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Tribology Testing of Lubrication and Surface Treatment of Tool Interfaces in Hot Forging of Aluminium

Carine Espeland Eggen

Mechanical Engineering
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Supervisor: Torgeir Welo, IPM

Norwegian University of Science and Technology
Department of Engineering Design and Materials

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FOR
STUD.TECHN. CARINE EGGEN

Tribology testing of lubrication and surface treatment of tool interfaces in hot forging of aluminium

Tribologitesting av smøremiddel og overfaltebehandling at verktøyoverflater i varmsmiing av aluminium

Raufoss Technology AS currently uses graphite based lubricants in their lines for hot forging of aluminum. Lubricant is used to provide low friction, control metal flow and to prevent petting of aluminum tools. Two types of lubricants are currently used: water-based or oil-based graphite mixtures. However, the oil-based lubricant is not environmental-friendly when it comes to line operators. In addition, the oil vapor must be collected inside the processing plants, and there is a certain fire hazard associated with the oil. A better option, more environmental-friendly solution, is to use water-based lubricants—however, these tend to evaporate and do not provide optimal lubrication. It is therefore of interest to reduce or eliminate the use of lubricants by considering different coatings and/or combinations of coating and lubricants.

Main goal of this MSc study is as follows:

Evaluate results from tribology tests designed and conducted to simulate hot forging of aluminium, with the overall aim to find a lubricant or a coating which can reduce the need for graphite and simultaneously reduce the galling of aluminium onto tools.

Tasks:

- Review and discuss the selected coatings and lubricants, and find applications from the literature.
- Execute reciprocating pin on plate wear test planned in the pre-master project.
- Evaluate the results from the tests in terms of the discussed parameters from the pre-master project, and compare the different coatings and lubricants.
- Compare the build-up of aluminium on the pins with different lubricants and coatings.
- Evaluate if the test results can be transferred to the forging process, and identify the limitations of the test with regard to generalization.
- Evaluate the costs of changing lubricant and/or applying a coating to the tools.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

The contact person is Dr. Frode Paulsen, Raufoss Technology - Neuman.

Torgeir Welo
Head of Division

Torgeir Welo
Professor/Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Preface

This master's thesis was written at NTNU at the Department of Engineering Design and Materials, as a part of my M.Sc. degree in Mechanical Engineering. The work was written in the spring semester of 2016, and the workload corresponded to 30 ECTS.

The work has been carried out in collaboration with the Department of Engineering Design and Materials and Raufoss Technology.

I want to thank my supervisor Torgeir Welo for support and guidance throughout the semester. I would also like to thank Cristian Torres for helping me with the tribological tests.

Finally I would like to thank Raufoss Technology for the opportunity to work with an industry relevant topic and for providing me the materials needed. Special thanks to Frode Paulsen and Øystein Ruste for knowledge about the practice of forging in Raufoss Technology.

Trondheim, June 10, 2016

Carine E. Eggen

Carine Espeland Eggen

Abstract

This thesis investigated the lubrication conditions in hot forging of aluminium. The most common lubricants to apply in hot forging of aluminium are oil-based and water-based, both containing graphite. Oil-based graphite lubricants give certain health and safety challenges and are not environmental-friendly. Water-based graphite lubricants tend to not give optimal lubrication at high temperatures. Therefore alternative lubricants were discussed and tested in this thesis. The possibility of coating the tools was also investigated as this process can improve the mechanical properties of the tools.

A literature study and the commercial availability of the coatings and lubricants were used to select which coatings and lubricants to test. The combination of recommended lubricants and coatings were tested in a TE 88 multi-station friction and wear test machine, with a reciprocating pin on plate configuration. The pin represented the forging tool and was made of steel. The plate was made of aluminium and represented the workpiece.

