DESIGN AND CONSTRUCTION ANALYSIS OF A DISCHARGE SCRAPER FOR A CHLORINE DIOXIDE BLEACHING STAGE

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Design and construction analysis of a discharge scraper for a chlorine dioxide bleaching stage.

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The objective of this thesis was to analyse and propose a discharge scraper design which could be manufactured cost-effectively and used in a chlorine dioxide bleaching stage. The chosen material used to achieve the objectives was grade 2 titanium. Literature review consisted of understanding the process environment of chlorine dioxide pulp bleaching, introducing a structure of a common discharge scraper, understanding why titanium grade 2 is a good material option and investigating titanium grade 2 construction possibilities and manufacturing options. Most realistic solutions for identified problem areas were found based on a points matrix system, optimization from cost-effective point of view, feasibility, CFD-analysis and DFMA comparisons. After final design for assembly was produced, a FE-analysis of structural behaviour was performed for extreme conditions and weight carrying conditions.

The new design was produced and made to be as cost-effective and manufacturable as possible without significant effect on discharge scraper function or dimensions. The biggest design changes were made for the flange connection area between scraper and tank connection flanges and for the hub structure. The results from FE-analyses showed that the design changes and material change do withstand weight carrying conditions and extreme conditions without great distortion or failure. However, optimal manufacturing methods and design can be achieved through first manufacturing, optimized FE-analysis and possible topology optimization. Constantly developing additive manufacturing could also provide more possibilities in the near future.

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Tämän diplomityön tavoitteena oli analysoida ja suunnitella pohjakaavari, joka voidaan valmistaa kustannustehokkaasti ja käyttää klooridioksidivalkaisuvaiheessa. Tavoitteiden toteuttamiseksi, käytettävä materiaali oli puhtausluokan 2 titaani. Kirjallisuuskatsauksessa selvitettiin klooridioksidivalkaisun prosessiympäristöä, yleisen pohjakaavarin rakenne, miksi luokan 2 titaani on hyvä materiaalivaihtoehto ja luokan 2 titaanin käyttömahdollisuuksia ja valmistuskäyttäytymistä. Realistisimmat ratkaisut tunnistetuille ongelma-alueille löydettiin käyttämällä pistematriisijärjestelmää, kustannustehokkaaseen valmistukseen perustuvaa optimointia, toteutettavuutta, CFD-analyysiä ja DFMA-vertailuja. Sen jälkeen, kun lopullinen kokoonpanosuunnitelma oli valmis, rakenteelle tehtiin FE-analyysi äärimmäisissä olosuhteissa ja painonkanto-olosuhteissa.

Uusi malli pyrittiin tekemään mahdollisimman kustannustehokkaaksi ja helposti valmistettavaksi ilman merkittävää vaikutusta pohjakaavarin toimintaan tai mittoihin. Suurimmat suunnittelumuutokset tehtiin kaavari- ja säiliöliitoslaippojen väliseen liitosalueeseen ja naparakenteeseen. FE-analyysin tulokset osoittivat, että mallimuutokset ja materiaalimuutokset kestävät painonkanto- ja äärimmäisolosuhteissa ilman suuria vikoja tai muodonmuutoksia. Optimaaliset valmistusmenetelmät ja mallit voidaan kuitenkin saavuttaa ensivalmistuksen, optimoidun FE-analyysin ja mahdollisen topologisen optimoinnin avulla. Jatkuvasti kehittyvä materiaalia lisäävä valmistus voisi myös tuoda lisämahdollisuuksia lähitulevaisuudessa.

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Niko Kristian Hotti 26.10.2023

SYMBOLS AND ABBREVIATIONS

Roman characters

F	Force [N]
g	Gravitational acceleration [m/s^2]
h	Depth [m]
m	Mass [kg]
P	Power [W]
p	Pressure [bar]
r	Radius [m]

Greek characters

ρ	Fluid density [kg/m^3]
τ	Torque [Nm]
ω	Rotational speed [rpm]

Abbreviations

ASTM	American Society for Testing and Materials
CFD	Computational Fluid Dynamics
DFA	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly

EB	Electron Beam Welding
ECF	Elemental Chlorine Free
FEA	Finite Element Analysis
FEM	Finite Element Method
FEP	Fluorinated Ethylene Propylene
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HIP	Hot Isostatic Pressing
ISO	International Organization for Standardization
MIG	Metal Inert Gas
PAW	Plasma Arc Welding
TCF	Total Chlorine Free
TIG	Tungsten Inert Gas

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1 Introduction

The motivation and relevance of the thesis topic are stated in the introduction. Introduction also presents the objective, context, research problem, research questions and briefly the methods to establish the contribution and scope of the thesis.

1.1 Background and motivation

According to European Commission (2013), the production of pulp in the world is still a massive industry and has room to grow as the technology in energy efficiency and hygienic packaging is developing. Pulp and paper industry as a whole is a pioneer in making the EU low-carbon economy an industrial reality. Innovation and resource efficiency allow pulp and paper industry to make a significant difference in reducing environmental impacts caused by the industrial sector.

The pulping processes are posing environmental risks with harmful emissions and pollutant caused by various substances that are used in the processes. Industries and scientific sectors are working more and more to find better raw materials and creating new pulping process methods. Installing environmentally friendly systems and constantly improving operating conditions are part of adopting a sustainable development strategy. (Bajpai 2023, 1-4.)

Bleaching with chlorine dioxide can be considered a quite old method as it was first used commercially in Canada and Sweden in 1946 (Bajpai 2012, 135-161). Due to it being a relatively old process, multiple different research on using titanium in the pulp industry has been done. For example, in 1992 Avery, Tuthill & Andrew (1992) investigated chlorine dioxide's corrosive effect on multiple different piping weldments, in which one of the investigated piping materials was titanium. In 1999 Suresh Kumar Danadurai & Rajeswari (1999) did an investigation on corrosion performance of 316L SS and titanium modified austenitic steels in the bleaching phase of a pulping process to find the best solutions for raw material selection. However, these researches and investigations are highly focused on material selection for piping and tank walls and they don't give a statement on how the material selection affects the manufacturing, construction and cost-effectiveness of equipment, sleeves, axles etc.

It is recommended that in the pulp bleaching towers titanium or stainless-steel material is used, and titanium is especially an ideal choice in bleaching stages where chlorine dioxide is present (Suess 2010, 21-91). According to Arima (2013), when using titanium, the need and construction methods must be critically analysed to justify the use of titanium as the manufacturing of titanium parts has a great economic and environmental impact.

Titanium can be considered as a difficult material to be worked with. The main challenges are especially in machinability but some difficulties in welding and heat treating of titanium and its alloys are also present. Properties of titanium that affect these problem areas are hardness, tensile strength, ductility, tendency to chip and crack, thermal conductivity, and high melting point. (Yadav 2022.)

1.2 Research problem

Technological changes in pulp production have caused a need to research and design a new high corrosion resistant discharge scraper for the bleaching stage in pulp manufacturing process to improve process flow in certain applications. It is expected that the commonly used discharge scraper cannot be utilized in the new environment without any modifications. This thesis is concluded by investigating the problem areas against corrosion on a previous scraper design and finding the best options to prevent corrosion using titanium grade 2 as a construction material. The highly corrosive environment is referring to the bleaching stage of a pulp production process and the discharge scraper is needed in a stage where chlorine dioxide is used in the bleaching process.

1.3 Objectives and research questions

The objectives of this thesis are to outline different problem areas of a discharge scraper in a highly corrosive environment and analyse solutions to prevent corrosion risk by using titanium grade 2. To use titanium effectively, the construction possibilities and behaviour need to be investigated. Based on the findings, the best manufacturing and construction solutions are applied to the design with cost-effectiveness being the main thriving factor for the selection process. Some lining and sealing solutions are also expected to be applied as it

is anticipated that some protective measures cannot be done cost-effectively by changing the material. Based on the objectives three research questions were formatted:

- How a titanium discharge scraper needs to be constructed to be used in a chlorine dioxide bleaching phase and how it can be done cost-effectively?
- How different titanium construction possibilities and solutions affect the manufacturing process, costs, and corrosion risks of a discharge scraper?
- How material change affects the discharge scraper structure, function, and construction?

1.4 Research methods and scope

The research process includes a literature review of what is the new process environment for the discharge scraper, why titanium is the best option for a pulp bleaching application and understanding different manufacturing and construction options with titanium grade 2 that could be realistically applied to a discharge scraper construction for a pulp bleaching stage. The scraper's structure and weak points for corrosion risk are analysed by observing CAD (Computer-Aided Design) models, machining pictures and manufacturing processes. Also, discussions are held with experts to identify problem areas based on experience and expertise. After the realistic manufacturing methods and needed protective measures are identified the design of the discharge scraper is altered to be manufactured cost-effectively and assembled in a way that all sealing and lining issues are covered without affecting the function of the scraper. The final design is optimized and analysed through using DFMA (Design For Manufacturing and Assembly) approach and FE-analysis (Finite Element Analysis). Specific parameters for machining and manufacturing such as tool materials, speeds, throat sizes, surface roughness, bending forces etc. are beyond the scope of this thesis. The manufacturing plan is made for parts that have significant design changes or are new when compared to a common discharge scraper, which means that the original manufacturing plans for previously known unchanged parts can be applied to the new assembly. Main focusing point is on analysing the scraper design, so the affects and design of tank connection flange, secondary shaft, sealing solution and motor bed are evaluated less. The references that are used are tried to be kept under ten years old, but as the pulp

bleaching process is a relatively old method and titanium is a common construction material, older references can also be used if the information can be considered as everlasting and still relevant. When referring to just “pulp bleaching process”, it refers to a chemical pulp bleaching process if not otherwise implied. This thesis is affected by confidentiality as current design pictures cannot be published and some designs, dimensions and tolerances for solutions could be censored.

1.5 Expected contribution

The expected contribution is to produce a discharge scraper design that utilizes titanium grade 2 manufacturing possibilities effectively so the design could be manufactured cost effectively. The contribution also includes comparisons of different titanium grade 2 manufacturing methods with a low volume of manufacturing. This thesis gives theoretical results on how the design should be manufactured and gives a basis for a potential concrete manufacturing of a discharge scraper for pulp bleaching application.

1.6 Thesis work premises

Work premises outline the surroundings and reasons on what, why and where this thesis work is done. They also help on understanding the starting point of this work.

1.6.1 Andritz group

Andritz is a company that provides a comprehensive portfolio for a large number of different industries all over the world. Its solutions and technologies thrive on any major business areas and Andritz provides plenty of customized solutions. Andritz is one of the world’s leading suppliers in hydropower stations, the pulp and paper industry, the metalworking and steel industries, and for solid/liquid separation. They specialize in supplying these industries with plants, equipment, and services. (Andritz group 2023.)

In Finland, Andritz Oy is one of the world’s leading pulp and paper industry system, machinery, and service providers. Their main focus areas are in wood processing, fibre

processing, chemical recovery, and pulp processing. Andritz Oy also offers different kinds of biomass boilers and gasification plants for energy production applications. It is a large employer in Finland, having over 1600 of staff members in various locations in Kerava, Kotka, Lappeenranta, Oulu, Savonlinna, Tampere, Vantaa and Varkaus. (Andritz in Finland 2023.)

1.6.2 Andritz Kotka division

Andritz Kotka division is considered as the fibre technologies division. This division is in charge of engineering machinery that is used in production of chemical pulp. It is also in charge of delivering the processes. The machinery consists of boiling systems, washers, industrial sieves, and bleaching systems.

1.6.3 Structure and location of a common discharge scraper

A discharge scraper is commonly used for discharging towers in various stages such as the boiling phase of the chemical pulp production process. Its purpose is to scrape and gather mass from the bottom of the tank and insert it to a discharge port by slowly rotating around its axle. At the same time, it makes the mass flow more homogenous and constant. The discharge scraper can be equipped with holes that from which washing filtrate can be added into the process. (KnowPulp 2023.)

The basic structure of a discharge scraper can be seen on figure 1. It mostly consists of scraping wings, connection hub, axle, gearbox, support structure, and electric motor. The scraper is connected to the bottom of a boiler or a tank with a flange connection. The discharge outlet or pipe can be located either under the scraper hub or beside the scraper hub. In the figure the discharge pipe is located beside the discharge scraper. (KnowPulp 2023.) For scale reference, the tank diameters where Andritz Oy use discharge scrapers can be from 3 meters up to 13 meters.

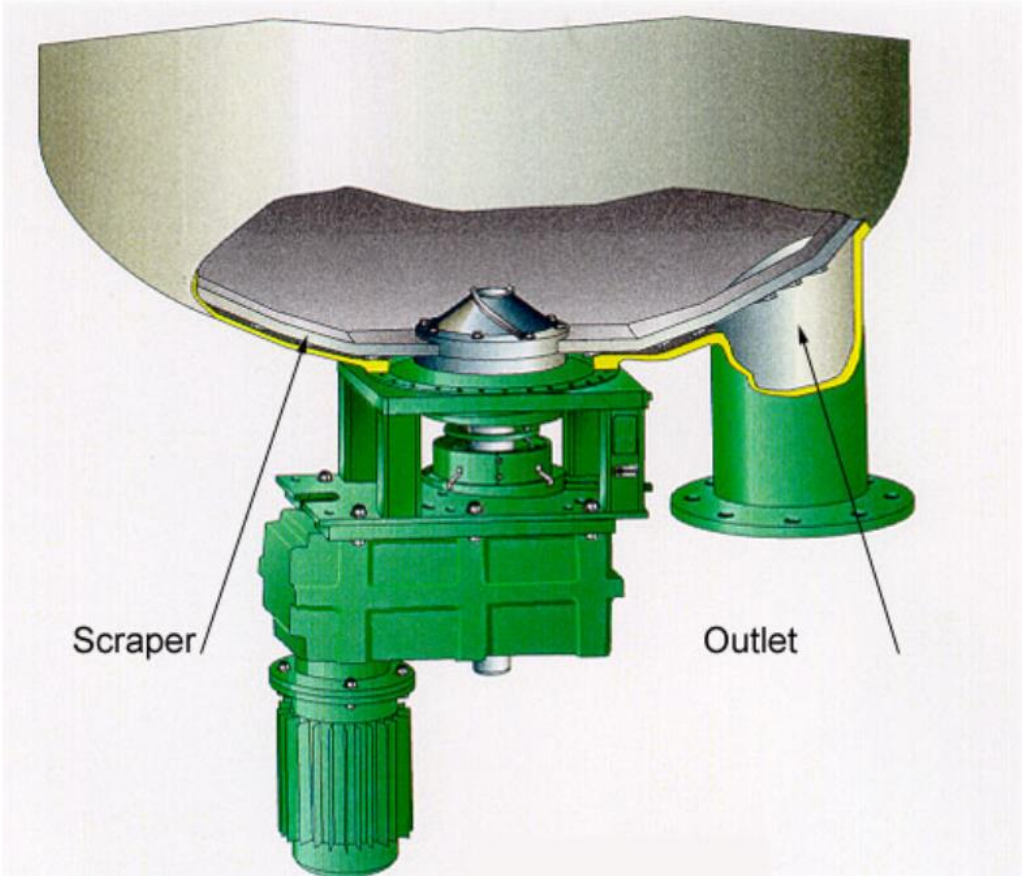


Figure 1. Discharge scraper sketch (KnowPulp 2023).

As previously mentioned, the working principle and function of a discharge scraper are now needed in a different phase of a chemical pulp production process than earlier. As the process environment and substances that are in contact with the scraper in the different stage of pulp production differ from the commonly used environment, the design, material, and structure that is currently used cannot be utilized in the new environment without any modifications.

2 Methods

Research methods are methods and tools that help to achieve the set objectives of the thesis. This chapter also validates the used methods and give a concise description of how they are applied in this thesis work. Finding the best solutions for construction is highly focused on the literature review, expert analyses and interviews, and utilization of method tools.

2.1 3D-modeling & FE-analysis

The modelling software that is used in this thesis is Autodesk Inventor 3D parametric modelling software. The Autodesk Inventor software is mainly used to observe and investigate existing models and machining pictures to highlight problem areas. It is also used to produce the necessary design and machining pictures based on new design needs and manufacturing methods. Autodesk Inventor is also equipped with a FEM (Finite Element Method) tool which can be used to approximate possible stresses in the structure by applying needed constraints and loads according to real world conditions and calculations.

Autodesk Inventor was first introduced in 1999 as an aspirational 3D modelling software based on parametric modelling. With Autodesk Inventor software it is possible to make 2D sketches, 3D models, drawings, assemblies, visualizations and much more (Waguespack 2011, 1-2). The stress analysis environment that is available in Autodesk Inventor uses FEA (Finite Element Analysis) technique. This technique is based on solving a complex object by splitting the object into multiple elements that then form a mesh. When applying a given set of wanted conditions onto the mesh, basic trends can be determined of the design. (Waguespack 2011, 773-775.)

2.2 Design for Manufacturing and Assembly

Premise of manufacturing and assembly friendly product design (Design for Manufacturing and Assembly = DFMA) is to close the gap between designers and manufacturing department. To achieve this, clear principles are needed to achieve an easier manufacturing and assembly process for a product, assembly, or a construction. Some DFMA

manufacturing related viewpoints are the basic starting points of manufacturing friendliness, grouping manufacturing methods and seeing different methods as alternatives, manufacturability key figures for different materials specific to manufacturing methods, and manufacturing method-specific planning instructions. When using DFMA analysing tools, it is always important to understand that the function of the analysed or optimized part cannot be compromised. In figure 2 it is shown how the product manufacturing, construction material, and product geometry are always based on the products functionality standards. DFMA method gives guidelines and various kinds of parametric evaluation forms that can be used to determine better manufacturing and assembly solutions for different kinds of products. (Eskelinen & Karsikas 2013a, 7-10.)

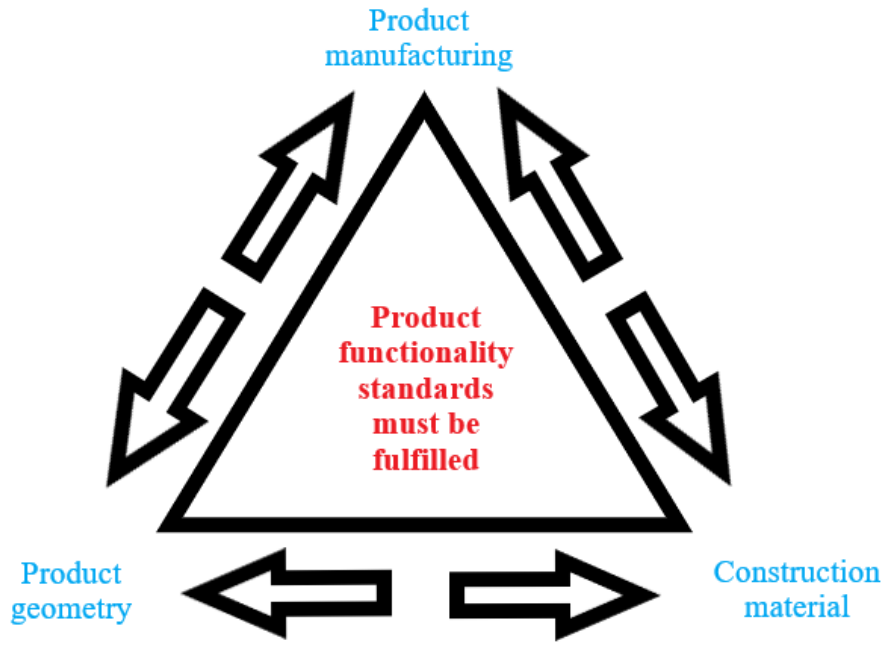


Figure 2. Visualization on how the functionality of a product must be fulfilled when using DFMA-analysis tools. Translated from (Eskelinen & Karsikas 2013a).

In this thesis the main focus area is not on using DFMA analysis and making a new design based on the DFMA results only. This method is mainly used as a tool to help and compare different applicable solutions and manufacturing methods that could be applied in the desired final design, especially from a DFM (Design for Manufacturing) point of view. DFMA

method gives great tools which can be used to compare different manufacturing methods and assembly options. This way the most realistic final product design could be decided with less effort and with actual parametric comparison results, not just opinions.

2.3 COBWEB-analysis tool in systematic material selection

COBWEB-analysis is a material selection tool that provides a comprehensive way to study multiple material properties in a cobweb-shaped analysis map. Each property is assigned a numerical value, allowing for easy comparison among them. A higher numerical value signifies a superior material property. The analysis map gives a good perspective on the material's characteristics and aids in identifying the most suitable material property based on specific requirements. Moreover, by comparing material properties to the product's component requirements, COBWEB enables a more detailed assessment of the material's suitability for the chosen product. Example of a COBWEB-analysis structure can be seen in figure 3.

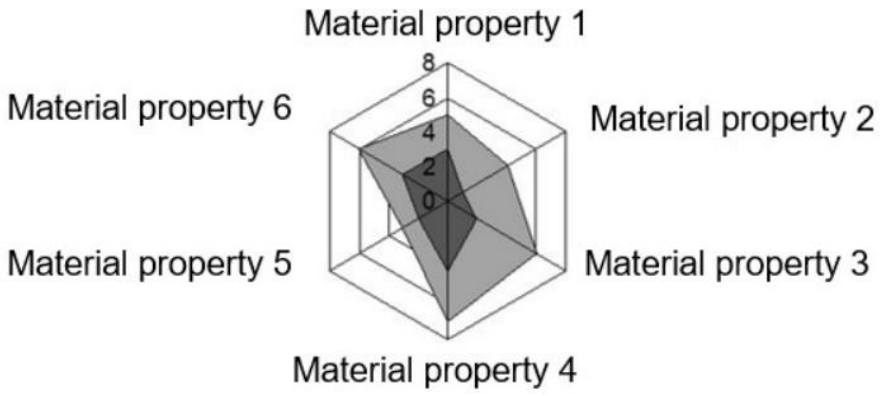


Figure 3. COBWEB-analysis tool. Translated from (Eskelinen & Karsikas 2013b, 51).

The mentioned COBWEB-analysis tool could be used to compare and justify the change of material in certain situations where needed. The possible comparisons are expected to be made between materials that are highly involved in this thesis.

2.4 ANSYS FLUENT CFD

ANSYS FLUENT CFD software is a Computational Fluid Dynamics (CFD) simulation software that can be used to simulate and study fluid flow. The software has a large variety of fluid flow simulation capabilities that can be utilized to solve problems and optimize components.

The results that are expected to be gained from these methods can be used for justification, optimization and comparisons. The Inventor modelling tool is mainly used for modelling and sketching possible solutions and the FE-analysis tool is used to ensure the function and structural integrity of possible designs. DFMA and COBWEB-analysis tools are used for optimization and comparisons to justify and ease the finding of the most applicable solutions. ANSYS FLUENT CFD is a tool to be used for the wing scraper related issues and investigations. With the results of different methods gathered in different phases of the design, the results will form a final entity progressively.

3 New operating conditions of a discharge scraper

In this chapter the new operating conditions are explained in more detail. It is important to understand and present the operating conditions regarding the object or matter in question so that the reasons and measures behind some decisions and actions are justified and understood. The fibre line is described briefly, and the bleaching phase is described in more detail with an introduction to the use of chlorine dioxide in pulp bleaching.

3.1 Chemical pulp production process

Pulp bleaching is part of a fibre line which is a part of the full process of pulp manufacturing. As seen in figure 4, the fibre line consists of everything else apart from the chemical cycle. The chemical cycle refers to the reuse and recycle of used chemicals in a pulp manufacturing process. The fibre line can be separated into six different sections that differ from each other: wood handling, cooking, washing and screening, oxygen delignification, bleaching, and drying and finishing. (KnowPulp 2023.)

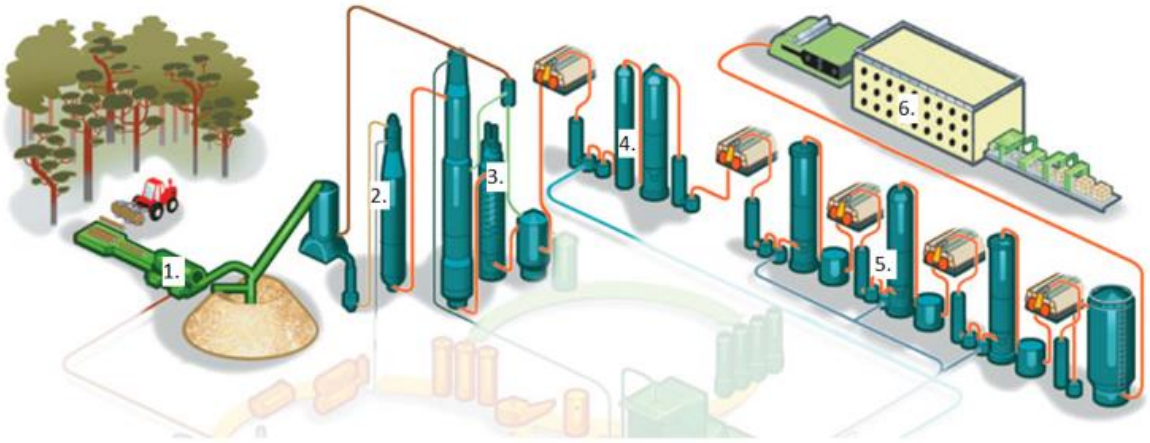


Figure 4. Fibre line: 1. Wood handling, 2. Cooking, 3. Washing and screening, 4. Oxygen delignification, 5. Bleaching, 6. Drying and finishing (KnowPulp 2023).

In the first step the raw wood material needs to be processed into wood chips at a mill and then transported to a pulp manufacturing site. At the pulp manufacturing site, the wood chips are cooked with a chemical called white liquor that consist of many different chemicals. The purpose of cooking in pulp production is to remove fibre binding lignin with chemicals and heat. Lignin is a natural polymer made of three different monomer types and it acts as a fibre binder in plants for which water conduction is important, such as wood (Heitner, Dimme & Schmidt 2010, 2). After the cooking a wet, dark coloured, pulp is achieved. This wet pulp needs to be washed and screened in the washing and cleaning phase. In the fourth stage, oxygen delignification phase, the residual lignin in the pulp is removed by using oxygen and alkali. After the oxygen delignification phase the pulp is ready to be bleached. Bleaching is explained more in detail in the next chapter. After the pulp is bleached into a white colour, the pulp is dried and finished into a form that can be then delivered to the customers. (KnowPulp 2023.)

3.1.1 Chlorine dioxide pulp bleaching

The main objective of bleaching is to improve the whiteness and cleanliness of pulp. The main methods to achieve the objective are to either remove or brighten the coloured substances inside the pulp. Lignin-removing bleaching is usually done by using chemical pulps and the lignin-preserving bleaching is usually done by using mechanical pulps. The chemical pulping can be considered better as it can achieve a long-lasting brightness and whiteness. (KnowPulp 2023.)

In 1990 it was largely acknowledged that chlorine dioxide would replace previous bleaching chemicals, chlorine and hypochlorite. The main factor in implementing chlorine dioxide into pulp bleaching phase was the fact that better final whiteness, greater strength, and a decrease in harmful sewage were achieved. Chlorine dioxide's efficiency is based on the fact that it doesn't react harmfully with carbohydrates even when bleaching to full whiteness. It can be used in conditions where there is almost no lignin present, when used in large doses and in fierce reaction circumstances. In these conditions even the difficult-to-react chromophore groups can be changed into a colourless state without damaging the structure. Impurities caused by sticks and fibre bundles are effectively removed in the chlorine dioxide stages of final bleaching. Chlorine dioxide is highly explosive and toxic, so it is never shipped or

stored in gas form. Therefore, it is always produced on site at a pulp manufacturing plant and only stored in small amounts in a water solution. Its hazardous properties also affect the consumption and production balance, which needs to be in a close margin. It is also important to utilize the by-products locally to minimize waste. The by-products of chlorine dioxide production are chlorine, sodium sulphate, and acidic waste. (KnowPulp 2023; Puusta paperiin 1990, 145.)

In the modern world the chemical pulp bleaching processes can be divided into two separate groups based on environmental issues, ECF (Elemental Chlorine Free) bleaching and TCF (Total Chlorine Free) bleaching. The aim of chemical bleaching is to continue the removal of lignin after the cooking and oxygen delignification phases. In addition to the chemical bleaching the washing phase between bleaching phases is also important as its purpose is to wash the residual lignin away. Commonly, the target whiteness and brightness cannot be achieved by only one bleaching step without affecting the strength properties of the pulp. This is why the chemical bleaching is done in a multi-stage process with several steps. The multi-stage method provides better results both economically and quality-wise. (KnowPulp 2023.)

One method of using multi-stage chemical bleaching is by using chlorine dioxide in the bleaching phases. This method can be considered as an ECF-method. The visualization of a bleaching process using chlorine dioxide can be seen in figure 5. As the figure shows, the bleaching phases can be separated into bleaching phases and the alkaline phase. The bleaching phases are marked with the letter D, with D0 being the initial bleaching and D1 and D2 being the final bleaching stages. The alkaline stage is marked with the code EOP. EOP or Eop refers to low pressure oxygen-peroxide delignification (Dimitris & Argyropoulos 1996). In between each stage, there is a washer to wash the dissolved lignin and bleaching chemicals out of the pulp mass. (KnowPulp 2023.)

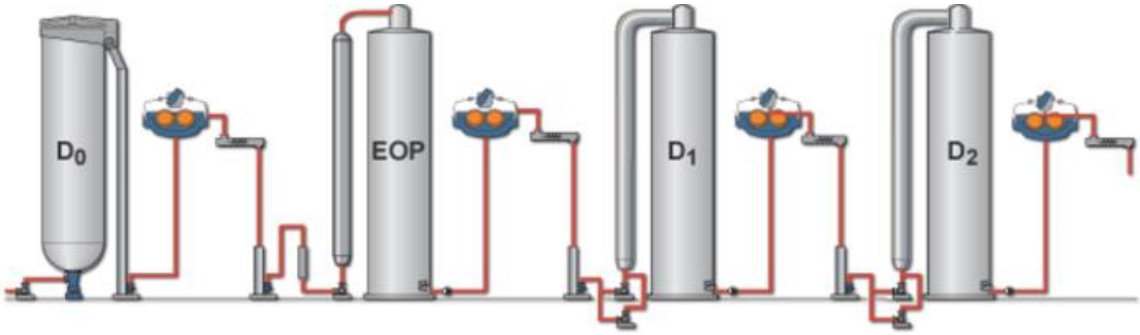


Figure 5. Chemical bleaching (KnowPulp 2023).

D0 stage, or initial bleaching stage, is done to dissolve the residual lignin with chlorine dioxide. The dose of chlorine dioxide depends on the kappa number of the entering pulp mass. According to the International Organization for Standardization or ISO (ISO 302:2015, 1-3), the kappa number describes the amount of lignin in pulp or bleachability of pulp and it is determined according to the ISO-standard measurements. After the D0 stage comes a EOP or alkaline stage where, instead of chlorine, other chemicals are used to partially neutralize the degraded fractions of residual lignin. The neutralization enables fractions to be washed out of the pulp during washing phases by increasing the solubility of the fractions. The last stages can be considered as the final bleaching phases. The job of stages D1 and D2 is to achieve full brightness for the pulp mass. The amount of inserted chlorine dioxide highly depends on the kappa number. Inserted amount is measured in kilograms of active chlorine dioxide per a tonne of pulp mass (kg/t). Active chlorine dioxide amount is usually 4-6 times the kappa number. Final bleaching stages are separated into D1 and D2 because the desired brightness cannot be achieved with just one stage. This is because the volume of products produced in chemical reactions slow down the bleaching and they need to be washed away between D1 and D2 stages to achieve effective bleaching reactions with chlorine dioxide. (KnowPulp 2023.)

The towers that are used in these chlorine dioxide stages are usually made with up-flow towers that have a top scraper at the top. As the pulp production technology is constantly developing and changing, there is now a possibility for a need to integrate a downflow tower into the chlorine dioxide stages of a pulp bleaching process to optimize the process flow in some applications. These downflow-towers that are equipped with a discharge scraper and

commonly used in different phases of pulp production cannot be directly integrated into the chlorine dioxide stages without changing the materials used and the design.

4 Titanium against chlorine dioxide

Chlorine and chlorine solutions have a high oxidizing effect. The same applies to chlorine dioxide. Titanium has a high corrosion resistance in these conditions which makes it an obvious choice for applications where these substances are used. For example, it is increasingly used in applications such as chlorine dioxide production and the bleaching sequences of the paper and pulp industry and in chlorine dioxide production. (Schütze & Kreysa A38.)

In figure 6. it is shown that according to ISM (2022), titanium is one of the best options against corrosion caused by chlorine dioxide and especially it is one of two metallic materials that have an excellent corrosion resistance rating in 8% aqueous chlorine dioxide solution. The ratings are representing the chemical effect as D meaning severe effect, not recommended for ANY use, C meaning moderate effect, not recommended, swelling may occur, B meaning good, minor effect, slight corrosion or discoloration and A meaning excellent.

	304 Stainless Steel	316 Stainless Steel	ABS Plastic	Acetal, POM	Acrylic (PMMA)	Aluminum	Brass	Bronze	Buna N (Nitrile)	Cast Iron	Copper	CPVC	EPDM	Hastelloy® - C	Hytrel® (TPE)	Kel-F® (PCTFE)	HDPE	LDPE	Natural Rubber	Neoprene (CR)	Noryl® (PPO)	Nylon (PA)	Polycarbonate (PC)	Polypropylene (PP)	PTFE	PVC	PVDF (Kynar®)	Silicone (VMQ)	Titanium	Tygon	Viton® (FKM)
Carbonated Water (Carbonic Acid)	A	A	A	A	A	A	D	A	A	D	B	A	B	A	D	A	A	A	C	A	A	A	A	B	A	A	A	A	B	A	A
Carbonic Acid (Carbonated Water)	A	A	A	B	A	B	D	B	D	D	B	A	B	A	D	A	A	A	C	D	A	A	A	B	A	A	A	A	B	A	A
Chlorine Gas, dry 10%	A	B	D	D	A	C	D	B	B	D	A	D	A	A	D	D	B	D	D	C	B	D	A	D	A	D	A	D	D	A	A
Chlorine Dioxide, 8% aqueous solution	D	C	B	NA	C	D	D	D	D	D	D	A	D	A	D	NA	C	C	D	D	NA	D	NA	C	A	A	A	B	A	C	B
Chlorine Water (5-10 ppm)	C	C	D	D	A	D	D	B	D	NA	D	A	C	A	D	A	C	B	C	D	C	C	NA	D	A	A	B	D	A	NA	A
Chloroacetic Acid	B	A	NA	D	C	D	D	C	D	D	D	D	B	A	D	A	A	D	D	D	NA	D	D	C	A	B	A	D	A	A	D
Chlorobenzene (mono)	A	B	D	D	D	A	B	C	D	B	B	D	D	A	D	A	D	C	D	D	D	D	D	C	B	D	A	D	B	A	A
Chlorobromomethane	B	B	NA	B	NA	D	NA	NA	D	D	B	NA	B	NA	D	NA	NA	A	D	D	C	C	NA	A	A	D	NA	D	NA	NA	A
Chloroform	A	A	D	A	D	B	B	B	D	B	A	D	D	A	D	B	D	C	D	D	D	A	D	C	A	D	A	D	A	B	A
Chlorosulfonic Acid	D	B[1]	NA	D	D	C	B	D	D	D	D	D	D	A	D	A	D	D	D	D	D	D	C	D	A	D	D	D	A	C	D
Chromic Acid, 5%	B	A	B	D	C	C	D	B	D	D	D	A	A	B	D	A	A	D	B	D	A	D	B	D	A	A	A	C	A	B	A
Chromic Acid, 10%	B	B	B	D	C	D	D	D	D	D	D	A	C	A	D	A	A	D	D	D	A	D	B	D	A	A	A	C	B	C	B
Chromic Acid, 30%	B	B	B	D	D	D	D	D	D	D	D	A	B	D	D	A	A	D	D	D	D	D	C	D	A	A	A	C	A	B	A
Chromic Acid, 50%	C	B	D	D	D	D	D	D	D	D	D	D	B	B	D	A	A	D	D	D	D	D	D	D	A	D	A	C	A	B	A
Citric Acid, aqueous 10%	B	A[1]	D	B	A	C	D	D	A	D	D	B	A	A	A	A	A	D	A	A	A	A	A	A	A	B	A	A	A	NA	A
Citrus Oil or Terpene (d-Limonene)	A	A	C	B	NA	C	A	D	A	D	D	A	B	A	NA	A	C	C	D	D	A	A	C	A	A	C	A	D	A	A	A
Clorox® Bleach	A	A	B	D	C	A	D	NA	D	D	D	A	B	A	C	D	NA	NA	D	B	A	A	A	D	A	A	A	NA	NA	B	A
Coffee	A	A	NA	A	A	A	D	A	A	NA	A	A	A	A	NA	NA	A	NA	A	A	A	A	C	A	A	NA	NA	A	A	NA	A
Copper Chloride	D	D	A	A	A	NA	D	D	A	NA	D	A	A	NA	A	A	B	NA	C	A	A	D	NA	A	A	A	A	A	D	A	A

Figure 6. Chemical compatibility chart (ISM 2022).

Titanium's high corrosion resistance is based on its stable, protective, strongly adherent oxide film which is formed instantly when a fresh surface of titanium is exposed to air or

moisture. This resistance achieved with the TiO_2 film is usually the reason and basis of using titanium in number of applications where chlorine, chlorates, hypochlorite, perchlorates, or chlorine dioxide are used. Chlorine dioxide applications include a modern pulp bleaching plant. (Timet 1997, 1-2.)

4.1 Titanium grade 2

With titanium there are four main alloys that can be considered as commercially pure titanium (CP titanium). These four commercially pure titanium are named as grade 1, grade 2, grade 3, and grade 4. The main difference between these grades is the oxygen content in the materials which differ from 0,18% (grade 1) to 0,40% (grade 4). (Lütjering & Williams 2007, 33-35.)

Grade 2 titanium is the most widely used CP alloy with a tensile strength between 390 and 540 MPa. Properties that cause the wide use are its excellent formability, moderate strength, and superior corrosion resistance. It is used for example in evaporators, condensers, tubing and tube headers in desalinization plants and heat exchangers, reactions vessels for chemical processing, cryogenic vessels and in many medical applications. (Polmear 2017, 273-274.)

5 Titanium construction possibilities

Titanium has been known to be one of the most used metals in industrial use and it was already widely used in military applications in the 1950's (Rönkönharju 1979, 1). More recently, it is known to be used in applications such as aircraft, aero-engines, biomedical devices, and in chemical processing equipment. Along the main thriving properties that make titanium an excellent choice for these applications such as high strength, low density and excellent corrosion resistance, there are some downsides in the use of titanium for wider use. For example, in automotive industry cost is a big downside. Because of the possible downsides it is always important to justify the use of titanium through titanium's overwhelming performance in other areas, such as the thriving properties mentioned above. (Lütjering & Williams 2007, 1-15.)

The titanium industry mainly provides three different varieties of goods to be fabricated into products. These three goods are sponge, ingot, and mill products. Sponge is refined from titanium ores and can be produced in various grades and purities. The sponge gets its name from its porous appearance that reminds a sponge. Ingot is commonly produced from titanium scrap, titanium sponge or in some cases both. The titanium ingot is usually made as an alloy that contains such metals as vanadium, aluminium, molybdenum, tin, and zirconium. Lastly, the mill products are products that are produced from titanium ingots through various fabrication processes such as rolling and forging. With these fabrication methods, the titanium is formed into shapes that are in the form of billet, wire, plate, sheet, and tube. The fabrication of finished titanium components and shapes is called secondary fabrication. An example of a titanium production process from titanium ingot can be seen in figure 7. (Sŏng, Younossi & Goldsmith 2009, 12-20.)

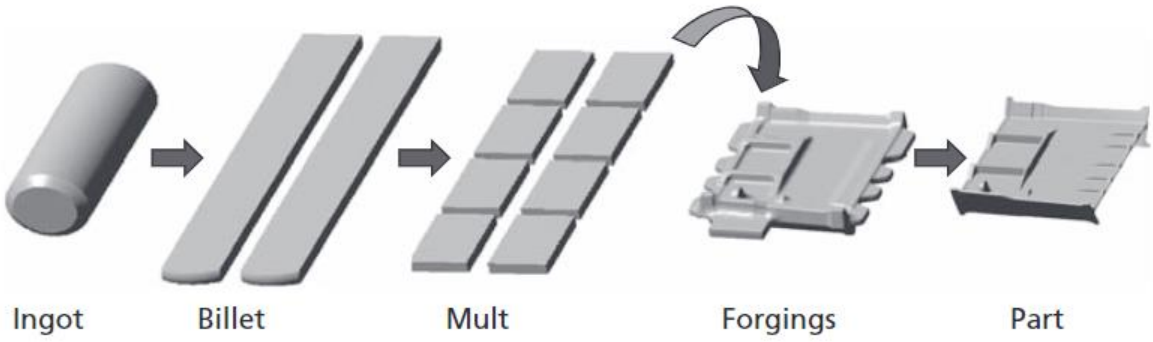


Figure 7. Converting a titanium ingot into a component (Sŏng et al. 2009, 15).

Parts made from titanium are usually costly as their fabrication and production into a final product is capital- and energy-intensive. The energy intensiveness refers to the fact that titanium's properties, such as hardness and tendency to reform when high heat is applied, affect the fabrication process energy use. However, the reuse possibilities of titanium from scrap make the cost-effectiveness better. The titanium scrap is gathered from fabrication processes and can be used to make titanium ingots. (Sŏng et al. 2009, 12-20.)

5.1 Cladding of titanium

Even though titanium is an obvious choice for highly corrosive environments, the use of pure titanium in these applications can get costly. One option to lower the amount of used titanium is to use titanium cladding plates on top of a base material. One cladding combination option is to manufacture a titanium-steel composite material. This way the final product will have the low cost and high strength of steel and in addition obtain the outstanding corrosion resistance of titanium. Cladding can be done with various methods such as explosion cladding and roll cladding method. (Su, Luo, Chai, Shen, Sun & Lu 2015, 977.) In recent years laser cladding deposition has also been used as a fabrication method for titanium parts, especially in large aircraft applications (Zhao, Chen, Guo, Tan, Lin & Huang 2017, 675).

5.1.1 Explosion cladding

Explosion clad plate manufacturing process is a unique and robust technology for welding plates together by using the high energy of an explosive detonation. The process can be divided into two main stages: Preassembly and the explosion event. Explosive clad manufacturing process is based on achieving a metallurgical bond between two plates. The preassembly stage consists of preparing the plates to be cladded and placing them correctly on top of each other with explosive powder added on top. In addition, preparing of the plates can consist for example material inspection and grinding of the surfaces. (Pauly 2012.)

The explosion stage can be seen in figure 8. The metallurgical bond can be achieved by detonating the explosive powder on top the flyer plate. Stand-off distance being the space between cladder and base plate, collision point being the point where the cladder plate gets in contact with the base plate and welded portion being the final welded bond. (Sherpa, Kumar, Upadhyay, Kumar, Agarwal & Tyagi 2021, 3303-3304.)

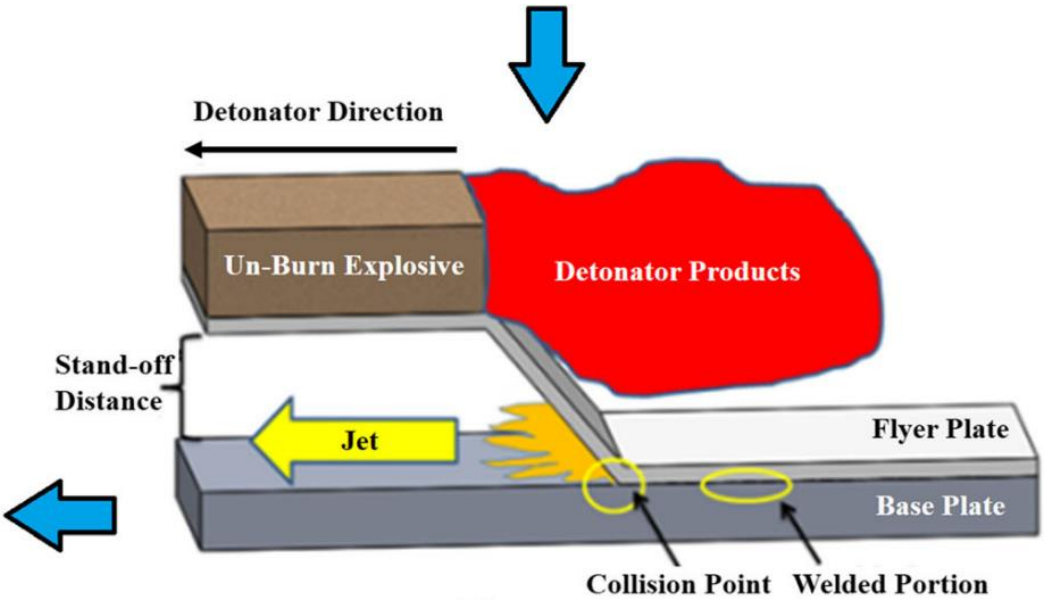


Figure 8. Explosion cladding process (Sherpa et al. 2021, 3306).

After the cladding phase, the achieved plate can then be flattened out with hot rolling and cut into desired shapes and sizes. It is expected that the material is inspected carefully after

the flattening and cutting. Inspection could be done by conducting ultrasonic examination of bond, mechanical tests, physical measurements, and certifications. (Pauly 2012.)

5.1.2 Roll cladding

The traditional hot rolling process is not very suitable for titanium cladding with steel backer. The achieved bond between these materials can be considered as weak. Titanium forms titanium-iron intermetallic compounds and titanium carbides when heated which drastically affect the bonding strength. Therefore, explosive welding process is better for titanium cladding processes. However, a vacuum rolling method has been introduced to prevent the reactions that affect the bonding strength between titanium and steel. (Yamamoto, Nakamura, Nishiyama & Kurahashi 1994, 34.)

The vacuum roll bonding method is an alternative method from explosion welding method. Roll bonding method requires a vacuum environment and a suitable intermediate in between the titanium and steel plate. Based on these requirements, the roll cladding method can be considered a more complicated process when compared to explosion cladding. Titanium and steel are initially assembled on top of each other, and the suitable intermediate is inserted in between. The sheets are then welded through the intermediate by using a suitable welding method under a high vacuum. After the welding, the plate can be hot rolled to achieve even better bonding strength and a desired thickness. (KLS 2021; Yamamoto et al. 1994, 34-35.)

5.1.3 Laser cladding

Laser cladding is a process where a covering layer of filler material is applied to a part, and it is fused to the base material by using a laser beam that acts as a source of heat or power. This process is relatively flexible and efficient for manufacturing specifically engineered coatings to enhance the desired hardness, corrosive resistance, and other metallurgical properties. Laser cladding is used in industries mainly in two separate ways. First way is to manufacture composite parts that need certain properties from different materials, for example. an application where certain mechanical properties and corrosion resistance is needed. Second way of using laser cladding is to repair worn parts rather that replacing them. Industrial applications where the repairing method is usually used is in aerospace industry

or the turbo-machinery industry. In aerospace there are many different titanium parts where laser cladding could be utilized but laser cladding with titanium is still a relatively new and expensive procedure. (Du Plooy & Akinlabi 2018, 19594-19595.)

5.2 Casting

Titanium's tendency to react with elements such as oxygen, nitrogen, and carbon and its high melting point of 1668 ℃ make the casting of titanium difficult. The usual problem that occurs during casting are the reactions with the investment material which are caused by the high reactivity between titanium and the used investment material. (Fischer, Ebinger, Hägi, Stawarczyk, Wenger & Keller 2009, 1376-1377.) According to Cheng, Ju, & Chern Lin (2007, 528) there has been a lot of different studies on the castability of commercially pure titanium or titanium alloys. The main cause and thriving factor of these studies is the fact that the machining of titanium is expensive and difficult so the accuracy and costs of casting could minimize the need of machining of titanium.

Couple of possible common casting methods for commercially pure titanium are rammed graphite moulding and investment casting. One system that is considered as a rammed graphite moulding is a vacuum-pressure arc-melting casting system. This casting process is visualized in figure 9. As seen on the figure the basic principle is simple. Before the casting process the chamber is pressured and vacuumed. Then a titanium or titanium alloy ingot is melted through a copper hearth with an electrode. After the melting the material is inserted through a pouring gate to the final graphite mould. Graphite mould casting method is known to be used for components with up to 700 kg of weight. (Saha & Jacob 1986, 121; Cheng et al. 2007, 528-530.)

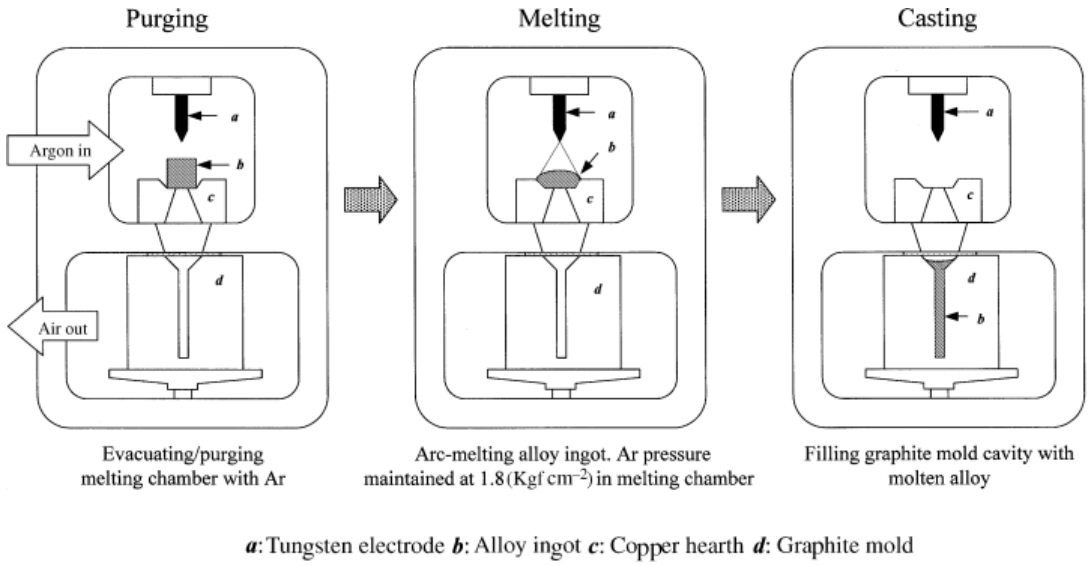


Figure 9. Commercial arc-melting, vacuum/pressure type casting system (Cheng et al. 2007, 530).

Investment casting method shows a high quality in reproducibility of castings with a small margin of deviation of dimensional limits (Lee & Kim 2017, 71). Investment casting of titanium is known to be used for components up to 30 kg in weight (Saha & Jacob 1986, 121). The main difficulties in titanium investment casting are commonly caused by the high melting point of pure titanium (1670 °C) and high reactivity of titanium with other materials. The basic principle of an investment casting process can be seen on Figure 10. The casting mould is made by moulding the wanted casting shape with wax. When the wax version of the wanted component is made, it is then dipped into ceramic slurry which contains materials that are resistant to decomposition by heat, such as silica or alumina. The coating is then stuccoed to achieve a hard shell-like mould. The coating dipping and stuccoing stage can be repeated several times to achieve a desired final thickness. The inside wax is then dewaxed by melting it out of the ceramic mould. After the dewaxing, the mould is then fired in a furnace. Next, the actual casting can begin by inserting melted material into the ceramic mould. The ceramic is then removed around the hardened cast material. (Campbell 2006, 154-158; Freitag, Schmidt, Hubálková, Bulling, Klotz & Aneziris 2022, 682-683.)

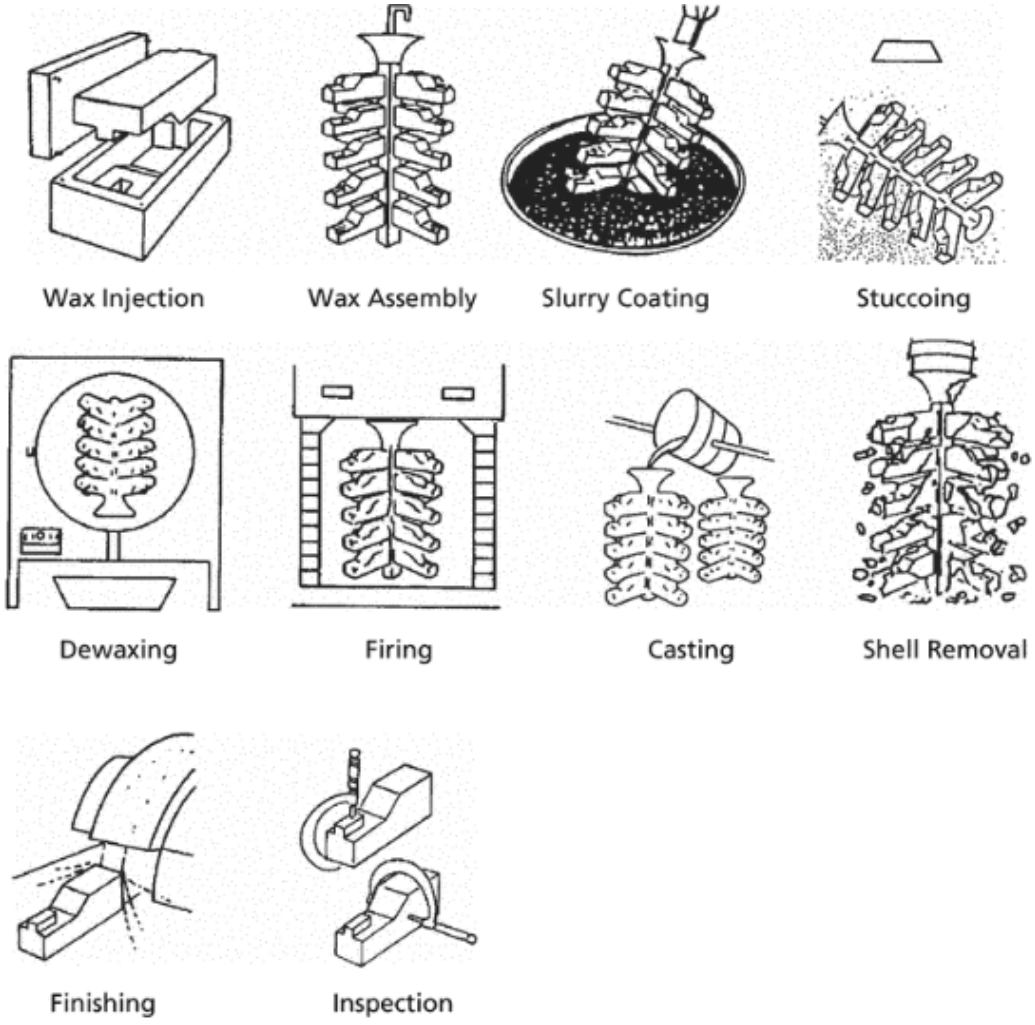


Figure 10. Investment casting process (Campbell 2006, 157).

The investment casting method is commonly done with Hot Isostatic Pressing (HIP) as a post treatment to achieve complex near-net-shaped geometries and to achieve the wanted strength properties for the wanted product. In a HIP process the components inside porosity is lowered and an improved fatigue performance is achieved. The improved fatigue strength is especially important for titanium components which tend to have a poor fatigue performance. (Campbell 2006, 155.)

5.3 Titanium plate fabrication

A large amount of titanium components is manufactured with cold forming and then hot sizing or by hot forming. Titanium has a vast number of properties that affect the wanted final quality such as: (Semiatin 2006, 656.)

- Galling, which is more severe than with steel.
- Poor ability to shrink, which affect some flanging processes.
- High notch sensitivity (Can cause cracks and tears).
- Tendency to embrittle from overheating or gas absorption.

Commercially pure titanium sheets can usually be cold formed when taking some fabrication measures into consideration. Titanium sheets commonly have a large springback in cold forming, as much as 15-25 degrees. Springback is a phenomenon where the shape of a formed sheet changes due to elastically driven forces (Wagoner, Lim & Lee 2013, 3). Due to the springback it is not rare that in cold forming of titanium the bending radii used, needs to be larger than in hot forming. In addition, titanium can be stretch formed in room temperature when applying a slow stretching speed and having the stretching dies heated up to 150 °C. The cold forming process commonly includes a post treatment of hot sizing and stress relieving to restore compressive yield strength, reduce residual stress, make the component more resistant to delayed cracking and improve dimensional precision. (Campbell 2006, 143-144.)

Hot forming substantially makes the formability better, eliminates the stress relief post processing stage and reduces springback. Downsides of hot forming are the increased costs that are caused by the heating of the material, the need for removal of surface contaminations, and more expensive process tools. In addition, hot forming can be a more complicated process due to various needs of surface cleaning and lubrication during the process. (Campbell 2006, 144.)

5.1 Welding of titanium

Titanium can be considered highly weldable. The downsides in welding of titanium are the importance of cleanliness and the use of inert gases to prevent any kind of contamination

from the atmosphere. Low thermal conductivity, low coefficient of thermal expansion, relatively low modulus, and high electrical resistivity are the main properties that have an effect on titanium's weldability. In table 1 is a relative comparison of titanium welding methods. Gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), plasma arc welding (PAW), and electron beam (EB) welding methods are well known to be effective with titanium and in addition laser welding of titanium is also an applicable process for titanium welding. (Campbell 2006, 165-170.)

Table 1. Relative comparison of titanium welding methods (Campbell 2006, 166).

	GTAW	GMAW	PAW	EB
Common thickness range (mm)	0,8-6,4	6,4-76,2+	3,2-9,5	Foil to 76,2
Ease of welding	Good	Fair	Good	Excellent
Grooved joint requirement	Often	Always	No	No
Automatic or manual	Both	Automatic	Both	Automatic
Mechanical properties	Fair	Fair	Good	Excellent
Quality of joint	Good	Fair-Good	Excellent	Excellent
Equipment cost	Low	High	Moderate	Very high
Wire required	Often	Always	Sometimes	No
Distortion	Very High	High	Moderate	Very Low

GTAW, or by another name tungsten inert gas (TIG), is the most common welding method for titanium because of its relatively low costs and the ease to control and produce the weld itself. In this method, an arc is providing and maintaining heat between a tungsten electrode and the workpiece. The power supply from a negative electrode creates a large current with the positive weld joint that achieves a deep welding penetration with a narrow bead. This

welding method is not recommended to be used to attach titanium with other metal materials as brittle intermetallic compounds will be formed in the fusion zone. When welding titanium with TIG welding, the welding current should be direct current, and the weld should be produced in the centre of the electrode. When comparing TIG welding to GMAW, or by another name Metal Inert Gas (MIG) welding, the arrangement of shielding gas and achievement of applicable weld is far more difficult with MIG welding. (Rönkönharju 1979, 43.; Campbell 2006, 166-169.)

In laser welding a precisely focused power density is applied onto a work piece to achieve high processing speeds and a fast thermal cycle with a keyhole welding method (Chaturvedi 2021, 84). Yunlian, Ju, Quan & Liying (2000) investigated and compared laser welding with a CO_2 laser to electron beam and tungsten inert gas (TIG) welding from a microstructure point of view. The main results implied that even though a relatively sufficient weld was achieved with laser welding, the electron beam welding method was more suitable for commercially pure titanium sheets and the final weld seam could be achieved without defects. According to an investigation made by Li, Muneharua, Takao & Kouji (2009, 110-113) relating to welding with Yb-laser, a full-penetration weld can be successfully achieved on CP titanium with weld speeds up to 9m/min. However, at increased welding speeds and with higher cooling rates the content of fine grained acicular α at the centreline of the weld increased. There is also some potential of several defects when welding with Yb-fibre laser, such as cracking, geometrical defects, and weld-metal porosity.

5.2 Lining with titanium

When lining with titanium, the main problem is the sufficient attachment onto the base material. For example, when attaching titanium lining onto a steel base, the welding attachments need to be made in a way that the steels own welds and the titanium linings welds are not mixed. Otherwise, the same problems that were introduced in TIG welding of titanium welding are expected to occur. Some lining attachment solutions with titanium sheet onto steel sheets can be seen on figure 11. The basic principle is that the titanium sheet is not welded with the steel sheet but tried to be attached to titanium itself. (Rönkönharju 1979, 53-54.)

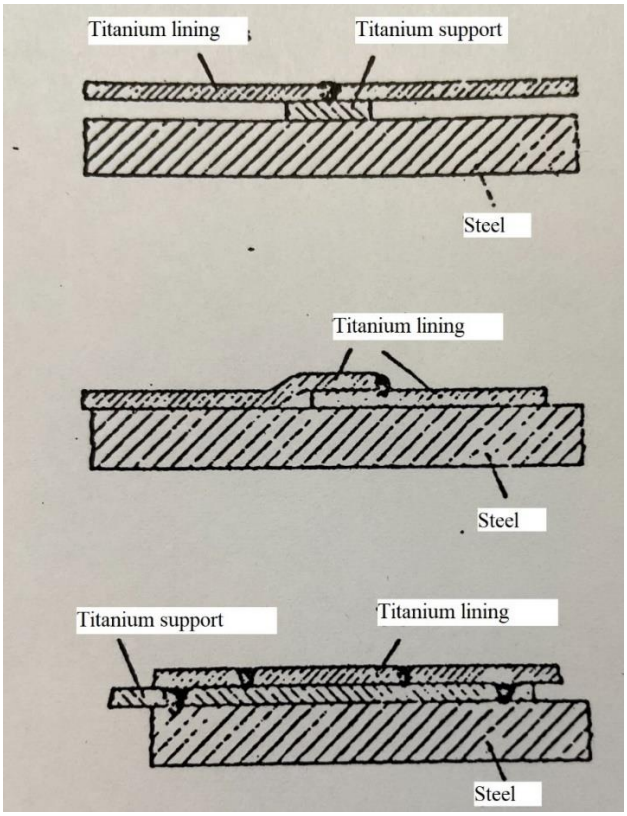


Figure 11. Titanium lining methods on steel (Rönkönharju 1979, 54).

More traditionally titanium lining can also be done by using fastener attachments. Fastening is usually done by using either titanium or steel bolts threaded into holes that are drilled and threaded on the steel material. The fastening can also be achieved by using a nut connection from the backside of steel material. The expected titanium sheet has holes aligned with steel components holes which allow the fastening procedure. It is common to fillet-weld the fastening bolts or overlap the titanium lining materials to achieve total linear sealing. (Cerny 2005.)

The most realistic and the most used manufacturing methods in discharge scraper construction are castings, welding, and sheet fabrications. In addition, the most realistic construction methods to make protective measures and solving sealing issues are lining and cladding solutions. The fact that these methods are familiar and easily available outlines roughly the wanted solutions for the discharge scraper construction solutions.

6 Corrosion sensitive areas of a discharge scraper in a pulp bleaching application

Corrosive sensitive areas were mainly identified by organized meetings with experts and analysing the design and construction of a common discharge scraper through 3D-models and machining pictures. It was quickly realized that the main problem areas were all the parts that are in straight contact with pulp containing chlorine dioxide and the attachment points of various locations such as flange connections and scrape hub to axle connections. As the wanted material for the new design was fixed as being titanium grade 2, some construction methods that were currently used for a discharge scraper in different operating conditions, were also expected to cause some issues from cost-effective and manufacturability point of view. An example of a certain discharge scraper structure can be seen in figure 12.

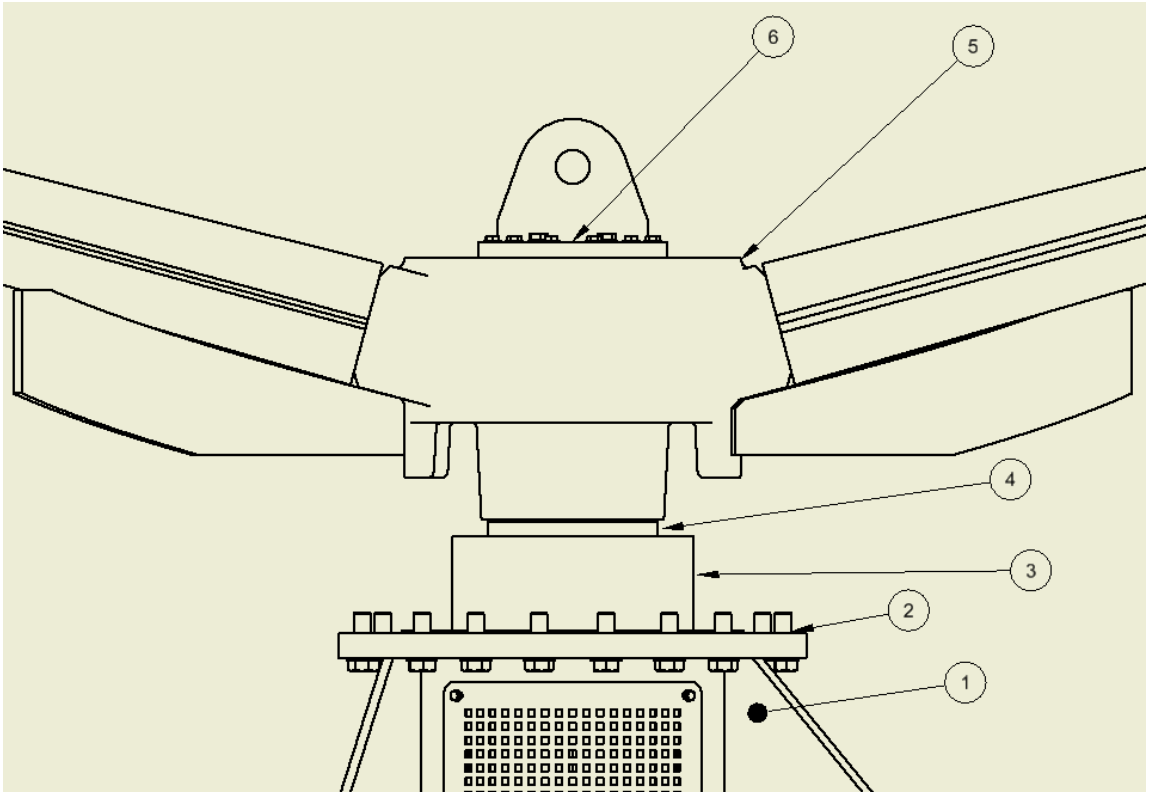


Figure 12. Structure of a certain discharge scraper design (1. Support structure, 2. Connection flange for tank connection, 3. Sealing housing support sleeve, 4. Axle wear sleeve, 5. Scraper hub with wings, 6. Scraper hub cover).

The components and surfaces that are in straight contact with pulp that contain chlorine dioxide are listed below. The contact areas are defined by analysing the machining pictures and 3D-models of a common discharge scraper and by expertise.

- Discharge scraper support structure flange (Attached to tank connection flange).
- Scraper hub and wings.
- Upper part of axle wear sleeve.
- Upper part of sealing cover sleeve.
- Scraper hub cover.

The flange connection of the scraper has two kinds of problem areas. The side that is connected onto the tank is partly in direct contact with the pulp containing chlorine dioxide. The other problem area is the connection point of the two flanges. This connection point needs to have a full seal to prevent any leakage of gaseous or liquid chlorine dioxide. Scraper hub and wings are fully in direct contact with the pulp, as the hub is resting on axle shoulder with a fit connection and a wedge connection inside the bleaching tank with the wings attached to the hub. This resting point connection also needs to be sealed to prevent any leakage. As it is expected that the hub and wings need to have a full resistance against chlorine dioxide, full change of material for the wings and the hub needs to be done as the sealing or lining of the wings and the hub are not realistic. On a typical discharge scraper design the axle wear sleeve partially extends inside the bleaching tank to protect the axle till the hub/axle connection point. Upper part of the sealing cover is part of the structural integrity of the scraper support structure, and it acts as a cover for the sealing components around the axle. To protect the axle and inner scraper hub area and help the assembly and possible disassembly for maintenance periods, the scraper hub usually has a cover on the top which is attached with bolts onto the end of the axle and on top the hub. This cover connection point can also be considered as a leakage risk area. A support sleeve in the upper part of the sealing housing, between the housing support sleeve and axle, is made from PTFE+25%Carbon which is chemically inert to most of known industrial chemicals.

6.1 Sealing and lining needs

All connection points that are exposed to pulp containing chlorine dioxide need to be sealed with titanium grade 2 lining or with separate O-rings or gaskets. O-ring material, which can be used for a chlorine dioxide application, and which is easily available, is FEP/Q (Fluorinated Ethylene Propylene). FEP O-rings are known to be sufficient and can withstand the demanding conditions of a bleaching application. However, a complete sealing could be done by integrating titanium lining over the connection points and then the sealing and the machining forb O-ring grooves are no longer needed. Gaskets need to be either PTFE or Viton gaskets, which are known as widely used gaskets for applications where aggressive chemicals such as chlorine dioxide are used. The lining can be considered as difficult in certain areas for reasons that were mentioned in chapter 6.2 and for the fact that installing small lining parts in tight spaces by welding could be difficult.

7 Design changes based on material change and corrosion risk areas.

As the material is changed from austenitic stainless steel to titanium grade 2, some design features or manufacturing methods from the commonly used discharge scraper cannot be used straight forwardly as there are differences in material properties, manufacturability, and manufacturing cost. In figure 13. is presented a COBWEB-analysis comparison on how this material change also affects the other properties that affect the construction. As seen on the analysis the main properties that can be considered as worse with titanium when compared to austenitic stainless steel are tensile strength, stiffness, and costs. Especially costs have a significant difference according to Ulrich (2023) as titanium can be up to four to five times more costly than stainless steel. Tensile strength, yield strength, stiffness, and yield strength to density ratio for titanium were gathered from an ASTM-standard (ASTM B 265-20a 2020 5) and for steel from an EN-standard (EN 10088-5:009, 26-39). Corrosion resistance was based on a material chart provided by ISM (2022). Stainless steels corrosion resistance is based on the Chromium content of the material which forms a protective layer against corrosion, but the present steel in the material still makes corrosion plausible in highly corrosive environments. In CP titanium materials the titanium itself forms the protective layer against corrosion which makes it superior in corrosion resistance, as also mentioned previously. However, it is always important to understand that these properties vary based on the material grade and manufacturing method. Another property that is not shown on the COBWEB-analysis and that might be affective for the structural integrity and function of the possible new design is hardness. Hardness especially affects the behaviour of the components when under compressive surface pressure. However according to a strength chart (Rapid Direct 2021) the Rockwell hardness is just a small amount less than with steel which is expected to have close to no affect in function or structural integrity of the new scraper design if the material is changed.

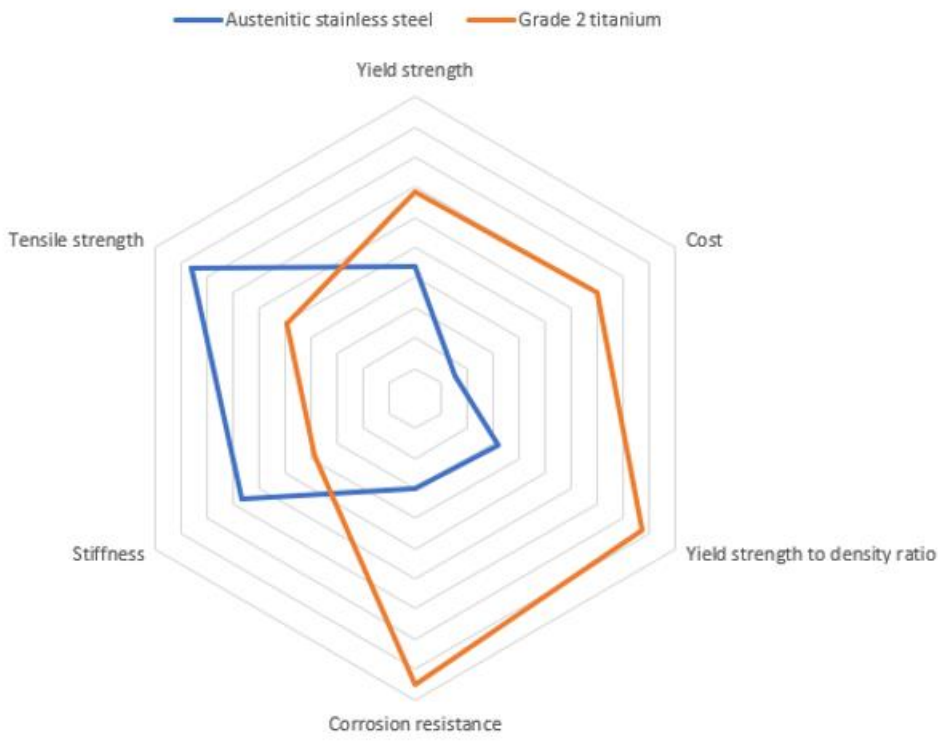


Figure 13. COBWEB-analysis between austenitic stainless steel and titanium grade 2.

One option to solve the sealing issues is to simply add titanium lining all around the pointed problem areas. This solution however would not be too applicable as titanium lining is difficult in tight places and some drastic changes for the discharge scraper design would be needed to allow the titanium lining to be possible. The welding and manufacturing of this full lining solution would be incredibly difficult and risky for it to be considered as a feasible solution and it would extremely affect the function of the scraper. Titanium welding solutions in some tight areas are difficult for reasons mentioned in chapter 6.2. The welding methods that are commonly used for titanium are also difficult to use in tight spaces due to the need for sufficient shielding gas and equipment. Some problems with lining welds could be solved by using simple fastening tools but the fastening areas become a leakage risk themselves and too many holes and fastening can cause problems in manufacturing and assembly from time consumption and stress point of view.

The approach towards the solutions to prevent corrosion risks on the contact areas and the problem areas listed in a previous chapter was by starting to analyse 3D-models and machining pictures of a common discharge scraper. Expert opinions were highly involved

in achieving preliminary solutions gathered in an ideation session seen in appendix 1. As the appendix shows, there were plenty of different possibilities and approaches to take but it was decided that the ideas needed to be first shortlisted based on feasibility. After the feasibility shortlisting the ideas were also filtered through a point matrix which is seen in appendix 2. The points for different ideas were based on the following criteria:

- Cost estimation.
- Potential risk.
- Benefit.
- Effect on function and current design.
- Manufacturability and availability.
- Problem solving index.

The matrix was made to filter out the least beneficial ideas and to identify the best solutions based on the criteria. As mentioned in the introduction chapter, the cost-effectiveness is considered as the thriving factor in pursuing different solutions so the decision to give cost estimation and problem-solving index a weighted value in the points matrix was made. The points threshold for a solution to be considered as beneficial was set to be as three. After the filtration, the solutions that were left are going to be taken into closer consideration for design sketching, cost estimation, availability, and manufacturability.

As the matrix shows, a conventional casting method that is used for a common stainless steel discharge scraper hub is being overlooked as titanium casting is considered to be too difficult and expensive to be used. Also, the fact that the mould for the casting was considered to be a large factor as the manufacturing of the mould is expensive especially when considering the low volume of the part in question. The expected used casting method would have been graphite mould casting where the mould would be usable for only one time. Volume to be manufactured is expected to be extremely low and the plate structure design is expected to be an easier solution. If the plate structured hub appears to be not suitable for holding the wings or the difference in design affects too much on the function of the discharge scraper, the idea of casting a titanium scraper hub could be revisited.

Even though the titanium axle solution did manage to achieve the set threshold of three points, the poor availability, and extremely high costs of a titanium axle of this size made the solution to be dropped from further consideration. The axle would have needed a titanium solid bar blank with approximately a length of 1,5 m and with a diameter of 240mm which also would have to be compatible with the motor and gearbox supplier. As previously mentioned, the cost of titanium compared to steel can be up to five times larger. In addition, the machining of the titanium would also raise the cost as the machining of titanium is more difficult compared to steel due to reasons presented in the literature review. The current axle material for the discharge scraper is 42CrMo4, which is a common axle material from gearbox suppliers.

The best solutions after ideation sessions and the points matrix were set to be modelled and analysed more in detail for a better investigation and comparison. Some of the solutions could be integrated into each other, however the modelling would be started by modelling the solutions in a larger scale to visualize the solution and to identify potential problems better. The solutions that are set to be modelled are the following:

- Multi-part frame structure with utilizing the lowering of the housing box structure.
- Multi-part frame structure (Titanium flange with separate connections to the support structure and housing box).
- Thin titanium sheet between flange connection (Tank/Scraper).
- Moving the sealing housing box structure lower to ease the titanium lining.
- Scraper hub cover material changed to titanium and bolt fastened.
- Scraper hub cover protected with thin titanium sheet.
- Scraper hub made from sheet or pipe structures (Titanium).

As previously mentioned, the scraper hub cover is meant to be used for protection, lifting and in disassembling purposes and it does not have a significant effect on the functionality of the scraper. The lifting lug attached to the top of the cover is not necessary and can be excluded from the design as it has close to no purpose in this process environment. This means that the cover can be designed as flat. Possible solutions are modelled in the first iteration as partly combined or as individuals.

7.1 First iteration of solutions

The first modelled solution was made by integrating a titanium plate structured hub with a titanium lining protected support structure which has a stainless-steel connection flange and a titanium support sleeve for the sealant housing box. Titanium connection flange is welded on the support sleeve inside the support structure to achieve a bolt fastening between the steel support structure and the titanium support sleeve (Figure 14). The titanium hub is designed to be assembled from four different parts excluding the scraper cover. It is designed to made out from an inner sleeve and an outer sleeve which are attached to each other with two titanium disc-shaped rings. The inner sleeve is supposed to be the connection point for the rotating axle and the outer sleeve's purpose is to act as an attachment point for the scraper wings. The sleeves are expected to be made either from hollow or solid titanium bar or by hot rolling titanium plate. All the hub attachments are expected to be welded with TIG welding as it is the most convenient option, has low costs and is easily available. The wear sleeve for the axle is also designed to be as a titanium part as upper part of the sleeve is expected to be in straight contact with the bleached pulp inside the tank. This design will be referred as "Titanium plate hub with steel flange connection and titanium linings". The design is presented in figure 14, with the sealing solution diameters represented by a yellow sleeve structure. The titanium sheet linings that are also seen on the figure are placed on top the connection flange and partly on the tank connection flange. The lining on the flange connection is expected to be attached by welding the thin sheet with the titanium parts of the structure and tightened between the flange connection. The welding of thin titanium sheet can cause some stresses and difficulties as large amounts of heat is applied onto the workpiece so one possible solution is to attach the sheet onto the steel flange by utilizing explosion cladding, which can be used to achieve a metallurgical bond between steel and titanium as also mentioned in the literature review.

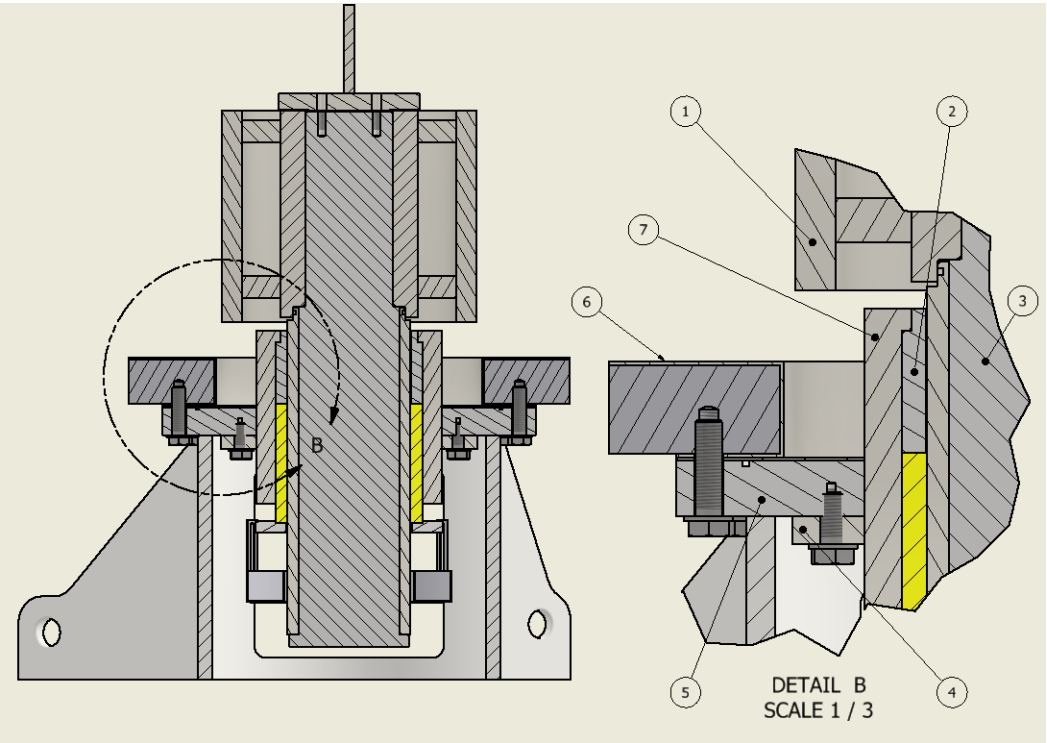


Figure 14. Titanium plate hub with steel flange connection and titanium linings (1. Titanium scraper hub, 2. PTFE+25%C sealing support sleeve, 3. Axle, 4. Titanium attachment flange, 5. Steel connection flange and support structure, 6. Titanium lining, 7. Titanium sealing housing support sleeve).

Second modelled version was a design that included the titanium plate structured hub design and a full titanium connection flange which was connected to the support structure with bolt fastenings (Figure 15). The support sleeve and the axle wear sleeve were also designed to be made from titanium in this version. The tank connection flange has a separate titanium lining. This design will be referred as “Titanium plate hub with titanium flange connection.”.

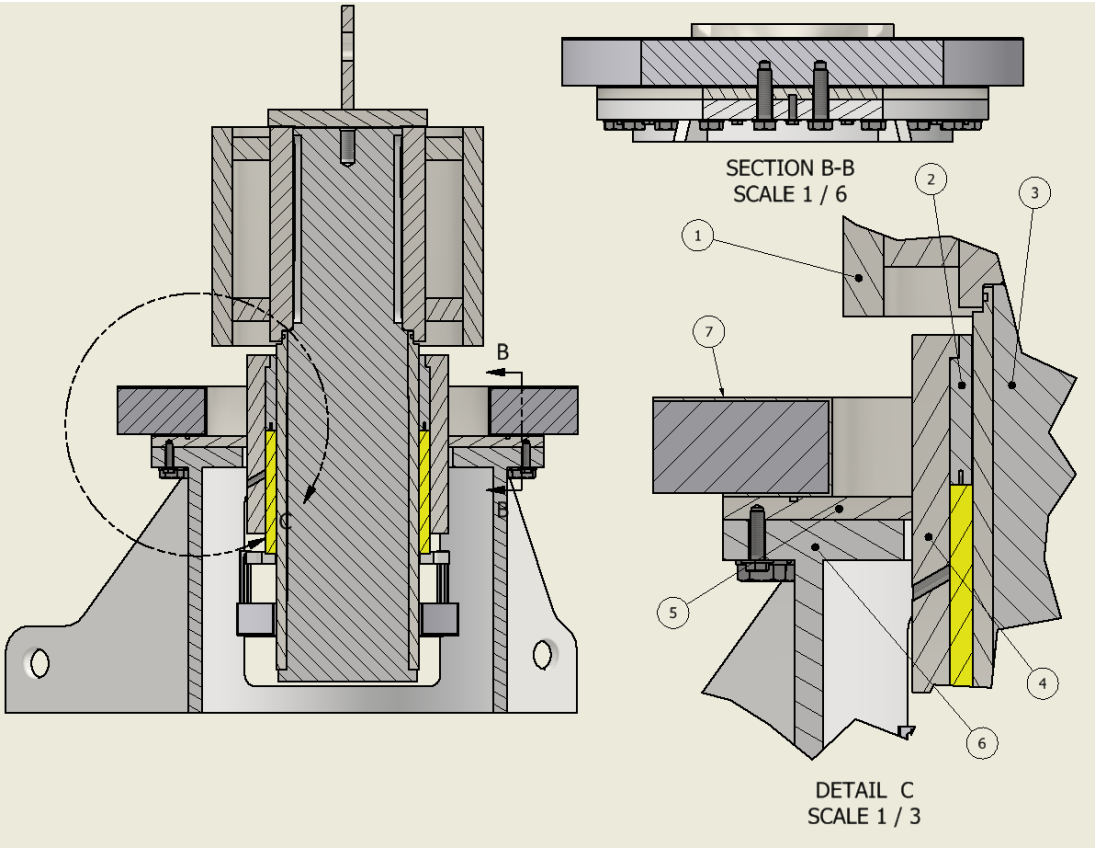


Figure 15. Titanium plate hub with titanium flange connection (1. Titanium scraper hub, 2. PTFE+25%C sealing sleeve, 3. Axle. 4. Titanium sealing housing support sleeve. 5. Titanium flange, 6. Steel support structure, 7. Titanium lining).

Third modelled preliminary design was the most effective on original scraper design. The idea was to combine the same hub as in designs: “Titanium plate hub with steel flange connection and titanium linings” and “Titanium plate hub with titanium flange connection” with a support design where the sealing housing support sleeve would be “lowered” to the same level with the connection flange to achieve a significant ease to the protection solution of corrosion sensitive areas. As seen in the figure 16., the “lowering” would be achieved by tightening the assembly below the flange connection (Water collection, sealing etc.) and designing a smaller support sleeve for the upper part of the sealing housing, as also seen in the figure as part number 3. for the sealing structure. It is located on the most upper part of the sealing housing unit which means that it is in straight contact with the process chemicals. Axle wear sleeve is designed to be made from titanium. This design will be referred as “Titanium flange and lowered housing sleeve”.

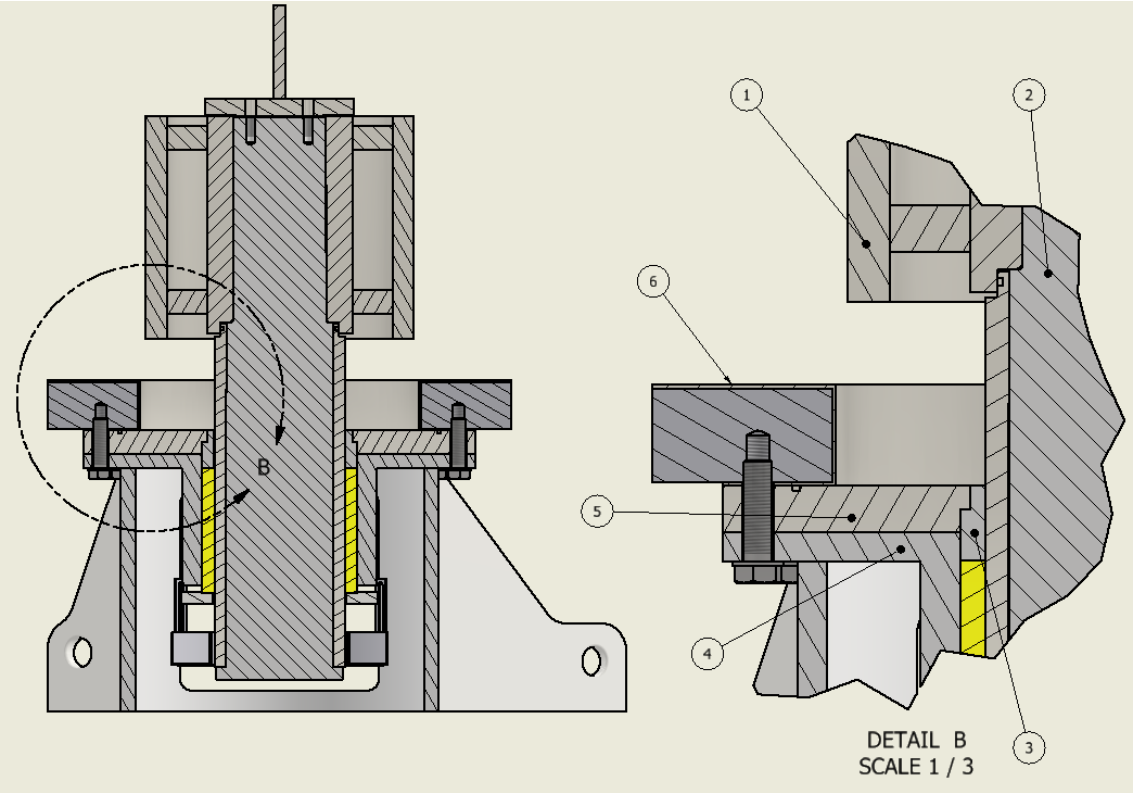


Figure 16. Titanium flange and lowered housing sleeve (1. Titanium scraper hub, 2. Axle, 3. PTFE+25%C sealing support sleeve, 4. Support structure, 5. Titanium flange, 6. Titanium lining).

When comparing the two first designs with the “Titanium flange and lowered housing sleeve”- design, the latter had major problems that occurred in the designing phase. First observed problem was that the axle sleeve might be too exposed from the support structure which may cause some bending issues and unnecessary wear on the outside of the wear sleeve, even though the rotation speed of the scraper is only approximately 12 rpm (Rounds per minute). Another major issue is that the assembly of parts that are near the bottom shoulder of the axle becomes fairly difficult when trying to tighten the space for the success of the lowering of the housing sleeve. There is also a possibility that the smaller sealing support sleeve might influence the function of the sealing unit. When comparing the cons of this design to the achieved easier lining on the bleaching contact area, it was decided to drop this design from further consideration.

The main differences with “Titanium plate hub with steel flange connection and titanium linings” and “Titanium plate hub with titanium flange connection”- designs are material

usage, manufacturing costs, and small assembly differences. These two protective solutions have no significant effect on the function of the scraper which is one the deciding factors in the design development. The use of a small titanium flange as a connection point between the sealing housing support sleeve and the steel support structure allow the use of thin titanium sheet linings on process side of the flange connection point. The problems of the "Titanium plate hub with steel flange connection and titanium linings"- design are that the bolt connections of the titanium attachment flange are in a difficult place from an assembly point of view and the welding of the thin titanium sheet can cause some deformation from the inserted large amount of heat during the welding process. The lining could bend or even fracture and these deformations cannot be repaired by post processing. As there is a large amount of heat applied on the thin titanium sheet, the steel structure below might also be damaged. The placement of the titanium attachment flange and its fasteners are inside the support structure which make the needed welds and tightening of the bolts to be a difficult task.

As the design "Titanium plate hub with titanium flange connection" is the most realistic solution for the lining and sealing needs, it is chosen for further development. In further optimization the possible weaknesses of the most realistic solution are to be solved and possibly the final solution for the identified problem areas can be chosen based on properties that affect the cost-effectiveness and manufacturability.

For the scraper hub cover the possible solutions were to either make a titanium cover which would then be corrosion resistant inside the bleaching tank or to protect a stainless-steel cover with a titanium grade 2 cover which would be attached to the scraper hub. If the cover would be made from titanium, another leakage point would need to be solved. The leakage point would be the bolt connection of the cover onto the axle. For assembly reasons the cover has four bolt fastenings into the top of the axle with the threads being on the axle. As the axle is not titanium, the bolt connection poses a leakage risk. If the scraper hub cover would be chosen to be made from stainless steel and to be protected with a separate titanium cover, the problems lay on the fact that the amount of assembly parts and needed machining rises which also affect the manufacturing costs. Based on these pros and cons, the two possible realistic solutions for the scraper hub cover were formed.

The first solution was to keep the original design and structure of the cover which means that it would be manufactured from stainless steel plate and then attached to the hub and axle

with bolt fastenings. As stainless steel is not sufficiently corrosion resistant for pulp bleaching with chlorine dioxide conditions, the cover would have to be covered with a separate protection cover. This protective cover would have to be manufactured from a ring-shaped part which would be attached to a round plate with welds. The fastening would be accomplished by machining additional holes into the scraper hub with threads, which would allow the titanium cover to be attached around the stainless-steel cover. A PTFE gasket would be inserted in between the titanium cover and scraper hub connection point to achieve full sealing.

Another Option for the cover design was to make the cover itself from a titanium grade 2 plate material. In this solution the bolt connections between the scraper hub cover and the axle have a great leakage risk. Possibilities of covering this leakage point would be to either weld the bolts shut or to cover the bolt connection point with sufficiently corrosion resistant material. The welding of the fastening bolts would produce significant difficulty, when disassembling the discharge scraper for maintenance reasons. For this reason, the covering of the bolts was considered as a more realistic option for the bolt protection. The coverage solution can be seen on figure 17. As seen on the figure, a thin titanium round plate is attached onto the top of the cover with the same fastening bolts which attach the cover onto the scraper hub. These fastening bolts are then directly exposed to the bleaching process environment, so they need to be titanium fastening bolts. The figure also shows that the contacting points between the cover and the hub, and between the cover and the thin titanium sheet are sealed with separate PTFE gasket.

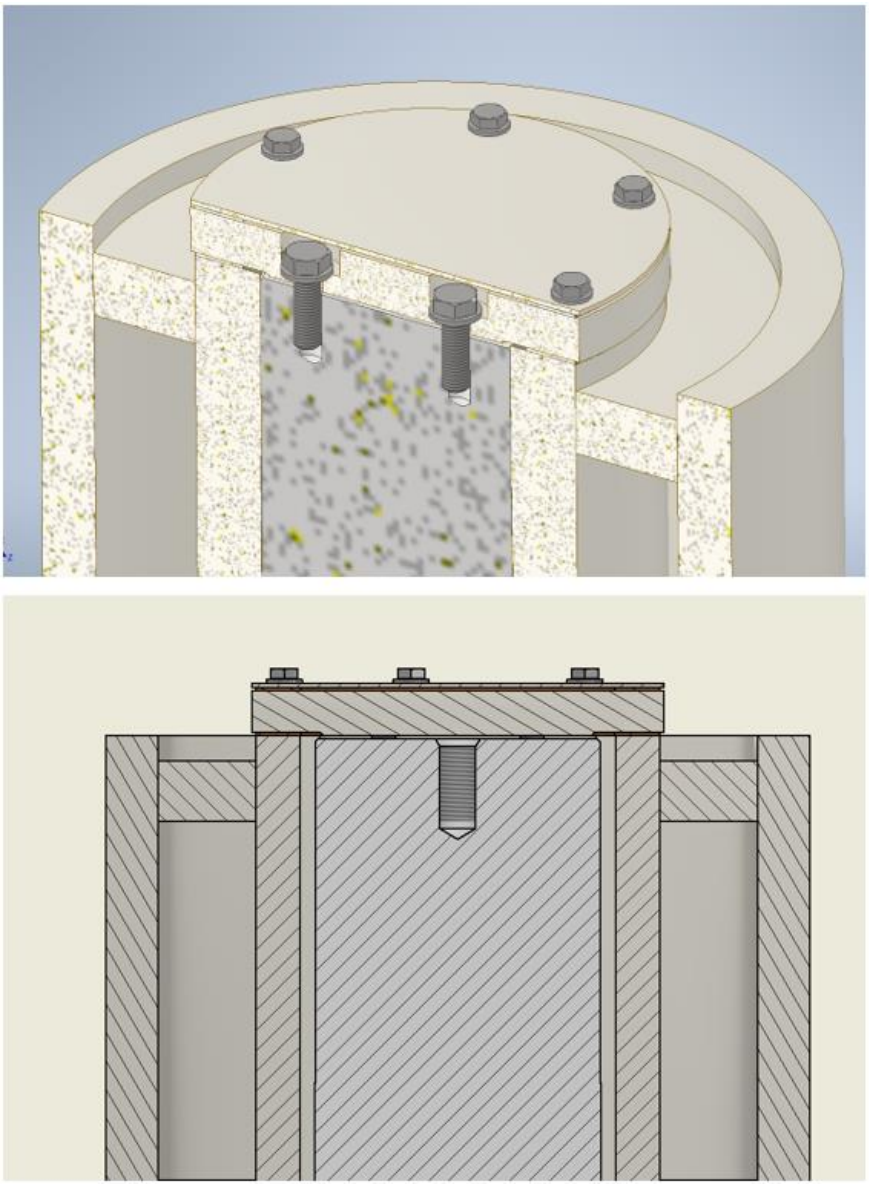


Figure 17. Titanium scraper hub cover with thin titanium sheet cover.

When comparing these solutions, the main differences from a cost-effective point of view are amount of needed material, material price and the manufacturing costs. With having the titanium cover on top of the cover, the amount of used titanium material can be lowered which then lowers the raw material pricing as titanium grade 2 can be considered as an expensive material especially when compared to stainless steel. Downside of the titanium cover solution is the large amount of work, effort and time to machine the separate holes for the cover and manufacture the cover itself. The manufacturing of a titanium grade 2 cover has more raw material usage when compared to the first solution but significantly less

manufacturing costs and effort. The needed manufacturing for second solution would be the cutting of the cover geometry and the sheet cover and machining the needed holes and recesses to achieve a simpler design. Due to the fact that welding of titanium can be considered as slow and difficult and unnecessary machining is not recommended, the pros of having less manufacturing costs and effort and having no need for any difficult titanium welds overcome the cons of having a higher amount of titanium material used. For these reasons, the chosen option for the cover design is to manufacture the cover from titanium grade 2 sheet and protect possible leakage points of bolt fastenings with a thin titanium sheet.

7.2 Optimization through DFMA-analysis

Eskelinen & Karsikas (2013a, 87-92) mention that in the DFMA-analysis, when the components of an assembly start to take shape, some rules of thumb are good to be used to ease the assembly. The main rules that can be applied in the case for the assembly of the connection point between the support structure and the tank connection are to optimize the parts with possible shoulders and to avoid unnecessary bolt or screw connections. These two rules lead to the optimization of the assembly between the titanium plate and the support structure. The differences between the previous fastening design and the new design can be seen on the figure 18. The small bolts of the previous design were changed into counter sink screws that would be used as fasteners from the upper side of the assembly. This change allowed the thickness of the titanium plate to be smaller which then has a lowering effect on the material costs. The number of screws for attaching the titanium plate onto the steel support structure was also lowered to just four pieces as the screws are only used for guidance and assembly reasons. The titanium plate is assembled onto the support structure before the attachment to the tank connection which is why the fastening screws are necessary.

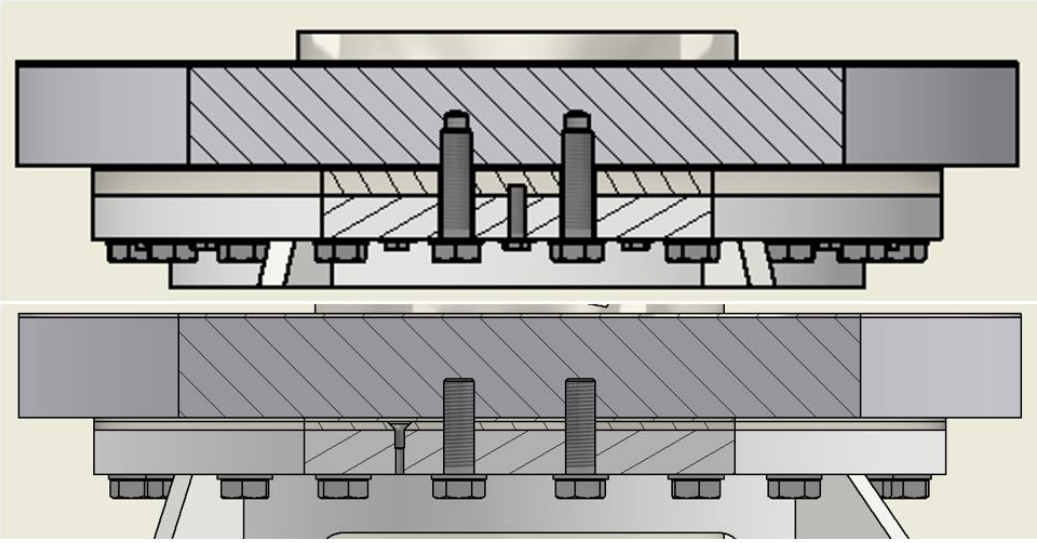


Figure 18. Differences between the old and the improved connection point design.

The first iteration of design only had a plate against plate connection between the titanium flange and the support structure flange. By designing a shoulder between the connection point, the assembly time and difficulty is expected to be significantly lower. This attachment method can be considered as a more convenient attachment method for the titanium plate when comparing it to explosion cladding. Even though explosion cladding might achieve a better bond between the titanium and steel, it is an expensive procedure and time consuming especially when adding the needed machining of the surface as a post treatment. Titanium flange and support structure contact area is shown on figure 19.

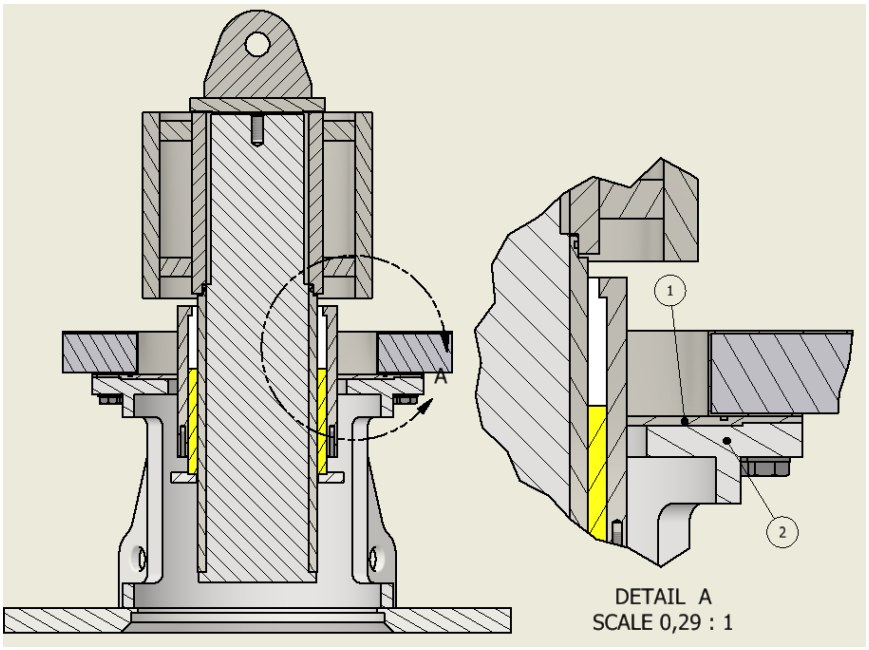


Figure 19. Shoulder assembly between the titanium flange (1.) and the support structure (2.).

These changes cause more need of machining for the titanium flange and the support structure. As mentioned in the literature review, the machining of titanium is more difficult and time consuming than the machining of steel, but the advantages in making the assembly easier and faster are expected to be more significant. In figure 20. the new improved titanium flange design can be seen with four countersunk bolt holes, 20 through holes for attachment bolts and a groove for a FEP O-ring.

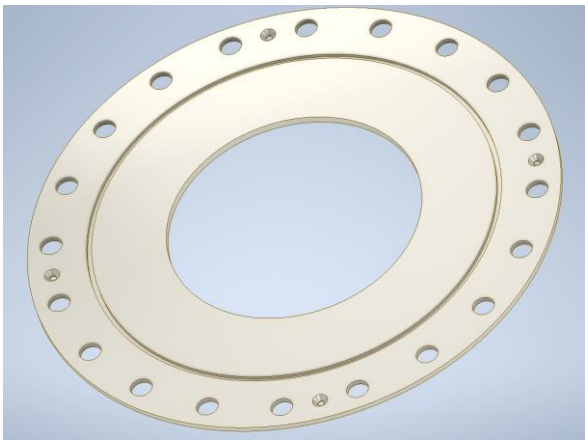


Figure 20. Improved titanium flange design.

One of the DFMA-analysis forms that can be applied for manufacturability and cost analysis comparison is form 3 from Eskelinen & Karsikas (2013a, 102) DFMA-guide examples. The form mainly reviews the aspects relating to manufacturability, justification and costs and the results can then be compared with each other to identify advantages. In appendix 3. is shown DFMA-analysis forms for comparing different manufacturing methods for the scraper hub. The conclusion from these forms is that the plate structured scraper hub should be more cost-effective and easier to manufacture in low volumes.

According to Eskelinen & Karsikas (2013a, 11) 20 principles for Manufacturing and assembly-friendly manufacturing, some of the thriving factors are the minimisation of needed parts and work phases. If the scraper hub could be made out of a commercially available titanium grade 2 solid bar, the amount of assembly stages and needed parts for the hub assembly are expected to be significantly less than with the manufacturing of a plate structured hub. According to a certain titanium solid bar provider, one available solid bar of the wanted titanium material is a 300⌀ bar. If the hub could be designed to be made out of this preform, manufacturing of the hub could be more convenient. The idea is to machine a simple titanium hub from the preform which allows the unnecessary welds and components to be neglected.

In appendix 4. is a DFMA-analysis with a DFMA-guided form to compare the assembly and manufacturing aspects of the plate structured hub and the solid bar blank hub for the discharge scraper. The comparison shows that the form’s points system gives better results for the simpler hub while the need for difficult welds is also neglected.

Based on the results that were gathered from these comparisons the most convenient option for the hub construction should be the solid bar hub. The thriving factors behind the comparisons were cost-effectiveness and difficulty of the manufacturing and assembly.

Even though the DFMA-analysis showed that the simpler hub design itself is more conventional for the design it comes with some disadvantages. The outer diameter of an original plate structured hub is large enough so that the wings can be attached onto the surface of the outer hub sleeve with weld attachments. This attachment method can be seen on figure 21.

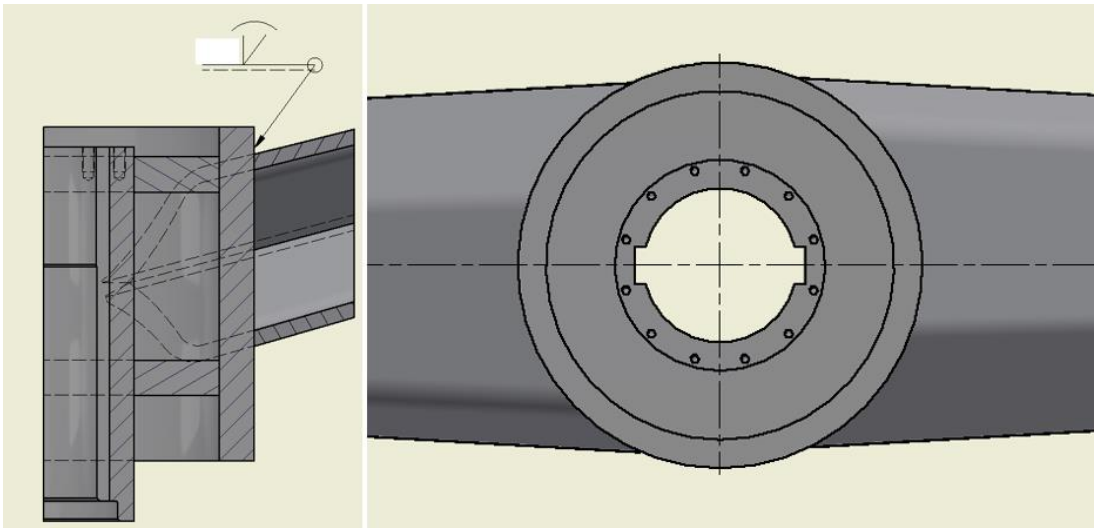


Figure 21. Wing attachment onto a titanium plate structured hub.

With the new possible hub design the outer diameter is smaller than in the previous design due to availability reasons from titanium solid bar suppliers and the desire to not have a unnecessarily large wall thickness for the hub. The smaller outer diameter causes the need for the wings to be attached partly as a butt joint. This attachment method can be seen on figure 22. The welding of the wing butt joint should be done with full penetration and with a J-groove to optimize the needed filler material and weld quality.

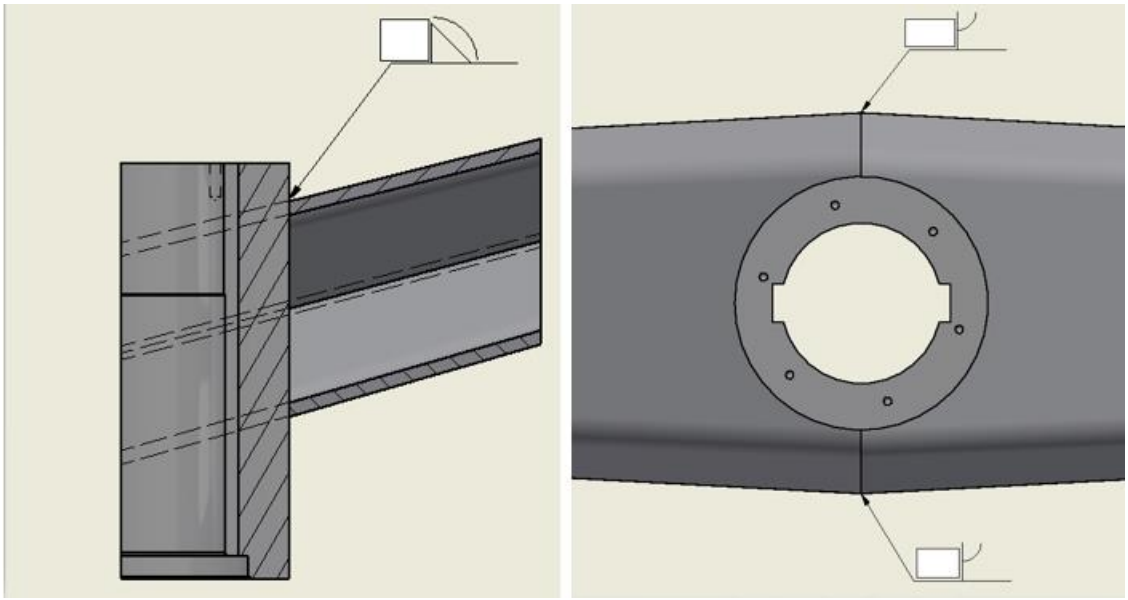


Figure 22. Wing attachment onto a hub with a smaller diameter.

To achieve a sufficient butt joint between the wings, the wing side cut needs to be symmetric on both sides in relation to the middle of the side cut. The symmetry was decided to be achieve by changing trailing edge of the wing main frame to be identical to the leading edge of the wing. The change in design can be seen on figure 23.

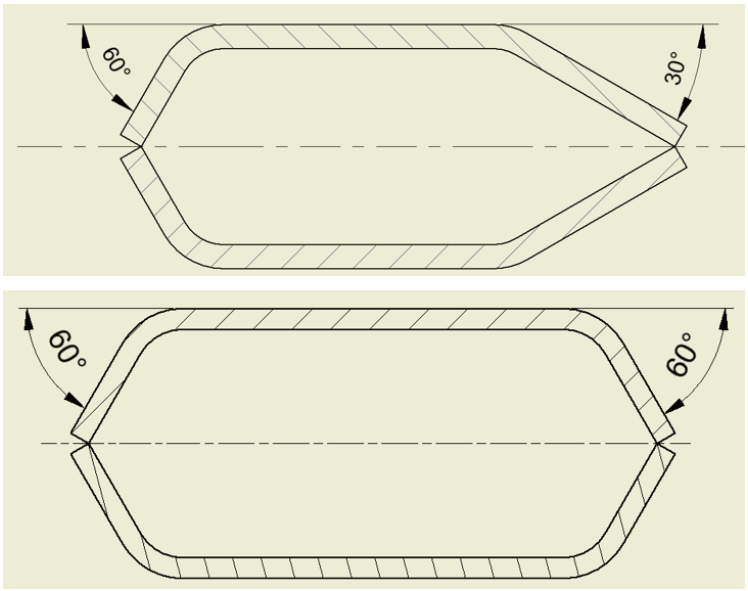


Figure 23. Comparison between non-symmetric and symmetric wings.

The forces exerted by the fluid on the solid in the direction of flow are called drag. These drag forces can be minimized by having a streamlined shape which lowers the number of turbulent vortices around the object. (Msubbu 2014.)

To assure that the profile change would not affect the function of the scraper or cause unnecessary drag forces, a CFD-analysis was conducted for investigating the momentum change and velocity field change. The analysis was done with ANSYS Simulation software. A report of the analysis can be seen on appendix 5. The results show that there is close to no affect expected with change of geometry for scraper wing profile due to the fact the scraper has a relatively slow rotational speed.

8 FE-analysis

FE-analysis was decided to be conducted for the most essential parts of the discharge scraper based on extreme conditions and weight carrying elements. Based on these viewpoints, the stress analyses are conducted in weight carrying conditions and in extreme condition where the tip of the scraper wing gets stuck while the motor is still producing torque on the secondary shaft of the assembly. Both conditions also consist of downward forces caused by the hydrostatic pressure inside the tank. Possible stresses or frequencies caused by vibration are neglected as the rotational speeds of the assembly are relatively low. Lack of frictional losses and model simplifications may cause some dissimilarities compared to real-world environments, as frictional losses are neglected.

8.1 Static analysis on weight and pressure carrying forces

The main components that are affected by the hydrostatic pressure inside the tank or by the weight of the assembly are the components that are inside the tank and the weight carrying components on the flange connection, which are the bolts and the support structure. The hydrostatic pressure was calculated by using the equation below.

$$p = \rho \times g \times h \tag{1}$$

where p is pressure [bar], ρ is fluid density [kg/m^3], g is gravitational acceleration [m/s^2] and h is the depth [m].

By inserting the following values into equation 1: water density 998 kg/m^3, gravitational acceleration on earth 9,81 m/s^2, and the depth of a largest tank at Andritz 70 m, the resulted hydrostatic pressure is 6,867 bar.

According to given weight from the Autodesk Inventor modelling software, the weight of the whole assembly without the tank connection flange is 1317 kg. After adding the weights

of the gearbox and the motor, the full weight of a discharge scraper assembly is approximately 5207 kg.

The force caused by the mass of the assembly can be calculated with the following equation below.

$$F = m \times g \tag{2}$$

where F is force [N], m is mass [kg], and g is gravitational acceleration [m/s^2].

By inserting the calculated mass of the scraper assembly and using the gravitational acceleration on earth, the force results as 51 080 N. The centre of mass is located 210mm away from the middle point of the motor bed towards the motor connection side of the bed. The safety factor for the simulation calculations was set to be 1,5. Load was distributed as a load on surface of the motor bed.

Before the FE-analysis the discharge scraper assembly was cleaned up and simplified to help the simulation process and achieve better results on the relevant parts of the assembly. After the simplification of the assembly, a static stress analysis of the assembly was performed. In figure 24. is shown a simplified model of the assembly where axle bottom is attached to the support structure bed in way that the forces caused by the hydrostatic pressure are approximately translated for the support structure. The only constraints that model has is the connections between axle and the support structure, and a fixed constraint for the tank connection flange. The mesh for the model was done with a fixed mesh with an average element size of 0,10 (Specifies the fraction of the longest axis of the model between adjacent nodes) and with a minimum element size of 0,20 (Specifies the fraction of the average mesh size to place the closest pair of element nodes). With these settings a mesh of 1158467 nodes and 702583 elements was created. The stress distribution and the maximum von Mises stress is also presented in figure 24.

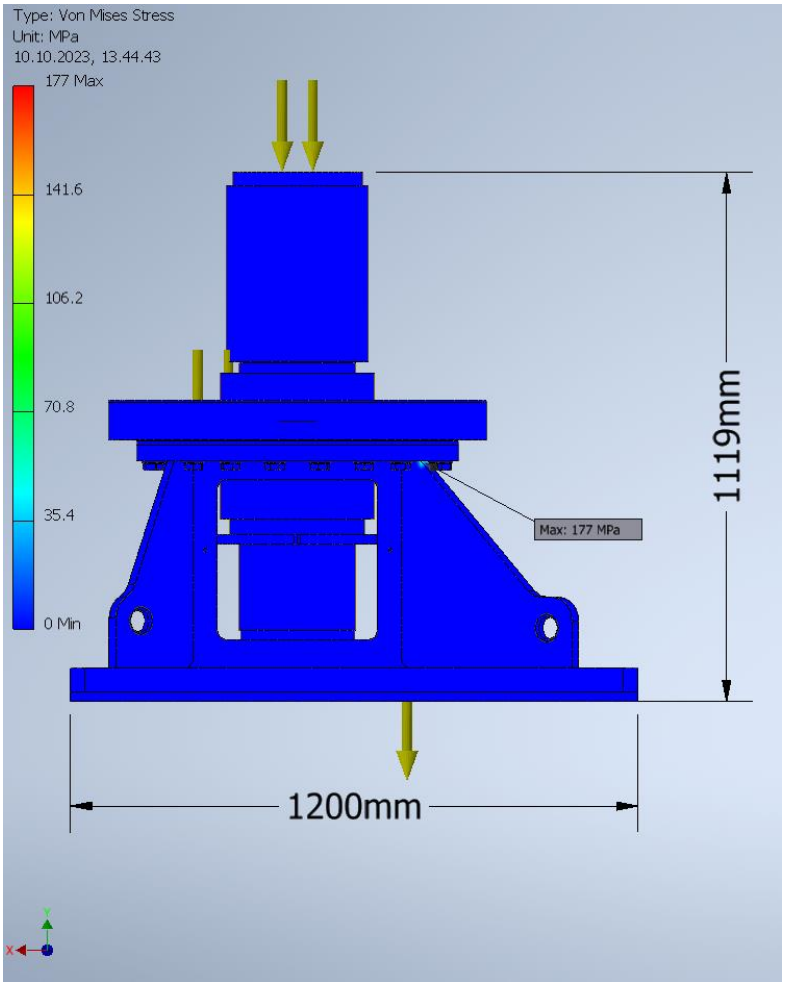


Figure 24. Simplified model of the scraper assembly.

Analysis results show that the largest stresses were focused on the bolts and the support plates of the support structure. The maximum von Mises stress according to the analysis was 177 MPa and it is focused on the bolt second nearest to the centre of mass on the angle between the longitudinal bar of the bolt and the hexagon shaped tightening part of the bolt, as also seen on the figure 25. Distortions are multiplied to show the behaviour of the bolt. Support structure is strengthened with four steel stiffening plates that had maximum stresses of approximately 55 MPa.

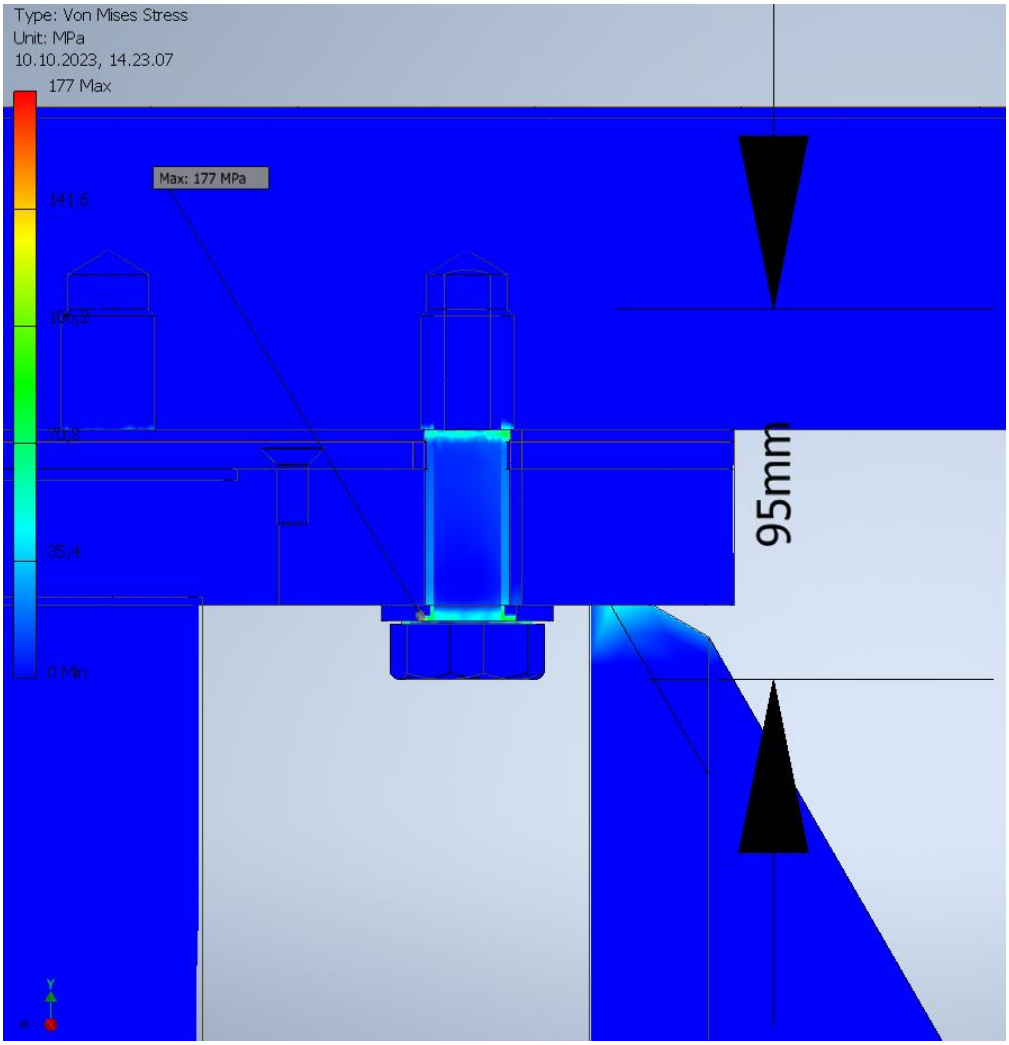


Figure 25. Close up section cut of maximum von Mises stress focusing on a bolt.

The reason why the maximum stress is focused on the bolt second nearest to the centre of mass is because the support structure has two large holes on each side and support plates which affect the stress distribution caused by the downward forces. The fastening bolts that are used for the flange connection assembly have the strength properties according to ISO 898-1 (ISO 898-1:2013, 13), which states that the lowest grade of yield strength for these bolts is 240 MPa. This means that the bolts should be able to carry the assembly in normal operation conditions.

8.2 Static analysis of extreme conditions

As previously mentioned, the extreme static conditions for the discharge scraper are referring to a situation where the tip of the scraper wing is held in place caused by an external factor. While the wing is stuck in place the motor is expected to produce torque with maximum power for the secondary shaft for a certain amount of time. This situation can be considered as a limiting factor that the design and construction should withstand without significant deformation or failure.

The motor that rotates the discharge scraper is located at the very bottom of the assembly and the rotational speed for the discharge scraper is adjusted through a gearbox between the motor shaft and the secondary shaft. The secondary shaft rotates the scraper hub through two key attachments. For design simplification reasons the motor and gearbox assemblies are represented by a solid plate which is connected to the secondary shaft of the assembly and the support structure. The friction losses caused by the gearbox or any other part that would affect the torque output or stress distribution are overlooked. The motor and gearbox parameters that are needed to calculate the needed force loads for the FE-analysis are presented in table 2. When the wing is stuck, the motor is expected to have the power of maximum momentum, which is approximately three times the normal output of the motor.

Table 2. Motor and gearbox parameters.

Motor power [kW]	110
Motor rotational speed [rpm]	1500
Gearbox gear ratio	122:1
Secondary shaft rotational speed [rpm]	12,3
Maximum power [kW]	330

The amount of torque that is present in the secondary shaft can be calculated with the equation below.

$$\tau = \frac{P \times 60}{2 \times \pi \times \omega} \quad (3)$$

Where τ is torque [Nm], P is power [W], and ω is rotational speed [rpm].

The force that is caused by the output torque of the secondary shaft can be calculated with the following equation below.

$$\tau = r \times F \times \sin\theta \quad (4)$$

Where τ is torque [Nm], r is radius [m], F is force [N] and θ is the angle between the force and the lever arm.

The perpendicular force applying to the tip of the wing while being stuck, can be calculated with equations 3. and 4., with using the parameters from table 2. The resultant force affecting the wing tip is 128,1 kN. With inserting the calculated parameters into the static stress analysis environment while having the tank connection flange as fixed, the analysis could be started. Applied forces and the simplified design can be seen on the figure 26. The forces caused by the mass and the hydrostatic pressure are also present in this static analysis.

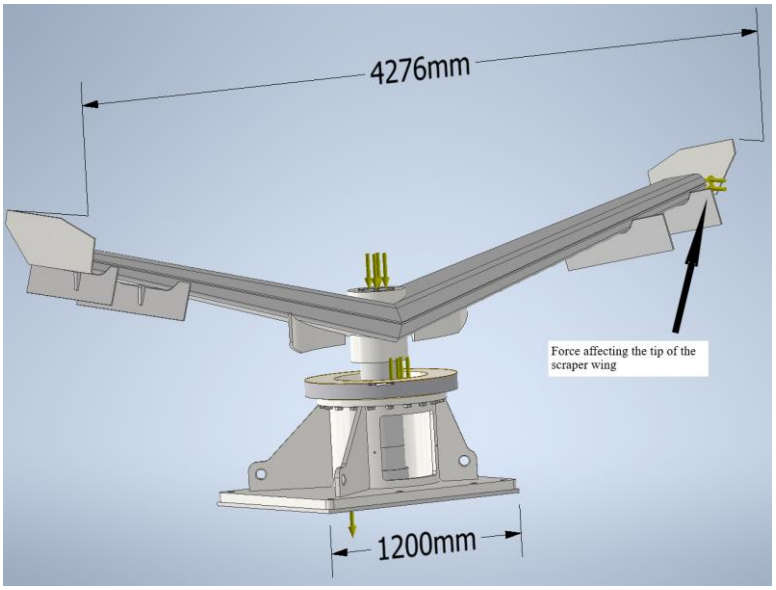


Figure 26. Simplified model for stress analysis with arrows representing affecting forces.

In figure 27. is shown where the secondary shaft axle keys are located on the assembly. The wing with the applied force is on the right side of the axle.

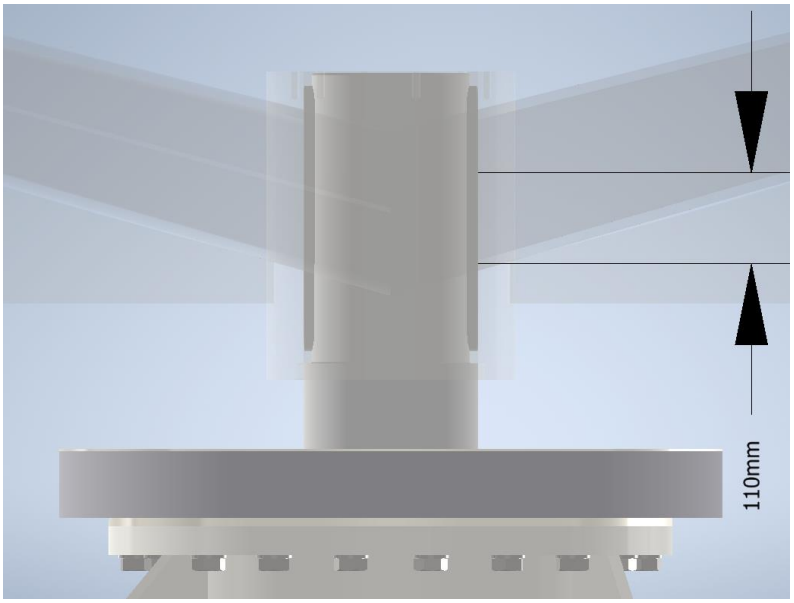


Figure 27. Location of secondary shaft axle keys.

The mesh was formed with having an average element size of 0,10 (Specifies the fraction of the longest axis of the model between adjacent nodes) and with a minimum element size of 0,20 (Specifies the fraction of the average mesh size to place the closest pair of element nodes). These mesh setting formed a mesh with 513688 nodes and 294376 elements. After running the analysis, the maximum von Mises stresses were located on the axle keys between the axle and the scraper hub, as also seen on figure 28. The high stresses were focused especially on the bottom area of the keys due to the fact that the force load point is in a higher position in the global coordinate system. These maximum stresses are significant especially when compared to the minimum yield strength of the key material which is 305 MPa according to EN standard (EN 10083-2:2006, 20-21). These two maximum stresses are very local stresses and as seen from the colour bar indicator in the figure, no stresses of the same magnitude can be seen on near elements of the analysis. The side part of the key that transfers the torque momentum into the hub has stresses between 100 and 400 MPa which are under the minimum tensile strength of 580 MPa for the key material.

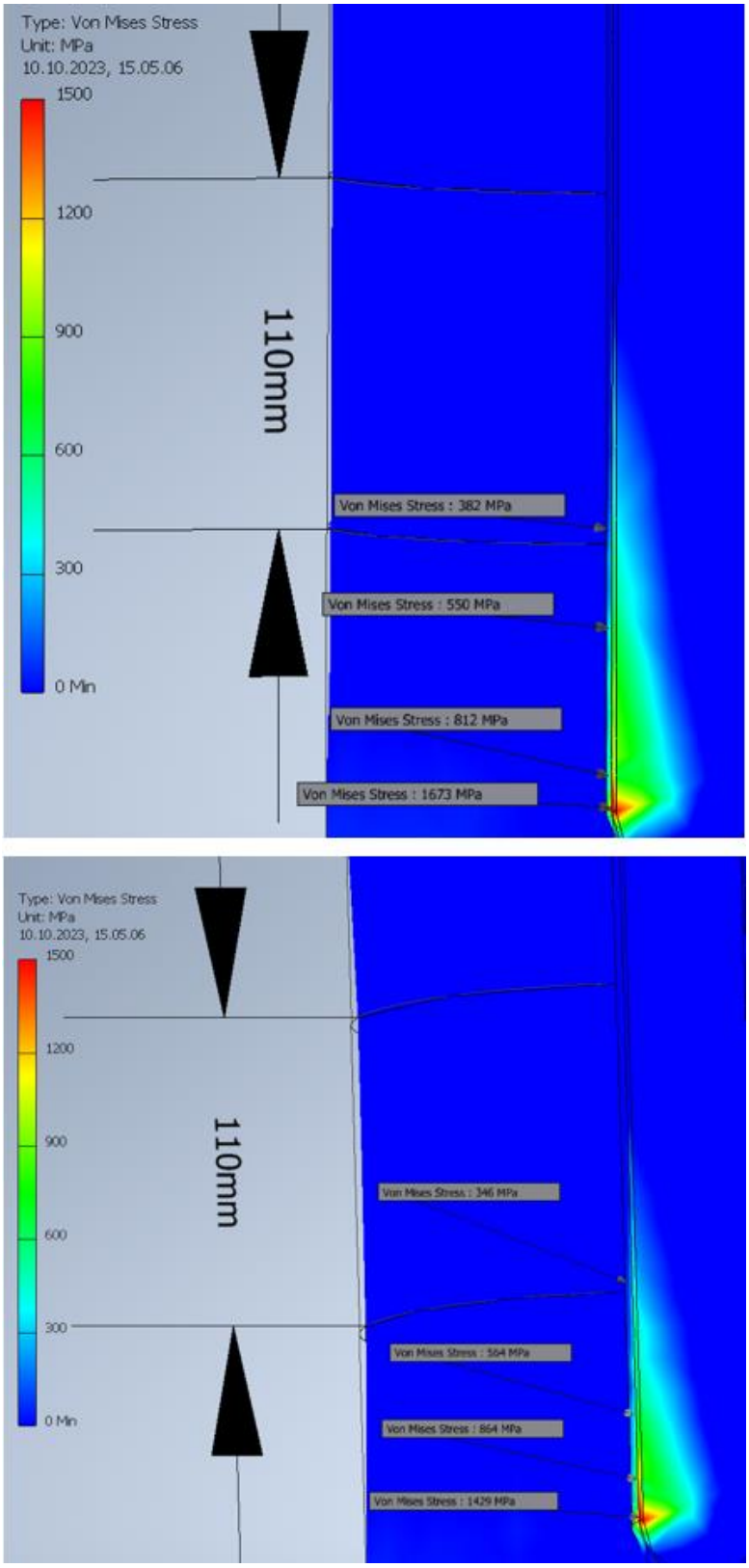


Figure 28. Maximum von Mises stress and location. (Applied force side key [Top], Far side key [Bottom]).

On figure 29. is seen the hub side of the key connection area, nearest to the applied force. The figure shows that the largest stress on the surface has a magnitude of 321 MPa which is lower than the typical yield strength for titanium grade 2. According to an ASTM standard (ASTM B 265-20a 2020 5), the yield strength of titanium grade 2 is approximately 360 MPa. This implies that the key groove on the titanium hub should withstand the stress on the key contact area.

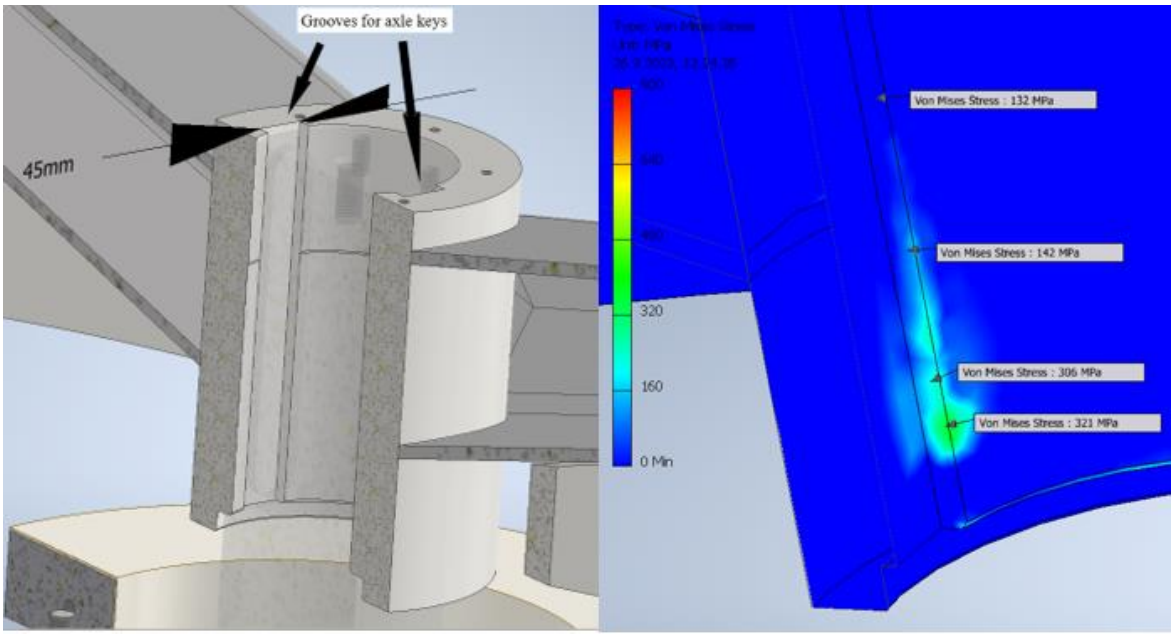


Figure 29. Hub surface von Mises stress on key attachment area.

Largest stresses that were formed on the wings were located on the root of the wing that wasn't exposed to the force loading caused by being stuck. The location for the largest von Mises stresses can be seen on figure 30. As seen on the figure, the high stresses have a magnitude of approximately 450-490 MPa.

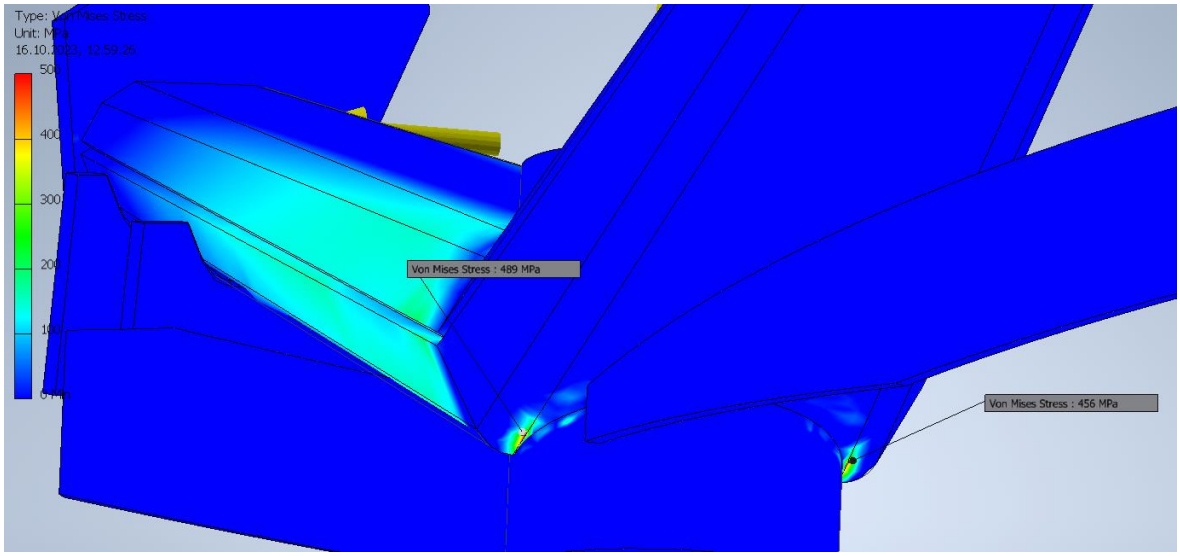


Figure 30. Location of largest von Mises stresses on scraper wings.

These localized high stresses on the wing root have a higher magnitude than the typical yield stress for titanium grade 2 which is 350 MPa. However, the stresses are highly localized and directly located on areas where penetrative fillet welds are connecting the wing onto the hub. These welds with a certain throat size are expected to strengthen these areas which helps to withstand any deformation caused by the high stresses.

On the wing that had the force applied it was noticed that the von Mises stresses on the structure had below 250 MPa stresses which expectedly were lower towards the tip where the force was applied. Some stress measuring probes of the formed stresses can be seen on the figure 31.

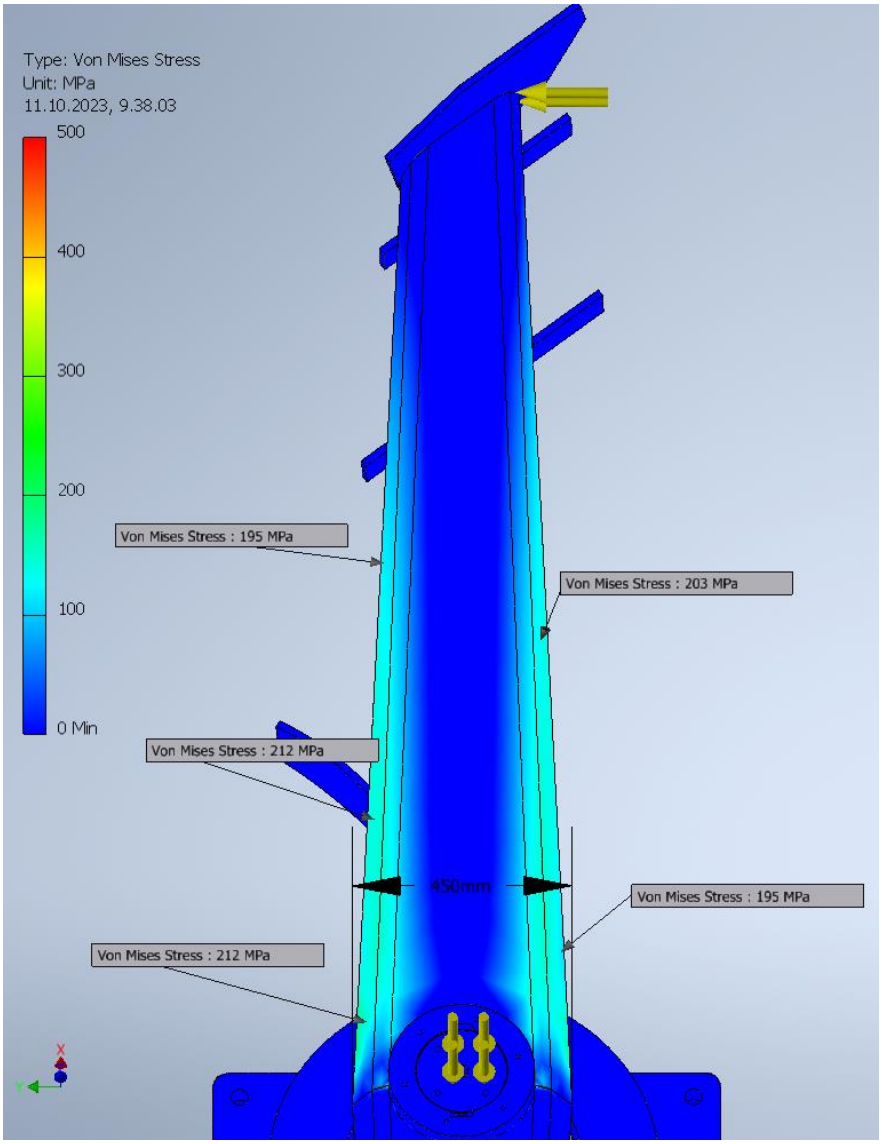


Figure 31. Von Mises stresses formed on a scraper wing where the force was applied.

When having the load forces of the extreme conditions affecting the assembly, it was noticed that the stresses formed on the support structure were significantly larger that when just applying the forces caused by hydrostatic pressure and the mass on the structure. The largest von Mises stresses affecting support structure were located on the corners of the support structure assembly and maintenance holes. The support structure sleeve should still withstand the extreme conditions as the highly localized high stresses are expected to be smaller in a real-world situation as the gearbox and motor have effect on the load distribution and frictional losses. These localized high stresses can be seen on figure 32.

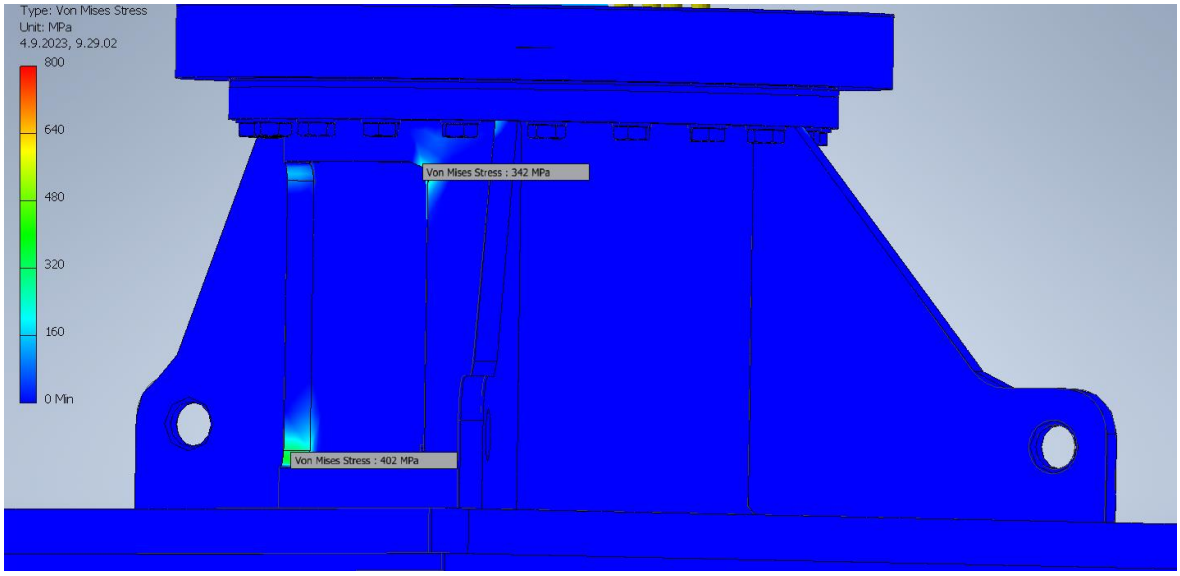


Figure 32. Von Mises stresses formed on support structure.

The colour graded static analysis figures show that the assembly had no more significant von Mises stresses on the assembly than presented in this chapter. In these static stress analyses the friction losses are neglected and the simplifications of the assembly models may cause some dissimilarities compared to a real-world situation.

Ultimate tensile strength of the axle key material is minimum 580 MPa according to EN standard (EN 10083-2:2006, 20-21). This means that there is a possibility of deformation or even cracking on the axle key. The stresses however are highly localized, and the stress maximums are expected to differ from real-world conditions, as there is a significant number of frictional losses and load distribution differences between the hub and axle connection. Main focusing area of interest was to investigate the behaviour and strength of the new titanium scraper hub, wing connections areas, wing structure and other parts which have had a change in design due to material change or corrosion prevention ability reasons. The titanium scraper hub and wings are expected to withstand the extreme conditions and the normal operating conditions while having small risks of deformation on the support structure and wing root connection in extreme conditions. The extreme condition of having the wing stuck is highly unlikely but plausible.

9 Discharge scraper for a chlorine dioxide pulp bleaching application

After all the identified problem areas were sufficiently covered and possible changes of design for specific parts were made based on titanium grade 2 fabrication and manufacturability possibilities without significant effect on function, the final assembly and manufacturing design could be formed. A side-cut of the discharge scraper that is applicable for a chlorine dioxide pulp bleaching application is presented on figure 33. The general dimensions such as full length, full width and wingspan are tried to be kept as same when compared to traditional discharge scraper. This allows dimensioning and function of the scraper to be compatible in previously known spaces and environments.

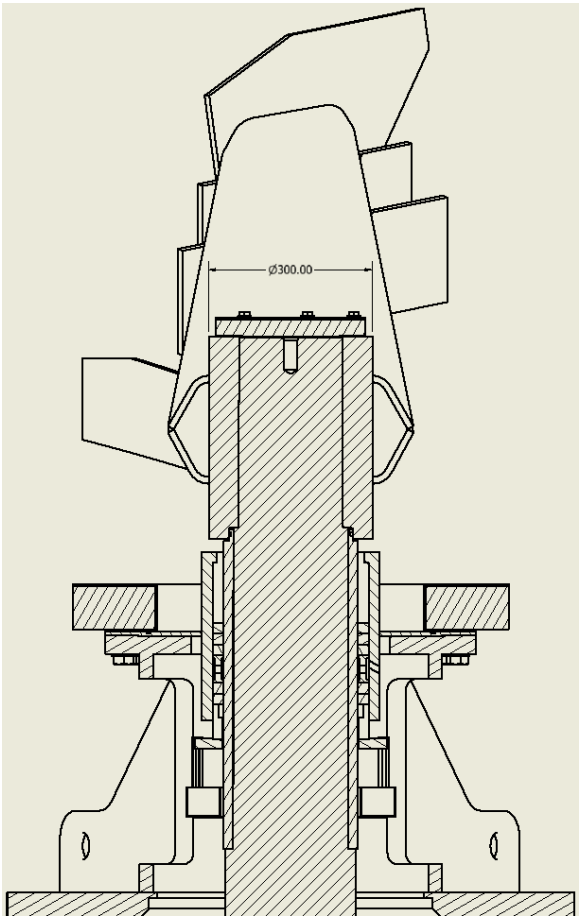


Figure 33. Halfway section cut of the final discharge scraper for chlorine dioxide pulp bleaching conditions.

After adding the sealing components into the assembly and defining needed welding points of the assembly, the finalized design for the tank and support structure connection area could be formed. The final connection area assembly can be seen on figure 34. The tank connection flange is protected with a titanium sheet lining which is manufactured from thin titanium sheet with cutting and welding. It is then fitted between the connection flanges. The sealing support sleeve is manufactured from titanium plate with hot rolling method. The seam is then grooved and welded shut and the surfaces are machined into desired dimensions, surface roughness and tolerances. Axle wear sleeve is manufactured from titanium grade 2 solid bar blank which is then machined and lathed. The wear sleeve is also surface treated with a ceramic coating to achieve better wear resistance. According to a certain subcontractor specialized in sleeve manufacturing, the manufacturing method is the most realistic option, and the ceramic coating has excellent corrosion resistance and good durability. Coating's purpose on a wear sleeve is to increase the lifetime of the wear sleeve and to avoid any unnecessary metal-to-metal interaction. A titanium flange is inserted in between the support structure connection flange and the tank connection flange with a FEP/Q O-ring seal to achieve full protection from bleaching substances for the steel support structure. The titanium flange itself is manufactured from a plate blank which is then cut and machined to the wanted dimensions. The O-ring groove, through holes, countersinks, and the guiding shoulder are also machined according to wanted surface roughness and tolerances at this point. The attachment between the titanium flange and steel support structure is performed by attaching the flange onto the support structure with steel M8 countersunk screws which is done for assembly reasons to keep the flange fixed on the support structure when attaching the support structure onto the tank connection flange. The threads for M8 bolts are on the support structure. Support structure with the titanium flange is connected onto the tank connection flange with steel bolts with having through holes in the support structure and the titanium flange and by having the threads in the steel tank connection. This allows the possibility of bolting steel bolts into steel threads without getting in contact with titanium components. Titanium flange is also attached onto the sealing support sleeve with a fillet weld from both sides which are performed with TIG-welding.

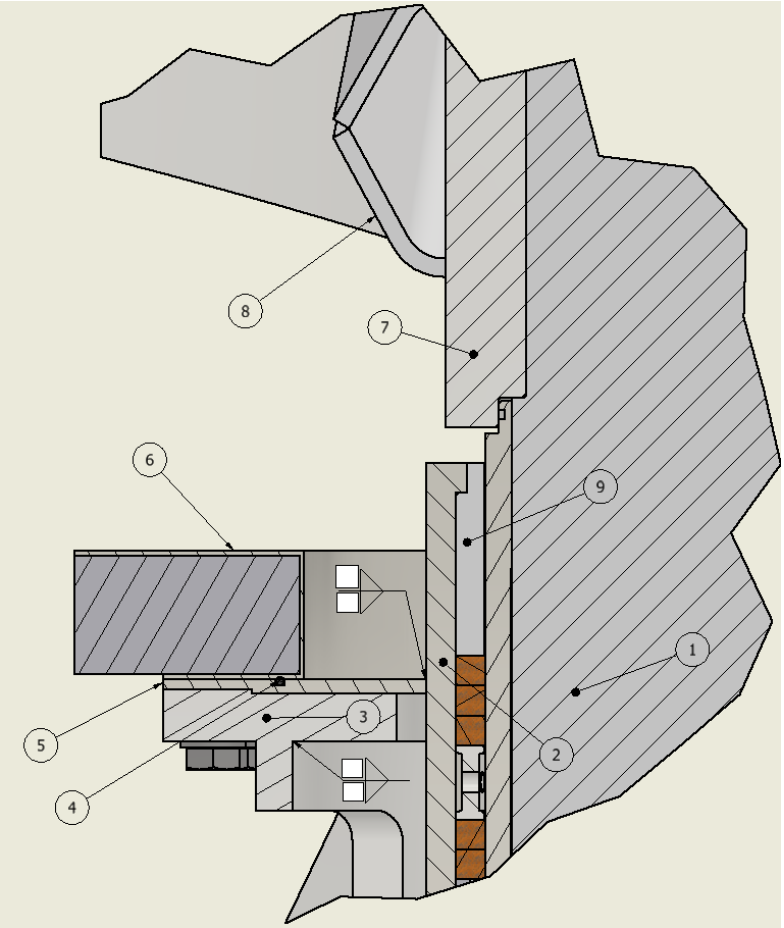


Figure 34. Connection area of support structure and tank connection flange with needed welds. (1. Secondary shaft, 2. Titanium sealing housing support sleeve, 3. Steel support structure, 4. FEP/Q O-Ring, 5. Titanium flange, 6. Titanium lining on tank connection flange, 7. Titanium scraper hub, 8. Titanium scraper wing, 9. PTFE+25%Carbon sealing support sleeve).

The scraper hub is designed to be manufactured from a titanium grade 2 solid bar blank which is then machined into correct dimensions as shown in figure 35. Five threaded holes are also machined into the scraper hub. Hub inside area is machined with a groove for the axle key attachment and with specific surface roughness. Attachment of the wings is done by welding the wing root partly on to the titanium hub and the outer sections of the wings are butt welded together with full penetration TIG welding. These connection welds between the wings and the scraper hub are possible when having a symmetric wing design which for the butt welds are done. It is advised to not to overlap the filler and butt welds of the wings to avoid any failure in welds. Scraper hub cover is made from a titanium grade 2 plate blank

which is then machined according to wanted dimensions and design. The hub is fitted onto an axle shoulder and partly on the axle wear sleeve. FEP/Q O-ring is sealing the connection between the wear sleeve and the hub. A cover manufactured from titanium plate is then attached onto the axle with four bolts, having recesses on the cover for steel bolts, and with six titanium bolts attaching to the titanium hub. The steel attachment bolts between the cover and the axle are protected with a thin titanium sheet to avoid possible leakage or corrosion. Two PTFE gaskets are inserted between the hub and the cover, and in between the cover and the thin titanium sheet to achieve a full seal from the process substances.

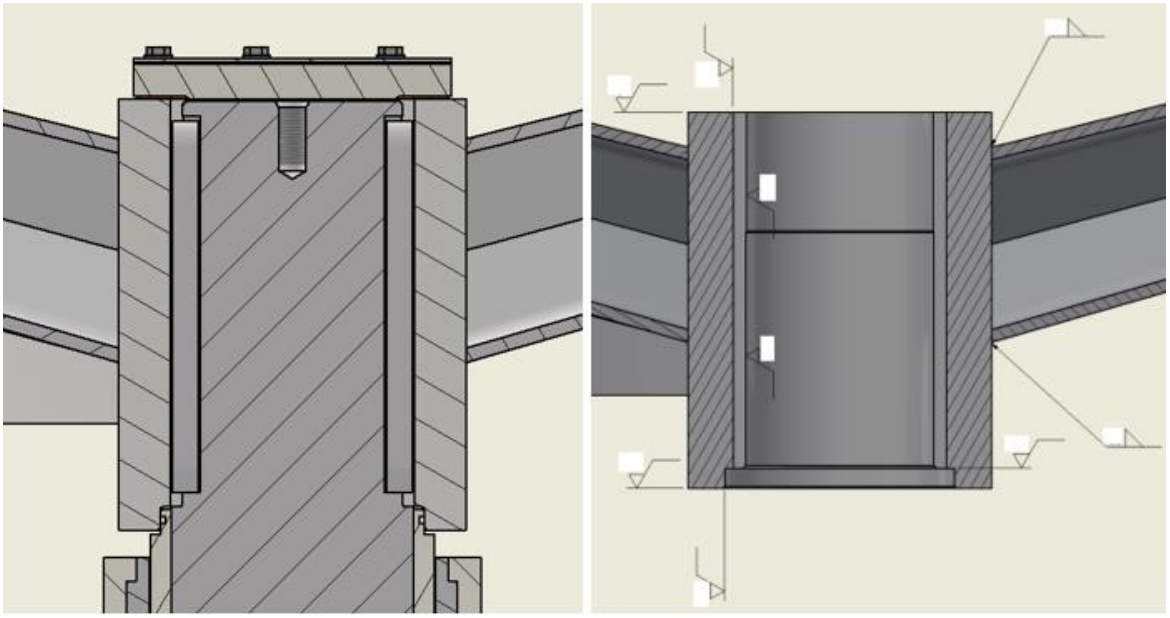


Figure 35. Titanium scraper hub design and manufacturing plan.

Manufacturing of the wing main frames are done from two titanium grade 2 plate blanks. The two separate blanks are then hot formed into a symmetric shape as common scraper wing would be formed. Literature review showed that the hot forming of titanium plates is a relatively common manufacturing method that needs different fabrication parameters due to difference in structural behaviour when compared to steel. The attachment points between the two parts of the wing main frame are welded with TIG welding in the longitudinal direction. Filler material used is titanium and the attachment point naturally forms a V-shaped groove for the weld. This longitudinal weld is expected to be one of the most time-consuming welds as it has a large throat size and a long seam length which requires several

runs with cooling time when the work piece temperature rises too much. As mentioned in the literature review the sufficient amount and volume of shielding gas is necessary for the formation of an eligible weld when using TIG welding. After the wing main frame is constructed all the smaller guiding wing parts can be attached to the main frame with fillet TIG welding.

10 Discussion

The final design and manufacturing plan for a discharge scraper for a chlorine dioxide pulp bleaching stage was made based on construction possibilities, cost effectiveness and effect on function. The construction possibilities were mainly investigated through literature review. Cost effectiveness and scraper design were analysed and optimized with using 3D-modelling tools, ideation sessions, DFMA optimization and FE-analysis. The first iteration of possible designs also included a points matrix to filter out least beneficial solutions. A ANSYS FLUENT CFD investigation supported the scraper wing frame structure change.

10.1 Comparison and connections with former research

The investigations made on chlorine dioxide's corrosive effect on multiple different piping weldments and corrosion performance of 316L SS and titanium modified austenitic steels in the bleaching phase of a pulping process are highly focused on the materials corrosion resistance itself against chlorine dioxide in simple forms such as plates and welds. The construction possibilities of highly corrosion resistant materials are important to investigate to allow a more optimized and convenient way of using these materials to prevent corrosion rather than just changing the material. With understanding the best ways to utilize the fabrication methods of titanium the cost effectiveness and design could be optimized. The previous investigations of the use of titanium in highly corrosive environments can also be considered as quite outdated, as they were done in the '90s.

10.2 Objectivity

The goal of this thesis was to have a neutral point of view when approaching the set objectives and problems. The use of titanium in bleaching equipment is a common method in preventing corrosion but it has usually been used as piping and wall tank material which are relatively feasible to manufacture. It is possible to use different materials or different titanium grades for bleaching environment, but use of grade 2 titanium is one of the most common and easily available corrosion resistant materials. The design solutions are highly

affected by previous expertise on the structure of a discharge scraper so it can be expected that the solution approach could have differed with an alternative design approach with a more neutral basis.

10.3 Reliability and validity

In the literature review a large amount different sources were used to cover the thesis scope. The sources were used from scientific journals, articles from titanium and bleaching industry, and from researches on using titanium as a construction material and pulp bleaching equipment. The sources were limited and, in some cases, outdated, but there still was a sufficient amount of source material for the validation of this thesis.

The oldest resources that were used were from late 70s and from the 80s. These resources can be considered as quite old but the used information from these resources were carefully ensured to be either everlasting or as still relevant.

10.4 Assessment of the results and sensitivity analysis

In the designing stage of this thesis multiple different approaches and tools were used. The differences between austenitic stainless steel and titanium grade 2 were analysed and compared with a COBWEB-analysis tool. This analysis tool showed properties that affect the advantages and disadvantages of manufacturing and using these materials for a discharge scraper for a pulp bleaching process. The main conclusion was that titanium grade 2 is superior in corrosion resistance and has a better strength to weight ratio but is significantly more expensive and has a lower tensile strength. DFMA approach was used as a tool to optimize the design and assembly of new parts. The optimization mainly used guidelines and forms provided by the approach. With the forms, a comparison of possible manufacturing methods for the scraper hub and hub cover was performed. The guidelines were used to optimize the structure and assembly of the titanium grade 2 flange between the support structure and bleaching tank connection point. DFMA approach was used to support and optimize the designing phase, but the solutions were also highly affected by expertise and experience.

To ensure that the new design and structure would be applicable in the new operating conditions, FE-analysis was used. The analysis was done in two different environments: static weight carrying conditions and in an extreme static condition. The FE-analysis results showed that the structure would easily withstand the weight carrying conditions, but the extreme conditions had significant stresses. In a situation where the wing would be stuck from its end and the motor would still produce torque, it was noticed that stresses larger than the yield strength of titanium grade 2 or stainless steel were formed. The largest stresses were formed on the keys of the axle which were larger than the tensile strength of the key material. This meant that if a part of the assembly would fail, it is expected to be the be axel key. Support structure and scraper wing roots had large highly local stresses that had a magnitude larger than the yield strengths of steel or titanium grade 2. However, these stresses are highly localized, strengthened with welds or expected to be smaller in real-world conditions so the risk of yielding would be expected to be small. The extreme situation happening in normal operating conditions is highly unlikely. An investigation in a ANSYS FLUENT CFD environment ensured that change in wing profile would not affect the function of the scraper.

10.5 Key findings

In the literature review the process environment, structure of a common discharge scraper, titanium's behaviour against chlorine dioxide and the realistic construction options for titanium grade 2 were investigated. As titanium grade 2 is an excellent choice of material for chlorine dioxide bleaching phase, the realistic construction and manufacturing options, disadvantages and advantages were important to understand. This would allow an effective use of the material in construction. The conclusion was that titanium grade 2 manufacturing methods, properties and material costs affect highly on the discharge scraper costs and the manufacturing process especially when compared to stainless steel.

Through ideation sessions and points matrix, the best possible design options were identified for further analysis. The design phase was carried through expert opinions, modelling, and various comparisons to identify the best possible solutions from the manufacturability and cost-effective points of view. DFMA approach was used to compare different assembling and manufacturing methods, and to optimize the design. With FE-analysis tool, the structural

behaviour of the design was analysed. The results showed that the discharge scraper should be manufactured with simple parts to mitigate the number of difficult fabrications, welds and machining. From a design point of view the altered structure should still withstand the normal weight carrying conditions and extreme conditions without significant failure or distortion.

The change of material from steel to titanium for the components that are in direct contact with the bleaching stage substances do significantly raise the material and manufacturing costs of the discharge scraper as titanium materials are significantly more expensive compared to materials commonly used. Main justifying reasons for manufacturing expensive titanium grade 2 components are its significant advantages in strength to weight ratio and its outstanding corrosion resistance. The cost-effectiveness of the discharge scraper was maximized with applying titanium lining or protective titanium parts instead of manufacturing large and expensive titanium components for the whole assembly. Cost-effectiveness of the new design was also tried to be optimized through selecting the most cost-efficient manufacturing methods which were chosen according to DFMA-analyses, comparisons, and literature review. In many cases the lack of automatization possibilities and low manufacturing volume had a significant effect on choosing the manufacturing method from a costs point of view. If the volume and the need of discharge scraper for chlorine dioxide bleaching stages increases remarkably, the possibility of automatization or re-analysing best possible manufacturing methods is recommended. Specific cost-analyses could be made for the whole manufacturing and assembly process when the specific machining methods, material costs and work costs are known.

10.6 Novelty value of the results

As Andritz Oy presented the need for a discharge scraper design for a pulp bleaching stage, the suggestion of using titanium grade 2 to prevent the corrosion risks was made. This led to a systematic designing process where the possibilities and properties of using titanium grade 2 were highly important. This thesis provided a design that could be theoretically manufactured to be used in highly corrosive environment. It also provides a basis for a first production and sets a foundation for further optimization for material selection, manufacturing and design.

The main thriving factors that affected the design process and chosen manufacturing methods were cost effectiveness and effect on function. This meant that the target would financially benefit from this thesis without affecting the function of the scraper significantly. The results from this thesis give competitive advantages as there is now a new design option that can utilized to optimize the bleaching process in certain applications.

10.7 Generalization and utilization of the results

The thesis results can be utilized with other components or assemblies that are used in highly corrosive environments. Especially the approach and technique to use titanium grade 2 effectively gives advantages in cost-effective manufacturing and assembly. However, volume of manufacturing highly affects the chosen manufacturing methods which should be taken into account when applied to a different application. The design approaches with DFMA results can be used to optimize different kinds of components or assemblies.

10.8 Topics for future research

There are several different welding possibilities for titanium welding such as laser and electron beam welding. It is difficult to predict the possible distortions of TIG welding which could be then avoided by choosing a more expensive welding method for the titanium work piece welds. Welding of titanium can be considered as time consuming and expensive when compared to traditional welding of steel. As previously mentioned, the automation possibilities of laser and electron beam welding are excellent so with larger manufacturing volume welding methods could be optimized. Constantly developing additive manufacturing technology for metallic materials allow the possibility of manufacturing titanium components for these purposes in the future. Tsephe, Akinwamide, Olevsky, & Olubambi (2022) mentions in a research relating to additive manufacturing of titanium, that there is a future for production of titanium-based alloys with high-end properties. Additive manufacturing would especially allow the manufacturing of components that are highly optimized from function and weight points of view with the freedom of making complicated designs. With applying additive manufacturing to a discharge scraper manufacturing with titanium components, the amount difficult time-consuming welds can be reduced, more

optimized complex parts can be manufactured, and weight of the assembly can be lowered. Additive manufacturing combined with topology optimization would especially allow a significantly lighter and optimized design for the titanium components of a discharge scraper.

The main focus of this thesis was not to produce detailed fully comprehensive FE-analyses of the discharge scraper, but to have a brief investigation on the behaviour of the components that are significantly changed due do material change and/or design alternation. For future reference, a more detailed FE-analysis of the assembly could be made by having less simplifications, adding frictional losses and optimizing bolts connections. The bolt stresses and friction forces can differ when calculating the analyses with having specific bolt preloads and better bolt mesh designs by designing beam elements with rigid bars similarly to figure 36. This method simulates the bolt connections better than having glued connections between bolts, threads, and washers.

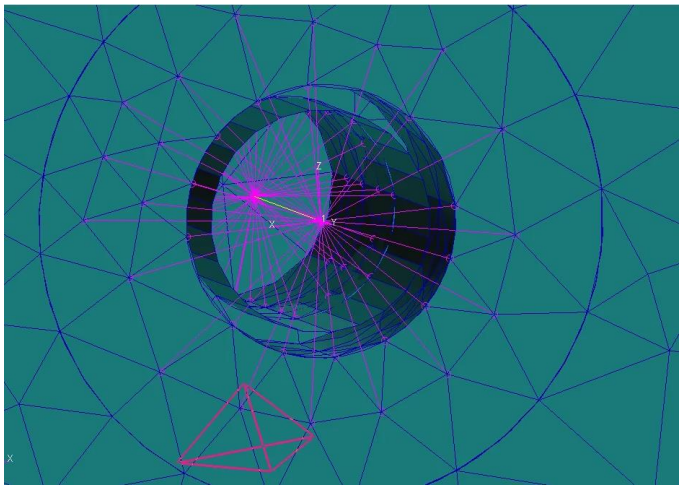


Figure 36. Structure of a bolt simulation with rigid bars and beams with preloads.

All possible distortions, faults, costs, or manufacturing issues are difficult to precisely predict without a concrete manufacturing of the new discharge scraper design. All the chosen designs and manufacturing methods are chosen based on previous experience, theories based on literature, DFMA results, and expertise. This means that the concrete manufacturing of a prototype and an actual assembly for a bleaching process gives more data and information

of the manufacturing process that can be expectedly used for optimizing the discharge scraper design.

11 Summary

This thesis relating to a design and construction analysis of a discharge scraper for a chlorine dioxide bleaching stage included a literature review, design process, DFMA optimization and FE-analyses on two kinds of static conditions. The design process was done by utilizing expert opinions, experience, points matrix and comparisons. Manufacturing methods and designs of possible solutions were further optimized using DFMA forms and guidelines. The FE-analyses showed how the structure behaves in weight carrying conditions and in extreme conditions. Parts and subassemblies that had their material changed or had a significant change in design, should withstand the conditions of the wing scraper getting stuck. In addition, an investigation in ANSYS FLUENT CFD environment was made to ensure the affect of wing profile change.

The most realistic design and manufacturing plan is presented by the results. As the results show, the theoretical manufacturing plan for the new discharge scraper was made based on expertise, literature review and DFMA forms. However, the chosen manufacturing plan is only an approximation based on theories and experience so the concrete first manufacturing would give more data to optimize the manufacturing process. The results and approach of this thesis can be utilized in similar applications with taking the volume into consideration. As mentioned in the introduction, the cost effectiveness and affect on function were the main thriving factors in this thesis. These factors highly affected the designing process and mindset when analysing and comparing different solutions. If a more environmentally friendly and sustainable approach would have been taken, the design process and final results would be significantly different. But would the environmental motives be more important than the economical motives?

References

Andritz in Finland. 2023. [Andritz in Finland www-page]. [Cited 2.5.2023]. Available. https://www.andritz.com/pulp-and-paper-en/locations/andritz-oy.

Andritz group. 2023. [Andritz group www-page]. [Cited 1.5.2023]. Available. https://www.andritz.com/group-en.

Arima, T. 2022. Titanium's Time: Considerations For Working With Titanium. [Online]. Forbes Business Council. Available. https://www.forbes.com/sites/forbesbusinesscouncil/2022/11/15/titaniums-time-considerations-for-working-with-titanium/.

ASTM B 265-20a. 2020. Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate. ASTM International. 12 Pages.

Avery, R. E., Tuthill, A. H. & Andrew, G. 1992. Corrosion Behaviour of Stainless Steel, Nickel Base Alloy and Titanium Weldments in Chlorination and Chlorine Dioxide Bleaching. Nickel Institute. P.20.

Bajpai, P. 2012. Environmentally benign approaches for pulp bleaching. 2nd ed. Amsterdam. Elsevier Science. e-book. [Online]. [Cited 31.05.2023]. Available. https://doi.org/10.1016/C2011-0-05483-2.

Bajpai, P. 2023. Environmentally Benign Pulping. Cham: Springer International Publishing AG. e-book [Online]. [Cited 15.05.2023]. Available. https://doi-org.ezproxy.cc.lut.fi/10.1007/978-3-031-23693-8.

Campbell, F. C. 2006. Manufacturing technology for aerospace structural materials. Amsterdam: Elsevier. P.537.

Cerny, M.X. 2005. Application of titanium linings in flue gas desulfurization systems. The Pfaudler Company. [Online]. Available. http://www.ginattatecnologie.it/Docs/Meeting4/IV%20Meeting%20-%2005.pdf.

Chaturvedi, M. C. 2021. Welding and joining of aerospace materials. Second edition. M. C. Chaturvedi (ed.). Duxford, England. Woodhead Publishing. P.452.

Cheng, W. W., Ju, C. P. & Chern Lin, J. H. 2007. Structure, castability and mechanical properties of commercially pure and alloyed titanium cast in graphite mould. Journal of oral rehabilitation. [Online]. Vol. 34, no. 7, p. 528–540. Available. https://doi-org.ezproxy.cc.lut.fi/10.1111/j.1365-2842.2003.01151.x.

Dimitris, Y. & Angelopoulos, S. 1996. Fundamentals of High Pressure Oxygen and Low Pressure Oxygen-Peroxide (Eop) Delignification of Softwood and Hardwood Kraft Pulps: A Comparison. Pulping conference proceedings. McGill University. Vol. 21, no. 4, p. 185-190.

du Plooy, R. & Akinlabi, E. T. (2018) 'Analysis of laser cladding of Titanium alloy', in Materials today: proceedings. Johannesburg, Gauteng, South Africa. 3.9.2018. p. 19594-19603 [Online]. [Cited 21.07.2023] Available. https://doi.org/10.1016/j.matpr.2018.06.322.

EN 10083-2. 2006. Steels for quenching and tempering part2: Technical delivery conditions for non alloy steels. European committee for standardization. 37 Pages.

EN 10088-5. 2009. Stainless steels – Part 5: Technical delivery conditions for bars, rods, wire, sections and bright products of corrosion resisting steels for construction purposes. European committee for standardization. 53 Pages.

Eskelinen, H. & Karsikas, S. 2013a. DFMA-opas : valmistus- ja kokoonpanoystävällisen tuotteen suunnittelu. Lappeenranta: Lappeenrannan teknillinen yliopisto. P.115.

Eskelinen, H. & Karsikas, S. 2013b. Vihreän teknologian näkökulmat konstruktiomateriaalien valinnassa. Lappeenranta: Lappeenrannan teknillinen yliopisto. P.364.

European Commission. 2013. COMMISSION STAFF WORKING DOCUMENT A BLUEPRINT FOR THE EU FOREST-BASED INDUSTRIES. EUR-Lex Access to European Union law. [Web document]. [Cited 02-05-2023]. Available. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52013SC0343.

Fischer, J., Ebinger, A., Hägi, T., Stawarczyk, B., Wenger, A. & Keller, E. 2009. Mold filling and dimensional accuracy of titanium castings in a spinel-based investment. Dental materials. [Online]. Vol. 25, no. 11, p. 1376–1382. Available. https://doi.org/10.1016/j.dental.2009.06.012.

Freitag, L., Schmidt, G., Hubálková, J., Bulling, F., Klotz, U. E. & Aneziris, C. G. 2022. Functionally graded calcium zirconate molds with alginate-based spray coating for titanium investment casting. Journal of the European Ceramic Society. [Online]. Vol. 42, no. 2, p. 682–692. Available. https://doi.org/10.1016/j.jeurceramsoc.2021.10.024.

Heitner, C., Dimmel, D. & Schmidt, J. A. 2010. Lignin and lignans: advances in chemistry. Boca Raton: Taylor & Francis. P.686.

ISO 302. 2015. Pulps — Determination of Kappa number. Third edition. Geneva: International Organization for Standardization. 13 Pages.

ISO 898-1. 2013. Mechanical properties of fasteners made of carbon steel and alloy steel - Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread. European Committee for Standardization. 62 Pages.

KnowPulp. 2023. pulp technology and automation learning environment. Version 21.0. Updated 1/2023. [Cited 23.05.2023]. Prowledge Oy, Helsinki. Available with paid login. http://www.knowpulp.com/www/english/kps/ui/knowpulp.htm.

KLS. 2021. How is titanium clad plate made? [Web article]. Available. https://www.klscladmetal.com/news/how-is-titanium-clad-plate-made.html.

Lee, S. & Kim, Y.-J. 2017. Evaluation of the α-Case with TiO2 in Mold for Titanium Investment Casting. International journal of metalcasting. [Online]. Vol. 11, no. 1, p. 71–76. Available. https://doi-org.ezproxy.cc.lut.fi/10.1007/s40962-016-0093-8.

Li, C., Muneharua, K., Takao, S. & Kouji, H. 2009. Fiber laser-GMA hybrid welding of commercially pure titanium. Materials in engineering. [Online]. Vol. 30, no. 1, p. 109–114. Available. https://doi.org/10.1016/j.matdes.2008.04.043.

Lütjering, G. & Williams, J. C. 2007. Titanium. 2. edition. Berlin, Heidelberg: Springer-Verlag. P.442.

Msubbu. 2014. Drag force on solid particles in fluids. Chemical Engineering Learning Resources. [Online]. [Cited 15.9.2023]. Available. https://www.msubbu.in/ln/fm/Unit-IV/Drag.htm.

Pauly, S. 2012. Manufacturing of large and heavy clad plates by explosion cladding. Dynamic Material Corporation. Dillinger Pressure Vessel Colloquium. [Online presentation]

Available. https://www.dillinger.de/imperia/md/content/dh/produkte/secdoc/9OSaeni15OHygGE/manufacturing_of_large_and_heavy_clad_plates_by_explosion_cladding_process_dmc.pdf.

Polmear, I. 2017. Light alloys: metallurgy of the light metals. Fifth edition. Oxford: Butterworth-Heinemann. P.525.

Puusta paperiin. 1990. M-405, Sellun valkaisu: diffusööri valkaisu. METLAS KY. P.165.

Rapid Direct. 2021. Metal Strength Chart: Which Material Has the Ideal Metal Strength. Rapid Direct prototyping and manufacturing industry blog, 11.12.2021 [Cited 1.9.2023]. Available. https://www.rapiddirect.com/blog/metal-strength-chart/.

Rönkönharju, H. 1979. Titaaniopas. Karhulan konepaja. Ahlström. P.60.

Saha, R. L. & Jacob, K.T. 1986. Casting of titanium and its alloys. Defence Scientific Information and Documentation Centre. [Online]. [Updated 13.09.2020]. Available. https://core.ac.uk/download/pdf/333721436.pdf.

Schütze, M. & Kreysa, G. 2008. DECHEMA corrosion handbook. 2nd rev. ed. and extended ed. [Database]. DECHEMA.

Semiatin, S. L. 2006. ASM handbook. Volume 14 B, Metalworking: sheet forming. Materials Park (OH): ASM International. P.923.

Sherpa, B. B., Kumar, P. D., Upadhyay, A., Kumar, S., Agarwal, A. & Tyagi, S. 2021. Effect of explosive welding parameters on Al/LCS interface cladded by low velocity of detonation explosive welding (LVEW) process. International journal of advanced manufacturing technology. [Online]. Vol. 113, no. 11-12, p. 3303–3317. Available. https://doi-org.ezproxy.cc.lut.fi/10.1007/s00170-021-06800-5.

Su, H., Luo, X-B., Chai, F., Shen, J., Sun, X. & Lu, F. 2015. Manufacturing Technology and Application Trends of Titanium Clad Steel Plates. Journal of iron and steel research, international. [Online]. Vol. 22, no. 11, p. 977–982. Available. https://doi-org.ezproxy.cc.lut.fi/10.1016/S1006-706X(15)30099-6.

Suess, H. U. 2010. Pulp bleaching today. [Online]. Berlin. De Gruyter. P.310.

Suresh Kumar Danadurai, K. & Rajeswari, S. 1999. Corrosion performance of 316L SS and titanium modified austenitic stainless steels in the bleaching stages. Anti-corrosion methods

and materials. [Online]. Vol 46, no. 1, p. 14–18. Available. https://doi-org.ezproxy.cc.lut.fi/10.1108/00035599910252604.

Sŏng, S., Younossi, O. & Goldsmith, B. 2009. Titanium industrial base, price trends, and technology initiatives. Santa Monica, CA: RAND Project Air Force. P.128.

Timet. 1997. Corrosion resistance of titanium. [Technical manual]. P.39 [Online] Available. https://www.timet.com/assets/local/documents/technicalmanuals/corrosion.pdf.

Tsephe, T.S., Akinwamide, S. O., Olevsky, E. & Olubambi, P. A. 2022. Additive manufacturing of titanium-based alloys- A review of methods, properties, challenges, and prospects. [Online]. 8/1, Available. https://doi.org/10.1016/j.heliyon.2022.e09041.

Ulbrich. 2023. Titanium Versus Steel: A Battle of Strength. Ulbrich Company blog article, 14.4.2023. [Blog]. [Cited 26.6.2023]. Available. https://www.ulbrich.com/blog/titanium-versus-steel-a-battle-of-strength/.

Wagoner, R. H., Lim, H. & Lee, M-G. 2013. Advanced Issues in springback. International journal of plasticity. Vol. 45. No. 20, p. 3-20 Available. https://doi.org/10.1016/j.ijplas.2012.08.006.

Waguespack, C. 2011. Mastering Autodesk Inventor 2012 and Autodesk Inventor LT 2012. 1st edition. Indianapolis: Wiley Pub. P.1000.

Yadav, B. 2022. Challenges facing titanium alloys manufacturing for aerospace appearances. The piping mart. [Web article]. [30.05.2023]. Available. https://blog.thepipingmart.com/metals/challenges-facing-titanium-alloys-manufacturing-for-aerospace-appearances/.

Yamamoto, A., Nakamura, H., Nishiyama, Y. & Kurahashi, R. 1994. Development of hot-rolled titanium-clad steel coils by using liquid phase at titanium-steel interface for bonding. Nippon steel technical report. [Online]. Vol. 62, p. 34-39. Available. https://www.nipponsteel.com/en/tech/report/nsc/pdf/6206.pdf.

Yunlian, Q., Ju, D., Quan, H. & Liying, Z. 2000. Electron beam welding, laser beam welding and gas tungsten arc welding of titanium sheet. Materials science & engineering. A. Structural materials: properties, microstructure and processing. [Online]. Vol. 280, no. 1, p. 177–181. Available. https://doi.org/10.1016/S0921-5093(99)00662-0.

Zhao, Z., Chen, J., Guo, S., Tan, H., Lin, X. & Huang, W. 2017. Influence of α/β interface phase on the tensile properties of laser cladding deposited Ti-6Al-4V titanium alloy. Journal of materials science & technology. [Online] Vol. 33, no. 7, p. 675–681. Available. https://doi.org/10.1016/j.jmst.2016.09.026.

Appendix 1. Ideation session based on approximated problem areas

16.6.2023 Ideation session Andritz Oy

Participants: Juha Heikkilä, Niko Hotti, Tuomas Kalmi, Tuomas Asikainen, Vesa Kaipainen, Saravirta Anton-Ilmari

Preliminary ideas or option from the session:

- Titanium secondary shaft?
- Is a coating possible for the titanium axle?
- Two-part frame structure for the discharge scraper? (Titanium/Steel)
- Spray coating? Is it useful?
- Interference fit? Possibly between the sleeve and the flange.
- Thin titanium sheet between flange connections (Tank/Scraper flange).
- Can titanium linings be loose, or do they need to be screwed onto something?
- Seal housing box sleeve or structure as multi parts? (Upper titanium and lower part something else).
- Moving the seal housing box lower to ease the titanium lining.
- Inner sleeve between the sealing and “black steel” and then lining on top.
- If the is titanium is not chosen to be titanium, then scraper “cover” needs sealed with probably titanium lining.
- Can the wings be made from plate structures so there would less need for welding.
- Discharge hub as a plate/pipe structure?
- Possibly welding the scraper “cover” into the hub to achieve full sealing or is fastening with bolts sufficient?
- Titanium sleeve between the scraper flange and the tank flange.
- Machine shop’s opinion on the need of attaching a thin titanium sheet lining onto the structure when it is between two machined surfaces.
- O-ring materials (Are they durable against chlorine dioxide?).
- Do the sealing unit braids withstand the chlorine dioxide or are there changes needed?
- According to previous titanium casting costs, the rough estimation for casting costs is 100e/kg.
- What kind different welding can or should be used?

Appendix 2. Points matrix for filtering possible solutions

	Titanium axel	Multi-part frame structure with utilizing the lowering of the housing box structure	Multi-part frame structure (Titanium flange with seperate connections to the support structure and housing box)	Fit attachment between titanium sleeve and support structure	Thin titanium sheet between flange connection (Tank/Scraper)	Moving the sealing housing box structure lower to ease the titanium lining	Scraper cap material changed to titanium and bolt fastened	Scraper cap protected with thin titanium sheet	Casting of scraper hub (Titanium)	Scraper hub made from sheet or pipe structures (Titanium)	Titanium lining without changing the current design (All possible leakage points covered)	
Cost estimation (weighted value 25%)	1	2	3	4	4	4	3	4	1	3	3	1=Really high costs 2=High costs 3=Moderate costs 4=Low costs 5=Close to insignificant costs
Potential risk (Weighted value 12,5%)	4	2	3	2	4	2	4	4	3	3	2	1=Really high risk 2=High risk 3=Moderate risk 4=Low risk 5=No risk
Benefit (Weighted value 12,5%)	4	4	4	2	3	4	3	3	3	3	3	1=Minimal benefits 2=Low benefits 3=Moderate benefits 4=High benefits 5=Really high
Affect on function and current design (Weighted value 12,5%)	4	2	3	2	5	2	5	4	4	4	2	1=Really high effect 2=High effect 3=Moderate effect 4=Low effect 5=Close to no effect
Manufacturability and availability (Weighted value 12,5%)	2	4	3	2	4	3	5	4	2	3	1	1=Really difficult 2=Difficult 3=Moderately difficult 4=Relatively easy 5=Really easy
Problem solving index (Weighted value 25%)	5	7	7	3	2	8	3	3	5	5	7	Problem solving index is an index that describes the amount and signifigance of the problems that the solutions solves (1-10)
Weighted average	3	3,25	3,65	2,6	3,625	3,75	3,675	3,625	2,725	3,375	2,925	
Info	Availability and costs are an issue	Might not be enough space for lowering the sealing housing box		Pros don't outweigh the cons		Might not be enough space for lowering the sealing housing box			Can get costly and not recommended if sheet or pipe structure is more convenient (Could be revisited if pipe or sheet strucutures are not suitable)		Even though problem solving index is good, the expenses and difficulty to make this solution are not conveniant	

Appendix 3. DFMA-analysis forms for collecting comparative information and evaluating the suitability

FORM 3 (Eskelinen & Karsikas 2013a, p.51)	COLLECTION OF COMPARATIVE INFORMATION ON A MANUFACTURING METHOD AND EVALUATION OF THE SUITABILITY OF THE METHOD
Product that is the subject of the method:	Discharge scraper hub
Product manufacturing document:	ADS_4300 Titanium HUB
Manufacturing method to be evaluated:	Graphite mould casting
Application of the manufacturing method:	Sand casting?
Writer:	Page 1/1
Date:	31.7.2023
Question	**Answer**
1. Which factors favour the use of the method?	- More complex structure can be made - Final product has less weight - Less material needed
2. Which factors limit or increase difficulty to use the method?	- Titanium is a difficult material to cast - Casting can get really expensive
3. What is the accuracy of the used method?	Standard tolerance grade (IT-grade): IT8 Ra: 6,3
4. What factors affect the most on the cost of the manufacturing method?	- Difficulty and an unconventional casting method - Shipment costs if the cast needs to be made far away
5. What are the most important process-, control-, and/or machining parameters of the manufacturing method?	- Melting temperature, casting time
6. Are there applicable basic methods, applications, standards tools etc.	ASTM: B367-22
7. How the method is suitable for mechanization, automatization and robotization? (1-5, 1 Being not suitable and 5 being highly suitable)	Mechanization: 2 Automation: 1 Robotization: 1
8. What is the typical size of mass production and product size?	Mass production is not expected. Weight of the final hub design according to Autodesk Inventor is 196, kg
9. Is there another manufacturing method specifically designed to	No

manufacture this type of components?	
10. Is it possible to use combinations of different manufacturing methods?	Not recommended as costs can get even higher
11. How does the manufacturing method fit with machinery that is easily available for the company?	Not suitable, casting needs to be outsourced in China. Machining can be done with available machinery.
12. What manufacturing method comparison values base on concrete numerical values?	- Costs, time consumption
13. Overall evaluation of the suitability of the manufacturing method	- Casting of titanium is a difficult and time-consuming process which is done in specific foundries. The manufacturing of the mould is also considered to be expensive as the volume of production for the is low. The plus side is that this manufacturing method doesn't need post processing welding.

FORM 3 (Eskelinen & Karsikas 2013b, p.51)	COLLECTION OF COMPARATIVE INFORMATION ON A MANUFACTURING METHOD AND EVALUATION OF THE SUITABILITY OF THE METHOD
Product that is the subject of the method:	Discharge scraper hub
Product manufacturing document:	Titanium sheet hub
Manufacturing method to evaluated:	Sheet fabrication
Application of the manufacturing method:	Roll bending and welding connections
Writer:	Page 1/1
Date:	1.8.2023
Question	**Answer**
1. Which factors favor the use of the method?	- Relatively cheap and easy. Material is easily available. Can be considered as a fast titanium fabrication method
2. Which factors limit or increase difficulty to use the method?	- Limited complexity of the final part. Need for welding
3. What is the accuracy of the used method?	Standard tolerance grade (IT-grade) IT7 Ra: 3,2
4. What factors affect the most on the cost of the manufacturing method?	- Material costs. Welding.
5. What are the most important process-, control-, and/or machining parameters of the manufacturing method?	- Bending radius, Plate thickness, welding parameters and chosen welding method

6. Are there applicable basic methods, applications, standards tools etc.	ISO: EN: SFS:
7. How the method is suitable for mechanization, automatization and robotization? (1-5, 1 Being not suitable and 5 being highly suitable)	Mechanization: 2 Automation: 2 Robotization: 2
8. What is the typical size of mass production and product size?	Mass production is not expected. Weight of the final hub design according to Autodesk Inventor is 151,74 kg
9. Is there another manufacturing method specifically designed to manufacture this type of components?	- No
10. Is it possible to use combinations of different manufacturing methods?	- Could be possible to combine casting and sheet fabrication but costs may get high
11. How does the manufacturing method fit with machinery that is easily available for the company?	- Roll bending machinery and titanium welding methods are easily available
12. What manufacturing method comparison values base on concrete numerical values?	- Costs, Time consumption
13. Overall evaluation of the suitability of the manufacturing method	- By designing a simple structure, the sheet fabrication method is highly suitable for the manufacturing. How ever the design is expected to have a need for welding post processing as it is relatively common for plate structured parts.

Appendix 4. Assembly comparison forms based on DFMA-analysis guidelines

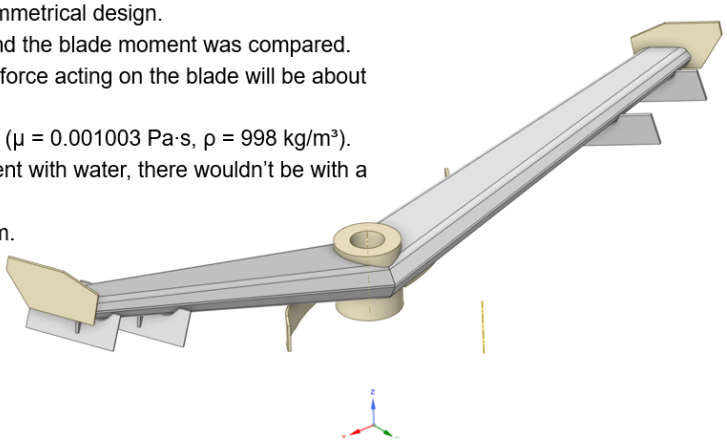
FORM 4 (Modified. Eskelinen & Karsikas 2013b. p.103)	DFMA PRINCIPLES IMPLEMENTED INTO PRACTISE		
	Page 1/1		
Assembly: Sheet structured hub with cover			
Writer: Niko Hotti			
Date: 21.8.2023			
Question	**Answer**	**Points**	**Grading**
1. How many parts are in the assembly?	6	-1	> 3 = -1p ≤ 3 = +1p
2. How many separate attachment parts are in the assembly?	7	+1	> 3 = -1p ≤ 3 = +1p
3. How many different attachment parts and attachment methods are in the assembly?	4	-1	> 3 = -1p ≤ 3 = +1p
4. How many different assembly directions are needed?	1	+1	> 1 = -1p ≤ 1 = +1p
5. How many different manufacturing methods are needed for the assembly parts?	3	-1	> 2 = -1p ≤ 2 = +1p
6. How many different attachment methods are needed in the assembly phase?	2	-1	> 1 = -1p ≤ 1 = +1p
7. How many standardized components are in the assembly?	1	+1	+ 1p/per standardized parts
Total points for the assembly	∑ = - 1		

FORM 4 (Modified. Eskelinen & Karsikas 2013b. p.103)	DFMA PRINCIPLES IMPLEMENTED INTO PRACTISE		
	Page 1/1		
Assembly: Machined bar hub			
Writer: Niko Hotti			
Date: 21.8.2023			
Question	**Answer**	**Points**	**Grading**
1. How many parts are in the assembly?	3	+1	> 3 = -1p ≤ 3 = +1p
2. How many separate attachment parts are in the assembly?	5	-1	> 3= -1p ≤ 3 = +1p
3. How many different attachment parts and attachment methods are in the assembly?	2	+1	> 3 = -1p ≤ 3 = +1p
4. How many different assembly directions are needed?	1	+1	> 1 = -1p ≤ 1 = +1p
5. How many different manufacturing methods are needed for the assembly parts?	2	+1	> 2 = -1p ≤ 2 = +1p
6. How many different attachment methods are needed in the assembly phase?	1	+1	> 1 = -1p ≤ 1 = +1p
7. How many standardized components are in the assembly?	1	+1	+ 1p/per standardized parts
Total points for the assembly	∑ = 5		

Appendix 5. Titanium discharge scraper Computational Fluid Dynamics (CFD) wing symmetry report

INTRODUCTION

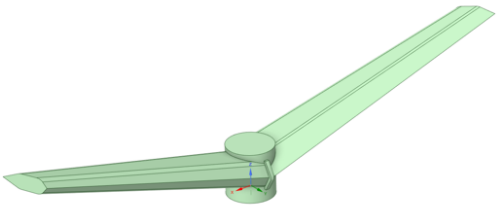
- The blade profile design of an ADS 4300 titanium scraper was changed from a non-symmetrical to symmetrical.
- It was required to find out, how much the forces acting on the symmetrical blade profile change compared to non-symmetrical design.
- The two blade designs were simulated, and the blade moment was compared. If the moment values are similar, also the force acting on the blade will be about the same.
- Fluid used in these simulations was water (μ = 0.001003 Pa·s, ρ = 998 kg/m³).
- If there is no difference in the blade moment with water, there wouldn't be with a more viscous pulp.
- The scraper rotation is quite slow 12.3 rpm.



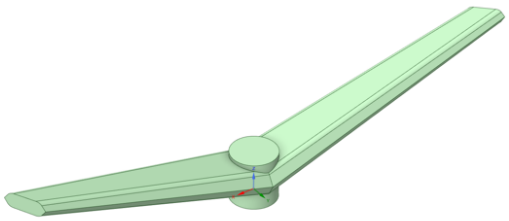
CFD BLADE GEOMETRY

- The scraper geometry for the CFD simulations was simplified.
- The original model included many fine details which can cause problems for CFD simulation.
- All unnecessary details were removed from the models. Only the blade profile is necessary for comparison.
- In this exercise, the effect of the blade profile change was of interest. Other scraper details were not needed to be modeled.

Non-symmetrical blades



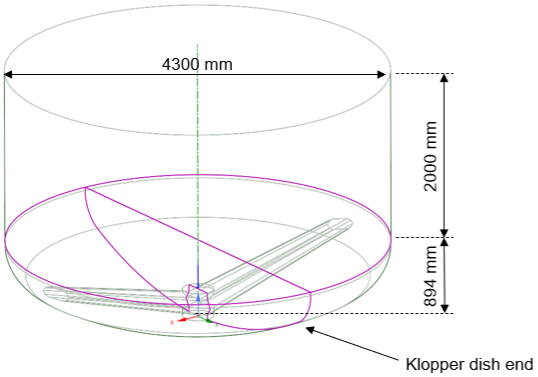
Symmetrical blades



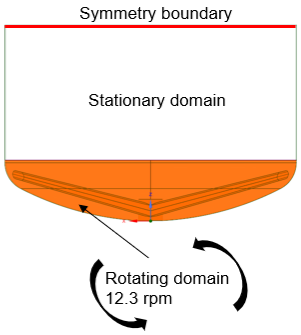
CFD GEOMETRY AND BOUNDARY CONDITIONS

- MRF “frozen rotor” simulation.
- Turbulence model = k-ω SST.
- Symmetry boundary is a good approximation for free surface on top of the vessel.
- Gravity on.

Vessel geometry



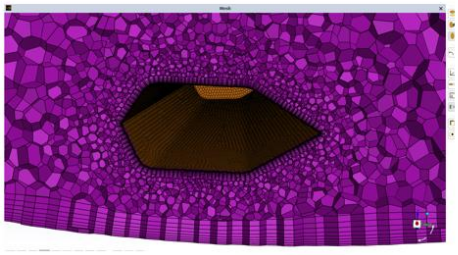
Boundary conditions



MESH

- Polyhedral volume mesh
- No. of cells in both models ≈ 850000
- Blade surface mesh size = 10 mm
- Vessel walls mesh size = 50 mm
- Volume mesh max. size = 100 mm
- No. of boundary layers = 8

Non-symmetrical blade

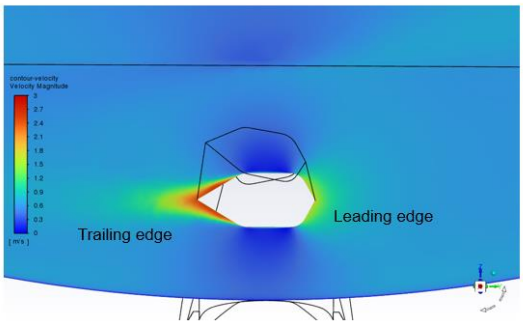


Symmetrical blade

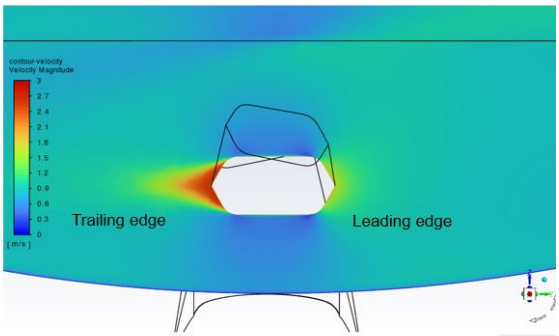
VELOCITY FIELD

- The velocity field around the blade, 1.5 m from center is presented below.
- The velocity field looks similar with both blade designs. This indicates, that the force caused by the fluid flow on a blade should be similar in both cases.

Non symmetrical blade



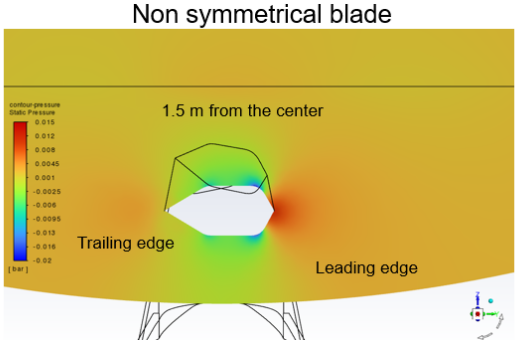
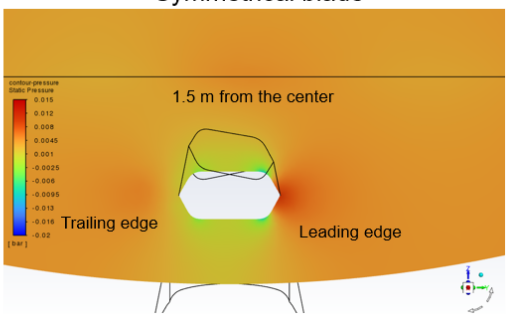
Symmetrical blade



BLADE MOMENT AND STATIC PRESSURE FIELD

- Moment caused by the blades rotating in the fluid:
  - Non-symmetrical = 214 Nm
  - Symmetrical = 218 Nm
- The blade moment is almost the same in both cases, because the leading surface in both blade design is the same. Also, the flow is not detached from the blade surface. If flow is detached from a surface, it causes more drag. The force on a blade is caused by the pressure difference between the blade leading and trailing surfaces. In both cases the pressure difference is very similar.

Non symmetrical blade



Symmetrical blade