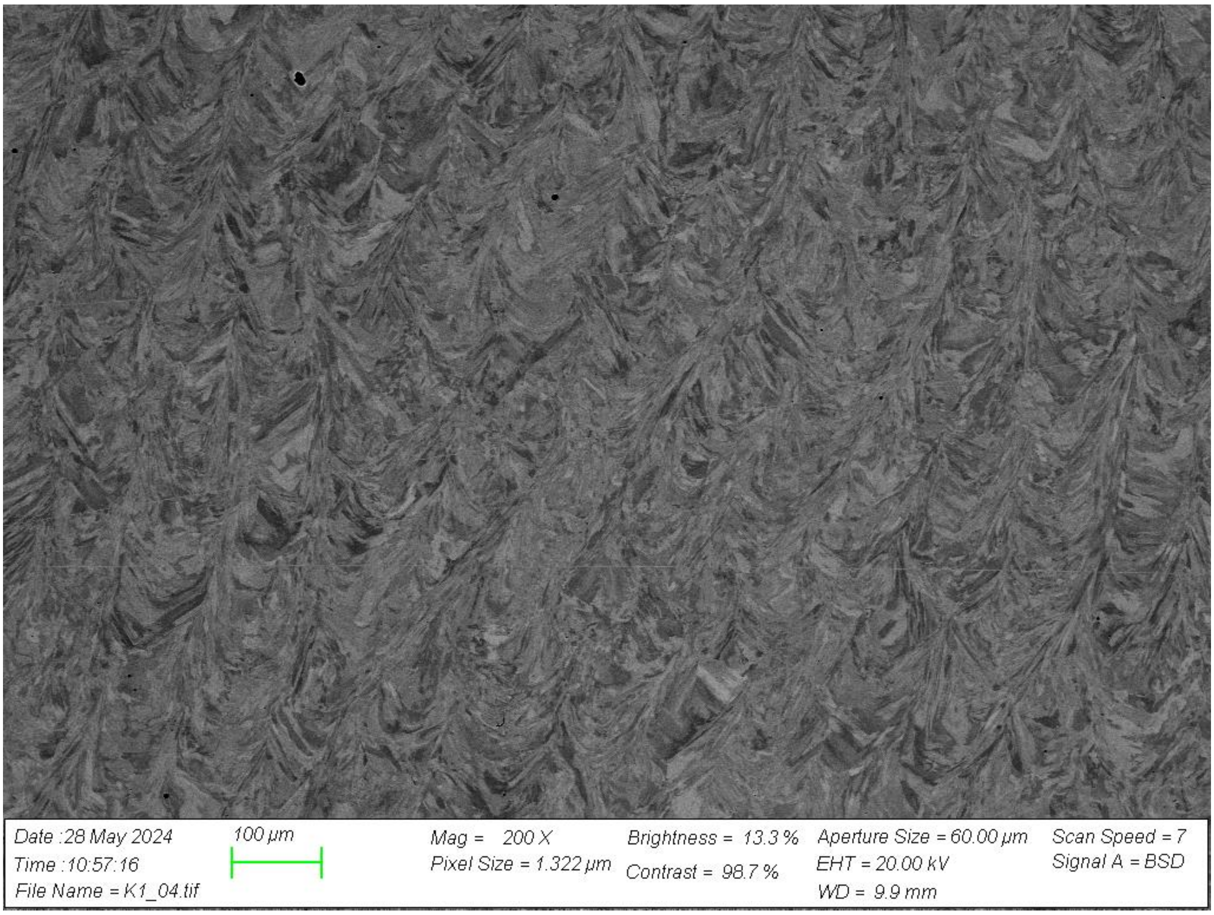


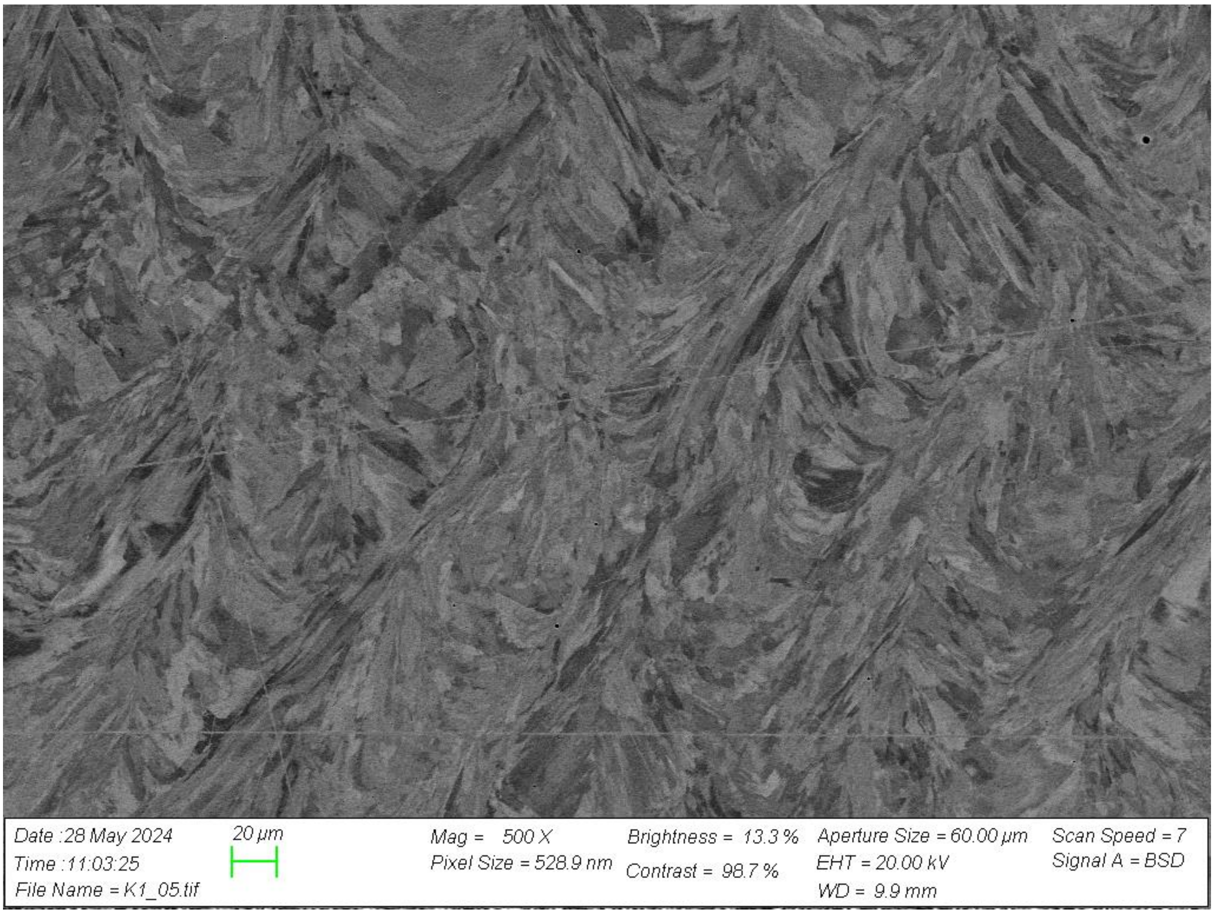
APPENDIX F - 11 Hardness test display

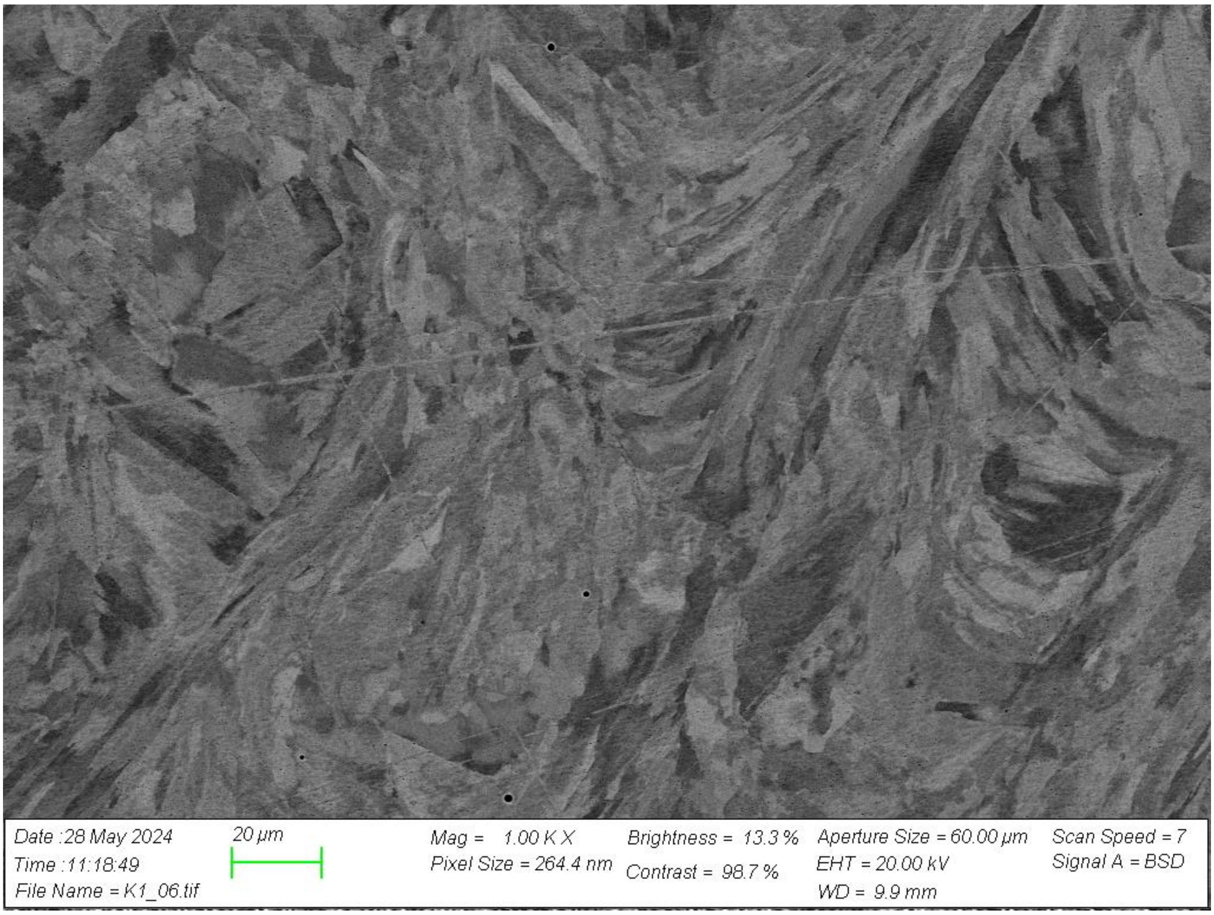


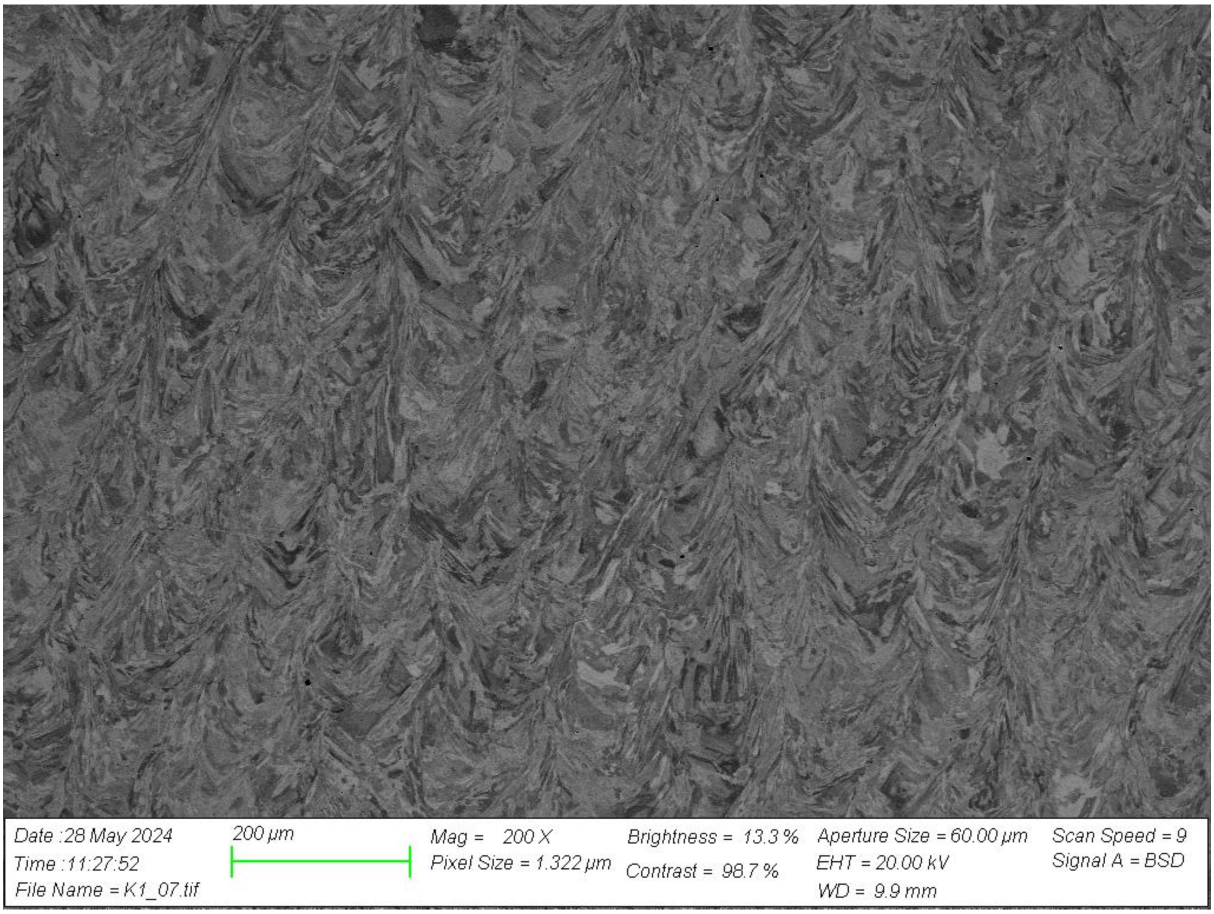


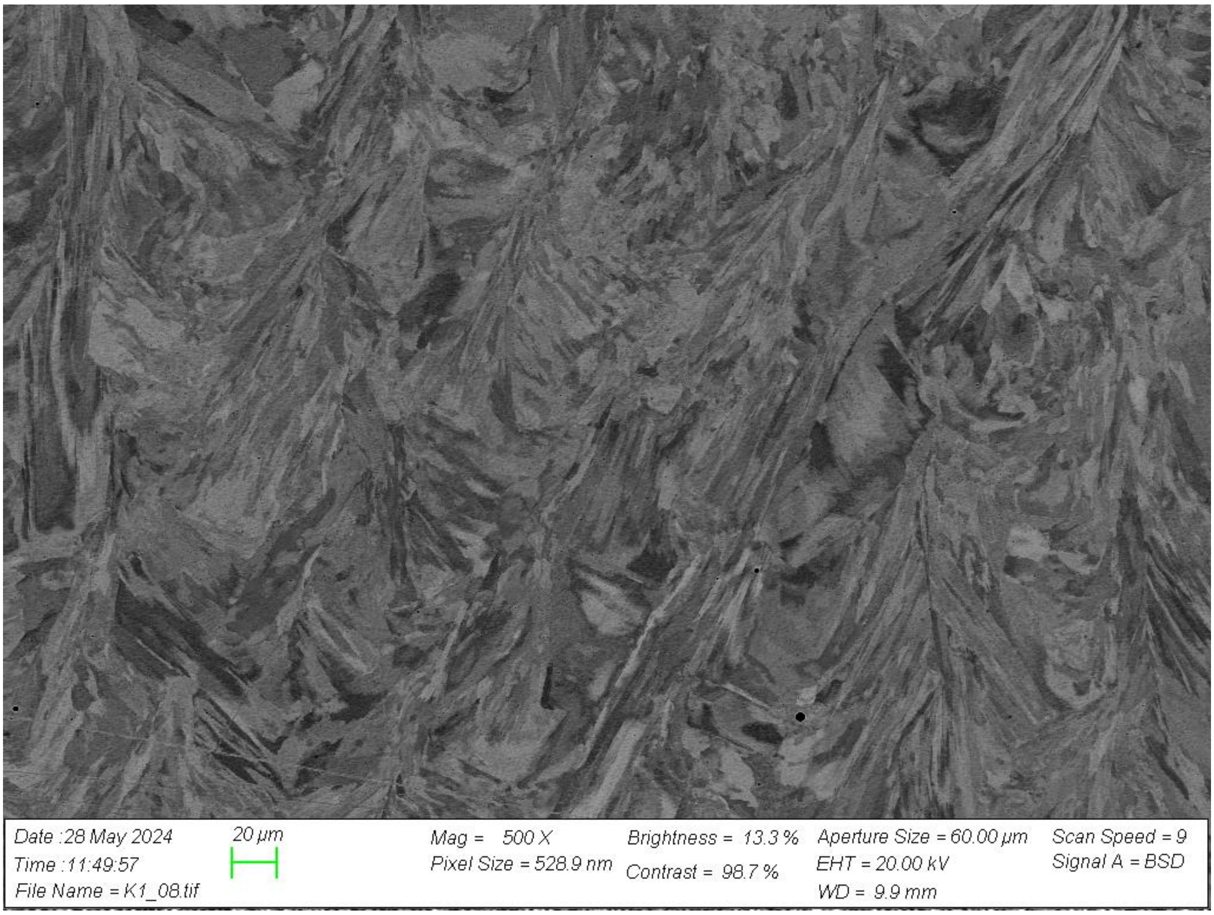
APPENDIX F - 12 Microstructural images from SEM K1

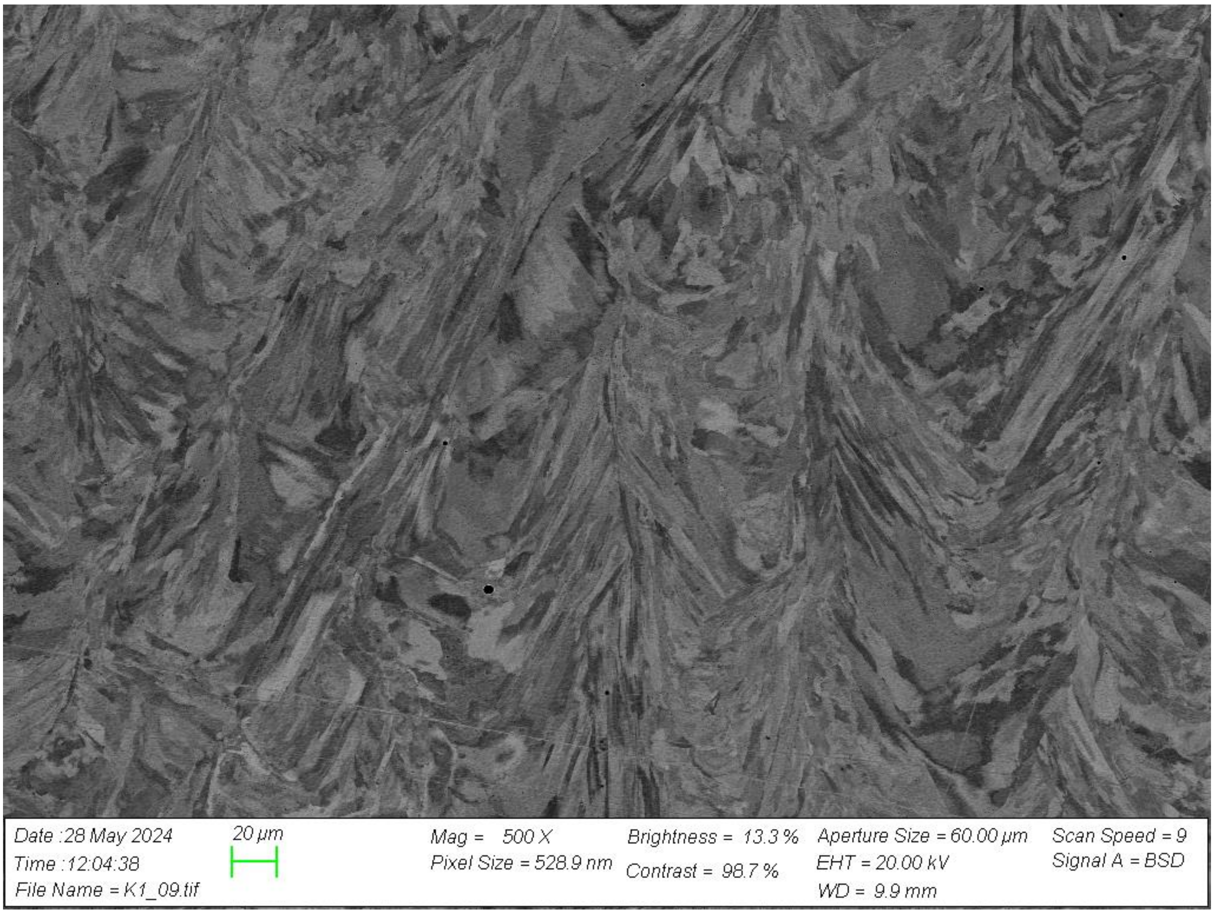

Date :28 May 2024
Time :10:57:16
File Name = K1_04.tif
100 µm
Mag = 200 X
Pixel Size = 1.322 µm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 7
Signal A = BSD

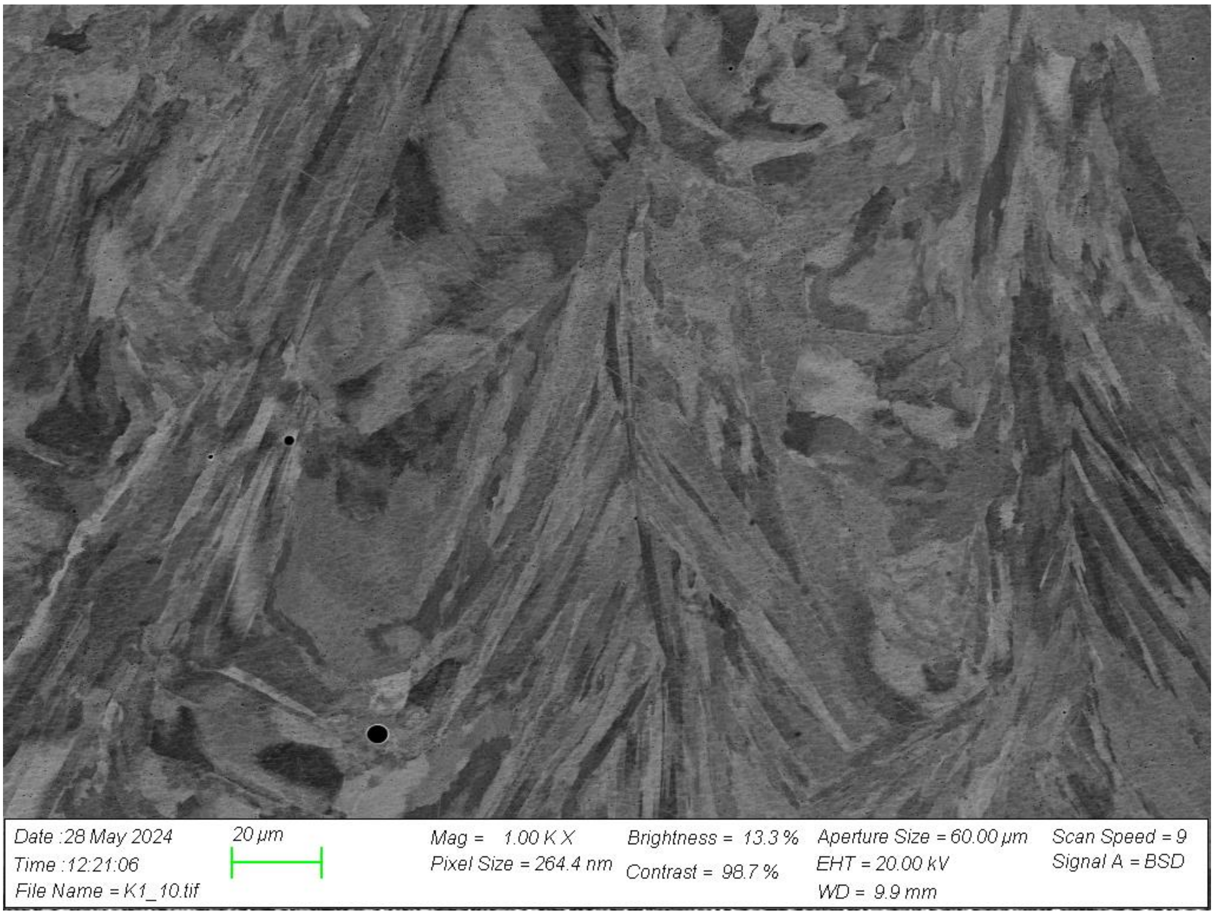

Date :28 May 2024
Time :11:03:25
File Name = K1_05.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 7
Signal A = BSD

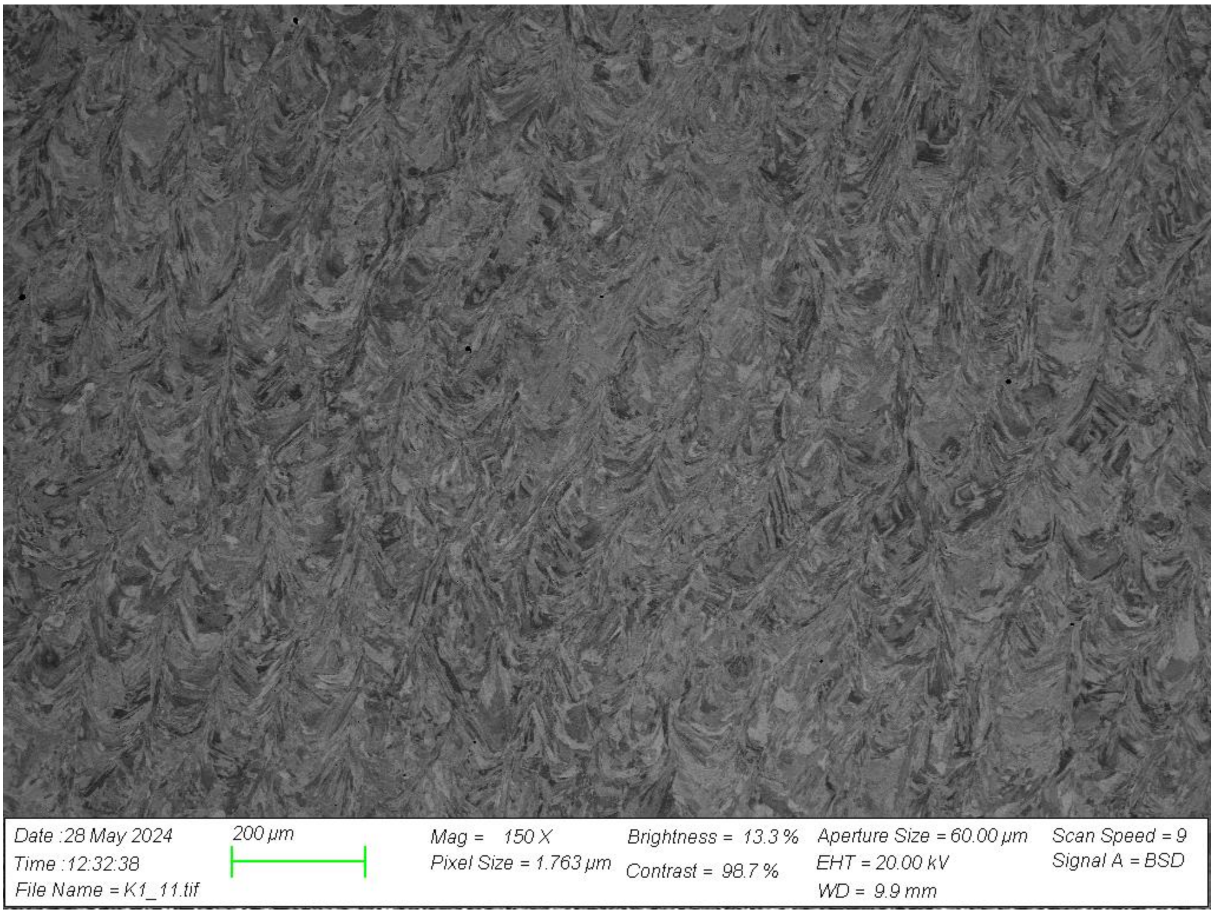

Date :28 May 2024
Time :11:18:49
File Name = K1_06.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 7
Signal A = BSD

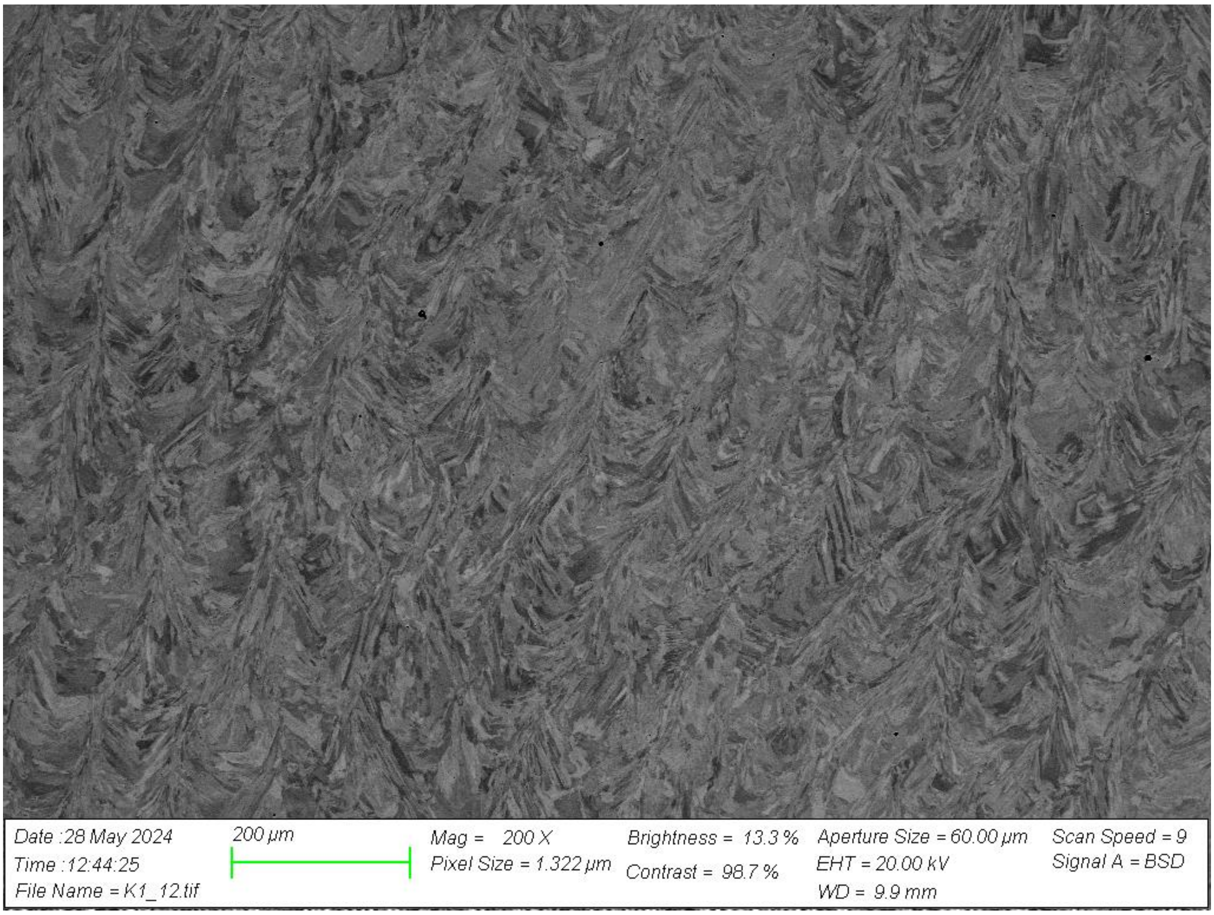

Date :28 May 2024
Time :11:27:52
File Name = K1_07.tif
200 µm
Mag = 200 X
Pixel Size = 1.322 µm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

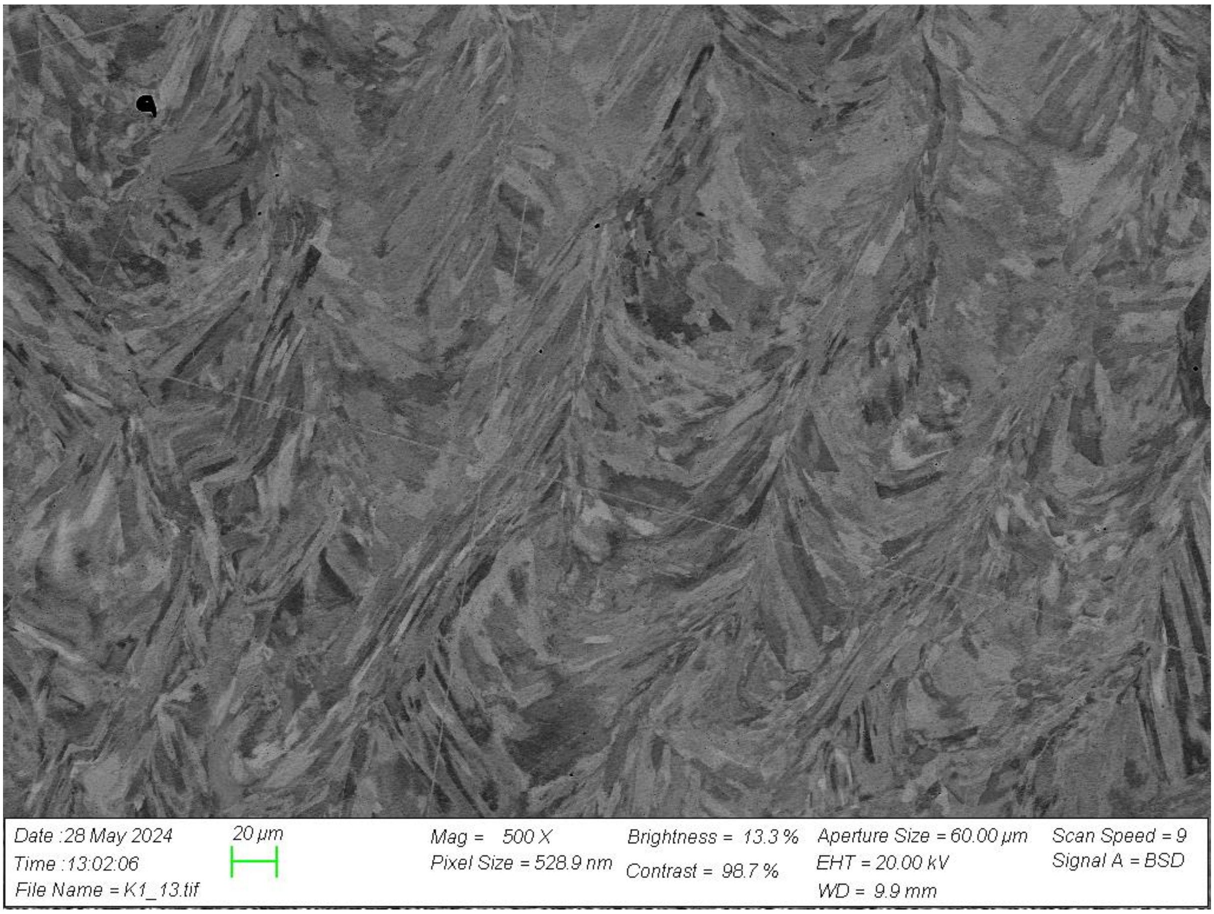

Date :28 May 2024
Time :11:49:57
File Name = K1_08.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

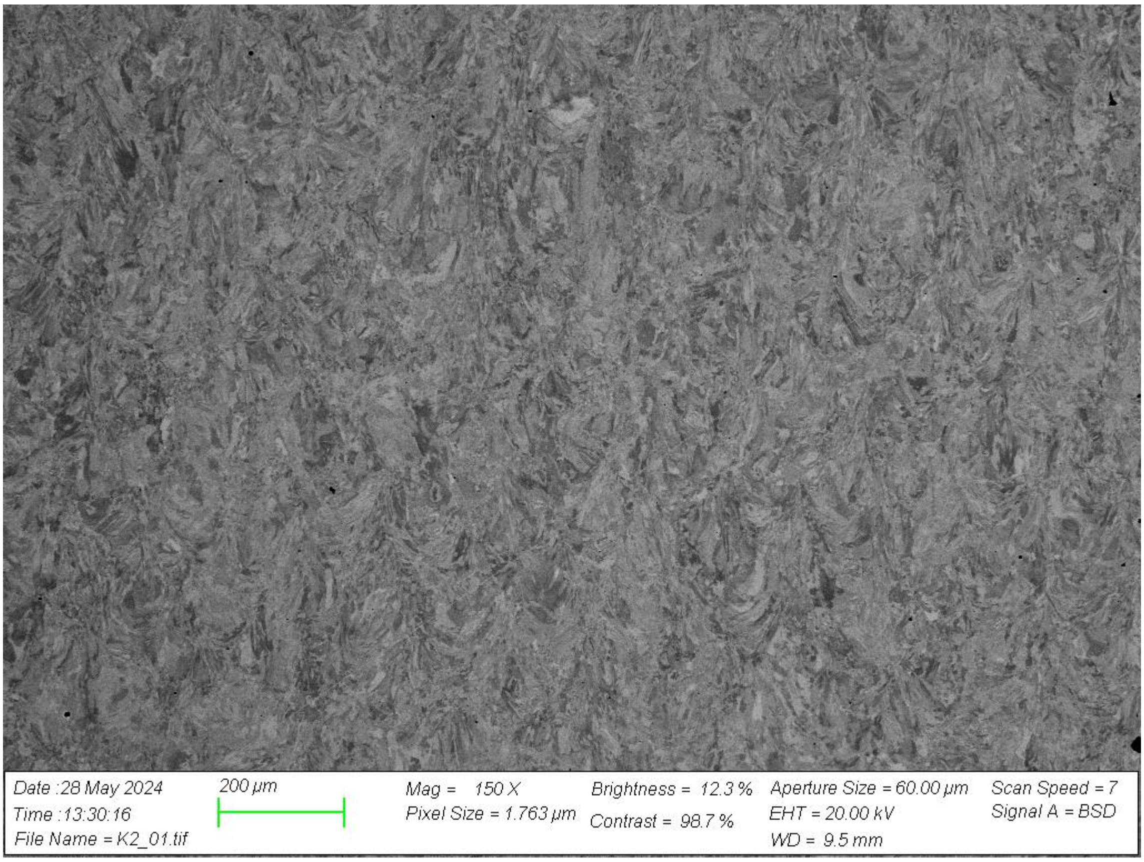

Date :28 May 2024
Time :12:04:38
File Name = K1_09.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

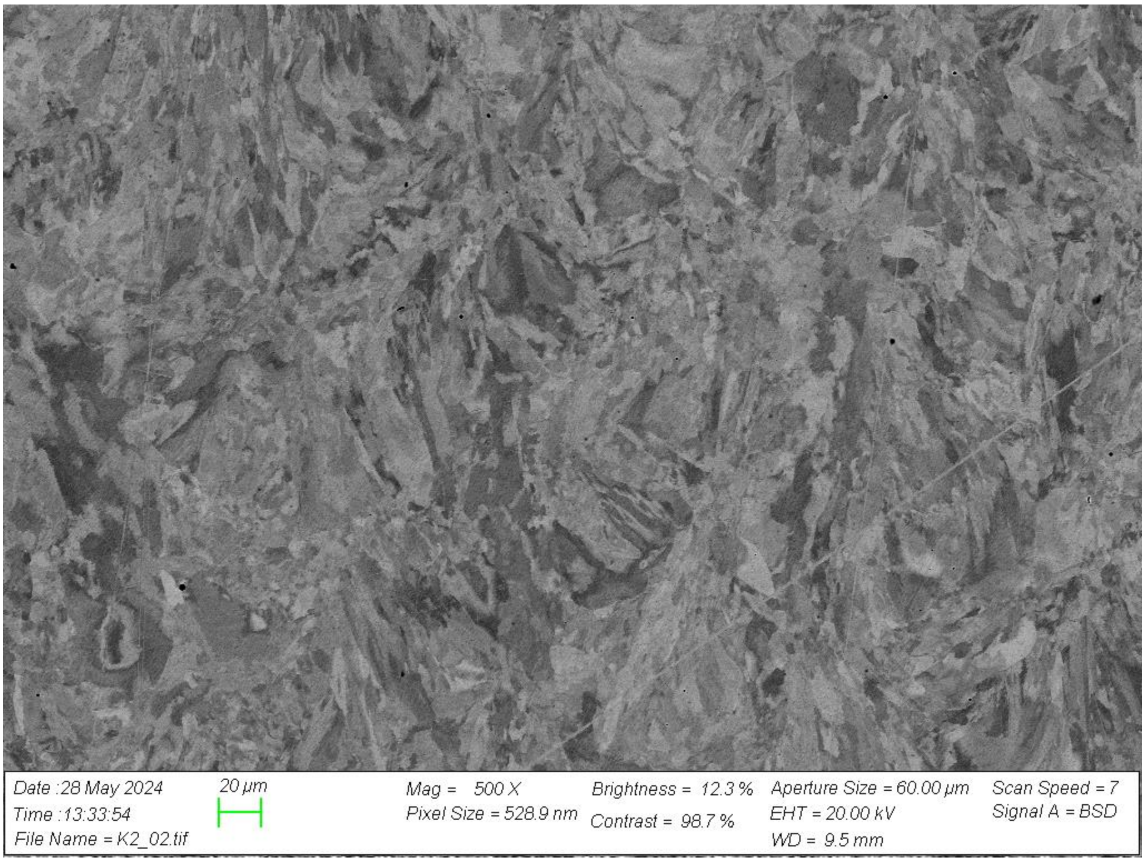

Date :28 May 2024
Time :12:21:06
File Name = K1_10.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD


Date :28 May 2024
Time :12:32:38
File Name = K1_11.tif
200 µm
Mag = 150 X
Pixel Size = 1.763 µm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

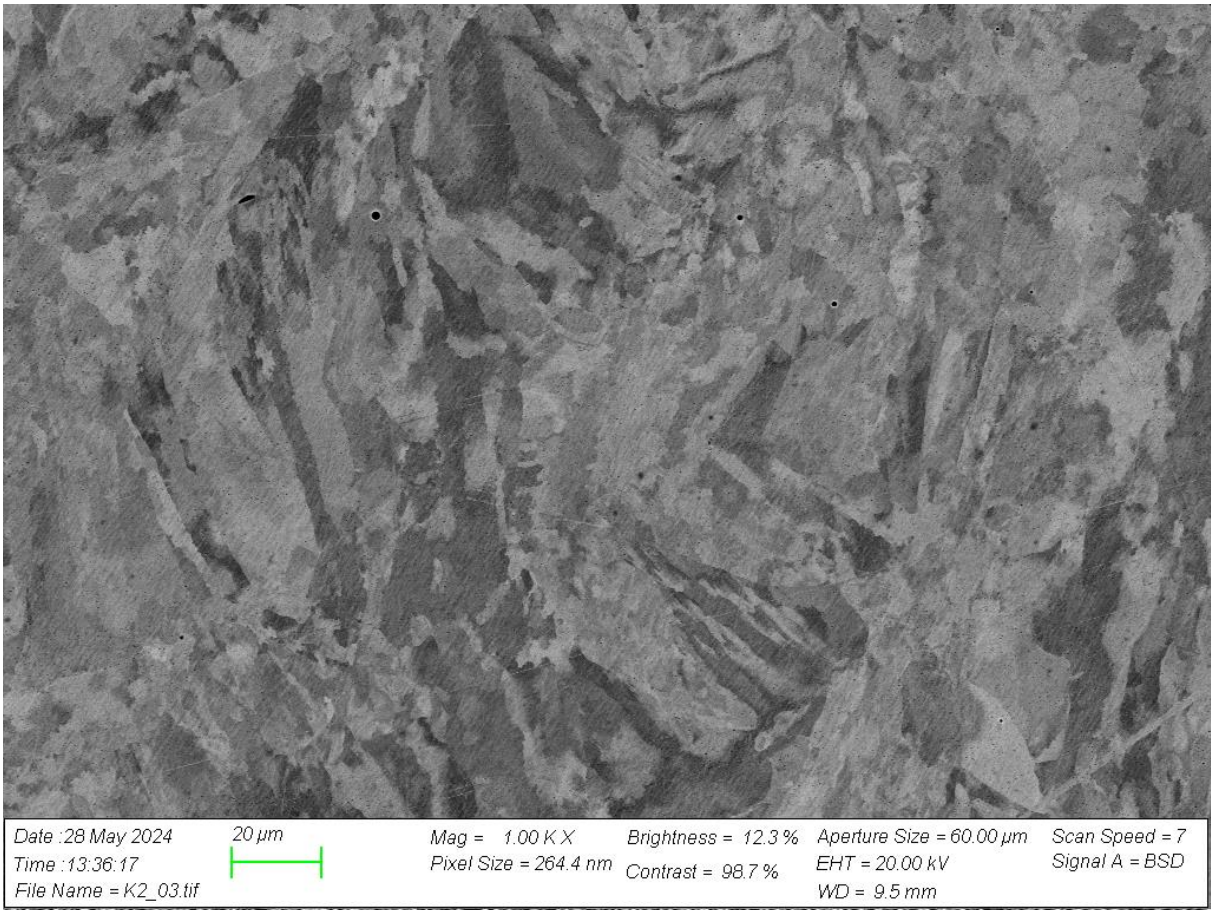

Date :28 May 2024
Time :12:44:25
File Name = K1_12.tif
200 µm
Mag = 200 X
Pixel Size = 1.322 µm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

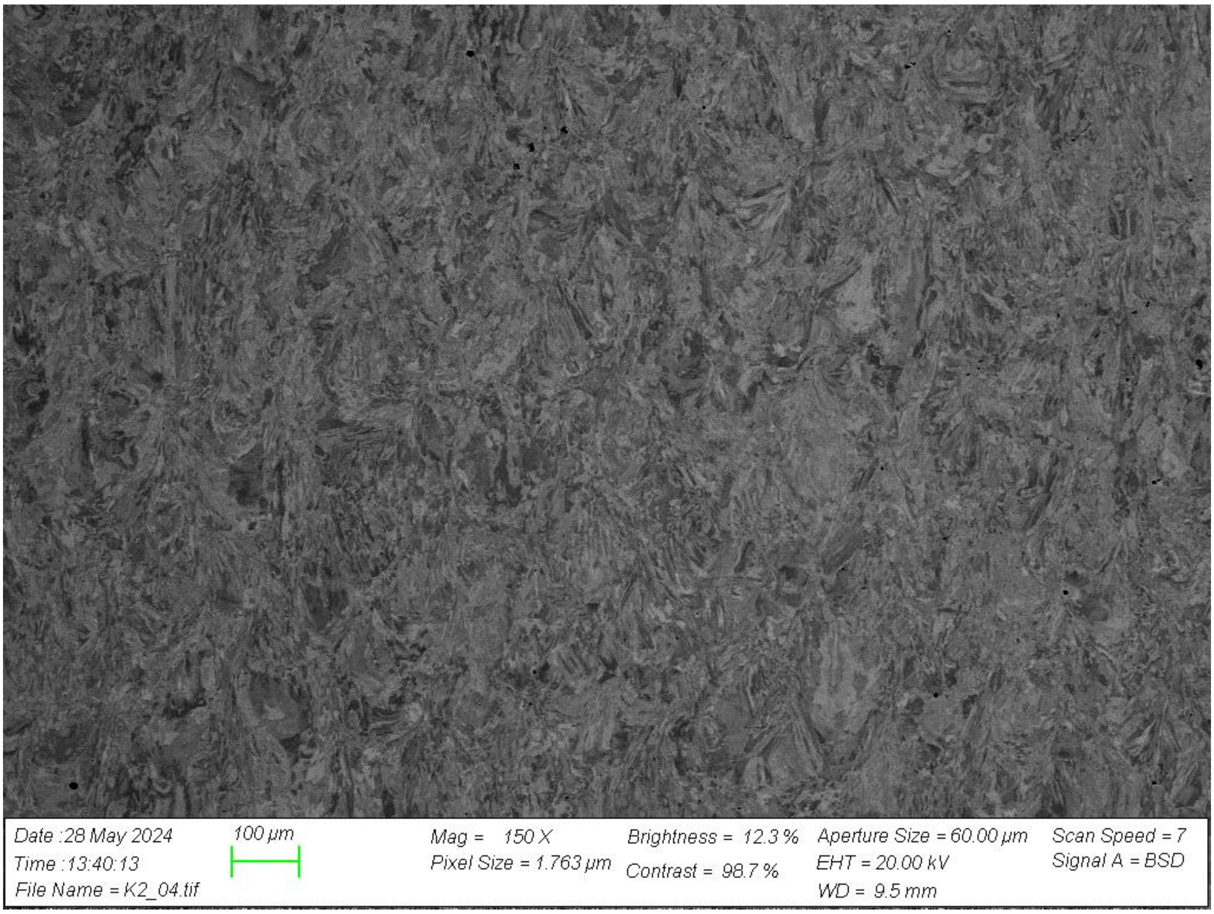

Date :28 May 2024
Time :13:02:06
File Name = K1_13.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 13.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.9 mm
Scan Speed = 9
Signal A = BSD

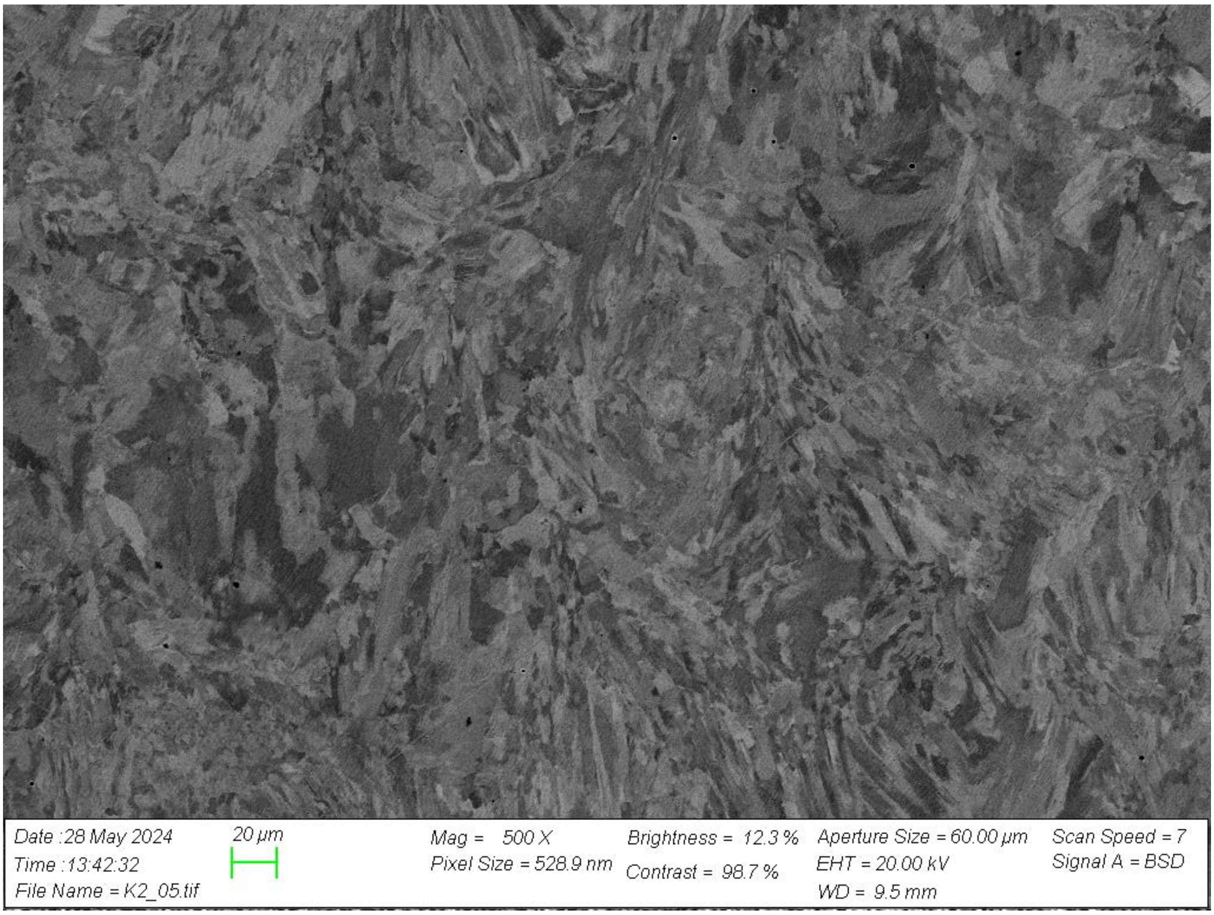


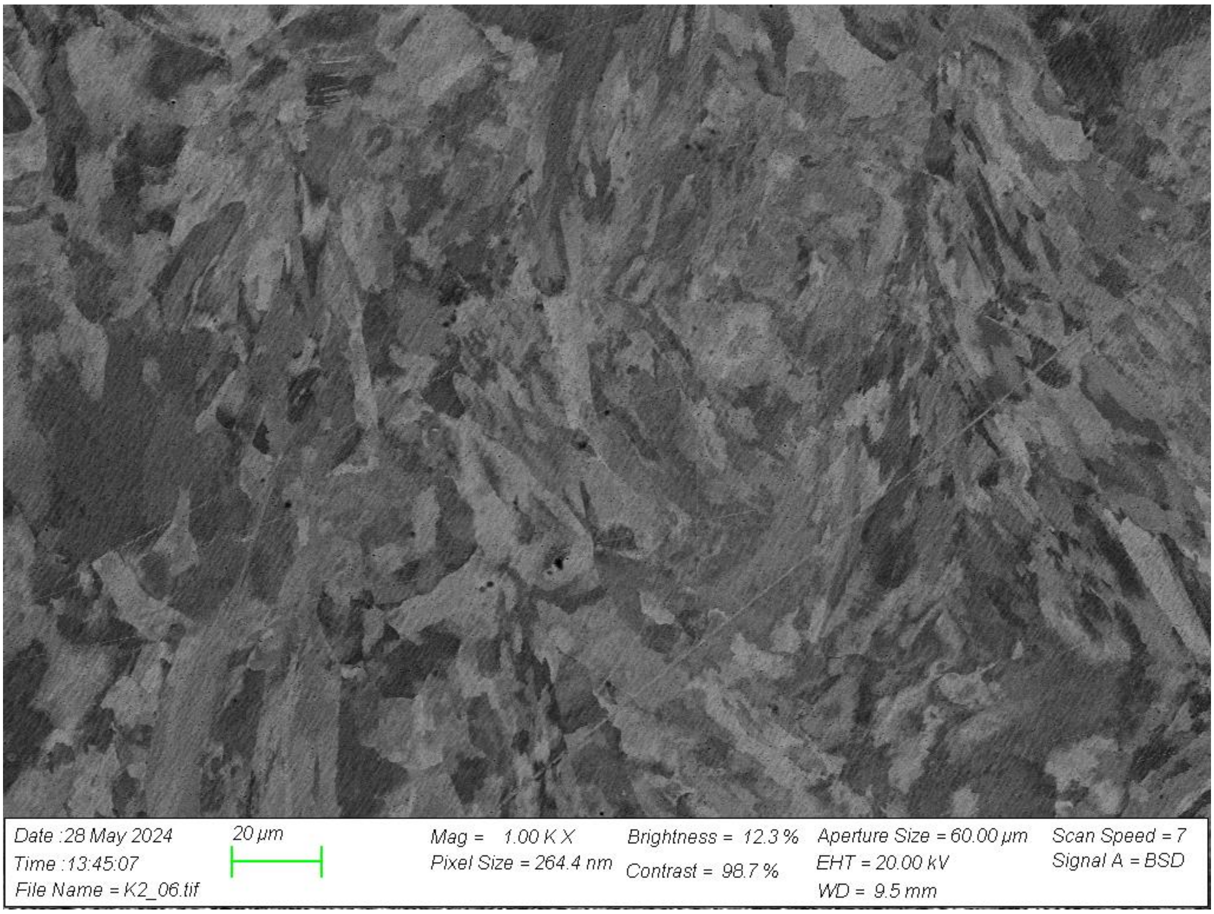


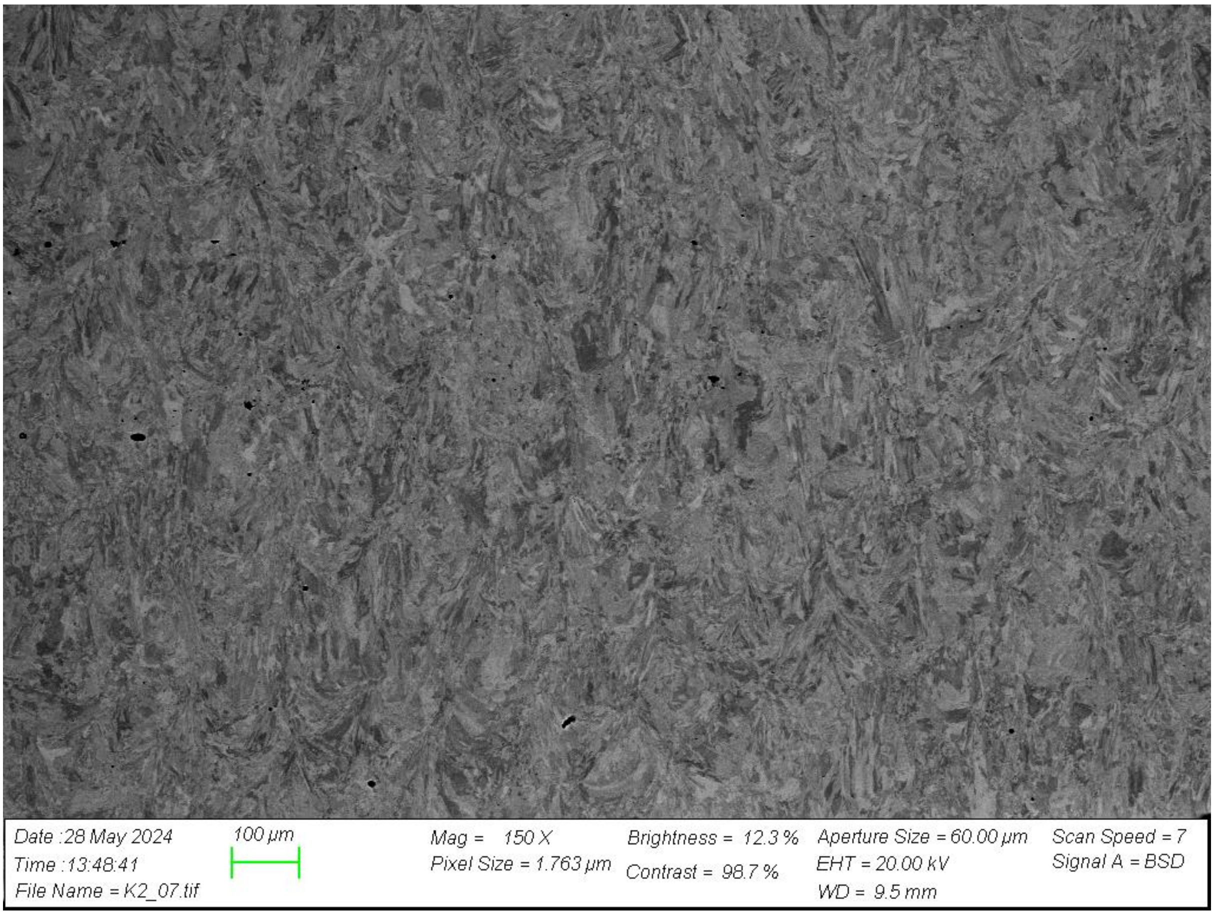
APPENDIX F - 13 Microstructural images from SEM K2

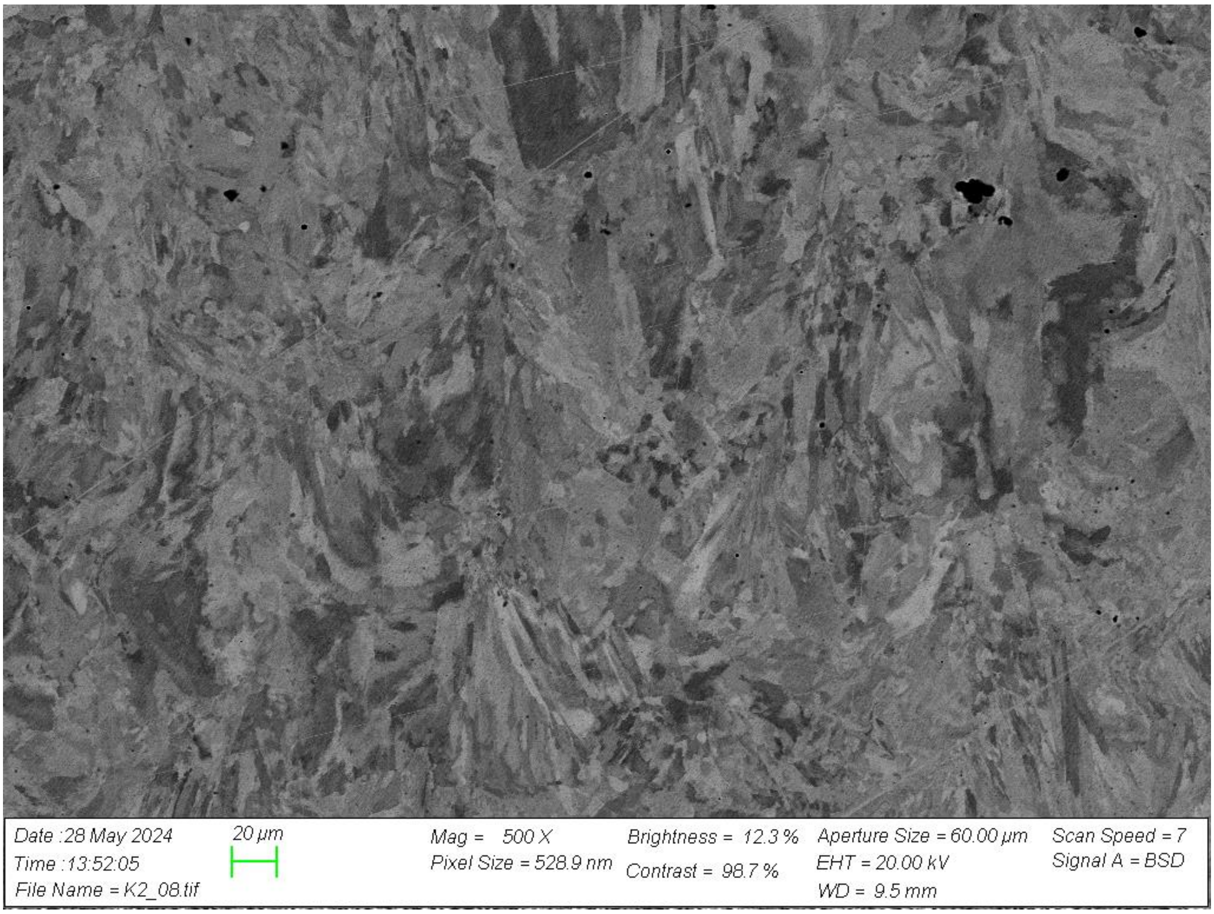

Date :28 May 2024
Time :13:36:17
File Name = K2_03.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

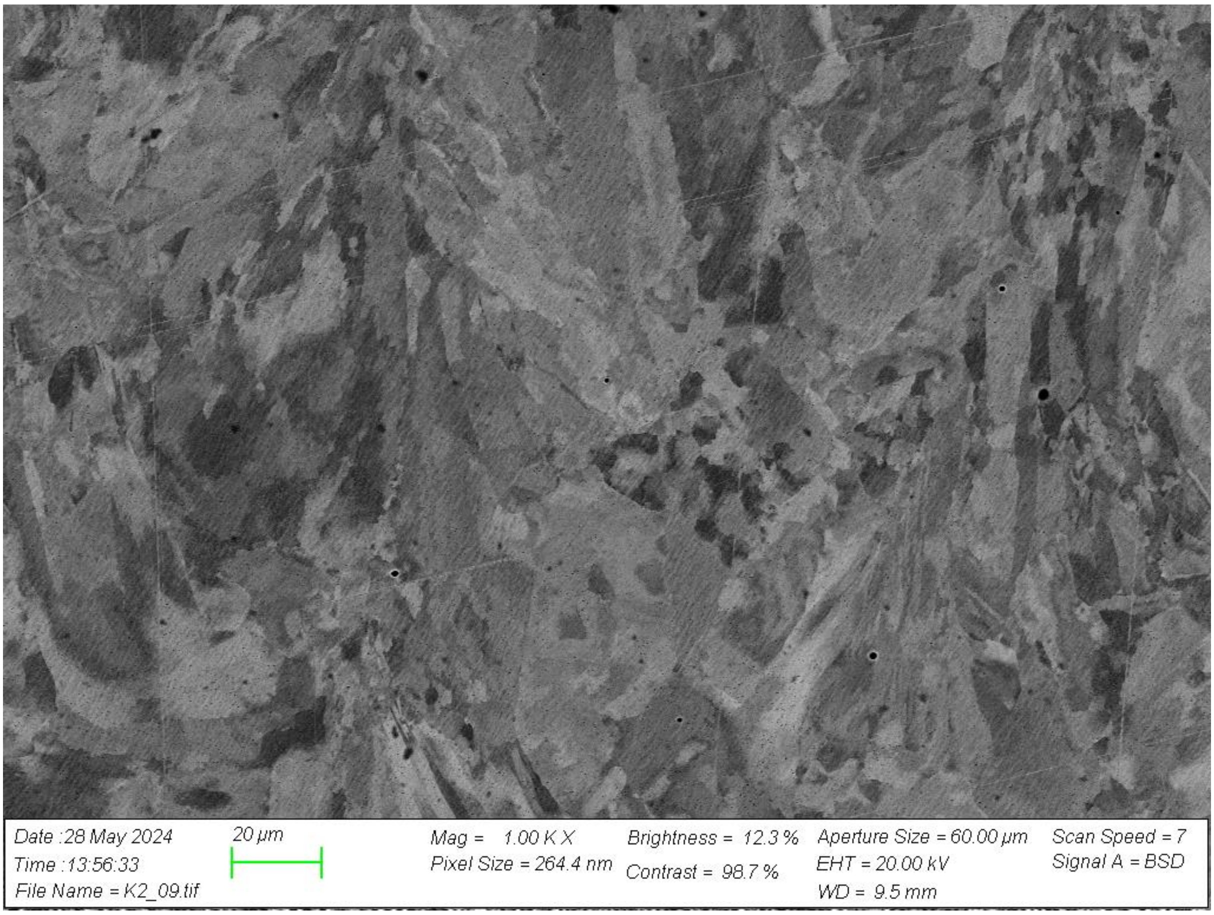

Date :28 May 2024
Time :13:40:13
File Name = K2_04.tif
100 µm
Mag = 150 X
Pixel Size = 1.763 µm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

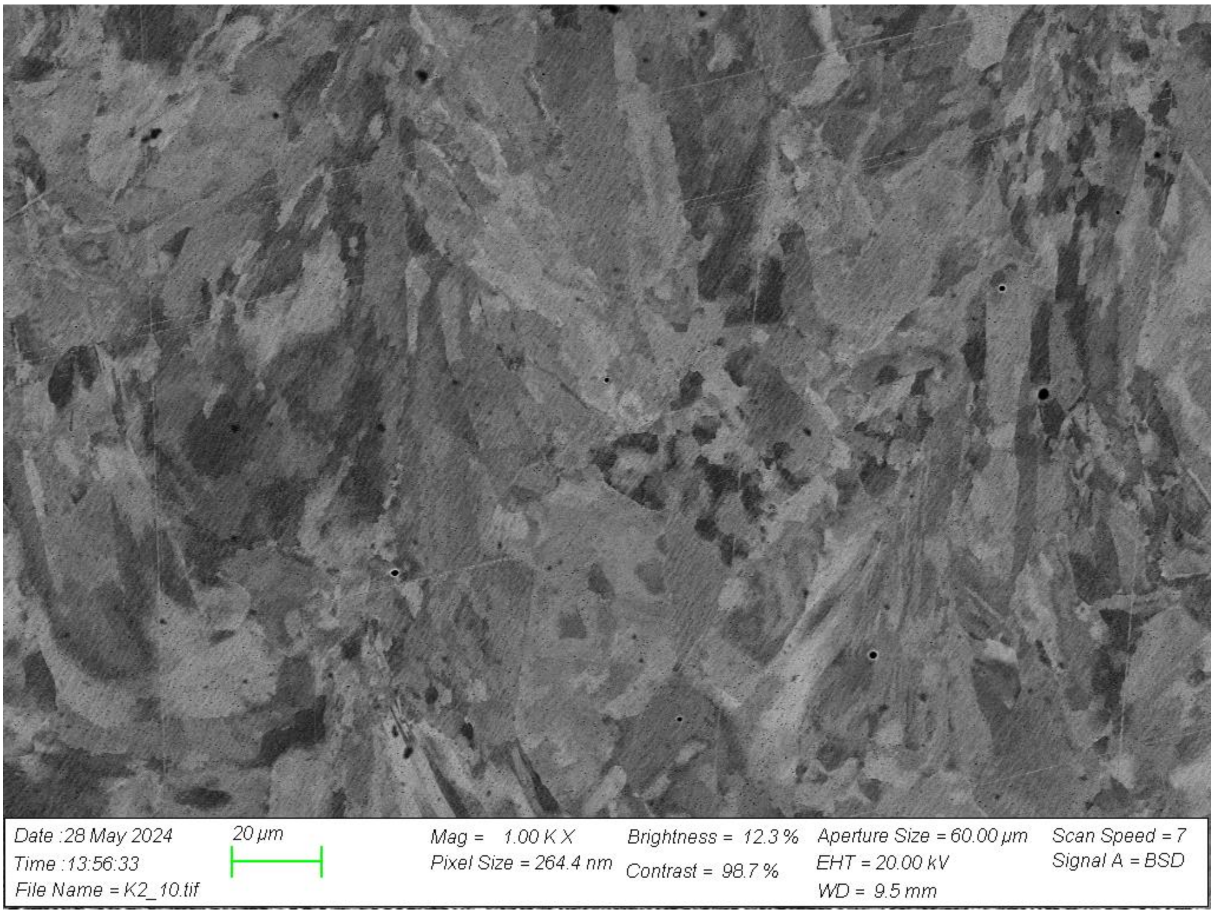

Date :28 May 2024
Time :13:42:32
File Name = K2_05.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

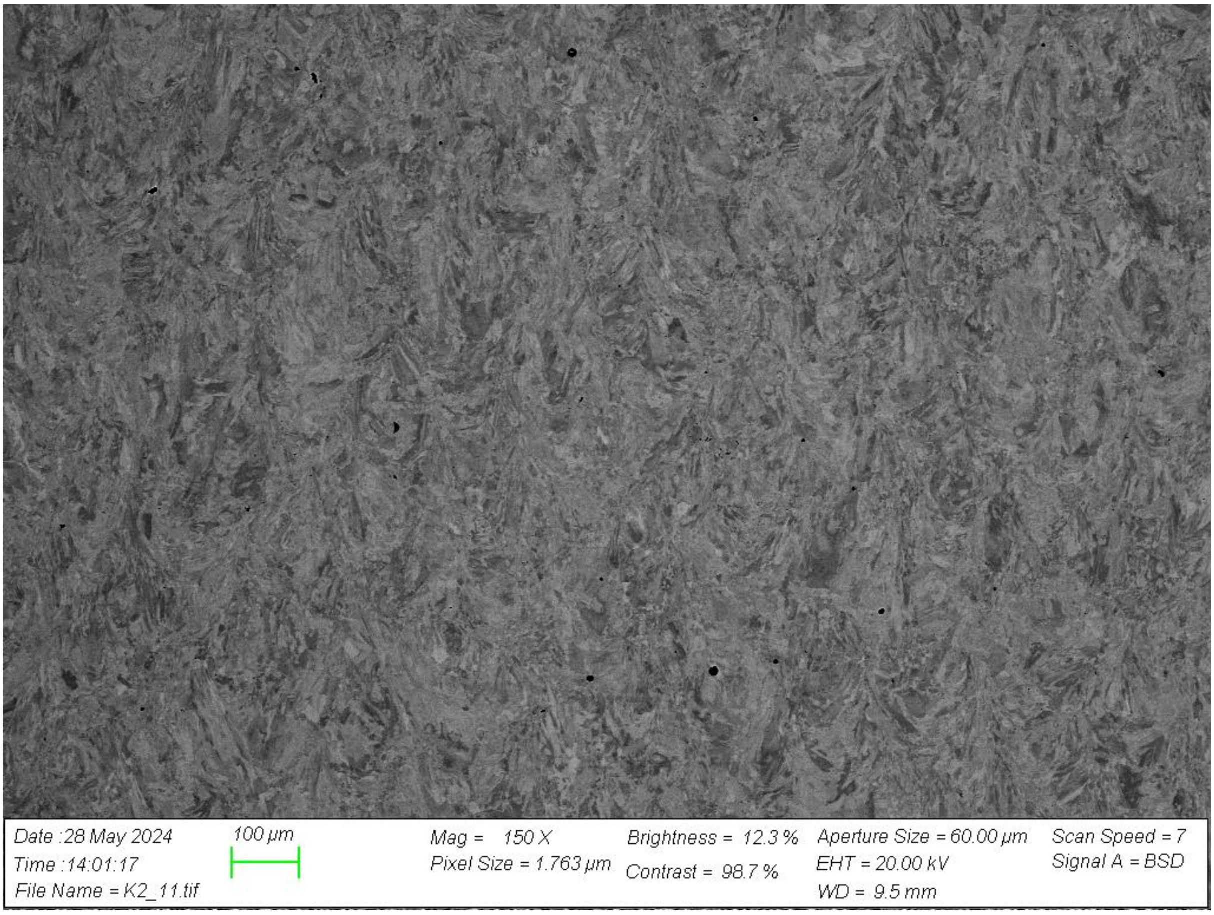

Date :28 May 2024
Time :13:45:07
File Name = K2_06.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

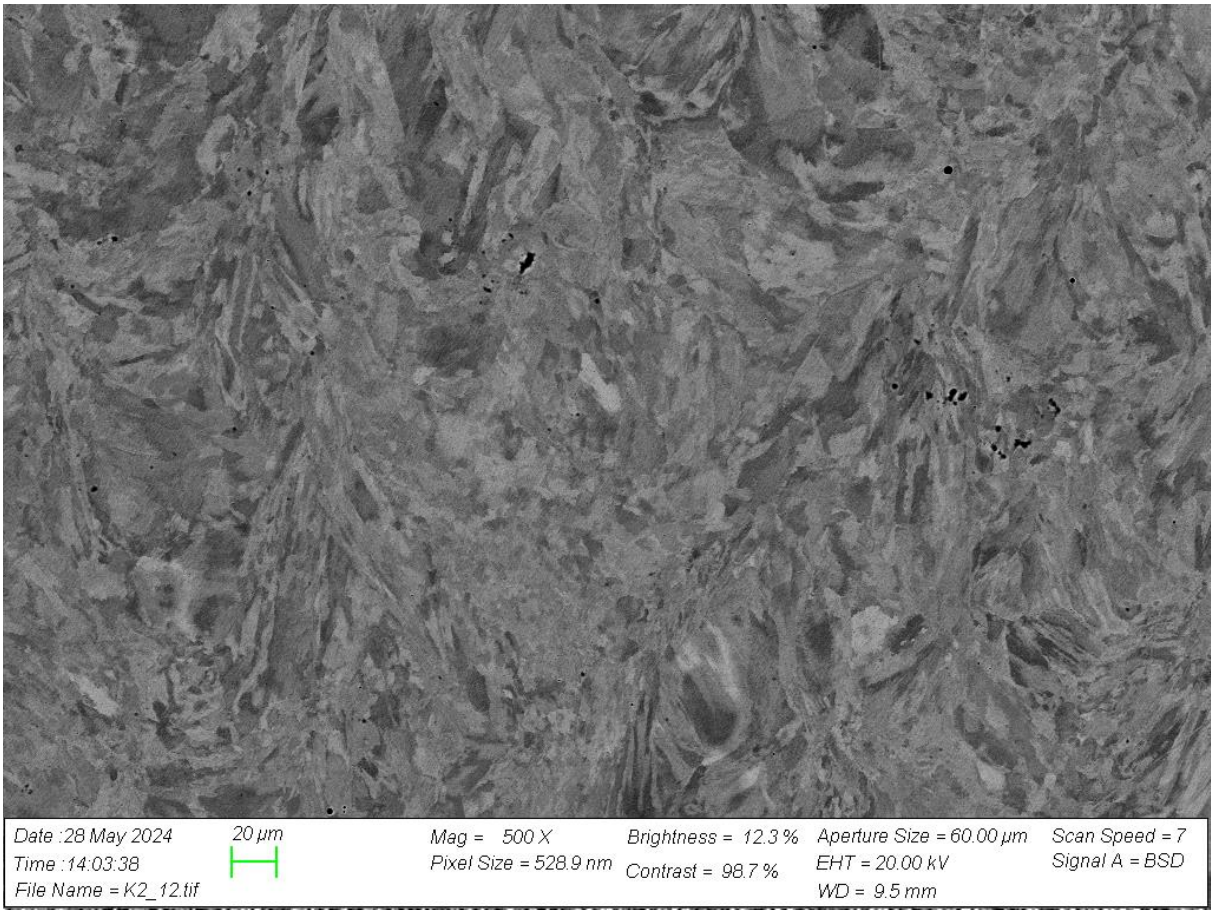

Date :28 May 2024
Time :13:48:41
File Name = K2_07.tif
100 µm
Mag = 150 X
Pixel Size = 1.763 µm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

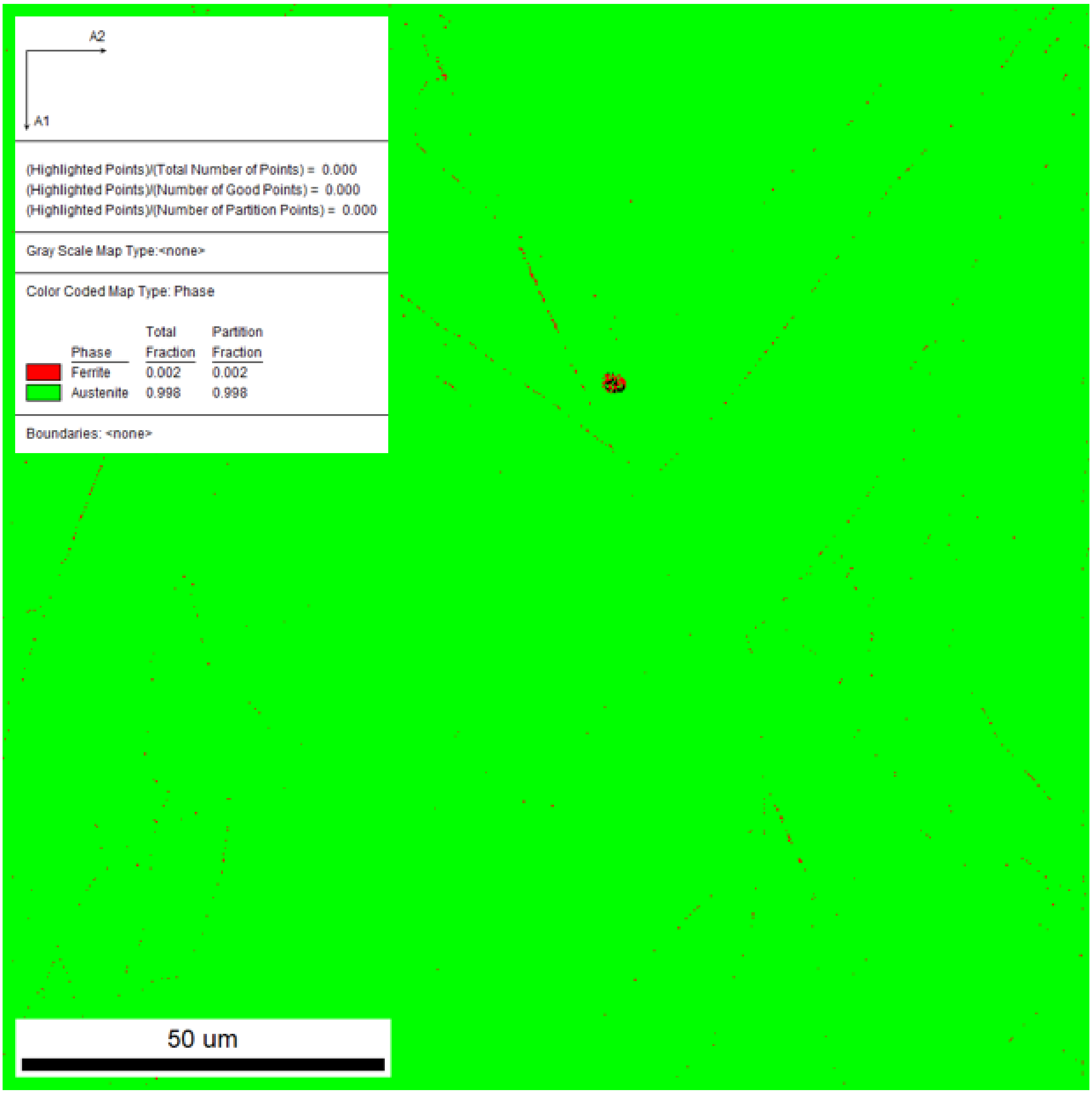

Date :28 May 2024
Time :13:52:05
File Name = K2_08.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD


Date :28 May 2024
Time :13:56:33
File Name = K2_09.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

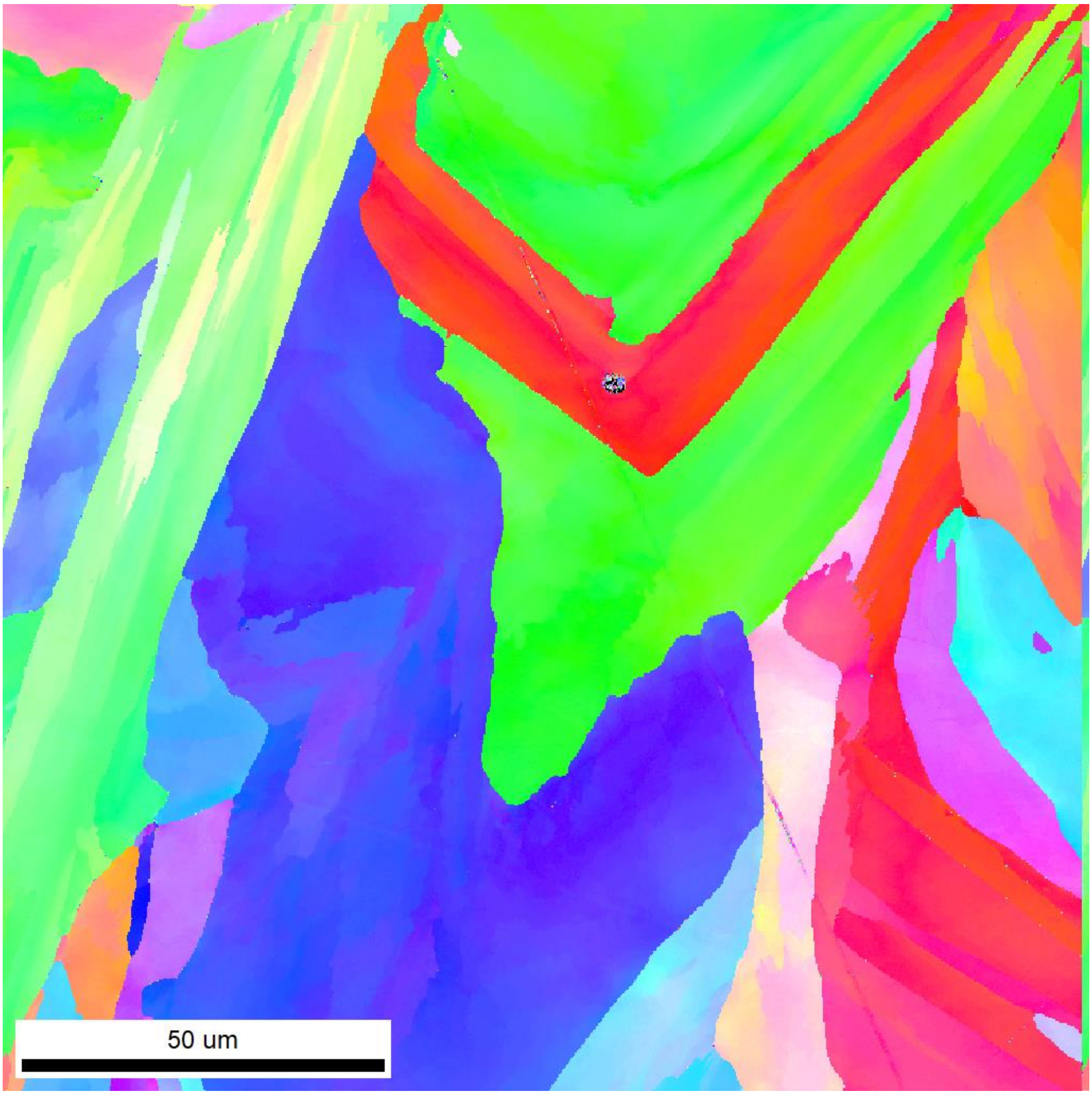

Date :28 May 2024
Time :13:56:33
File Name = K2_10.tif
20 µm
Mag = 1.00 K X
Pixel Size = 264.4 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD


Date :28 May 2024
Time :14:01:17
File Name = K2_11.tif
100 µm
Mag = 150 X
Pixel Size = 1.763 µm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD

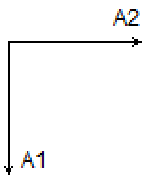

Date :28 May 2024
Time :14:03:38
File Name = K2_12.tif
20 µm
Mag = 500 X
Pixel Size = 528.9 nm
Brightness = 12.3 %
Contrast = 98.7 %
Aperture Size = 60.00 µm
EHT = 20.00 kV
WD = 9.5 mm
Scan Speed = 7
Signal A = BSD



APPENDIX F - 14 Phase map in 500x magnification (99.8% Austenite, 0.2% other phase)



APPENDIX F - 15 IPF in 500x magnification

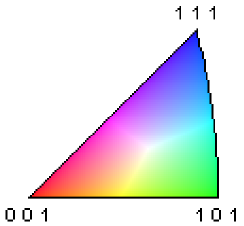


(Highlighted Points)/(Total Number of Points) = 0.000
(Highlighted Points)/(Number of Good Points) = 0.000
(Highlighted Points)/(Number of Partition Points) = 0.000

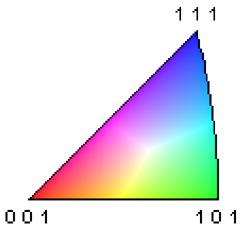
Gray Scale Map Type:<none>

Color Coded Map Type: Inverse Pole Figure [001]

Ferrite



Austenite



Boundaries: <none>

APPENDIX F - 16 Legend for the IPF in 500x magnification

APPENDIX F - 17 Zeiss Supra 35VP

APPENDIX F - 18 Jeol JSM-IT800