The coatings that were selected to test were an aluminium chromium nitride coating, and an aluminium titanium nitride coating, which were applied to the pins. Uncoated pins were also tested to represent the tool steel Raufoss Technology uses today. Some pins were polished without applying a coating. Two new types of lubricant were tested, in addition to the current water-based graphite lubricant, Lubrodal F 33 Al, used by Raufoss Technology today. The new types of lubricants were produced by Klüber lubrication. Wolfraco WF 51 W is a water-based graphite free lubricant, and Klüberplus S 08-107 is a solid graphite lubricant.

The friction coefficient was lower at the tests with the coated and polished pins compared to the untreated pins. There was no significant difference between the performances of the surface treatments, the surface roughness had a much larger impact. No aluminium transfer was found at any of tests when the lubricant worked well.

The lowest friction coefficient was with an AlTiN coated pin tested together with Lubrodal F 33 Al. There was some trouble with the water-based lubricants not sticking to the hot surface at temperatures above 200 ^{o}C. Klüberplus S08-107, which is a solid lubricant, worked well also at 300 ^{o}C. The tests done with Klüberplus S08-107 had the highest coefficient of friction but it was significantly reduced after the pin was coated.

Klüberplus S08-107 is applied to the workpiece before it enters the forging press, so the forging time will be reduced. This enables the machine to produce more parts, and the costs per part will be reduced. Klüberplus S08-107 combined with coating or polishing of the tools was recommended as the best combination for further testing.

Sammendrag

I denne masteroppgaven ble det forsket på smøreforholdene i varmsmiing av aluminium. De smøremiddelene som er mest vanlig å bruke i varmsmiing av aluminium er oljebaserte og vannbaserte grafittblandinger. Oljebaserte grafitt smøremidler er forbundet med visse helse og sikkerhets utfordringer, og de er ikke miljøvennlige. Vannbaserte grafitt smøremidler har en tendens til å ikke gi tilstrekkelig smøring ved høye temperaturer. Derfor ble alternative smøremidler diskutert og testet i denne oppgaven. Muligheten for å belegge verktøyene ble også undersøkt, siden denne prosessen kan forbedre de mekaniske egenskapene til verktøyene, som kan føre til lengre verktøylevetid.

Et litteratur studie og den kommersielle tilgjengeligheten til beleggene og smøremidlene ble brukt til å velge hvilke belegg og smøremidler som skulle testes. Kombinasjonen av anbefalte smøremidler og belegg ble testet in en TE 88 multi-stasjon friksjon og slitasje test maskin med en resiprokerende pinne på plate konfigurasjon. Pinnen representerte smiverktøyet og var laget av stål. Platen var laget av aluminium og representerte arbeidsstykket.

Beleggene som ble valgt å teste var et aluminium krom nitrid belegg, og et aluminium titan nitrid belegg, som ble påført pinnene. Ubelagte pinner ble også testet for å representere verktøystålet Raufoss Technology bruker i dag. Noen av pinnene ble polert uten å påføre et belegg. To nye typer smøremidler ble testet, i tillegg til det vannbaserte smøremiddelet Lubrodal F 33 Al, som brukes i Raufoss Technology i dag. De nye typene smøremidler ble produsert av Klüber lubrication. Wolfraco WF 51 W er et vannbasert grafittfritt smøremiddel, og Klüberplus S 08-107 er et grafitt smøremiddel i fast form.

Friksjonskoeffisienten var lavere i testene med de belagte og polerte pinnene sammenlignet med de ubehandlede pinnene. Det var ingen signifikant forskjell mellom prestasjonene til overflatebehandlingene, overflate ruheten hadde en mye større innvirkning. Ingen klining av aluminium ble funnet ved noen av tesene når smøremiddelet fungerte bra.

Den laveste friksjonskoeffisienten var med en AlTiN belagt pinne testet sammen med Lubrodal F 33 Al. Det var noen problemer med at de vannbaserte smøremiddelene ikke festet seg til den varme overflaten ved temperaturer over 200 ^{o}C. Klüberplus S 08-107, som var et fast smøremiddel, fungerte bra ved 300 ^{o}C. Testene utført med Klüberplus S 08-107 hadde den høyeste friksjonsfaktoren, men den ble betraktelig redusert etter at pinnen ble belagt.

Klüberplus S 08-107 blir påført arbeidsstykket før det trer inn i smipressen, dermed blir tiden i smipressen redusert. Dette gjør at maskinen kan produsere flere deler og kostnadene per del blir lavere. Klüberplus S 08-107 kombinert med belegg eller polering av verktøy ble anbefalt som den beste kombinasjonen for videre testing.

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Abbreviations

Al	Aluminium
AlCrN	Aluminium Chromium Nitride
AlTiN	Aluminium Titanium Nitride
BN	Borin nitride
CrN	Cromium Nitride
COF	Coefficient of friction
CVD	Chemical Vapour Deposition
DLC	Diamond-Like Carbon
EDS	Energy-dispersive X-ray spectroscopy
FEA	Failure Element Analysis
HV	Hardness Vickers
MOS_2	Molybdeum disulfide
M.Sc.	Master of Science
NCL	Nitrided sample with Compound Layer
NDL	Nitrided sample with Diffusion Layer only
NOK	Norwegian Krone
NTNU	Norwegian university of Science and Technology
PACVD	Plasma Assisted Chemical Vapour Deposition
PECVD	Plasma-Enhanced Chemical Vapour Deposition
PVD	Physical Vapour Deposition
RMS	Root mean squared
SEM	Scanning Electron Microscope
SiAlON	Silicon Aluminium Oxynitride
SiC	Silicon Carbide
SINTEF	The Foundation of Scientific and Industrial Research
TiB_2	Titanium diboride
TiAl	Titanium Aluminide
TiAlN	Titanium Aluminium Nitride
TiC	Titanium Carbide
TiCN	Titanium Carbo-Nitride
TiN	Titanium Nitride
TMS	Trimethylsianol
WC	Tungsten Carbid

1 Introduction

1.1 Background

Automotive manufacturers are using an increasing amount of aluminium for vehicle components. Forging of aluminium makes components with good mechanical properties. The forging process should have optimal friction conditions for the forged parts to be within the product specification. In hot forging of aluminium it is today necessary to utilise lubricants to obtain optimal friction conditions in the process. Low friction is essential for reducing the required forging load and to prevent sticking of aluminium onto the tools, also known as galling. However, some friction must be present to ensure filling of the die cavity.

Raufoss Technology is a company which develops, forms and supplies front lower control arms for automobiles in aluminium, see Figure 1. In the old production line, called L01, they use oil-based graphite lubrication in the forging press. This is a problem for the environment of the operators and the oil damp must be gathered in a cleaning facility. In addition, there is a fire risk connected to the oil. In their new production line, called L05, they are using water-based graphite lubricants. The disadvantage with this is that the water-based lubricants have problems with giving optimal lubrication at high temperatures. Therefore, Raufoss Technology wants to find alternatives to the lubricants they are using today.

To apply a coating to the forging tool or to change the lubricant are possible solutions to reduce or eliminate oil- and water-based graphite lubricants. The topic in this master's thesis is tribology testing of lubrication and surface treatment of tool interfaces in hot forging of aluminium.

Up to now, limited research work has been done on the tribology in hot forging of aluminium. It would be beneficial to find out if it is possible to improve the forging process. By gathering the knowledge from experts and literature of similar processes it should be possible to provide some solutions for improving the lubrication conditions in the forging process.

Figure 1: Front lower control arm *[1]*

1.2 Aims of the Master's thesis

The aim of this master's thesis was to identify the tribological issues in hot forging of aluminium and try to improve these conditions. "Tribology is the field of science and technology dealing with contacting surfaces in relative motion – which means that it deals with phenomena related to friction wear and lubrication [2]."

The automotive industry is very competitive and constantly looking for innovative ideas to reduce costs and to be one step ahead of the rivals. Raufoss Technology has some problems related to the surface conditions and lubrication in hot forging of aluminium. Therefore, Raufoss Technology seeks an alternative to the oil- and water-based graphite lubricants used in the forging process today. This can be done by changing the lubricant and/or to coat the tools. This thesis describes some lubricants and coatings recommended for hot forging. In order for a lubricant or coating to be considered as appropriate for the forging process in Raufoss Technology, certain factors must be considered regarding the HSE requirements and the conditions present in the forging process.

Goals:

- To fill the knowledge gap on tribology of hot forging of aluminium with a primary focus on exploring new options for lubrication in this process.
- To investigate opportunities for improved friction and wear conditions through tribological tests of different lubricants and coatings in hot forging of aluminium.

Tasks:

- To choose lubricants and coatings to be tested, justified by a literature study of forming processes and recommendations from specialised companies.
- To perform a simplified tribological test to simulate the forging process, to be able to test and compare the different coatings and lubricants.
- To evaluate the lubricant by measuring the friction present in the test and at how high temperatures the lubricant can tolerate.
- To investigate if there is any spallation of the coating or galling of aluminium after the tests.

1.3 Structure and scope

A tribological test on a TE 88 friction and wear machine was used to simulate the forging process. This was to study the frictional and wear behaviour of the selected coatings and lubricants to find the best combination which could be used in hot forging of aluminium.

This master's thesis contained four main topics. Chapter 2 was about the theory and practice of forging, and described the forging process and the challenges connected to friction, lubrication, metal flow and thermal conditions in hot forging. The forging process in Raufoss Technology was also described.

Chapter 3 contaied a literature study of different coatings and lubricants which have been tested in the metal forming industry. This chapter also described some alternative commercially available lubricants and coatings recommended to be tested.

Chapter 4 described the testing equipment and setup, and how the tests were performed.

Chapter 5 presented the test results.

Chapter 6 discussed the test results and evaluated the costs of changing lubricants and applying a coating.

Chapter 6 was the conclusions where a combination of lubricant and surface treatments was recommended and further work was described. It contained an executive summary explaining the most important results and recommending lubricants and surface treatment for further testing.

2 Theory and practice of forging

2.1 Process

2.2 Metal forming

Metal forming is a process where a workpiece is formed into a desired shape through plastic deformation. Extrusion, rolling, forging, drawing and sheet metal forming are examples of metal forming processes. For this work, forging was the primary topic.

2.2.1 Theory of forging

Forging is a metal forming process where the work material is formed by a tool consisting of two dies which can move relative to each other. When the tool closes there are compressive stresses due to high pressure, which plastically deforms the workpiece into a new shape, defined by the shape of the tool dies [3]. There are two main types of forging, closed-die forging and open-die forging. Open die forging is when large parts of the workpiece are formed without full contact with the dies. Closed-die forging refers to when the workpiece is confined in a closed space between the dies in the end of the process. The excess material is called flash and flows out a flash gap. The flash acts as a safety valve to prevent the dies to explode during the high pressures which is present during the process. Figure 2 shows an example of closed die forging with flash [1].

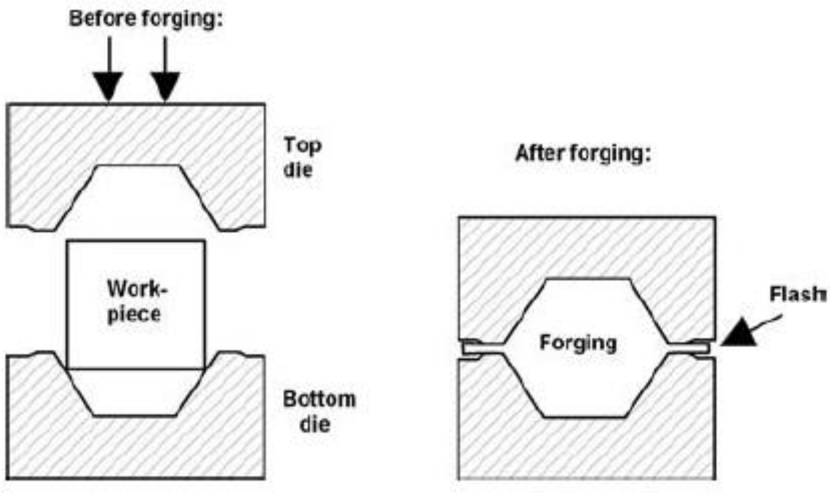

Figure 2: Closed-die forging [3]

Hot forging

Hot forging is when the work material is heated and deformed at temperatures and strain rates, so that substantial recovery occurs during the deformation process [4]. This master's thesis focused on hot closed die forging.

Before the forging process the initial workpiece is often made by casting and extrusion [4]. The material may have a distinct microstructure inside the initial workpiece. It is important to control the microstructure to have the best material properties in the desired directions. The heat treatment of the final and initial workpiece is a way to control the microstructure. The forged part has stronger mechanical properties in the direction of the material flow compared to the transversal direction [4].

Forgeability

Forgeability is the ability of the workpiece to be formed into a desired shape. Forgeability is dependent on the ability to fill narrow die cavities, its ductility and workability. The forging temperature should be adjusted to an interval with a good workability to prevent cracking, but at the same time have a high ductility. The flow stress of the material is also important because it influences the required die pressure and forging load. The flow stress is dependent on temperature. It is important to have an optimal temperature in the process to get the best ductility and workability of the material, to obtain the right properties of the forged component. The high ductility and workability of aluminium makes it possible to forge complex parts [1].

To forge complex shapes it is often necessary to complete the forging process through a number of stages, to ensure complete filling of the die cavities. The first steps of the process are called preforming steps. The last step which forms the final shape is called the finishing step and is obtained in the finishing die. The number of steps needed is dependent of the ductility of the workpiece material and the complexity of the shape [1].

2.3 The forging process in Raufoss Technology

2.3.1 Forging steps

Raufoss Technology is forging front lower control arms for cars. The component is made of EN-AW 6082 aluminium alloy, hardened to get high strength and ductilitypla. The tool is made of hardened steel and it is called Uddeholm Dievar. The work material is made from an extruded rod of aluminium. It is cut to appropriate lengths and preheated to 500 ^{0}C in an oven [5].

The tools are heated by a heater in the beginning and during the forging process. The tools are warm to keep the high temperature of the workpiece after the forging, so the workpiece can be quenched to avoid growth of precipitates to be able to age to maximum strength. Since the tools and the workpiece have around the same temperature, the process is called isothermal forging. The following sections described the forging process in the old production line called L01 where oil-based graphite lubricant is used [5]:

Step 1 – Cross wedge rolling, optimal die temperature 350 ^{0}C

The first step of the forming process is cross wedge rolling to relocate the amount of material to the part which requires the thickest cross section. The rolling process is done by putting the initial extruded cylinder shaped component between two rollers. Figure 3 shows the rolling process. The geometry of the rollers varies over the periphery, which means the roll gap varies in shape. The shape of the rollers defines the final cross section of the rolled component.

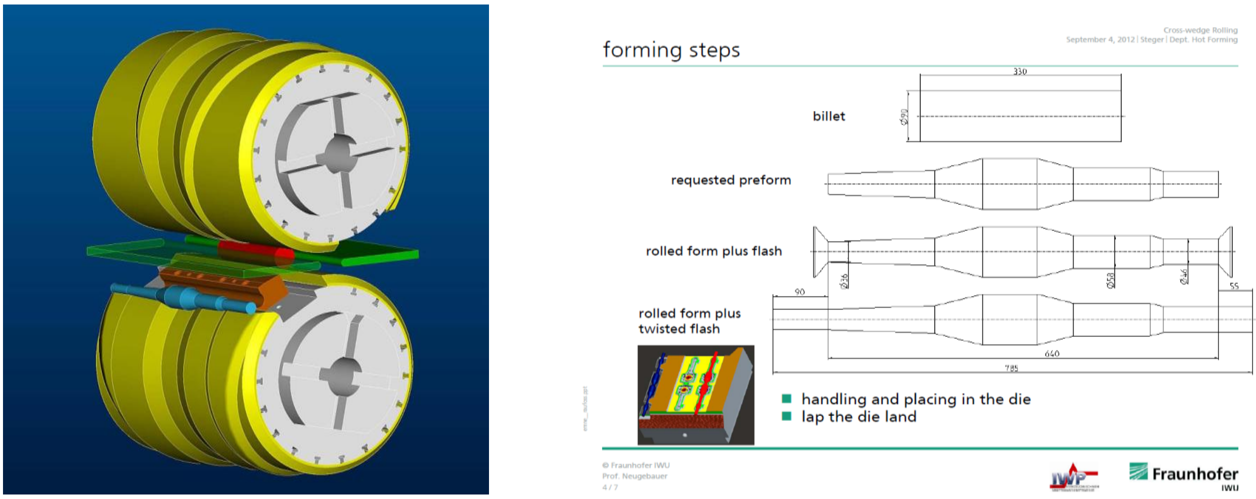

Figure 3: Cross Wedge rolling, the yellow rollers rotate and shape the rod. The right picture shows the change in shape of the rod *[5]*.

Step 2 – Flattening and splitting, optimal tool temperature 420 ^{0}C

Some of the control arms require a different shape than a cylinder, to obtain this structure, it is possible to perform a separate step where the cylinder is flattened and split. This is shown in Figure 4. After this step the workpiece goes through a solution heat treatment where it is heated for 6 minutes at a temperature of 535 ^{0}C.

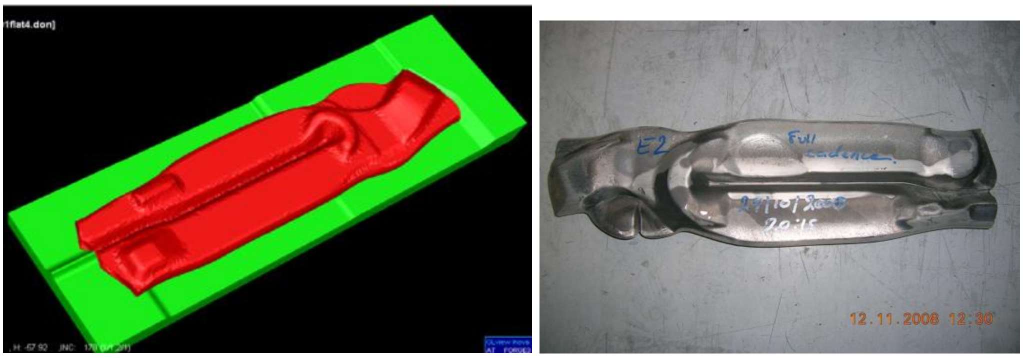

Figure 4: Flattening and splitting *[5]*.

Step 3- Bending, optimal tool temperature 420 ^{0}C

The workpiece is bended to obtain a curvature as in the finished product. The bending tool and process are shown in Figure 5.

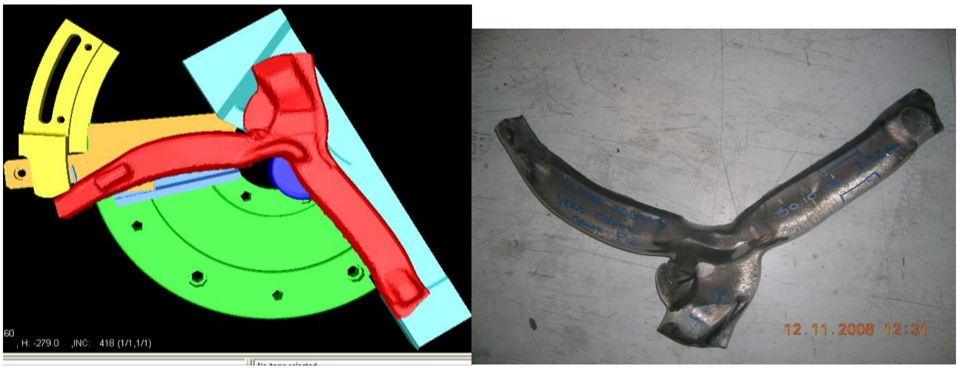

Figure 5: The bended workpiece placed in the bending tool *[5]*.

Step 4- Forging, Optimal die temperature 420 ^{0}C

The workpiece is placed between two hot dies, which close and shape the workpiece into its final shape. The forged component is shown in Figure 6. After the forging the hot workpiece is quenched in water at 20 ^{0}C for 5 seconds.

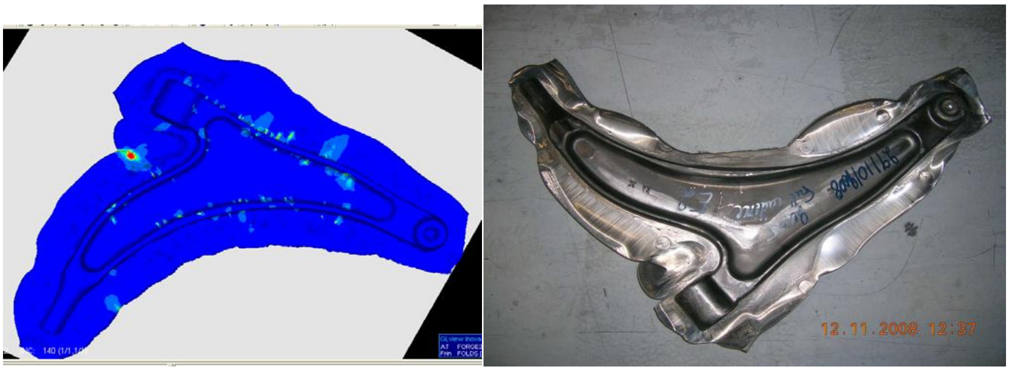

Figure 6: The forged component *[5]*.

Step 5 – Trimming and calibration

The last step is to remove the flash, which is the excess material formed during the forging. This is done by a trimming press, which cuts off the excess material.

2.3.2 Problem areas in Raufoss Technology regarding lubrication

Raufoss Technology wants to find alternatives to the currently used lubricants. In their old production line called L01 they use an oil-based graphite lubricant. There is a fire risk connected to the oil-based graphite lubricants so it is required to have an operator to continuously watch the process. Previously there has been an accident with a forging station setting on fire. Another problem with the oil-based lubricant is that oil damp is produced which is not so good for the environment of the operators. A ventilation system which gathers the oil damp in a cleaning facility must be present.

The new production line called L05 in Raufoss Technology uses water-based graphite lubricant, which is better for the environment. The disadvantage with the water-based lubricant is that it tends to not attach to the surface at temperatures above 250-280 ^{o}C. This is because at high tool temperatures a phenomenon called Leidenfrost effect occurs, which is the instant formation of a damp barrier between the surface and the lubricant. Therefore, the tool temperature is lower than in the old production line L01. The tools are cooled down by over-spraying of lubricant to make the graphite attach to the tool surface. Typical tool temperature in L05 is 260 -280 ^{o}C.

In both of the lines the forging process requires a lot of lubricants and graphite, so it is desirable if the amount can be reduced to save the cost and the environment.

Sometimes the production has to be stopped because of aluminium sticking to the tools which is a result of starved lubrication. The tool has to be cleaned to remove the aluminium, if not the following forged parts may not be within the tolerance limit, because they can get a change in the shape. This means a stop in production which results in less produced parts and less revenue.

2.4 Materials

2.4.1 Workpiece material for forging

There is a great variety of materials which can be used in forging, depending on the desired properties of the product. Different temperatures and forging loads will be required for the different materials. Forging of steel requires a larger force than forging of aluminium since the flow stress of aluminium is lower, which makes it easier to form. Some possible materials for forging are steel, aluminium, copper, titanium, nickel and magnesium alloys [6].

Aluminium has a high strength relative to its low weight, good corrosion resistance, workability, price, and electrically and thermally conducting properties [3]. The automotive industry is using aluminium increasingly because of its good properties and light weight [7]. