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Alternative materials for high-temperature and high-pressure valves

Degree Project of 30 credit points
Master of Science in Engineering
Mechanical Engineering,
specialisation in Materials Engineering

Date/Term: 2010-11-11
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Abstract
AB SOMAS Ventiler manufactures valves for different applications. A valve of type DN VSSL 400, PN 100, used in high-temperature and high-pressure applications was investigated in this thesis. This type of valve is coated with high cobalt alloys to achieve the tribological properties needed for this severe condition. However there is a request from AB Somas Ventiler to find another solution. This request is based on the fact that demands on higher temperatures, from customers, yields higher requirements on the material. It is also a price issue since cobalt is quite expensive. Materials investigated were high-nitrogen steel, Vanax 75, nickel-based superalloy Inconel 718 and hardened steels, EN 1.4903 and EN 1.4923 presently used as base material in the valve.

Calculation of contact pressure that arises when the valve is closed was first approached by using finite element method (FEM). Several models were constructed to show the behavior of the valve during closing in terms of deformation. Hot wear tests, in which a specimen was pressed against a rotating cylinder, were performed to be able to compare the materials to the solution of today and among each other. Data extracted from the tests were compiled in the form of coefficients of friction. Profilometer examinations were used to reveal the volumes of worn and adhered material and together with scanning electron microscopy (SEM) the wear situation for each material couple could be assessed.

Wear mechanisms detected in SEM were adhesive and abrasive and the results clearly showed that the steels were not a good solution because of severe adhesive wear due to the similarity of mating materials creating a more efficient bonding between the asperities. Vanax 75 showed much better performance but there was still an obvious difference between the steels and the superalloy in terms of both coefficient of friction and amount of wear. On this basis, Inconel 718 was selected as the most suitable material to replace the high cobalt alloys used in the valves today.
Sammanfattning

AB Somas ventiler är ett företag som tillverkar ventiler för ett brett spann av applikationer. I det här examensarbetet har undersökningar genomförts på en ventil av modell DN VSSL 400, PN 100, som normalt används i applikationer för höga tryck och höga temperaturer. Ventilen beläggs i dag släget med höghaltiga koboltlegeringar för att uppnå de tribologiska egenskaper som krävs i de påfrestande arbetsförhållanden som råder. AB Somas Ventiler har dock framfört en förfrågan om att hitta en alternativ lösning, en förfrågan som grundar sig i att kundernas ständiga önskemål på att ventilerna ska klara högre arbetstemperaturer också medför högre krav på ventilmaterialen. Det är även en prisfråga, då kobolt är en dyr legering att använda sig av. De material som inkluderades i undersökningen var det kvävelegerade stålet Vanax 75, nickelfaserade superlegeringen Inconel 718 samt de två stålen EN 1.4903 och EN 1.4923 i härdat tillstånd. De två sistnämnda används idag som basmaterial i ventilen.


De nötningssmekanismer som påvisades med hjälp av SEM-undersökningen var adhesiv och abrasiv nötning, och resultaten visade tydligt att nötningen av stålen var omfattande, på grund av att lika material i kontakt med varandra skapar starkare band mellan ytorna, och att de därför inte var en intressant lösning. Det kvävelegerade Vanax 75 uppförde sig visserligen bättre men en tydlig skillnad mot superlegeringarna kunde dock fortfarande konstateras, sett till både friktionskoefficient och mängden slitage. Baserat på dessa resultat valdes Inconel 718 som det bäst lämpade materialet att ersätta de höghaltiga koboltlegeringarna som idag används i ventilen.
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1. Introduction
This investigation is a master thesis performed by two students at Karlstad University to claim their master degree in mechanical engineering and material science.

1.1. Problem description
The project proposed by AB SOMAS Ventiler is focused on the analysis of possible new materials as alternatives to the cobalt-based alloys used in steam valves nowadays. At AB SOMAS Ventiler, they produce valves for a wide range of applications; this thesis will focus on valves regulating steam at high temperatures and high pressures. In such severe working conditions, tribological mechanisms become a critical factor for the life time of the valve.

Even if these cobalt-based alloys fulfill the requirements, AB SOMAS Ventiler is interested in finding a less expensive solution that maintains the valves operation properties in terms of friction, adhesion and wear of the coating.

1.2. Aim of the thesis
The aim of the thesis is to analyze possibilities to substitute the high-cobalt alloys with a new material. Materials to be investigated are the new metallurgy steel Vanax 75 provided by Uddeholms AB and some superalloy. The possibility to harden the martensitic steel used today should also be investigated. In order to approach the problem properly and pinpoint other possible alternative materials, a literature survey will be carried out containing previous research on the subject and other current solutions. By FEM-simulations and calculations, the contact situation of the shaft and the disc shall be investigated and critical parameters for each application are to be defined. For the high-cobalt alloy and the new potential materials, experimental tests will be designed based on FEM results and working conditions in the valve.

A shared opinion of the importance of being equally involved in all sections of this thesis has been an important issue from the beginning. With the ambition to understand all aspects of the project, and to learn as much as possible along the way, there was reluctance to dividing the workload very distinctively. Instead this has been a process where both contributing students have performed as equal parts as possible on all sections of the thesis, such as literature study, FEM simulations and real testing, and where as much work as possible has been performed in a joint effort.
2. Valves

2.2. Valves
A valve is a mechanical device with the main function to control either pressure or flow of a gas or liquid. Its main components, regardless of valve type, are a housing, in which a seat is located, and a closing element that is attached to a spindle. The flow control can be performed in a manual manner or the valve could be attached to an actuator, which controls the opening- and closing process through hydraulic actions. There are several valve types performing the task of controlling flow differently and they can be divided into groups in several ways. One way of dividing valves is by the way in which they function.

*On-off valves* have a basic way of operating where the flowing media is either fully allowed to pass through the valve, or fully stopped by blocking the outlet.

*Throttling valves* have the extra function, in comparison with the on-off valves, that they can regulate flow in any state in between fully stopped and fully opened. This is achieved by adjusting the opening angle of the valve to obtain a desired state of flow.

*Non-return valves* only allow the flowing media to pass in one direction through the valve.

Apart from function, valves also come in a very wide range of sizes and can be divided based on this criteria. There are valves existing in sizes anywhere between a couple of millimeters or centimeters and range up to sizes of several meters. Which type of valve to use is, of course, strongly dependent on the application in which it will be in use. With that aspect in mind different valves can be divided into groups based on applications instead. [1]

2.2.1. Different applications
When focusing on the application for a valve several new parameters come into play, apart from design. Environments and the conditions, in which a valve will be working, becomes an important factor and it is vital to consider requirements on materials concerning pressures and temperatures carefully.
Valves working at high temperatures or containing high-temperature flowing media make up one of these groups. When temperatures are increased from room temperature, restrictions change drastically on materials and design of mechanical components. Standard valve materials are no longer able to function properly. For example materials such as plastics and elastomers will have to be replaced in elevated temperatures mainly due to their creep properties [2]. Hot blast valves, figure 1, are examples of valves that contain a flowing media of high temperatures. These are valves located between a stove and a blast furnace in the process of iron making [3]. There are also valves handling steam, hot oil or similar mediums where pressure and flow is regulated by the valve. The high temperature gas or liquid flowing through the device is then in direct contact with the surfaces inside the valve.

In places such as fluid power systems, there are valves that can be exposed to really high pressures. Pressure relief valves are commonly used in these areas where their purpose is to prevent the pressure in the system from becoming too high. In case of dangerously high pressures, the valve open to gradually let the gas or fluid out until the pressure reaches an acceptable level and the valve can close again. The pressure at which the valve will begin to open is a pre-defined value, set to maintain a safe situation in the system. These pressure relief valves are often found close to the pressure source, which is usually a pump. Pressure regulating valves can also be exposed to really high pressures, however in this case the valve is usually connected to a supply system in one end where pressures are much higher than in the system on the other end. The main purpose of the valve is to regulate the pressure in such a manner that this pressure difference remains constant [4].

Cryogenic applications are where a component is working at low temperatures, usually below -100°C. These temperatures create problems for valves and materials; just as in high temperature environments they demand specific material properties. At low temperatures many materials
become brittle, therefore they risk failing by brittle fracture in exposure to a cryogenic environment [2]. One example of a cryogenic application for valves is in modern rocket engines where fluids such as liquid hydrogen and liquid oxygen can be a flowing media through the valve; in this case valves also need to withstand other difficult conditions such as high pressures and high sliding speeds [5].

Some valves are operating in media that are extra demanding in terms of corrosion resistance. These are environments with a tendency to react with the valve material in a chemical or electrochemical order. This can be devastating for a valve that lacks a sufficient corrosion resistance. Some materials are more suitable than others for these kinds of environments and at the same time different corrosive media can be more critical for some materials than others. One example of valve applications in this type of demanding environment, is valves that operate somewhere along the process in a pulp or paper mill. In these processes there are liquids of corrosive nature containing salts and ions from fibers and papermaking additives. Its corrosivity is also partly depending on its low pH values, creating tough requirements on materials to use when designing the valve. Similar situations can be found in industries handling chemicals [6]. Another critical situation regards valves operating in marine applications, where the material is in contact with seawater. The main reason why seawater is considered to be such a critical environment from a corrosion aspect is the salinity of the water, in other words the amount of inorganic salts in the water. There are two main ways in which the salinity affects the corrosion rate in seawater. Firstly, it tends to increase the conductivity of the water causing higher rates of galvanic corrosion. Secondly, salts contain chlorides that are highly reactive and have the ability to break down the passive films formed on some metals in seawater, such as stainless steels [6].
2.2.2. Valve types
A ball valve consists of a seat with a round structure which provides housing for a ball, see figure 2. The ball in itself has a port going through it along its centerline in a straight-through design, to minimize pressure drops along the port. It acts as the regulating element and is controlling flow by turning in any angle between 0 and 90 degrees. That way a fraction of the port is directed towards the flow and it enables desired amount of the media to pass through the port [7].

In the same way as the ball valve, a butterfly valve has a regulating element that rotates anywhere between 0 to 90 degrees for control of flow. However, in this case the ball is replaced by a disc, which is attached to a shaft and rotated around its axis. Yet another difference when comparing the butterfly valve to the ball valve is that it does not have the same straight-through design since the disc will always be more or less disturbing the flow. When the valve is closed there is a contact between the edge of the disc and the seat of the housing. One example of a butterfly valve can be seen in figure 3 [7].
The basic idea of a globe valve, figure 4, is to enable a smooth flow with linear motion through the valve. Therefore, the housing is constructed without any sharp corners or turns. In the middle of the housing the seat is placed and the construction is arranged so that some kind of plug is lowered into the seat when decreasing the flow, or fully closing the valve. In the same way the plug is removed from the seat to increase flow all the way until full flow is allowed and the valve is entirely opened [7].

![Cross-section of a globe valve](image)

**Fig. 4. Cross-section of a globe valve [7].**

Another type of valve with an emphasis on linear motion is the gate valve. Here the closing element is as simple as a flat feature, which slides into the flow with a 90 degrees angle towards it, making it come to a complete stop. The simplicity of the design is also what limits it, which is why this type of valve is mostly used as an on-off type. Gate valves can also have some problems when it comes to opening or closing in an environment with really high pressure drops. This type of valves, as can be observed in figure 5, is divided into two main groups. Parallel gate valves, which have a flat closing element that is sliding in between two parallel seats and wedge-shaped gate valves, that consist of two seats that have somewhat of an angle from the vertical plane together with a gate with mismatching angles allowing a much tighter closing [7].

![Wedge-shaped gate valve](image)

**Fig. 5. Wedge-shaped gate valve [7].**
A pinch valve, figure 6, consists of a liner through which the liquid or gas is travelling. The liner is constructed from an elastomeric material in order to enable the walls to be pinched together by an outer force. When the force is large enough, the walls are pressed together tightly, leaving the valve in a closed position. Since elastomeric materials are used as liner materials, there are stricter limitations on pressures and temperatures on a pinch valve than for many other valve types. However, elastomers provide larger possibilities in terms of corrosion resistance instead. Flowing media that would have large corrosive effect on a metal can be allowed when using the proper elastomer [7].

Plug valves, in the same way as ball- and butterfly valves, are quarter-turn valves. In this case the turning element is a cylindrical plug that rotates around its axis, see figure 7. Just as the ball in a ball valve, the plug has a port going straight through it which can allow full or partial flow. The amount of flow is directly depending on the angle of the port relative to the direction of the flow. In other words they can be used as both on-off and throttling valves [7].
2.3. Valve materials
Valves are constructed in different ways both regarding material and design depending on the specific area of application. A crucial factor for the material selection is the environment in which it will operate.

2.3.1. Requirements and environmental effects on material
When designing or selecting a valve there are many parameters which are important to consider. What is required from the valve is completely depending on the application for which it will be used. The size can be of great importance if there are tight restrictions for the valve to fit the applications. In other situations design can be a more interesting parameter. This could, for example, regard streamlined components for optimization of flow. Yet another parameter to closely consider is material selection for the valve. There is a wide range of environments in which valves are used. Therefore one cannot manufacture the device in one material, good for a certain environment, and believe that it will be suitable in all applications. Different environments will require different things from a valve and the material it is made from, this is mainly controlled by properties of the flowing media in terms of pressure, wear, corrosion and temperature properties [8]. It is vital to carefully investigate, which of these parameters are affecting the valve of interest, since it will put restrictions on which materials can be applied and what properties it will have to possess.

2.3.1.1. Wear
When a valve is opening or closing, sections of the design are set in motion and parts will inevitably be in contact with each other. These contacts are most commonly located between the valve seat and the closing element, which could be for example a disc, or between the spindle and a bushing in a control valve. The emerging contact situation will lead to some amount of removal of material of one or both of the surfaces in contact. This is the definition of wear. If one of the surfaces consists of a material that contains hard particles at the surface, the valve will suffer from two-body abrasive wear, under the condition that the particles are harder than the other surface. Those harder particles will wear down the asperities of the softer material. Hence, two-body abrasive wear is directly coupled to mechanical properties such as hardness and surface roughness of the surfaces in contact. Abrasive wear can also arise from particles in the flowing media, if these particles are harder than the valve material and cause removal of material at the surface. That type of abrasive wear is called three-body abrasive wear and can be seen on valves.
that operate in applications where liquids are contaminated or where two-body abrasive wear causes removal of debris into the flowing media. A common rule of thumb is that the resistance to wear is related to surface hardness, with higher hardness leading to better wear resistance. However it is important to have a good balance between hardness and ductility since high hardness is demonstrated as brittle material and if the material is too brittle there is a risk of failing by brittle fracture. This is the case for ceramic materials. If the contact situation between the two surfaces is caused by an impact the impact wear can become the main mechanism. When an impact repeatedly occurs, causing elastic deformation of the surface, then fatigue cracks form and grow until they eventually de-attach from the surface. Another type of wear that can be of interest in a valve is adhesive wear. In adhesive wear, asperities that are in contact under high local pressures are locally weld together, causing material to be either removed or transferred from one surface to the other. This can happen if the surfaces are sufficiently clean and uncorroded, so that they can come close enough for atomic forces to come into play. The removal or transfer of material happens if the locally welded asperities are set into motion, relative each other, and the bonds at the junctions between them break [9]. Galling is the name for this adhesive wear mechanism if the situation gets severe and large volumes of material are removed or transferred. In this case, the strength in the joints, where the surfaces are fused together, is greater than the strength of the bonds within the host materials. Such a situation is most likely in friction situations if the two host materials are of the same type. This is due to the occurrence of strain hardening of the joints. The severity of such a situation is related to the fact that the strong forces in the joints cause shearing to happen deeper into the host material, removing larger amounts of material. Whichever wear mechanism is acting on the valve, the severity of the wear will decide how much focus should be on this aspect when considering material selection [10] [11].

2.3.1.2. Corrosion
Corrosion appears when the valve material experiences chemical or electrochemical reactions with the environment in which it is working. This is a common problem for valves in pulp and paper processes as well as valves handling other chemical media. The surface of the material could be attacked in various ways. Either it can happen equally over the entire surface and it is then called direct chemical attack, which is the most common type, or it can also occur in a localized manner. In such a localized situation, the corrosion creates pits and holes in the surface
and is then called pitting corrosion. It could also happen that the corrosive attack is localized to grain boundaries, intergranular corrosion, or to cracks and defects on the surface, crevice corrosion. These types of corrosion act much faster than the common type. If the flowing media suffer from differences in vapor pressure, the bubbles and cavities can collapse within the fluid leading to exposure of fresh surface of the material. Stress corrosion cracking is another important mode of corrosion. In this case, intergranular and transgranular cracks are formed and developed due to a combination of tensile stress and a corrosive environment. It is important to consider that stress corrosion cracking is induced by different corrosion media for different alloys and materials. As an example, chloride environments are critical for austenitic steels, while they have no problem handling ammonia environments critical for brasses. There are some additional types of corrosion such as galvanic corrosion, selective leaching, erosion corrosion, hydrogen damage and biological corrosion [11].

2.3.1.3. High temperatures
When a valve is acting at elevated temperatures the situation becomes drastically different. Previously mentioned parameters are affected by elevated temperatures, wear and corrosion properties greatly differ in comparison to situations at room temperature. This is also true for mechanical properties of materials at high temperatures. At elevated temperatures a time dependency comes into play since the material will exhibit a behavior referred to as creep. Creep can be explained as a plastic strain that arises in a material at elevated temperatures when it is subjected to stress during a certain time period. A typical creep curve can be seen in figure 8, where the secondary creep also can be titled steady-state creep since it is a region where the creep rate is more or less constant. If the plastic strain exceeds those requirements set for a specific component creep failure can occur. An even worse situation is when the strains are severe enough to cause rupture of the component, defined as creep rupture. If the component fails without experiencing steady state creep, the constant state also referred to as secondary creep in figure 8, it is defined as

![Fig. 8. Creep curve showing the different stages [12].](image)
stress rupture [11]. As mentioned previously, corrosion resistance is also affected by the temperatures of the environment. Most alloys, which provide good corrosion resistance, rely on the ability to form an oxide layer. That layer is protective against other aggressive substances in the environment or against further and more extensive oxidation. When temperature increases, so does the rate at which oxides grow. If the temperature reaches beyond a certain limit, this rate will be so high that the protective layer will eventually start to crack and scale off, leaving the base material more exposed to the surrounding environment. It is consequently vital to look for materials that possess good oxidation resistance, if the material is expected to perform satisfactory in oxidative atmospheres [14].

![Fig. 9. Effect of temperature upon metal penetration of some common alloys by oxidation after exposure for 1 year to air [13].](image)

Alloying elements, which are preferentially used to enhance corrosion resistance by enhanced oxidation resistance, are first and foremost Chromium, Aluminum, Silicon and Nickel. Chromium is the most common alloying element to use until temperature reaches values above 1200°C when Al is more preferable, since alloys with this alloying element forms Al₂O₃, which is a much slower growing oxide than Cr₂O₃ [13][14]. In environments where sulfidation, instead of oxidation, is a problem high temperatures tend to increase the degradation rate of the material.
It can be observed in figure 9, how the penetration of some alloys by oxidation is dependent on temperature [15].

For valves operating in environments with demanding contact situations, from a tribological aspect, effect of temperature becomes a critical factor for properties such as friction and wear. The effects of temperature on wear are connected to the mentioned changes in mechanical properties, for instance hardness and strength, of the materials in contact. It is also related to a higher oxidation rate and, in the case of adhesion, to the fusion of asperities. An increase in temperature will give higher lattice energy in the materials in contact with each other and this could lead to an increased tendency of the materials to fuse together [9][16]. However the formation of oxide layers on material surfaces plays the most decisive role in terms of wear, and much research was done with a focus on wear mechanisms at elevated temperatures.

Metals in contact with air or other oxygen-rich environments will inevitably start to form oxide layers at the surface. This acts as a protective coating to prevent metal-to-metal contact. At lower temperatures the oxidation rate is rather low and, since sliding will cause some of the layer to be worn, there will not be enough time for the layer to grow thick. Hence, such a situation can be defined as a regime of mild wear. When temperatures increase then so does the oxidation rate. Above a certain temperature, which is different for different materials, the oxide layer will reach a critical thickness and parts of the layer will be broken down. A clean metal surface is then exposed, causing a much worse situation. Oxide particles, which are removed as debris, can then either disappear from the system or act as a third-body abrasive, leading to severe wear. However, if temperatures become high enough, these oxide particles begin to clad. A new, load-bearing layer is then formed and provides protection as well as a good wear resistance. Such a layer is referred to as a “glaze” layer. These effects of oxide formation on wear have been studied, by Inman et al., to describe the behavior of the alloys Incoloy MA956 and Stellite 6 sliding against each other at different temperatures, see figure 10, [17].
There are two main types of oxidative sliding wear at high temperatures. One, where high temperatures are acting on the whole surfaces of the materials and exist due to high ambient temperatures, and the other in which high sliding speeds cause high temperatures to arise in localized areas at the contact points between surfaces. It is clear from the previous study, [17], that the severity of the wear greatly depends on sliding speed. Three different sliding speeds were tested and for the lower one, 0.314 m/s, the wear never reached a severe level but instead, the protective “glaze” layer started to form. At the higher speed of 0.654 m/s, loose oxide debris is produced, causing a regime of severe wear. The “glaze” layer can then start to form when the combination of ambient temperature and flash temperatures at asperities, caused by sliding speed, is high enough. At even higher speeds such as 0.905 m/s flash temperatures are so high that the protective layer can start to form at even lower ambient temperatures, but the severity of the previous wear regime are also more extensive. The information obtained from these types of tests has been used together with studies of microstructures of the both alloys after the different tests has been used by Inman et al. in order to establish a wear map, see figure 11, for the specific materials couple. The main goal of the map is to distinguish between the different wear regimes depending on both sliding speed and temperature.
2.3.2. Stainless steel

Steels with a chromium content of at least 10.5 percent and a carbon content of maximum 1.2 percent are said to be stainless because of their high corrosion resistance [18]. Unlike the plain carbon steels, the stainless steels will not corrode when subjected to air and moisture because of the protective layer of chromium oxide that forms on the surface [19] [20].

Stainless steels can be divided into groups depending on their microstructure, their properties or by their main alloying

Fig. 11. Wear map for Incoloy MA956 slid against a Stellite 6 counterface (load 7 N), with weight loss (contour) data superimpose [17].

Fig. 12. Phase diagram showing the effect of amount of chromium present in the stainless steel [19].
element. When dividing by microstructures the different types are martensitic, ferritic, austenitic or duplex (austenitic-ferritic) steels, see figure 13 [18].

The microstructure of the steel is highly dependent on both the heat treatment process and the amount of chromium and nickel content in the alloy. The influence of chromium can be seen in the phase diagram in figure 12.

To facilitate the formation of martensite, the martensitic stainless steels contain up to 17 wt% chromium. The reason for this is that if the chromium content is too small, the austenite region will decrease, see figure 12, making it more difficult to control the formation of martensite. Different hardness is achieved by controlling the amount of carbon, which usually lies between 0.1-1.0 wt%. Due to the high strength and hardness of these steels, they are commonly used in valves and ball bearings. Ferritic stainless steels are rather inexpensive and exhibits excellent corrosion resistance. They are unable to be heat treated since the high amount of both chromium and nickel stabilizes the ferritic phase, making it stable in all temperatures [19]. These steels are magnetic.

Fig. 13. The microstructure of (a) austenitic stainless steel and (b) duplex stainless steel [19]
The carbon content, in the ferritic steels, is below 0.12 wt% and the amount of chromium is about 30 wt% and, hence, higher than in the martensitic steels. Ferritic steels have BCC structure and can be solid solution strengthened and strain hardened to obtain good strength and modest ductility. Austenitic stainless steels are characterized by their nonmagnetic properties and they exhibit excellent ductility. A high amount of nickel is added to stabilize the austenitic phase and, together with the high chromium content, this makes the austenitic steels quite expensive. Even though the steel is referred to as stainless, it actually can corrode. When heated to a temperature of about 480-860°C, chromium rich carbides precipitates on the grain boundaries. This decreases the amount of chromium present in the grain, hence the material does no longer have enough chromium available to react with oxide creating the protective oxide layer and finally it corrodes [19]. This phenomenon is known as sensitization, see figure 14. The most common stainless steel is the austenitic 18-8 steel that contains 18 wt% chromium and 8 wt% nickel. The strength of stainless steels can be increased by mixing austenitic and ferritic phases creating duplex stainless steel. These steels exhibit high strength due to the grain refinement caused by the mixing of the phases, see figure 13 [19] [20].

**2.3.3. High-temperature superalloys**

When selecting the right material for a high-temperature application both the required mechanical properties and the mechanical degradation due to high-temperature corrosive attack have to be taken into consideration and be weighed against each other to achieve the optimal material for each specific application. Materials used in high-temperature applications have to maintain good mechanical properties even at high temperatures. The most important properties, as mentioned above, are high-temperature strength, stress rupture strength, creep strength, thermal stability, thermal shock, fatigue and toughness [21].

In the past, stainless steels were used to exhibit good corrosion resistance even at elevated temperatures but according as the temperature demand increased for new, advanced, modern
applications it was discovered that the stainless steels did not exhibit good strength at these high temperatures (about 540°C). There was a need for materials that could withstand higher temperatures and still maintain the important properties required for the specific application. Superalloys, mainly based on nickel, iron-nickel or cobalt were introduced to the market. They can be used to a higher rate of their melting point, than other materials, [21] and show superior high temperature properties even above 540°C where degradation of other materials will occur due to high-temperature corrosive attacks [21]. One disadvantage is that they are rather expensive because of the expensive base material. Mechanical properties of the superalloy are not only dependent on the microstructure but on the melting process, the manufacturing process and the heat treatment process too. By carefully controlling these processes, the superalloy may be tailored to fit the exact application by controlling the most important properties. Regarding the manufacturing process wrought superalloys are used at lower temperatures than the cast ones. The solidification process causes segregation leading to formation of more inhomogeneous microstructures, which means that the wrought alloys are more ductile and show more homogeneity than the cast ones [22]. Iron-based superalloys are usually used wrought, while nickel- and cobalt-based are used as cast and wrought. [23]

Superalloys show high oxidation resistance at elevated temperatures but they may sometimes demonstrate insufficient corrosion resistance. In those cases, the alloy can be coated to be able to withstand the severe working conditions that high temperature implies. In applications where the temperature exceeds 760°C or if working during long periods of time in 649°C the superalloy may need a corrosion protective coating [22]. In cases when it is desired to increase the strength of a superalloy, it can either be strengthened by solid solution strengthening or by precipitation hardening mechanisms. Cobalt based superalloys can also be strengthened by carbides. [22] Hence, basically the temperature limitation of a superalloy is dependent on the base material, the volume of precipitates and the manufacturing process. [22]
Table 1: Influence of alloying elements in cobalt-, iron- and nickel-based superalloys [23].

<table>
<thead>
<tr>
<th>Solid solution strengtheners</th>
<th>Cobalt based</th>
<th>Iron based</th>
<th>Nickel based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr, Mo, Ni, W, Ta</td>
<td>Cr, Mo</td>
<td>Co, Cr, Fe, Mo, W, Ta, Re</td>
<td></td>
</tr>
<tr>
<td>MC</td>
<td>Ti</td>
<td>Ti</td>
<td>W, Ta, Ti, Mo, Nb</td>
</tr>
<tr>
<td>M₇C₃</td>
<td>Cr</td>
<td>Cr</td>
<td>Cr</td>
</tr>
<tr>
<td>M₂₃C₆</td>
<td>Cr</td>
<td>Cr</td>
<td>Cr, Mo, W</td>
</tr>
<tr>
<td>M₆C</td>
<td>Mo, W</td>
<td>Mn</td>
<td>Mo, W, Nb</td>
</tr>
<tr>
<td>Carbonitrides, M(CN)</td>
<td>C, N</td>
<td>C, N</td>
<td>C, N</td>
</tr>
<tr>
<td>Al, Mo, Ti, W, Ta</td>
<td>Al, Ti, Nb</td>
<td>Al, Ti, Nb</td>
<td></td>
</tr>
<tr>
<td>Oxidation resistance</td>
<td>Al, Cr</td>
<td>Cr</td>
<td>Al, Cr, Y, La, Co</td>
</tr>
<tr>
<td>Improve hot corrosion</td>
<td>La, Y, Th</td>
<td>La, Y</td>
<td>La, Th</td>
</tr>
<tr>
<td>resistance</td>
<td>B</td>
<td>B</td>
<td>B, Ta</td>
</tr>
</tbody>
</table>

2.3.3.1. Ni-based alloys

Even though nickel-based superalloys have melting temperatures in the same range as ordinary steels, the superalloys have a higher limit for their maximum service temperature [20]. There are no other materials available today that can be used to such a high proportion of its melting temperature than nickel based superalloys. The main key to the superior high-temperature properties they exhibit are the alloying elements present. Nickel-based superalloys can contain more than ten different alloying elements making the alloy one of the most complex materials available on the market [24].

Alloying elements in the nickel-based superalloys can be varied to maintain desired properties. In cases where the service conditions are severe, aluminum, silicon or chromium can be added to the alloy to increase the life time of the component by formation of a protective oxide layer. As mentioned above there are different ways to enhance the strength of a nickel-based superalloys. Cobalt, chromium, molybdenum, tungsten, titanium or niobium are all used to achieve solid
solution strengthening of the alloy. If age hardening mechanisms strengthening is required aluminum, titanium, niobium or tantalum are added. Another way to improve the strength is by introducing carbides into the nickel matrix. Chromium, molybdenum, tungsten, titanium, zirconium, tantalum and niobium are all strong carbide formers [21].

The microstructure of nickel-based superalloys is mainly consisting of three phases. The primary, gamma phase, has FCC structure and forms a continuous nickel matrix containing alloying elements. In many cases, there is a coherent precipitate phase known as the gamma prime intermetallic precipitates. This phase often contains aluminum and titanium. Besides there can be different forms of carbides. In nickel-based superalloys, MC carbides are formed by the reaction between carbon and one or more of the strong carbide formers mentioned above. M23C6 and M6C carbides can also be detected due to decomposition of the MC during service or different manufacturing processes [24].

2.3.3.2. Fe-based alloys
Iron-based superalloys are high-temperature alloys that maintain their good strengths up to temperatures about 650°C. They have a chemical composition with a base of iron and are thought of as an extension of the stainless steels [25]. But most of these alloys also contain a large amount of nickel, which has the main function to stabilize the austenitic FCC phase in the matrix material. That is why this group of alloys is not always defined as a separate group but is sometimes referred to as a sub-group to nickel-based alloys, or as iron-nickel alloys. Apart from iron and nickel, these alloys consist of chromium, to provide solid solution strengthening and at the same time enhance corrosion resistance, molybdenum, also for solid solution strengthening, and other alloying elements to obtain precipitation hardening, such as niobium, titanium and aluminum [26]. In the Fe-base superalloys, fine precipitates are introduced to improve creep strength. It has a lower resistance to elevated temperatures in comparison to both nickel- and cobalt-based superalloys [27].

Iron-nickel alloys, that are mainly alloyed with aluminum and/or titanium, primarily have γ' precipitates, Ni₃Al or Ni₃Ti, in the matrix for the strengthening effect. The Al-Ti ratio is critical when it comes to the efficiency of the strengthening effect. The range of Al-content, in which fine precipitates with efficient strengthening form, instead of coarse precipitates in form of platelets, is not very broad. Therefore, this alloying element is not used in very large doses, but
instead Titanium is used, producing hardening precipitates Ni$_3$Ti. Niobium, which produces even more effective hardening phase of BCC-structured Ni$_3$Nb, $\gamma''$, can also be used. However, all of these three phases are metastable and will coarsen to the form of platelets, being exposed to elevated temperatures above 650°C for long times. This is one of the reasons why iron-nickel alloys are not as good as nickel or cobalt alloys when elevated temperatures reach too high values, as they lose some of their strength [28] [26].

### 2.3.3.3. Co-based alloys

Cobalt-based superalloys are solid solution strengthened and hardened by the formation of carbides instead of being hardened by precipitation hardening, as nickel- and iron-based alloys. They are very good for high-temperature applications since they have higher melting point and, at the same time, they have much more constant creep behavior than nickel- and iron-based superalloys. Therefore, they are not as suitable as the other alloys for applications at lower temperatures but become very useful at temperatures above a certain limit. Compared to nickel-based superalloys, cobalt-based ones maintain their corrosion resistance much better at elevated temperatures. They are also easier to weld, which is an advantage for applications where laser welding is the preferred coating technique [27].

Cobalt-based superalloys have three main application areas: hard grades with high carbon content for wear resistance, softer grades with low carbon content for high temperature applications and grades with a low carbon content that are suitable for applications where both corrosion and wear are significant factors. Examples of wear resisting cobalt alloys are the well-known Stellites or the Tribaloy grades, while Haynes grades belong to the group of heat resisting grades and for example Ultimet grades are used for corrosion resistance. There are several factors that give cobalt-based superalloys the properties they possess. As for many other alloys, the good corrosion resistance comes from the chromium, which is solute in the alloy. Chromium, as an alloying element, also provides a solid solution strengthening effect together with solute tungsten and molybdenum. The role of cobalt in the group of cobalt-based superalloys is to provide high yield strength, high work-hardening rate, low fatigue damage when exposed to cyclic stress and an ability to absorb stresses. The last of these four properties comes from the change in crystal structure from FCC to HCP, which is triggered either by stress, or by temperature or time, at continuous exposures to elevated temperatures. High yield strengths, high work-hardening rates
and low fatigue damage are thought of as the main reasons for the low damage of these alloys in sliding wear, while low fatigue damage and the ability to absorb stresses are contributors of cavitation and erosion-corrosion resistance. These interesting tribological properties of cobalt-based alloys, to improve wear resistance, are obtained by controlling size, shape and amount of carbides in the material. This can be done by regulating cooling rate and chemical composition for the alloys. Dominating carbide type is Cr$_7$C$_3$. However, in some low-carbon alloys large amounts of chromium-rich carbide, Cr$_{23}$C$_6$, also exist. The effect of tungsten and molybdenum on cobalt-based alloys is mainly an increase in strength, due to their large atomic size and tendency to participate in carbide-form M$_6$C [25].

2.3.4. Coatings
Materials that exhibit superior properties from a tribological point of view often fail as a construction material because of their mechanical properties. Therefore, it is difficult to find a material that suits both as a bulk and as a surface material. This problem is solved by a coating process in which the bulk material, with the good mechanical properties, is coated with a superficial layer of a material that gives good surface properties to withstand the impact from the surroundings such as for example sliding or indentations. Materials used as coating materials are often quite expensive and this is another reason to use the coating technique since a less expensive material can be used as a substrate material without affecting the properties needed to fulfill the requirements at the surface of the component [29]. Additionally, huge construction can be created with a lighter bulk material, decreasing the total weight of the component, coated with a denser material that provides the required functional properties [29].

There are several coating techniques present to choose among, to obtain the desired surface roughness and microstructure, and to enhance the performance of the component. They can be divided into surface modification or surface coatings. In the first method, as the name indicates, the surface layer is either modified by addition of atoms changing the chemical composition or changing microstructure by deformation or heating. The most common surface modifications by deformation are shot peening and blasting. Regarding thermal methods, flame hardening, induction hardening and laser hardening are the most frequently used ones. To increase the hardness of the surface layer, carbon and/or nitrogen atoms are usually added to form carbides and/or nitrides by a carburizing or nitriding process. The surface may also be modified by an
electrolytic process or by ion implantation. Surface coatings are methods in which a superficial layer is added onto the bulk material. This can be performed in different ways depending on the geometry and shape of the component. Requirements of surface roughness and quality also have to be considered when deciding which surface coating method to use. The coating material can be applied atomistic, particle by particle or as a complete layer. PVD and CVD are two methods in which atoms are added one by one until the thickness of the coating is enough to satisfy the needs. They both are quite expensive methods. The layer can also be achieved by thermal spraying, which means that the material is heated and particles are sprayed onto the bulk material. Weld hard facing is one of the processes in which the material is applied as a complete layer at the surface. Cladding is another process where the material is added as a complete layer [30] [29].

2.3.4.1. Wear resistant and low-friction coatings

In tribological applications it is often desirable to have a surface coating which exhibits low friction and at the same time minimizes the wear rate to create an optimal tribological system increasing the lifetime of the components. The coating material then has to have a low coefficient of friction and high hardness.

There are several reasons to desire low friction of a component. In applications were the cleanliness is of great importance, such as in the food industry, surface coated components with a low friction are used to avoid lubricants that otherwise may contaminate the food. This type of coating can also be desired in terms of energy consumption, because a low friction component may reduce the energy consumption of the system [29]. Low coefficient of friction is usually achieved by having a superficial layer of easily sheared material on top of the bulk material. [30] However it is obviously not desired to have low friction in all applications. A good example is brakes, in which friction is needed to create the braking moment [29].

Wear resistant coatings are developed to increase the life time of components used in tribological applications in which the surface are subjected to severe loads. One huge area of application is the metal cutting industry where the cutting tools are coated with a hard, wear resistant coating to be able to cut the material properly. Since there are different types of wear, see section 2.3.1.1., there are several approaches to create wear resistant coatings. In cases where adhesive wear could occur, the bulk material is coated with a material with different morphology and microstructure.
so that adhesion between surfaces in contact becomes more difficult. When dealing with erosion and abrasive wear, it is more important to have a high hardness to avoid severe wear. Therefore the bulk material is coated with a material containing hard particles or phases [31].

2.3.4.2. Corrosion resistant coatings.
Not only for valves, but for all mechanical components operating in corrosive environments, it is important to find a good and economic solution to protect the material from corrosion. Commonly, one aims to increase several properties, apart from corrosion, at the same time, either by additional alloying elements in the same coatings or by coating in several layers. The corrosion resistance of a coating depends on a number of factors. Chemical composition is important, as is the structure of the coating and the substrate surface, as well as the type and conditions of the media which the coating is exposed to. Corrosion protecting coatings, also called protective coatings or anti-corrosion coatings, can be divided into organic, inorganic and metallic coatings. It is also common to combine these types of coatings to obtain optimal properties [15].

Organic coatings create a physical barrier but at the same time they can contain so called inhibitors, which slow down the corrosion process. Examples of such coatings are paints and resins. Inorganic coatings can be used for several reasons. Some of them are used for their inertness in water and resistance in many weathers, while others provide protection against contamination. Conversion coatings are a type belonging to the group of inorganic coatings. These are created by intentionally, but in a controlled manner, corroding the surface of the base material creating a layer, which protects from further corrosion. In the case of metallic coatings, a layer of a metal is deposited onto the base material creating a barrier between the substrate and the environment. By using a metal with desired corrosion properties, one can obtain a material that shows a good combination of corrosion resistance, from the coating, and mechanical properties, from the substrate. Some of the main metallic elements used for protective coatings are Aluminum, Cadmium, Chromium, Nickel and Zinc, pretty much the same as was mentioned in section 2.3.1.2., regarding corrosion in base materials [32]. Metallic coatings are regularly the most common alternative for components which are exposed to severe impact, abrasive wear or high temperatures [15].
2.4. Comparison of materials

Some interesting materials that could be suitable for the valve of type DN VSSL 400, PN 100 are mentioned above in previous sections. To select a specific material that is to be tested as a substitution for the high cobalt alloys used in valve DN VSSL 400, PN 100, the most interesting superalloys were compared regarding their mechanical and high-temperature properties. These values and comparisons can be seen in the tables below. Table 2 shows the ranking of the materials depending on the yield strength at 650°C while table 3 shows the ranking depending on the tensile strength at the same temperature.

Table 2. Ranking of superalloys according to yield strength at 650°C [33] [34].

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Yield at x°C</th>
<th>UTS at x°C</th>
<th>Term. Exp. at x°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>540</td>
<td>650</td>
</tr>
<tr>
<td>Inconel1718</td>
<td>1185</td>
<td>1065</td>
<td>1020</td>
</tr>
<tr>
<td>Nimonic 942</td>
<td>1060</td>
<td>970</td>
<td>1000</td>
</tr>
<tr>
<td>Inconel1006</td>
<td>1005</td>
<td>910</td>
<td>860</td>
</tr>
<tr>
<td>Nimonic 115</td>
<td>865</td>
<td>795</td>
<td>815</td>
</tr>
<tr>
<td>Nimonic 105</td>
<td>830</td>
<td>775</td>
<td>765</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>810</td>
<td>725</td>
<td>685</td>
</tr>
<tr>
<td>Stellite 6(B)</td>
<td>638</td>
<td>464</td>
<td>321$^1$</td>
</tr>
</tbody>
</table>

$^1$(at 816°C)

Table 3. Ranking of superalloys according to ultimate tensile strength at 650°C [33] [34].

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Yield at x°C</th>
<th>UTS at x°C</th>
<th>Term. Exp. at x°C</th>
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<td>865</td>
<td>795</td>
<td>815</td>
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<tr>
<td>Nimonic 105</td>
<td>830</td>
<td>775</td>
<td>765</td>
</tr>
<tr>
<td>Nimonic 90</td>
<td>810</td>
<td>725</td>
<td>685</td>
</tr>
<tr>
<td>Stellite 6(B)</td>
<td>638</td>
<td>464</td>
<td>321$^1$</td>
</tr>
</tbody>
</table>

$^1$(at 816°C)
2.5. Valves at AB SOMAS Ventiler

There are several different types of valves at AB SOMAS Ventiler to satisfy the requests from the market. This thesis is focused on the butterfly valve of type DN VSSL 400, PN 100 used to regulate flow of media in both gaseous and liquid state.

2.5.1. Working conditions

Depending on the specific area of application, the working conditions of the valve are obviously altered. Regarding the butterfly valve of type DN VSSL 400, PN 100 at AB SOMAS Ventiler, the highest temperature reached during operation is in the range of 500-600°C. Working temperatures are depending on demand from the customers and increases continuously with time as the steam turbines developed for increased efficiency. Since the working conditions gradually change with the requests from the market, the materials in the valve have to be designed to be able to perform well even when the temperatures and pressures increase.

Under normal operation the valve is opened or closed in about 5 seconds but in case of emergency the valve has to be closed quickly. At such conditions the closing occurs rapidly and to avoid high impact pressure, caused by the high velocity, a brake will be active in the end of the closing decreasing the speed at the moment of impact. The shutting of the valve is accomplished by an external force from a hydraulic system, which is attached to the valve spindle, creating a torque that rotates the disc.

During operation the flowing media will transfer forces to the spindle resulting in both torsion and bending of the shaft. The spindle is also subjected to torsion from the actuator during maneuvering of the valve. When fully opened, there is no contact between the disc and the seat at any point. First point of contact, during closing of the valve, will occur at three and nine o’clock of the valve opening, see figure 15. At these points the most severe adhesive wear is found, caused by high contact pressure but at relatively short sliding distance. At the top and the bottom of the valve the sliding distances are longer but the contact pressure is lower resulting in severe scratching and

Fig. 15. First point of contact during closing of a butterfly valve of type DN VSSL 400, PN 100.
adhesive wear [35]. This has been shown in a case study performed at Karlstad University.

2.5.2. Materials in the valve
Material selection for the valves is limited by performing parameters such as the highest allowable temperature and pressure for example. To obtain desired properties for the butterfly valve of type DN VSSL 400, PN 100, different materials are used in the valve parts.

2.5.2.1. Martensitic steel, EN 1.4903
The 9Cr-1Mo-V steel (EN 1.4903) was developed for an environment in which temperature and pressure are high. It is due to its special microstructure that shows superior properties at these conditions. It contains submicroscopic carbides with a high melting temperature that prevent dislocation movement and hence, works as a strengthening mechanism at elevated temperatures [36]. Another contributing factor to the excellent high-temperature properties is that martensitic stainless steels have lower thermal expansion and higher thermal conductivity than austenitic stainless steels, which results in a higher thermal fatigue resistance [37].

Since the microstructure is of great importance, the process by which the steel is produced is crucial. In the first step of the casting process, when the steel is melted, dissolved oxygen presents in the melt. To avoid the formation of porosity because of the oxygen, several deoxidizing elements are added to the melt. Because of their high affinity for oxygen, they form solid oxide inclusions in the alloy. When introducing deoxidizing elements into EN 1.4903, an important thing is that the nitrogen also has high affinity for many of the most common used deoxidizing elements. If the nitrogen reacts with the deoxidizing element, it prohibits the formation of the niobium carbonitrides during the heat treatment and large carbide phases will form instead of the submicroscopic carbides, that are needed to obtain the desired high-temperature properties. Another important aspect regarding the formation of the microstructure is the tempering temperature. Steel EN 1.4903 is an alloy that contains both vanadium and niobium, which are martensite stabilizers and, therefore, prevent softening at normal tempering temperatures. The tempering is often performed between 745-770°C and it is important that the temperatures are controlled so that austenite does not start to re-form. The temperature, at which austenite starts to re-form, is a function of the alloying elements and it may decrease to as low as 815°C. Austenite re-formation leads to formation of untempered martensite during cooling, which, in turn, will result in decreased high-temperature properties and a lower toughness. [37]
2.5.2.2. Martensitic steel - EN 1.4931/EN 1.4923
Steel grades EN 1.4931 and EN 1.4923 are both martensitic steels with the chemical composition, which can be seen in table 5. They differ from each other from the manufacturing point of view. The first one is casted and the last is wrought. This give rise to slightly different properties but they are still in the same order of magnitude. Table 6 shows some physical and mechanical properties for EN 1.4923.

These alloys were developed to get enhanced corrosion properties at elevated temperatures and with a chromium content of about 12 wt% they can be referred to as corrosion resistant steels [40] [41]. The materials are used in high-temperature applications like turbines, valves, petrochemical plants and thermoelectric generators [41].

The good high-temperature properties in these steels are achieved by the carbides formed during the heat treatment. Most important property during long time exposure to high temperatures is the creep resistance which is increased by introducing thermally stable carbides distributed evenly in the material [40].

The EN 1.4923, used in the valves at SOMAS is in a hardened, tempered and stress relieved conditions to achieve the requested properties. The hardening takes place above the austenitization temperature at 1020°C and held for 2.5 hours to obtain a fully austenitic material. The steel is then quenched in air to form martensite. In the next step, the material is tempered and that is performed slightly below the austenite temperature at 720°C for 5 hours resulting in dispersion of cementite and ferrite giving a softer and more ductile martensitic structure. To avoid failure due to internal stresses in the material, caused by the volume change that occurs when transforming austenite to martensite, it is stress relieved for 6 hours at 650°C [42].

2.5.2.3. Stellite
Stellite is a cobalt based alloy developed to get increased wear resistance, and together with a combination of good corrosion resistance and high strength, it results in a material with superior properties for tribological applications. The main characteristics are low coefficient of friction and resistance to galling.

Several grades of Stellite, with different amount of alloying elements, have been developed to provide a more tailored material with physical and mechanical properties required for the specific
application. As for other materials, chemical composition, see table 5, is not the only determining factors regarding the properties of the material, see table 6. No less important is the manufacturing process of the material, which determines the microstructure. The toughness is dependent on morphology and wt% of carbides, less carbides gives a more ductile material [43].

Stellite maintain FCC-structure at all temperatures unlike cobalt, which transforms to HCP-structure when the temperature decreases below 417°C. This is due to the alloying elements that stabilize the FCC-structure. However, this transformation can also be detected in Stellite when stresses in the material are high enough to cause shear resulting in transformation from FCC to HCP, even though last described is not a stable phase. Hence, in tribo-applications, when the contact pressure is high enough, there will be shear stress-induced phase transformation in the top layer resulting in deformation hardening of the material. This is the main key to the high wear resistance of Stellite, see figure 16. On top of the deformation hardened layer, another, much thinner, layer that is just a few nanometer thick is formed during sliding contact. Sliding results in rearrangement of the HCP crystal structure so that the planes are aligned parallel to the sliding plane. Parts of the layer are worn, a new thin layer forms at the surface. This creates an easily sheared layer that acts as a solid lubrication in the tribological system leading to the low friction coefficient of Stellite. Important is that if the stresses are not high enough, this thin layer is not formed, therefore, the coefficient of friction is not that low. The easily sheared layer is also the reason to good galling resistance of Stellite. Since the wear only occurs within the thin layer, there is not severe adhesion and galling does not happen. [43]
Stellite 6 is the most commonly used grade and is a standard material used in applications where high wear resistance is required. It is generally used in valve seats, pump shafts, bearings and rolling couples. A distinguishing property of this grade is the excellent anti-galling property it shows when self-mated and, hence, it is commonly seen self-mated in tribological applications. The impact and cavitation erosion resistance is also high for this material as well as the resistance to chemical and mechanical degradation for a wide temperature range. Stellite 6 also exhibits high hardness at elevated temperatures up to 800 °C. The carbon content is higher in Stellite 6 than in Stellite 21, which enables for more carbide formation and hence a higher hardness, see table 6, [43]. In the Stellite 6, carbides are found in the form of chromium-rich M₇C₃ in a matrix of solid solution of cobalt, together with the intermetallic phases Co₇W₆, Co₃W and M₂₃C₆ [43].

Regarding manufacturing processes, it is excellent to use as a hardfacing material and can be lathe machined using carbide tooling. It has W and Cr as main alloying elements, see table 5. [44] [46] [47]

Stellite 21 has Mo and Cr as main alloying element, resulting in better resistance to complex environments than Stellite 6. Stellite grades alloyed with molybdenum also exhibit better cracking resistance than those alloyed with tungsten. This also means that the cobalt-rich solid solution contains intermetallic phases based on molybdenum instead of tungsten. Hence, Co₃Mo
and Co₇Mo₆ are present together with M₂₃C₆ carbides. The material is resistant to reducing atmospheres and oxidizing up to 1150°C. This grade is mainly used in applications in which the material is subjected to an erosive or corrosive environment or when exposed to high temperatures or cavitation. It can also be useful when temperatures are drastically changed or during mechanical impacts, since it shows excellent resistance to thermal and mechanical shock. It also exhibits excellent galling resistance and cavitation properties and, the tribological properties during sliding between two metal surfaces are also excellent. Nevertheless, it is not recommended to use this material in applications were hard abrasive particles are present. Stellite 21 can be manufactured by powder metallurgy, casting or by hardfacing processes [45] [47].

2.5.3. Substitution materials
There are three different materials that are to be tested as possible substitution for the high-cobalt alloys. Vanax 75, hardened EN 1.4903 or the superalloy Inconel 718 may suit for this application.

2.5.3.1. Vanax 75
Vanax 75 is a powder metallurgy (PM) steel developed at Uddeholm AB, a follower up to the earlier Vancron grades. It belongs to a group of steels referred to as high-nitrogen alloyed tool steels, which are known to possess a combination of good low-friction properties and good corrosion resistance. Such a combination is not entirely easy to obtain for a material since an increase in one usually results in a decrease in the other [48].

For a steel to be characterized as high-nitrogen, it should contain more nitrogen in the metal matrix than it is possible to obtain at atmospheric pressure. This is a number that usually lies in a region around 4 wt% for austenitic alloys, while only about 0.08 wt% for ferritic materials [50]. In a similar manner as carbon does in carbon steels, nitrogen provides solid solution strengthening in high-nitrogen alloyed steels and at the same time it reacts with other alloying elements to form a hard phase in the metal matrix.

The role of the hard phase in tool steels is very important and there are clear advantages of replacing some Carbon for Nitrogen. First and foremost, in the case of carbon steel, carbon will react with chromium to a large extent and form chromium-carbides. With a lot of Chromium being tied up in carbides, much smaller amounts form a solid solution matrix. Since Chromium in solid solution is the main contributor to corrosion resistance, this will be a drawback in terms of this property. The hard phase which is distributed throughout the matrix is the main contributor to
hardness and good low-friction properties, and therefore its features have a large impact on material properties. Carbon has the tendency to form a hard phase consisting of $M_7C_3$-carbides, which are less stable and not as hard as are the MN-nitrides mainly formed by nitrogen in high nitrogen alloyed steels [48]. This can be seen in the table 4 below.

Table 4. Comparison of type of hard phase in two high nitrogen alloyed steels and two carbon based ones [48].

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>MN</th>
<th>MC</th>
<th>$M_6C$</th>
<th>$M_2N$</th>
<th>$M_7C_3$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanax 75</td>
<td>24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>Vanax 35</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Elmax</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>AISI 618</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

Size and distribution of the hard phase is an important factor in both carbon- and nitrogen-alloyed steels. A well distributed, dense and homogeneous hard phase provides a material with better properties, as will a high height to width ratio. As can be seen in figures 17 and 18 below, the homogeneity and distribution as well as the density of hard phase in Vanax 75 is quite different from a carbon-alloyed corrosion- and wear-resistant steel, AISI 440C, which contains a larger amount of the hard phase, evenly distributed over the surface [48].
Vanax 75 contains high amounts of vanadium and nitrogen, leading to a large distribution of vanadium nitride particles, VN, in the metal matrix. It is believed that the tendency of VN particles to form low-friction oxides, which are also called Magnéli oxide phases, could be the key to why they resist galling so well. These oxides show easy shear planes, which make them suitable for dry sliding and have very low melting point, the reason why they act in a self-lubricating manner and decrease friction coefficient at elevated temperatures [51] [52]. However, this has only been proven for VN-coatings, it is yet to determine whether or not the same oxides form in Vanax 75, but it could possibly be an explanation to its good anti-galling properties.

The same behavior has been shown to exist for coatings of VN type. Vanadium oxides, such as V₂O₅, VO₂ and V₆O₁₃, are formed above 400°C resulting in a decrease in the coefficient of friction, see figure 19. An increase can be noted instead at temperatures below 400°C, however these are believed to be the result of wear debris that becomes loose and acts as a third-body abrasive in the contact between coating and counterpart [53][52].

2.5.3.2. Hardened EN 1.4903

When following the right heat treatment process, steel EN 1.4903 can be hardened due to microstructural changes. Depending on heat treatment temperature and the time during which the specimen is held at the specific temperature, different transformations are attained. The CCT-diagram in figure 20 shows the transformation that can occur in EN 1.4903 dependent on time and temperature.
Specimens of EN 1.4903 used in this thesis were hardened by first being normalized at a temperature above the austenitic temperature, in this case 1020°C for 2.5 hours, to create an entirely austenitic structure. The heat treatment was subsequently followed by rapid cooling to produce a martensitic structure. In the next step the steel was tempered in 720°C for 5 hours, resulting in transformation of martensite to ferrite and cementite. The specimens were then quenched in air to achieve the optimal microstructure.

![CCT-diagram for EN 1.4903.][54]  

**Fig. 20.** CCT-diagram for EN 1.4903. [54]

### 2.5.3.3. Inconel 718

Inconel 718 is an age-hardenable, nickel-based alloy - one of the largest grades of superalloys in use today, representing almost 50 percent of the total tonnage used [28]. It has good mechanical properties, see table 6, together with good corrosion resistance at elevated temperatures and, at the same time, it can easily be welded [55]. Inconel 718 belongs to a group of nickel-iron alloys which also contain large amounts of chromium, see table 5, and present a good corrosion resistance in many environments. The alloy also shows both a high rupture strength and high fatigue strength at elevated temperatures but, as most iron-nickel alloys, it starts to lose its strength at temperatures above 650°C [11].

Inconel 718 can be solution treated by adding Mo to the material matrix. Precipitation hardening (age hardening) can be performed, as a second step, to obtain a material containing precipitations in order to gain additional hardening effects. For example, the same precipitates as were
mentioned in the section about Ni-Fe based superalloys, namely $\text{Ni}_3\text{Ti}/\text{Al}(\gamma')$ and $\text{Ni}_3\text{Nb}(\gamma''')$, are also present in this alloy. Among these two types of precipitates, the Nb-phase is the most contributing to age in this superalloy. Carbides, in the form of MC, are also formed in the metal matrix to provide hardening effects, but in carefully controlled amounts, since too high values make it hard for Nb and Ti precipitation to occur [55]. It can be observed in the Precipitation-Time-Temperature diagram below, figure 21, how the different precipitates form at different aging temperatures and holding times.

![Fig. 21. PTT-diagram of different phases in Inconel 718. [57]](image)

There is also a third precipitation phase which is yet to be mentioned. This is the $\delta$ phase which, has the same composition as $\gamma'''$, $\text{Ni}_3\text{Nb}$, but has a different crystal structure. Therefore, in difference to both gamma phases, $\delta$ does not contribute in strengthening the material. Instead, the main fraction of the phase, the particles that precipitate at the grain boundaries, will provide resistance to grain boundary creep. These grain boundary $\delta$ precipitates are seen in figure 23 below. One should consider, when performing aging to obtain $\delta$ precipitates in the matrix, that there is a risk that the presence of the $\delta$ phase can lead to a decreased resistance to hot cracking [56].
Owing to its beneficial properties at elevated temperatures together with its ability to be age-hardened and the weldability, Inconel 718 is typically used in application such as components for jet engines, pump bodies, rocket motors or spacecraft [11].

2.5.3.4. Comparison of materials
Materials used for different parts in the valve have different physical and mechanical properties to satisfy the requests for each part, as mentioned before. A comparison of the materials used in the valves today at AB Somas and the potential materials for substitution of high cobalt alloy 6 and 21 can be seen in table 5 and 6. As mentioned above, the high-cobalt alloys are represented by values for the corresponding Stellite grades.

The modulus of elasticity is of the same range for all the materials but the yield stress is highest for Inconel 718. Vanax 75 exhibits highest hardness at elevated temperatures. Difference between the coefficient of thermal expansion of the bulk material and the coating material is of the same order of magnitude for the two Stellite grades as for both potential substitution materials – Vanax 75 and Inconel 718.
Table 5. Comparison of chemical composition of materials used in the valve today (EN 1.4903, EN 1.4923/EN 1.4931, Stellite 6 and Stellite 21) and potential substitution materials (Vanax 75 and Inconel 718) [38] [42] [44] [45] [48] [33].

<table>
<thead>
<tr>
<th>Element</th>
<th>EN 1.4903</th>
<th>EN 1.4923/EN 1.4931</th>
<th>Stellite 6</th>
<th>Stellite 21</th>
<th>Vanax 75</th>
<th>Inconel 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Base</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>Base</td>
<td>18.5</td>
</tr>
<tr>
<td>C</td>
<td>0.08 - 0.12</td>
<td>0.215</td>
<td>0.9-1.4</td>
<td>0.20-0.35</td>
<td>0.2</td>
<td>0.04</td>
</tr>
<tr>
<td>Mn</td>
<td>0.30 - 0.60</td>
<td>0.56</td>
<td>*</td>
<td>*</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>P</td>
<td>0.020</td>
<td>0.021</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>≤ 0.010</td>
<td>0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Si</td>
<td>0.20 - 0.50</td>
<td>0.29</td>
<td>*</td>
<td>*</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Co</td>
<td>-</td>
<td>-</td>
<td>Base</td>
<td>Base</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cr</td>
<td>8.00 - 9.50</td>
<td>12.12</td>
<td>27-32</td>
<td>26-29</td>
<td>21.2**</td>
<td>19.0</td>
</tr>
<tr>
<td>Mo</td>
<td>0.85 - 1.05</td>
<td>0.89</td>
<td>*</td>
<td>4.5-6.0</td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Ni</td>
<td>≤ 0.40</td>
<td>0.59</td>
<td>*</td>
<td>2.0-3.0</td>
<td>-</td>
<td>Base</td>
</tr>
<tr>
<td>V</td>
<td>0.18 - 0.25</td>
<td>0.265</td>
<td>-</td>
<td>-</td>
<td>9.0</td>
<td>-</td>
</tr>
<tr>
<td>Nb</td>
<td>0.06 - 0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.1</td>
</tr>
<tr>
<td>W</td>
<td>-</td>
<td>-</td>
<td>4-6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>0.03 - 0.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.2</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Ti</td>
<td>≤ 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Zr</td>
<td>≤ 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Elements present in small amounts.
**17.7 in solid solution.
Table 6. Comparison of mechanical and physical properties of materials used in the valve today (EN 1.4903, EN 1.4923/EN 1.4931, Stellite 6 and Stellite 21) and potential substitution materials (Vanax 75 and Inconel 718) [37] [39] [40] [58] [44] [45] [49] [33] [59].

<table>
<thead>
<tr>
<th>Properties</th>
<th>EN 1.4903</th>
<th>EN 1.4923/EN 1.4931</th>
<th>Stellite 6</th>
<th>Stellite 21</th>
<th>Vanax 75</th>
<th>Inconel 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus [GPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at RT</td>
<td>218</td>
<td>216</td>
<td>209(^1)</td>
<td>250(^2)</td>
<td>242</td>
<td>200</td>
</tr>
<tr>
<td>at 600°C</td>
<td>167</td>
<td>127</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>585</td>
<td>800-950</td>
<td>850</td>
<td>710</td>
<td>-</td>
<td>1435</td>
</tr>
<tr>
<td>Yield stress [MPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at RT</td>
<td>450</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1185</td>
</tr>
<tr>
<td>at 600°C</td>
<td>215</td>
<td>-</td>
<td>700</td>
<td>565</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>at 650°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300-400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hardness [HV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at RT</td>
<td>-</td>
<td>274-316</td>
<td>410</td>
<td>347</td>
<td>-</td>
<td>400-500</td>
</tr>
<tr>
<td>at 600°C</td>
<td>-</td>
<td>-</td>
<td>235</td>
<td>181</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>at 650°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>440-510</td>
<td>-</td>
</tr>
<tr>
<td>at 700°C</td>
<td>-</td>
<td>-</td>
<td>155</td>
<td>153</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Density [kg/dm(^3)]</td>
<td>7.70</td>
<td>7.70</td>
<td>8.44</td>
<td>8.33</td>
<td>7.30</td>
<td>8.20</td>
</tr>
<tr>
<td>Thermal expansion(^3) [µm/m-K]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 200°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.5</td>
<td>-</td>
</tr>
<tr>
<td>at 540°C</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.4</td>
<td>-</td>
</tr>
<tr>
<td>at 600°C</td>
<td>12.6</td>
<td>12.5</td>
<td>14.5</td>
<td>13.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>at 700°C</td>
<td>-</td>
<td>-</td>
<td>14.7</td>
<td>14.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermal conductivity [W/m-K]</td>
<td>-</td>
<td></td>
<td>14.82</td>
<td>14.5</td>
<td>15</td>
<td>11.4</td>
</tr>
<tr>
<td>Melting range [°C]</td>
<td>-</td>
<td></td>
<td>1285-</td>
<td>1295-</td>
<td>-</td>
<td>1260-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1410</td>
<td>1435</td>
<td>-</td>
<td>1340</td>
</tr>
<tr>
<td>Maximum service temperature [°C]</td>
<td>20-600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>630-700</td>
</tr>
</tbody>
</table>

\(^1\) As cast.
\(^2\) Investment casting or undiluted weld metal.
\(^3\) From 20°C to given temperature.
3. Model and experimental conditions
To approach the problem in a good manner and to be able to find the best solution, several steps were included in the process. Simulations, as well as hot wear tests, were carried out to compare the materials to each other. This section describes the way in which they were performed.

3.1. FEM-simulations
To be able to estimate the contact pressure between the seat and disc when a valve is fully closed, numerical simulations were performed in ABAQUS.

First, models of the disc and the seat were created in Pro Engineer and then imported to the FEM-analysis program ABAQUS to perform the calculations.

Since geometry of the disc is quite complicated and, there is only one symmetry line, the whole disc was first simulated. When assembling the seat and the disc, the disc was rotated a few degrees from fully closed position so that no contact occurred in the initial step. The parts of the seat, which is in contact with the housing, were set to be fixed in x-direction to simulate the attachment to the housing. At the same time the disc was only allowed to rotate around the y-axis. Interaction properties between the two sliding surfaces were set to be “hard contact” in the normal direction with an estimated coefficient of friction of 0.18 in the tangential direction. The simulation was performed in three steps. In the first, a small rotation of the disc was introduced so that contact should occur in some points around the disc. In the next step, a small torque was applied on the disc, creating a closing moment so that the area of contact increases. In the third and last step, the actual torque used to close the valve was applied on the disc. To be able to mesh the complicated geometry properly tetragonal elements were used.
Another simulation was performed by simplifying the geometry so that just a piece of the valve was simulated. A slice of the disc, with reduced length in the radial direction, was created and assembled with a part of the seat, see figure 25. This was performed to confirm the results from the simulation of the whole disc performed earlier. The materials were set to the same as before but the boundary conditions were slightly different since there was no longer a whole ring that prevented the seat from indefinitely motion in the y- and z-direction. Hence the boundary conditions for the disc were the same but for the seat a condition that the edges are fixed in the y- and z-directions was added. Regarding the interaction properties, they were also the same as for the first simulation. This simulation was also performed in three steps corresponding to those mentioned above. Since the geometry was simplified, the mesh elements could be assigned to be hexagonal.

### 3.2. The test equipment

The machine, which was used to perform testing within this project was originally designed for high-temperature wear testing in protective atmosphere containing Ar and He. It was designed so that a cylinder, made from one of the materials of interest, rotates in contact with a specimen made from another material. The cylinder was fixed on a spindle, which, in its turn, was inserted into a chamber box with isolated walls and with outlets sealed from the environment, preventing heat from exiting. The specimen was inserted to the chamber from the top and connected to a load-controlling device. The assembly can be seen in figure 26. Until rotation starts, the specimen was not in contact with the cylinder. To suit the specific project better, the equipment was redesigned to perform the same high-temperature wear tests but in a steam environment. Such an environment was obtained by creating a
water inlet in which a small needle was inserted, to produce a steady flow of small water droplets that entered the system and was turned into steam by the high temperatures.

When everything was arranged in the right manner and cylinder as well as specimen was placed correctly, and then the equipment was set to the right temperature and heated up during a couple of hours. At about 500°C the water droplets were introduced into the system. When the right temperature was reached, the rotation of the spindle and the cylinder was induced by starting of an engine connected to the spindle. To simulate the cyclic opening and closing of the valve, the engine was set to run in intervals. The load was set, pressing the specimen against the cylinder and data of load and friction forces was transferred to a computer software for later evaluation.
3.3. Material configurations

Two specimens were tested at each specific combination of materials and test conditions to obtain more data for the same situation, all in order to ensure reliable results.

The load in table 7 is the normal load, which was used in the hot wear tests. When it comes to the amounts of cycles with which the tests were performed, the numbers were chosen based on an assumption on how many cycles the valve should be able to withstand during a lifetime.

<table>
<thead>
<tr>
<th>Cylinder material</th>
<th>Block material</th>
<th>Load</th>
<th>Speed</th>
<th>Distance (open-close cycles)</th>
<th>Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardened martensitic steel, EN 1.4923</td>
<td>Surface hardened EN 1.4903</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Hardened EN 1.4923</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Vanax 75</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Inconel 718</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Laser-welded Stellite 21</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Laser-welded Stellite 6</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td>Laser-welded Stellite 6</td>
<td>Laser-welded Stellite 6</td>
<td>107 N</td>
<td>500 mm/s</td>
<td>2000</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7. Materials tested for substitution in the valve.
3.4. Test conditions
When performing the hot wear tests it is important to use the right test parameters to get as good approach as possible to the real situation. The speed, at which the cylinder will rotate, should correspond to the actual speed of the sliding of the disc against the seat. This speed was estimated in two steps. First the periphery velocity of the disc when rotated 90 degrees was calculated by simple geometry and the formula for velocity, see figure 29 and eq. 1. Since there is a braking moment present during the closing of the valve, the next step has taken that into consideration by simply assuming that the velocity, at which the two bodies slides against each other, will be 80 percent of the actual periphery velocity obtained without the brake, see eq. 2.

Periphery velocity:

\[ v = \frac{\pi d}{4 \cdot t} \quad [\text{mm/s}] \quad \ldots (1) \]

, where \( r \) is the radius of the disc and \( t \) is the closing time.

Velocity with braking moment taken into account:

\[ v_b = 0.8 \cdot v \quad [\text{mm/s}] \quad \ldots (2) \]

, where \( v \) is the periphery velocity.

Test temperature was decided together with AB Somas Ventiler to a temperature slightly above the one that is used today. This is due to the constant increase of the working temperature originated by demands from the market.

Contact pressure between the seat and the disc was estimated by FEM-simulations as mentioned in section 3.1. It was also analytically estimated by a theory which says that the contact pressure between two cylindrical surfaces of which one of them has a radius of zero (flat) can be calculated by multiplying the yield limit for the weakest material by 1.67.[60]
Hence,

\[ p = 1.67 \cdot \gamma_{\text{weakest}} \] \hspace{1cm} ...(3)

where \( p \) is the contact pressure between the two surfaces and \( \gamma_{\text{weakest}} \) is the yield strength for the material with the lowest value.

Since the hardness of all test materials are of the same magnitude and the material in the seat is always the one with the lowest yield strength, same contact pressure was used for all tests.
4. Results
Calculations and values for the test condition parameters as well as the results from the simulations and experimental parts are compiled in this section.

4.1. Test condition parameters
By using eq. 1, the periphery velocity of the disc during closing was calculated to 628 mm/s. When estimating the actual sliding speed between the disc and the seat, with the braking moment in consideration, eq. 2 resulted in approximately 500 mm/s. See calculations below.

Periphery velocity:

\[ v = \frac{2\pi \cdot 200}{4 \cdot 0.5} = 628 \text{ [mm/s]} \]

Velocity with braking moment taken into account:

\[ v_b = 0.8 \cdot 628 = 502.4 \approx 500 \text{ [mm/s]} \]

Valves produced at AB Somas Ventiler are used up to 500-600°C today, and hence it was decided to test the materials at 620°C.

The contact pressure between the seat and the disc, according to Eq. 3, 517 MPa.

\[ p = 1.67 \cdot 310 = 517 \text{ [MPa]} \]

4.2. Simulation of contact pressure
Simulation of the contact pressure was performed in different ways to be able to approach the real situation in the best manner. The entire contact situation was simulated together with a simplification of the model.

4.2.1. Entire contact situation
When simulating the entire contact situation between the seat and the disc, see figure 31, it could be seen that the closing of the valve resulted in an elastic deformation of the seat creating an elliptical shape. The seat was stretched at three and nine o’clock where the first contacts occurred, see figure 30.
Yield limit for the material in the seat was reached early in the second step in which the small torque was applied. The highest stress was observed at three o’clock with a magnitude of 220 MPa which can be seen in figure 32.

Fig. 30. Pictures from ABAQUS that reveals that the undeformed seat, (a), will take an elliptic shape when deformed, (b), after the torque is applied and the valve is shut. The deformation scale factor in (b) is 50.

Fig. 31. Von Mises stress in the seat and the valve. At this point yield limit for the seat is reached and hence plastic deformation will occur. (a) shows the assembly from the front and (b) from the side.
Another observation was that full contact was obtained all around the line of contact. This is visible in figure 33 which shows the contact opening between two nodes located on the seat and the disc respectively.

Fig. 32. Contact pressure when yield limit is reached. Highest contact pressure is observed at three o’clock with a magnitude of 220 MPa which can be seen in (a). (b) Contact occurs as points around the contact line.

Fig. 33. Contact opening at nodes located on the seat revealing a fully closed valve. The contact opening is slightly below zero at the contact line.
4.2.2. Simplification of contact situation
As previously mentioned, the simplification was performed using a section of the disc together with the corresponding section of the seat. When von Mises stress reached a value of 310 MPa, which is the yield strength of the seat at about 600°C, the deformation went from elastic to plastic characteristics, see figure 34.

Figure 35 below demonstrates, in which parts of the seat the von Mises stresses were highest, represented by the red areas in the figure.
At the onset of plastic deformation in the model – the yield point of 310 MPa – a contact pressure of about 200 MPa could be observed, see figure 36. The results demonstrated an evident line of contact, in the simplified case, along which the pressure was distributed.

**Fig. 36. Image from the simplified FEM-model of the contact situation, taken at the onset of plastic deformation where values of the contact pressure reached about 200 MPa. The picture clearly shows the contact in the form of a line.**

### 4.3. Experimental

#### 4.3.1. Coefficient of friction

From the dry sliding tests, performed in the test equipment for high temperature wear, data was extracted describing how friction force and normal load was fluctuating with time. By using the simple equation for friction coefficient; \( \mu = \frac{T}{N} \) (where \( T \) is the friction force and \( N \) is the normal load), the data could be converted into a variation of friction coefficient over time. These values can be seen in figures 38 to 49 below. For each regime; a certain contact pair at a certain number of cycles, two specimens were investigated and two similar graphs were produced to secure more reliable results. Since the obtained graphs for all contact pairs showed the same trends, one out of two is presented in order to represent each regime.
Fig. 37. Coefficient of friction varying over time for steel EN 1.4903 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.

Fig. 38. Coefficient of friction varying over time for steel EN 1.4923 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.

Fig. 39. Coefficient of friction varying over time for steel EN 1.4923 slid 4000 cycles against steel EN 1.4923 at a temperature of 620°C.
Fig. 40. Coefficient of friction varying over time for Vanax 75 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.

Fig. 41. Coefficient of friction varying over time for Vanax 75 slid 4000 cycles against steel EN 1.4923 at a temperature of 620°C.

Fig. 42. Coefficient of friction varying over time for Inconel 718 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.
**Fig. 43.** Coefficient of friction varying over time for Inconel 718 slid 4000 cycles against steel EN 1.4923 at a temperature of 620°C.

**Fig. 44.** Coefficient of friction varying over time for Stellite 6 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.

**Fig. 45.** Coefficient of friction varying over time for Stellite 6 slid 4000 cycles against steel EN 1.4923 at a temperature of 620°C.
Fig. 46. Coefficient of friction varying over time for Stellite 21 slid 2000 cycles against steel EN 1.4923 at a temperature of 620°C.

Fig. 47. Coefficient of friction varying over time for Stellite 6 slid 2000 cycles against Stellite 6 at a temperature of 620°C.

Fig. 48. Coefficient of friction varying over time for Stellite 6 slid 4000 cycles against Stellite 6 at a temperature of 620°C.
4.3.2. Profilometer investigations
Examination of the block specimen from the hot wear tests resulted in a 3 dimensional picture demonstrating the topographical features of the worn area. The height of the specimen in different points can be obtained from color schemes ranging from the highest to the lowest point.

Results from the hot wear tests showed that the specimens were subjected to both removal and accumulation of material during sliding, which could be seen with the naked eye. This was also proved when performing the profilometer investigation. Beside the 3D pictures that clearly show the topography, data of volume values of worn as well as accumulated material was obtained too.

4.3.2.1. Profilometer results for EN 1.4903 vs. EN 1.4923
For the specimen of steel EN 1.4903 the highest and the lowest point obtained when slid 2000 cycles against the cylinder of steel EN 1.4923 was 172 µm and -105 µm respectively, as seen in figure 49. The accumulated material is concentrated in the centre of the area of contact and has an extensive height relative the zero level in comparison with the negative height difference (the removed material).

Amount of accumulated material was calculated by the software to be 0.347 mm³ while the volume of removed material reached a value of 0.397 mm³. Hence the amount of removed material is greater.
4.3.2.2. Profilometer results for EN 1.4923 vs. EN 1.4923

Evaluation of the results for steel EN 1.4923 specimen, run 2000 sliding cycles against the cylinder of steel EN 1.4923, showed that the highest point attained was 276 µm and the lowest -72 µm, as seen in figure 50. Accumulated material is spread over the contact surface and the highest point is more displaced toward the right end of the contact area than what is the case for the steel EN 1.4903 specimen. There is a large height difference from the lowest to the highest point were the height of the peak is large relative to the depth of the valley.

![3D picture extracted from profilometer investigations displaying the worn surface of EN 1.4923 slid 2000 cycles against EN 1.4923, where the rotation of the cylinder was clockwise in relation to the block in the picture.]

The amount of worn and adhered material is 0.526 mm$^3$ and 0.404 mm$^3$ respectively.

When increasing the number of sliding cycles for self-mated EN 1.4923 from 2000 to 4000 the variation in height was observed to be greater. The highest point was 562 µm and the lowest -162 µm. The placement of the accumulated material was concentrated at the first part of the contact area, at the right end, and was followed by deep grooves, see figure 51.
The amount of the removed material was measured to a volume of 0.315 mm$^3$ while there was a volume of 1.08 mm$^3$ adhered material.

4.3.2.3. Profilometer results for Vanax 75 vs. EN 1.4923

Results for the Vanax 75 specimens were similar to those of steel in terms of material being accumulated in a central part of the contact region. This material is observed to be more focused to one small area and is not particularly spread out over the contact area. When Vanax 75 slid 2000 cycles against the EN 1.4923 cylinder, the results also show small depths of the grooves in the material while the heights of the peaks were more extensive, with a lowest point at -21 µm and a highest one at 219 µm.

Values of the amount of accumulated material as well as the amount of material removed from the specimen were calculated by the software to be 0.128 and 0.074 mm$^3$. 

![3D picture extracted from profilometer investigations displaying the worn surface of EN 1.4923 slid 4000 cycles self-mated, where the rotation of the cylinder was clockwise in relation to the block in the picture.](image)
Increasing the number of sliding cycles to 4000 did not affect the highest or lowest points much for the block of Vanax 75. The highest point is now at 215 µm and the lowest at -38 µm. However results from the profilometer showed that for 4000 cycles the material seemed to have more grooves in the surface at the region where contact has occurred, see figure. 54.

The volume of the material that had been removed and the material accumulated at the contact area was once again estimated by the software to a value of 0.057 mm$^3$ and 0.058 mm$^3$ respectively.
4.3.2.4. Profilometer results for Inconel 718 vs. EN 1.4923

Investigations in the profilometer of the superalloy Inconel 718 block, slid 2000 cycles against the EN 1.4923 cylinder, showed small areas of accumulated material concentrated along one of the longer sides of the specimen, with the highest peaks reaching 28.4 µm above zero level, see figure 54. At the same time shallow grooves with a depth of 29.7 µm could be seen close to both of the longer sides but located in the centre part of the contact area.

The volumes were calculated to 0.0104 mm³ of removed material and 0.0065 mm³ of accumulated material.

At 4000 cycles there were even smaller areas of accumulated material with the highest peak reaching a level of 17.4 µm. Grooves that could be observed at the surface of the specimen were also smaller, more shallow, than for 2000, reaching a depth of -23.7 µm into the surface of the superalloy. In this case the accumulated material as well as the grooves is centered closer to one of the long sides of the specimen, with almost no sign of accumulated material along the other long side.

Fig. 54. 3D picture extracted from profilometer investigations displaying the worn surface of Inconel 718 slid 2000 cycles against EN 1.4923, where the rotation of the cylinder was clockwise in relation to the block in the picture.
The volumes of material removed and accumulated were respectively estimated to 0.00927 mm$^3$ and 0.00050 mm$^3$.

4.3.2.5. Profilometer results for Stellite 21 vs. EN 1.4923
For the specimen of Stellite 21, slid 2000 cycles against the steel cylinder of EN 1.4923 at 620˚C, it became visible that the specimen had a region of contact, which contained both a lump of accumulated material and a region with grooves on the surface. The accumulated material was located towards one of the long sides of the specimen, with a highest peak of 27.6 µm, while the grooves were centered more towards the other long side with a deepest point of -26.4 µm, see figure 56.
The volumes of material, which was removed from and accumulated at the specimen reached values of 0.011 mm$^3$ and 0.00672 mm$^3$ respectively.

4.3.2.6. Profilometer results for Stellite 6 vs. EN 1.4923

The 3D image of the specimen of Stellite 6, slid 2000 cycles against the steel EN 1.4923 cylinder at 620°C, showed distinct signs of a surface where contact had caused both a region of worn material accompanied by a region of accumulated material. These two regions where both aligned across the specimen, from one long side to the other, with the worn region located after the accumulated material in the direction of the movement of the counterpart, see figure 57. Its deepest groove reached down to -20.6 μm while the highest peak of the accumulated material measured 30.2 μm.

![3D image of specimen showing worn and accumulated material.](image)

The material, which was gathered on top of the specimen surface measured a volume of 0.00306 mm$^3$. As for the worn material it had a volume of 0.00542 mm$^3$.

The same pattern could also be seen when increasing the amount of sliding cycles, between the specimen of Stellite 6 and the cylinder of steel EN 1.4923, to 4000 instead of 2000. An area of contact was recognized, where a line of gathered material was followed by a line of grooves into the surface, both lines reaching from one long side of the specimen to the other, see figure 58. The highest and the deepest peak were measured to 35.3 μm and -58.6 μm respectively. Volumes of accumulated and removed material were calculated to 0.00846 mm$^3$ and 0.0233 mm$^3$. 
4.3.2.7 Profilometer results for Stellite 6 vs. Stellite 6
The last specimens that were investigated with a profilometer were the Stellite 6 specimens that were self-mated. Stellite 6 slid against Stellite 6 for 2000 cycles displayed a contact area with a region of gathered material reaching a height of 83.7 µm followed by a region of some small grooves with a depth of -6.7 µm, see figure 59.

The volumes were 0.0279 mm³ of gathered material and 0.000568 mm³ of removed material.
For 4000 cycles of Stellite 6 sliding against Stellite 6 at 620°C the result was similar. However for that regime the region of accumulated material was more spread along the line crossing the specimen. It also showed a lower peak, reaching 44.3 µm. At the same time the grooves were more visible and also had a larger depth, -36.6 µm, than for the 2000 cycle specimen.

This specimen was calculated to have a volume of 0.00476 mm$^3$ of material that had been adhered to the surface and a volume of 0.00327 mm$^3$ which was removed from the specimen.

4.3.2.8. Comparison of the materials
Values of volume in terms of both accumulated and removed material were gathered for all materials and regimes. These values were then inserted into diagrams, see figure 61 and 63 below, in order to enable comparisons of the different materials in terms of wear. The diagram in figure 61 shows differences in adhered material, while the diagram in figure 62 presents data for the amounts of removed material.
Fig. 61. Diagram showing data on volumes of the adhered material for all materials and sliding cycles.

Fig. 62. Diagram showing data on volumes of the removed material for all materials and sliding cycles.
4.3.3. SEM investigations

After the hot wear tests, all the specimens were investigated in a scanning electron microscope (SEM) to reveal the main wear mechanism for each material couple and test condition. In this section, the results from the different material configurations are presented.

4.3.3.1. SEM results for EN 1.4903 vs. EN 14923, 2000 cycles

It is obvious that the surface on the block of EN 1.4903 has oxidized, which can be seen in figure 63(a, b) in two different states; common oxidation of the regular surface, which was not in contact with EN 1.4923 and oxidation layers on the surface of contact. Last mentioned was taken from an area in the contact zone where part of the oxide layer was worn revealing a fresh surface where the oxide morphology is different.

Regarding the wear mechanisms, it can be seen that the material was subjected to severe adhesive wear. It is already observed at the beginning of the contact area where big lumps of adhered material are accumulated, seen in figure 63(c). In figure 63(d), one can see that the materials in contact have stuck to each other and on continuing sliding, forces got large enough for the material to shear leaving a wavelike pattern behind. These waves are a typical sign for severe adhesive wear.
4.3.3.2. SEM results for EN 1.4923 vs. EN 14923, 2000 cycles

An oxide layer was observed at the surface of the self-mated steel EN 1.4923 for which 2000 cycles were performed. In figure 64, this layer can be observed from an area of the specimen where no contact had occurred (a) and from a point on the surface where sliding contact had caused adhesion and parts of the oxide layer were scratched, forming debris on the surface (b). The investigation also showed that the main wear mechanism was severe adhesive wear indicated by the wave pattern and the lumps in figure 64(c). However, there were also obvious grooves in the material.

Fig. 63. SEM pictures of the worn surface of EN 1.4903 slid against EN 1.4923 during 2000 cycles. (a) and (b) shows the oxide layer caused by the high temperature. At (a) the materials are not in contact with each other resulting in an undisturbed oxide layer while the layer in (b) has been subjected to wear and part of it has been removed. Severe adhesive wear is shown in (c) at the beginning of the contact area and (d) in an arbitrary point in which the characteristic wave pattern can be seen.
4.3.3.3. SEM results for Vanax 75 vs. EN 14923, 2000 cycles

After 2000 cycles of sliding at 620°C between the Vanax 75 specimen and the steel cylinder of EN 1.4923, it was observed that the Vanax 75 specimen also had an oxide layer covering the entire surface. The same type of oxide morphology of the surface was observed as for steel EN 1.4903, see figure 67(a).

The first part of the contact area is displayed in figure 67(b), where the main piece of adhered material is visible. Adhesion of steel EN 1.4923 was verified by EDX investigation of the lump of accumulated material on the surface and in a point where no contact has occurred. Analysis of amount of material in the mentioned lump shows a value of vanadium that is ten times lower than
the value in the point with regular oxidized Vanax 75, see Table 8. This implies that the adhered material comes from the cylinder of steel EN 1.4923.

Fig. 65. Selected point for EDX investigation, to verify adhered EN 1.4923 on Vanax 75. Point taken from suspected adhered material.

Fig. 66. Selected point for EDX investigation, to verify adhered EN 1.4923 on Vanax 75. Point taken from material outside of the contact area.

Table 8. Wt% of elements present in spectrum 1 and 2 in figure 65 and 66.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>O</th>
<th>V</th>
<th>Cr</th>
<th>Mn</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum 1</td>
<td>38.89</td>
<td>0.05</td>
<td>2.33</td>
<td>0.29</td>
<td>58.43</td>
<td>100</td>
</tr>
<tr>
<td>Spectrum 2</td>
<td>35.32</td>
<td>0.58</td>
<td>1.91</td>
<td>-</td>
<td>62.19</td>
<td>100</td>
</tr>
</tbody>
</table>

There is a clear sign, in figure 67(c), that contact occurred between the two surfaces in the shape of a tribolayer with areas of smeared material from the counter body (EN 1.4923) on a scratched surface of Vanax 75. The scratches, which also can be seen in lower magnification in (d), are caused by oxide debris distributed over the surface. Thus there are two wear mechanisms present in this tribocouple and to distinguish the main mechanism the surface was further investigated by EDX.
Evaluation of EDX showed that the scratches were shallow, only damaging the oxide layer, leaving the Vanax 75 matrix untouched. This was explained by the investigation of the chemical composition, which showed that the amount of oxygen was relatively high indicating a remaining oxide layer on top of the matrix of Vanax 75, hence the abrasive wear is not as severe as the adhesive wear.

**Fig. 67.** SEM pictures of the worn and oxidized surface of Vanax 75 slid 2000 cycles against steel EN 1.4923 at 620°C. (a) shows the oxide morphology of the untouched surface. In the first contact point (b) there is adhesive wear and there are also scratches on the surface, due to oxide debris, which can be seen more evident in (c) and (d).
When the Inconel 718 specimen was investigated in SEM, the results clearly showed a much rougher surface than for the earlier investigated materials; steels EN 1.4903, EN 1.4923 and Vanax 75. This was despite the material was prepared in the exact same manner as the others. It could also be noted, for the specimen that slid against the steel cylinder of EN 1.4923 at 620°C for 2000 cycles, that the area of contact reached across the middle of the specimen in a narrow line, see figure 69(a). The same observation was also made just by looking at the specimen with the naked eye. At a closer look at the worn area of the specimen, a layer of smoothened material was recognized at the surface of the material, mapping of a part of that area showed that this layer was a mixture of oxide, material from the counterbody and fresh Inconel 718. A tribolayer seems to have been formed at the surface, making the specimen much smoother in the area of contact than at the rough, untouched surface.

**Fig. 68.** Diagrams extracted from EDX demonstrating amounts of different elements along the scanning line, visible in the micrograph. The lower amount of vanadium and chromium together with the higher value of iron, at the section of the line corresponding to the adhered particle, indicates that the particle comes from the counterbody of steel EN 14923.

The scratches of the surface do not penetrate the oxide layer all the way through to the Vanax 75 matrix, proved by the high oxygen levels.

### 4.3.3.4. SEM results for Inconel 718 vs. EN 14923, 2000 and 4000 cycles

When the Inconel 718 specimen was investigated in SEM, the results clearly showed a much rougher surface than for the earlier investigated materials; steels EN 1.4903, EN 1.4923 and Vanax 75. This was despite the material was prepared in the exact same manner as the others. It could also be noted, for the specimen that slid against the steel cylinder of EN 1.4923 at 620°C for 2000 cycles, that the area of contact reached across the middle of the specimen in a narrow line, see figure 69(a). The same observation was also made just by looking at the specimen with the naked eye. At a closer look at the worn area of the specimen, a layer of smoothened material was recognized at the surface of the material, mapping of a part of that area showed that this layer was a mixture of oxide, material from the counterbody and fresh Inconel 718. A tribolayer seems to have been formed at the surface, making the specimen much smoother in the area of contact than at the rough, untouched surface.
It was also noted that the surface, where contact took place, contained some darker spots, which were analyzed by chemical composition and shown to be adhered material in combination with oxide. This could be proven by mapping of the darker spot, seen in figure 70, where nickel was the main element in the surrounding matrix, together with some chromium, while iron and oxygen were the two predominant elements of the dark spot.

**Fig. 69.** SEM pictures of the worn surface of Inconel 718 slid 2000 cycles against steel EN 1.4923 at 620°C. Inconel 718 has a narrow area of contact (a) and a rougher surface than earlier materials (b). The area where contact has occurred contains darker areas corresponding to oxides (c) and a tribolayer, where the material has been smoothened (d), consisting of material from oxides, counterbody and fresh Inconel 718.
The specimen that run against EN 1.4923 at 620˚C for 4000 cycles showed the same tendencies as the one run for 2000 cycles in terms of a rougher surface at the untouched areas of the material and a smoother layer, a tribolayer, at the area where contact occurred. In the same way as the previous specimen it also contained dark spots corresponding to oxides, see figure 71, and after 4000 cycles these spots were many more than after 2000 cycles, see figure 71(c).

**Fig. 70.** SEM pictures from mapping of a darker spot found at the surface of Inconel 718 slid 2000 cycles against steel EN 1.4923 at 620°C. Lighter areas represent areas where a specific element is present in large amounts. The matrix material, surrounding the dark spot, shows large amounts of nickel (a) and some chromium (b). The spot, on the other hand, seem to consist mainly of iron (c) and oxygen (d).
The particle, which is displayed in figure 72(b), was further examined in SEM by mapping, to see differences in chemical composition and investigate what elements were present in the particle and surrounded it. Mapping resulted in the knowledge that the particle in itself was consisting of mostly iron and oxygen and it could, therefore, be assumed that it was iron-oxide. The area surrounding the particle mainly consisted of nickel together with some chromium and oxygen. This result is shown in figure 72.

*Fig. 71.* SEM pictures of the worn surface of Inconel 718 slid 4000 cycles against steel EN 1.4923 at 620°C. The specimen shows a smoothened area of contact (a) containing oxide particles seen with backscattered electrons (b). These oxides were spread out over the surface (c) and were more than after 2000 cycles. A tribolayer was observed, consisting of material from oxides, counterbody and fresh Inconel 718 (d).
The nature of the surrounding material reminded of the tribolayer which was mentioned for the specimen of Inconel 718 run for 2000 cycles. To investigate this more thoroughly, scanning was performed along a line at the surface. It showed that there were several phases existing within the tribolayer. There was one area along the line, on top of the image (figure 73), which was rich of iron and oxygen but low of nickel and chromium, indicating a layer of iron-oxide, which might originate from the counterbody of steel EN 1.4923. Then there was an area at the center of the line with high amounts of nickel and chromium, indicative for fresh surface of the superalloy itself. At the lower part of the line, bottom of the image, the layer was constituted by nickel, chromium and oxygen resembling the tribolayer from the 2000 cycle specimen where a mixture was formed of worn material from both the specimen and the counterbody. These results are demonstrated in figure 73.

**Fig. 72.** SEM pictures from mapping of a darker spot found at the surface of Inconel 718 slid 4000 cycles against steel EN 1.4923 at 620°C. Lighter areas represent areas where a specific element is present in large amounts. The dark spot show some amounts of oxygen (a) and large amounts of iron (c), while the matrix material consists of nickel (d) and some chromium (b) and oxygen (a).
4.3.3.5. SEM results for Stellite 21 vs. EN 14923, 2000 cycles

An analysis was made in SEM of the Stellite 21 specimen which slid 2000 cycles against the steel cylinder of EN 1.4923 at 620°C. This analysis showed that the Stellite specimen had an oxidized surface in the untouched areas, just as previous specimens showed. However, the oxidized surface did not look exactly the same but contained both a flake-like phase and a triangular phase, see figure 74(a). The first contact point displayed evident signs of adhered material. A closer look at the area of contact revealed that not much of the scratches in the base alloy material could be seen in the worn region, implying a rather high amount of wear. By using backscattered electrons in SEM, it could also be determined that the area of contact consisted of regions of a darker shade of grey apart from the light grey regions of the regular surface. Part of the region where contact was observed, figure 74(d), was further explored by mapping to investigate what these darker regions were.

Fig. 73. EDX pictures from scanning along a line at the surface of Inconel 718 slid 4000 cycles against steel EN 1.4923 at 620°C. The dark grey area at the top of the image show large amounts of iron and oxygen, corresponding to iron-oxide. The light part in the middle consist mainly of nickel and chromium, corresponding to a fresh surface of Inconel 718, and the light grey area at the bottom contain both nickel and chromium as well as oxygen, a tribolayer formed by a mixture of worn material from specimen and cylinder.
From mapping an area within the contact zone, the chemical analysis, figure 75, could be attained. It became clear that the light-grey regions consisted mainly of cobalt, chromium and some molybdenum. These are all elements present in the chemical composition of the base alloy, Stellite 21, and the results, therefore, imply that at these regions the oxygen layer is very thin almost exposing the base material. At the same time the darker regions consist mostly of oxygen and iron, implying adhered material in the form of iron-oxide which would then be debris from the steel counterpart. This theory is also supported by the scan performed, seen in figure 76, displaying a line scan along the contact region where signals of the different elements are shown.

Fig. 74. SEM pictures of the worn surface of Stellite 21 slid 2000 cycles against steel EN 1.4923 at 620°C. The specimen shows an oxidized surface at the untouched regions (a) containing oxide flakes seen with backscattered electrons. The area of first contact display adhered material (b) and when looking closer at the area of contact it could be seen that almost no scratches were visible, implying high wear (c). A region in the contact area was examined with backscattered electrons (d) and was used for mapping and line scanning.
Fig. 75. Maps from SEM of chemical elements present in the different regions in the area of contact (seen in a)) where light regions represents regions where the specific element is present. The darker parts seem to consist of iron, b), and oxygen, c), while the lighter areas consist of chromium, d), cobalt, e), and some molybdenum, f).

Fig.76. Line scan performed in EDX across a part of the contact region showing signals of different elements present along the line. A high signal means that the specific element is present in rather high amounts at that point. Dark regions give high signals for oxygen and iron, while light regions have high signals for chromium and cobalt especially.
4.3.3.6. SEM results for Stellite 6 vs. EN 14923, 2000 and 4000 cycles

Adhered material was also observed in the beginning of contact for the Stellite 6 specimen, which slid 2000 cycles against the steel cylinder of EN 1.4923. It also contained oxides attached to the surface, seen in figure 77. When the areas with adhered material were examined at a higher magnification one could see that in between the adhered material and the oxides, polishing scratches were still visible. These came from previous polishing operation of the specimen and they imply that the base material was not worn down much, but the main wear mechanism was adhesion.

**Fig. 77.** SEM pictures of the worn surface of Stellite 6 slid 2000 cycles against steel EN 1.4923 at 620°C. The specimen shows adhered material (a) and signs of oxidation at the beginning of contact (b). These oxides were spread out over the surface but in between one could clearly see the scratches from matrix (c). An area of the contact region was investigated with backscattered electrons (d) and was also used for examination with point spectra.
Two images of the contact area, taken in the backscattered electrons mode, were used to perform mapping as well as a line scan in the area. This was in order to establish what kind of material was adhered to the surface and which other elements were present on the surface.

The image chosen for mapping demonstrated a region of the contact zone containing two distinct particles, and the aim of mapping was, therefore, to determine the nature of those particles. Results, which can be seen in figure 78, showed that two particles were consisting of mainly four elements - iron, oxygen, chromium and manganese. This result yielded the conclusion that the adhered particles were debris from the counterpart fabricated of steel EN 1.4923.

![Maps from SEM of chemical elements present in the two particles at the surface of the specimen, in the area of contact. Light regions represent regions where the specific element is present. The two particles seem to consist of oxygen, chromium, iron and manganese.](image)

The line scan was then made along a line reaching through another selected region of contact in a way so that it covered all the regions of different gray colors. This resulted in figure 79, exhibiting high values of oxygen and iron in the grey particle to the right, high values of magnesium, potassium, calcium and silicon in the dark grey area and high values of cobalt and chromium in the lightest region, which is corresponding to the base alloy. It can, therefore be believed that the larger particle on the right side is constituted of iron-oxide and that it is adhered material coming from the steel counterbody. The values of magnesium, potassium, calcium and...
silicon were confusing but believed to be contaminations or some sort of particle of a foreign material.

After 4000 cycles the material showed the same tendencies as for 2000 cycles, apart from the fact that more oxidation and more wear occurred as a result of the longer sliding time. The Stellite 6 specimen, which slid against the steel cylinder of EN 1.4923 at 620°C, had adhered steel at the surface within the area of contact. It also demonstrated a region of abrasive wear following the region of adhered material, a typical sign for all the Stellites, which can be seen in figure 80(a).

**Fig. 79.** Line scan performed in EDX across a part of the contact region showing signals of different elements present along the line. A high signal means that the specific element is present in rather high amounts at that point. The grey particle, to the right, contains mainly iron and oxygen. Dark regions give high signals for oxygen, magnesium, calcium, silicon, potassium and tungsten, while light regions have high signals for chromium and cobalt but also contain some amount of oxygen.
4.3.3.7. SEM results for Stellite 6 vs. Stellite 6, 2000 and 4000 cycles

The experimental section of the thesis also consisted of a reference part, corresponding to the materials which are in use in the bushings and bearings today and which are thereby slid against each other. This reference contact pair consisted of Stellite 6 slid against Stellite 6 at a temperature of 620°C. The specimen run for 2000 cycles was examined in SEM and, as one can see in figure 81 below, the material surface had regions with adhered material on top. When looking at those regions of adhered material at a higher magnification, a special patterned at the surface was noted. The adhered particle seemed to be mechanically alloyed by repeated deformation during contact between the two counterbodies. Once again it was interesting to

Fig. 80. SEM pictures of the worn surface of Stellite 6 slid 4000 cycles against steel EN 1.4923 at 620°C. The specimen shows a typical wear pattern, as for all Stellites (a) with adhered material at the beginning of contact (b) followed by a region of abrasive wear (c). An area of the contact region can also be seen with backscattered electrons (d) where the same phases are present as for 2000 sliding cycles.
explore these regions by mapping and line scanning to determine the origin of the adhered material and its constitution.

**Fig. 81.** SEM pictures of the worn surface of Stellite 6 slid 2000 cycles against Stellite 6 at 620°C. The specimen shows adhered material (a) which seem to have been mechanically deformed, mechanically alloyed (b). One can also see a region of different phases on top of the surface (c) and (d).

Mapping of the region in figure 82, (c), showed that the oxygen level was not remarkably different in the different zones, apart from two regions at the edges of the particle. Concentrations of iron were small and consistent throughout the area. Consistent values were also seen for chromium and molybdenum, while cobalt had high values throughout the area but demonstrated two regions where the values were lower. These were the same regions as contained the highest values of oxygen, see figure 82. These results implied that the oxygen-rich regions were oxides while the larger adhered particles consisted of a mixture of the different materials, into which oxygen was embedded by mechanical alloying during contact.
A line scan was additionally performed examining the signals from different elements in the area of contact. These results are demonstrated in figure 83 below. They supported the results from mapping by displaying rather consistent signals, along the line, for all elements apart from oxygen and cobalt. Oxygen levels were extra high at the edge of the adhered particle, and in the same area the signal from cobalt was lower than along the rest of the line.

**Fig. 82.** Mapping made in SEM showing contents of various elements in a region of adhered material. Light areas in the maps represent high values of that specific element. There is a consistent amount of aluminum, chromium, molybdenum and iron within the region. Oxygen and cobalt also appear to be evenly distributed, apart from two areas at the edge of the adhered particle, where there is more oxygen and less cobalt.

**Fig. 83.** Line scan performed in EDX showing rather consistent signals from all elements apart from Oxygen and Cobalt which give higher and lower signals, respectively, at the part of the line lying on the edge of the adhered particle.
The reference test of Stellite 6 against Stellite 6 was also performed for 4000 cycles at the same temperature of 620°C. From investigations of this specimen in SEM information of wear patterns was extracted. These were similar to those observed for the specimen after 2000 cycles, namely adhered material was observed on the specimen surface. However, there were larger regions of oxidation observed after tests in this regime. Among the adhered material at the surface larger particles were observed, see figure 84, similar to the ones observed for the 2000 specimen, which was mechanically alloyed. It was determined that these particles came from the counterbody, since the original scratches on the base alloy surface could still be visible around the adhered material and were not removed. This would have been the case if the specimen had been much worn.

**Fig. 84.** SEM pictures of the worn surface of Stellite 6 slid 4000 cycles against Stellite 6 at 620°C. The specimen shows an area of contact containing adhered material (a) with some larger adhered particles (b). These particles could also be seen with backscattered electrons (c) and in higher magnification (d) and was mechanically alloyed in the same way as the 2000 cycle specimen.
Mapping in SEM of one of the particles observed on the surface was performed, figure 85. Signals were observed for oxygen, cobalt, chromium, tungsten and iron and was not homogeneous, but the result was of the same kind of mechanical alloying as for the specimen after 2000 cycles.

**Fig. 85.** Mapping made in SEM showing contents of various elements in a region of adhered material. Light areas in the maps represent high values of that specific element. The particle is inhomogeneous showing signs of oxygen, cobalt, chromium and tungsten as well as iron.
5. Discussion

Inconel 718 was selected as an alternative superalloy that may suit as substitution for the high-cobalt alloys. As a base for this selection, table 2 and 3 were used. The tables were compilations of high temperature values of yield strength, tensile strength and thermal expansion. It can clearly be seen that at 650°C Inconel 718 and Nimonic 942 are the best ones, where Inconel 718 has the highest yield strength, while Nimonic 942 has the highest tensile strength. However, if taking the price in consideration, the obvious choice between those two is Inconel 718. This was also supported by the fact that Inconel 718 has a good weldability and slightly better thermal expansion at a temperature of 538°C, which are important properties to consider in the valve industry.

The simulation of the entire contact situation for the valve showed that the seat behaved in an expected manner with an elliptical deformation as well as a bending in the rotational direction of the disc, making the valve possible to fully close. The simulation also verified that maximum contact pressure is located at three o’clock corresponding to the case study. The maximum value of 220 MPa, is not reliable since the value was highly dependent on the degree of fineness of the mesh. Unfortunately there was no line contact between the seat and the disc either, even though there should be, since it is obvious in figure 32 that the valve is totally closed. Instead there was a point contact all around the contact surface. The reason for this is uncertain but it may depend on the interaction properties, which were set for the mating surfaces. Since the geometry, and hence the surfaces, of the valve are quite complicated it may be difficult to find a proper way of defining the contact situation without making any further simplifications. In the second simulation, the parts were scaled to smaller sections resulting in a line contact. Another simplification, as mentioned before, was that the boundary conditions were more restricted since the seat could not move in the radial direction. This removes the possibility for the seat to elastically deform in the elliptical manner and may cause higher stresses than in reality. However, it is hard to say how much this influences the result but since the value for the highest contact pressure, 220 MPa, is in the same order of magnitude as the analytically calculated value of 517 MPa for the contact pressure, this source of error is not that extensive. The analytically calculated value is probably more reliable than the simulated value, being derived from the Tresca yield criterion, and was therefore used in the hot wear tests. Value for contact pressure was taken when
the yield limit for the seat material was reached, at 310 MPa, since very little plastic deformation of the seat is allowed and contact pressures obtained after this point will, therefore, not be of interest for this application.

Common for all specimens that were tested in the hot wear machine was that the highest peak of accumulated material was located at the beginning of the contact area. This is due to the rotational direction of the cylinder. At the first contact point, material that stuck to the surface of the cylinder will be released and attached to the specimen surface. Another observation for all materials was that they all were exposed to oxidation during the operation. The oxide layer, which was detected, was similar in the areas of the specimen surface untouched by the cylinder. On the other hand the continuous oxidation in the contact area differed between the materials. Important to consider, during evaluations of tests and wear rates, is that the contact area increases due to wear and deformation of the specimens. This means that the contact pressure decreases from 2000 to 4000 cycles, which, in turn, results in a decrease in wear rate. This decrease varies between the investigated materials since the contact area does not increase in the same way, depending on the mechanical properties of the material. Therefore the amounts of wear of two materials may be similar after 2000 cycles but the differences in wear rates may cause one of the materials to exhibit much more extensive wear than the other after 4000 cycles.

One thing to bear in mind when considering the results from the hot wear tests is that the test conditions were somewhat modified and do not completely correspond to the real application. Main determining factor for these tests was the rotation speed of the. According to calculations, the rotational speed of the cylinder should be 628 mm/s, but 500 mm/s with the braking moment in consideration. This braking moment is, however, just an assumption because no values for how much the disc slows down before contact could be estimated either by AB SOMAS Ventiler or the manufacturer of the actuator. This was of less importance for the results since none of the velocities mentioned above were reached during the tests even though the settings were adjusted to achieve the right value of 500 mm/s. Seeing as the settings were right, the conclusion was that the machine needs a certain time to both accelerate and decelerate. Since the sliding time was set to a narrow interval of 0.3 seconds the machine will probably never have time to reach the intended speed. Even if it would do so, it would be for a short period of time. Another, probably not with the same effect on the results, was that the amount of water vapor and the applied
normal force was manually regulated and, hence, differed between the tests. Additionally the pressure in the valve is not represented in the test equipment.

Coefficients of friction for all material couples were very similar to each other but it was obvious that the three steels showed slightly higher values. This is believed to be due to the lower hardness of these materials and the fact that there is a steel against steel situation resulting in the same complications as for the wear situation, discussed later in this section. Inconel 718 versus EN 1.4923 and self-mated Stellite 6 exhibited the lowest values of coefficient of friction. But a closer look at the curves reveals that the friction is higher at the beginning, with values similar to the steels, and decreases after a couple of minutes. Such behavior is caused by glaze layer formation for Inconel 718 and by deformation hardening and the formation of an easily sheared layer for self-mated Stellite 6.[30][43]

Steel EN 1.4903 was only tested for 2000 cycles and for this regime the amount of accumulated material was 0.347 mm$^3$. The lump of adhered material seemed to be located in the middle of the area of contact since there is visible deepenings on each side of the lump. However, from the SEM investigation, it was discovered that the lump was actually situated in the beginning of the contact, which is more consistent with the theory described above. It was also determined that the lump was actually the adhered material from the counterbody. It could also be seen that there was a wavelike pattern on the surface of the material suggesting a situation of severe wear. That sort of pattern is formed when the mating materials get stuck, due to adhesion, and are then released if the sliding force is high enough to break the bonds between the material surfaces. The severity depends on the strain hardening which occurs at surface junctions, mentioned in the section about wear, 2.3.1.1, causing the material to shear and break.

![SEM Images of the Worn EN 1.4903 Specimen](image.png)  
*Fig. 86. SEM images of the worn EN 1.4903 specimen, illustrating the characteristic wave pattern of severe adhesive wear.*
deeper within the structure and resulting in larger amounts of adhered material [10]. Severe wear was also expected since the two materials slid against each other were both steels with comparable chemical composition, see table 2 and 4. This contact usually leads to the creation of stronger bonds, increasing the probability for strain hardening to occur. There were also parts of the material that was worn off and the amount of worn material reached 0.397 mm$^3$. Removal of material could, in this case, be caused by several factors. On one hand, the adhesive wear could lead to the arising of two sorts of abrasive wear. Either adhered material from the block of EN 1.4903 stuck to the cylinder of EN 1.4923 created a situation of two-body abrasive wear, described in chapter 2.3.1.1, or the material formed debris between the surfaces resulting in three-body abrasive wear. Abrasive wear was implied by scratches on top of the accumulated material, seen in figure 63. Another explanation is that breakage occurs within the weaker material, EN 1.4903. This would mean that the worn material was removed due to adhesion and in a second step once again stuck to the specimen surface but in the shape of a lump. Scanning of the adhered material could not prove whether the lump consisted of EN 1.4903 or EN 1.4923.

Steel EN 1.4923 was tested for 2000 and 4000 cycles. Regarding the tests for 2000 cycles, it was observed that the amount of adhered material was 0.404 mm$^3$, which is more than that observed for the specimen of EN 1.4903, even though it is a harder material and should therefore be more wear resistant. Self-mating of the steel is the reason for this, according to the earlier explained theory of adhesive wear and the effect of the similarity of the two materials in contact, in contrast to the previous section where there was a slight difference between the steels [10]. Even in this case, the accumulated material was situated at the first contact, which was observed in SEM. Severe adhesive wear was, in this case,
proved by the same wave-like pattern on the surface and this was the main wear mechanism. Amount of removed material was greater than for the specimen of EN 1.4903 with a value of 0.526 mm$^3$. In this case, it is clear that the removal of material was caused by both adhesive and abrasive wear.

Removal of material by adhesive wear is the same as for the EN 1.4903 specimen but here it is also obvious that abrasive wear caused deep groves at the surface. The mechanism causing abrasion is wear debris formed from the scratching of the oxide layer. At 4000 cycles, the changes of the surfaces morphology looked a lot like those for 2000 and hence the conclusion was made that the same wear mechanisms were active in this case. Amount of adhered material was larger for 4000 cycles, 1.08 mm$^3$, and this is believed to originate from the longer exposure to sliding contact.

Investigations of the Vanax 75 specimen revealed that the main piece of adhered material was stuck in the center of the area of contact and profilometer tests showed small traces of removed material in the area. This was verified by the values of 0.074 mm$^3$ removed material. Amount of adhered material was less than for the other two steels with 0.128 mm$^3$. The key to the higher wear resistance of this material is the hard phases present in the matrix, as was discussed by Odd and Alf Sandberg in their paper on nitrogen alloyed steels [48]. This phase is densely and homogenously distributed in the microstructure and all over the surface. Another explanation could be that Vanax 75 contains vanadium nitrides. Research on the subject, performed by Fateh et al., has revealed that vanadium nitrides have the tendency of forming oxides (Magnéli oxides) with easily sheared planes when observed in VN-coatings[52].

SEM investigations revealed a tribolayer existing on the surface of the block of Vanax 75, probably built up by the easily sheared planes within the oxides. When relating this to the wear map, developed by Inman et al. [17] in figure 11, it can be believed to be in a region comparable to the high Co-Cr glaze formation in the bottom right corner. However, this is a specific wear map constructed for Incolloy MA956 against Stellite 6 and it is difficult to predict what a similar map would look like for the tribocouple of Vanax 75 against the cylinder of EN 1.4923. Important is that the velocity in the tests was not as high in the reality, as mentioned above. Tests at higher velocity would increase the flash temperature on the y-axis in the wear map so that severe adhesive wear would be active before the glaze layer formation could start. If that would
be the case, the wear of Vanax 75 might be worse than the hot wear tests revealed. Areas of smeared material at the surface were proven by EDX to come from the counterbody of EN 1.4923. These conclusions were drawn from comparisons of chemical compositions of EN 1.4923, Vanax 75 and spectrum analysis of the lump, based on tables 5, 6 and 8. Most evident is the small amount of vanadium present in the accumulated material together with the presence of manganese, which should not be detected if the material was Vanax 75. This was verified by EDX performed in a point outside of the area of contact, which showed higher amount of vanadium, 0.58 compared to 0.05 in the accumulated material, and no manganese at all. However, this amount of vanadium is still quite low as Vanax contains 9 wt% of this element. This is due to the oxide layer covering the surface of Vanax 75 decreasing the amount of vanadium detected during EDX investigation. Scratches seen on top of the lumps are believed to be caused by oxide debris stuck between the two surfaces. Other scratches that were observed on top of the Vanax 75 surface, where no adhesion had occurred, were also investigated by EDX. The results stated that those scratches only penetrated into the oxide layer but never through the layer into the fresh surface of Vanax 75, indicating that the oxide layer acts as a protective layer [17]. This means that the main wear mechanism for these materials was adhesion, since it affects the Vanax 75 surface in a greater manner with small adhered particles spread across the surface. Abrasion, on the other hand, only damaged the oxide layer which has the ability to reconstruct itself during operation.

When increasing the number of sliding cycles to 4000, there was a decrease in amount of adhered material in comparison to 2000 cycles tests. An explanation to this is that when the operation time is extended more oxide debris will be formed and, hence, there will be more particles able to wear down adhered material on the surface. However, the abrasive wear on the free Vanax 75
surface behaves in the same manner as before, which is indicated by the amount of removed material for 4000 cycles comparable to that for 2000. The values were 0.057 and 0.074 mm$^3$ respectively.

For the Inconel 718 specimens, observations with the naked eye showed that the area of contact was much smaller than for the previous materials and the total wear was smaller. The profilometer demonstrated lower amounts of adhered and removed material, 0.0065 mm$^3$ and 0.0104 mm$^3$, and smaller grooves and accumulations on the surface. SEM showed a surface covered with dark spots and a tribolayer of smeared materials. EDX mapping of one of the spots in SEM discovered that it contained high amounts of oxygen and iron and it was, therefore, concluded that the spot was actually an iron oxide. The tribolayer observed on the surface was proved to consist of a mixture of adhered EN 1.4923 and Inconel 718, by the line scan in figure 73. The layer reminds of the glaze layer formation present in several regimes within the wear map, by Inman et al., in figure 11 [17]. Of reasons stated above, it can not be decided exactly in which regime it is, only that glaze formation occurred. There were no prominent signs of scratches visible on the surface of the Inconel 718 specimen and, therefore, it can be concluded that abrasive wear does not play a decisive role for this tribocouple. This could be because the tribolayer acted as a solid lubricant between the surfaces. Increasing the number of cycles to 4000 resulted in similar wear of the surface with the same observation of a tribolayer but with a higher amount of oxides, which is caused by a prolonged time exposure at high temperature.

Results for investigations with profilometer of the reference couple Stellite 21 slid against the cylinder of EN 1.4923 showed that there are regions of both removed and adhered material. The areas of removed material were concentrated towards one of the long sides of the specimen and

![Fig. 89. SEM image of the specimen of Inconel 718, showing a surface covered with a tribolayer and with dark spots visible.](image_url)
the adhered material towards the other. However, this pattern does not completely coincide with the typical wear pattern, which was observed for all the other Stellite specimens, where a narrow region of adhered material across the specimen was followed by a similar region of removed material. An explanation for this could be that the specimen, when mounted within the test equipment, was not aligned correctly, causing wear mechanisms to be irregular across the specimen. The volumes of material, which were removed and accumulated, reached values of 0.011 mm$^3$ and 0.00672 mm$^3$ respectively. These low values can be connected to the much smaller area in which wear occurred for the specimen of Stellite 21 in comparison with the other steels. But a closer look at that area, in SEM, revealed that within the worn areas, the effect of wear on the surface was rather extensive. These results, together with the fact that the scratches produced by polishing the specimen were almost not visible in the area of contact, implied a rather high amount of wear in the small region. But when looking at the big picture, the total amount of wear is still quite low for the Stellite 21 specimens. The high wear in the small region was, however, expected since Stellite 21 exhibit lower hardness than Stellite 6, see table 6, even though they are both referred to as hard materials.

![SEM image of the specimen of Stellite 21 slid against EN 1.4923, showing a rather extensive wear with almost no polishing scratches visible.](image)

The specimen of Stellite 6 slid against the EN 1.4923 steel cylinder, showed the typical wear pattern mentioned above with a region of accumulated material followed by a somewhat broader region of worn material. They measured up to values of 0.00306 mm$^3$ of accumulated and 0.00542 mm$^3$ of removed material. Adhered material on the surface of the Stellite 6 specimen was not as smeared out as for the specimen of Stellite 21 and was visible in the shape of small and spread out glomerations.
In between these glomerations, the regular surface of the specimen was clearly visible. Mapping showed that the adhered material was oxidized EN 1.4923 from the counterbody. One could also easily detect the scratches originating from preparation, indicating that the surface was kept relatively undeformed. This is evidence for a much lower degree of abrasion than for the Stellite 21 specimens, which was also confirmed by the mentioned values. Reasons to why this Stellite behaves like this is discussed in a thesis on the behavior of Stellites, by Daniel Persson. It describes how these superalloys form a strain hardened layer, at the very top of the surface. This layer is caused by a stress induced phase transformation from FCC to HCP. Layers within the HCP structure align themselves parallel to the sliding plane, making the abrasive affect less severe due to easily shearing. This superficial layer acts as a solid lubricant and can be compared to the glaze layer, with the same function, which is active for other superalloys. Increasing the amount of sliding cycles to 4000 showed the same wear behavior as for 2000 cycles, with the only difference that the wear was more extensive due to the longer operation time at high temperature. This could also be verified by the volumes of accumulated and removed material, which were calculated from the profilometer investigation to be 0.00846 mm$^3$ and 0.0233 mm$^3$ respectively.
Examinations of self-mated Stellite 6 specimens showed very small amounts of removed material from the specimen surface. A value of 0.000568 mm$^3$ was reached for this material couple. This can be connected to the recently mentioned Stellite characteristics yielding a top surface of an easily sheared layer, serving as a solid lubricant [43]. This, in its turn, decreases the friction between the surfaces and reduces abrasion. In this case, the tribocouple consists of a set of two easily sheared layers sliding against each other, resulting in the very low tendencies to be abrasively worn. Adhesive wear seemed to be the main wear mechanism in this test with a value of adhered material of 0.0279 mm$^3$. Self-mating is the key to the higher adhesive wear since two equal surfaces tend to bond more easily to each other, see section 2.3.1.1. [10], as for the case with steel EN 1.4923. At 4000 cycles of the same self-mating tribocouple the same wear mechanisms were observed, with a larger adhesive part than the abrasive part. But in this case, the difference in removed and adhered material was smaller since the abrasive part increased while the adhesive decreased. The numbers were 0.00476 mm$^3$ of adhered material and 0.00327 mm$^3$ of removed material. A reason for this is that at the longer operation time, more abrasive particles are produced, in the shape of wear debris, which results in more pronounced third-body abrasion. At the same time the debris wears the surface of the adhered particles and hence the adhered volume decreases.

The materials were compared to each other from a wear point of view, according to figure 61 and 63, where the volume of the lumps in the contact regions correspond to adhesive wear and the volumes of the grooves correspond to abrasively worn material. It is obvious that the steels, EN 1.4903 and EN 1.4923, experienced higher wear rates both for the adhesive and the abrasive mechanisms. The steels both showed an adhesive wear that was 3 times the amount of adhesive wear for the Vanax 75 specimen, which was the second worse. When considering in which part

![Fig. 92. SEM image of the specimen of Stellite 6 slid 2000 cycles against a Stellite 6 cylinder, revealing a high amount of adhered material accumulated on the surface](image)
of the valve the substitution material is to be used it becomes interesting to compare it to its reference material. For EN 1.4903, the values of adhered material was about 50 times higher than Stellite 21, while the amount of worn material was just under 40 times higher. Hence, the differences were way too extensive in order to consider using steels as a replacement. The steel specimen of EN 1.4923, on the other hand, was compared to Stellite 6. With an adhesive wear that was about 130 times higher both for 2000 and 4000 cycles, and an abrasive wear that was 100 and 13 times higher respectively, even this material is rejected as a substitution material for the valve. As discussed, the specimen of Vanax 75 showed much higher wear resistance than the other steels, probably due to the easily-sheared layer of oxides. Vanax 75 was compared to both Stellite 6 and Stellite 21. When comparing to Stellite 6 specimens, it showed an adhesive wear 42 times greater for 2000 cycles and about 7 times greater for 4000 cycles. Regarding the abrasive wear, the amounts of worn volume was also greater than for the reference with about 14 times higher at 2000 cycles and a little less than 3 times higher at 4000 cycles. It seems as the differences in volumes between the block of Vanax 75 and the references decreases as the operation time increases, so it may be so that the materials become more equivalent by time. However this is not of interest for this specific application since the operation times will not exceed the times represented by the 2000 and 4000 cycles in the tests. Since there are no values specified for the amount of worn material allowed for the valve, it is difficult to make a conclusion whether or not Vanax 75 is a sufficiently good substitution for the Stellites. It does, however, exhibit much better wear properties than the other tested steels.

Inconel 718 was compared to Stellite 6 and Stellite 21 specimens. Comparisons of Inconel 718 with Stellite 6 showed that the adhesive wear was only two times greater for the Inconel 718 specimen after 2000 cycles but at the same time it was 17 times lower when the number of cycles was increased to 4000. This implies that the assumed glaze layer, formed on the Inconel 718 specimen, during sliding will act more effectively during time than will the easily sheared layers of Stellite 6. When comparing the worn volumes, the block of Inconel 718 showed a similar tendency with almost twice as much worn material after 2000 cycles but 2.5 times lower amounts at 4000 cycles. When instead comparing to Stellite 21, it was observed that the wear of the Inconel 718 block and the Stellite 21 block was almost equal. Therefore, this would be the most interesting material, of all tested, for substitution from a wear perspective.
Materials that were tested as substitution for Stellite 6 were earlier compared to results for the hot wear tests performed on Stellite 6 versus EN 1.4923. However, in the real situation it is actually self-mated Stellite 6. The reason why Stellite 6 was not tested against Stellite 6 was merely due to the high cost and time consuming process of producing such coated cylinders. Even though the comparisons were not to the self-mated Stellite 6 it was assumed that if the material is good in comparison to Stellite 6 versus EN 1.4923 it will be good even when comparing to the self-mated Stellite 6.

When it comes to the price issue it is difficult to make any conclusions since there are many aspects to consider. The price is not only dependent on the raw material but on the suppliers, delivery state, amount of ordered material and the manufacturing and treatment. Some of these factors, together with the choice of material, are dependent on the technique with which the coating is produced. Since some coating processes are more expensive than others and since it is not within the scope of this thesis to determine which techniques that are the most suitable for the materials tested, the price is not included in the comparison and selection of the materials.
6. Conclusion
To simply harden the existing martensitic steels used in the valve today proved not to fulfill the tribological requirements as good as the solution with high cobalt coatings since the wear was more severe.

Results from the hot wear tests also showed that the ability to form a tribolayer in any form is a great advantage from a wear perspective. It is, therefore, evident that the superalloys exhibits better wear resistance than EN 1.4903, EN 1.4923 and Vanax 75 due to their superior tribological properties at elevated temperatures.

It was also established that among the steels, Vanax 75 demonstrated superior wear resistance due to its good resistance to adhesive wear.

On this basis Inconel 718 was selected as the most suitable substitution material for the Stellites in the DN VSSL 400, PN 100 valve.
References


[49] Estimated values from Odd Sandberg, Uddeholm AB.


[59] CES Edupack, computer software.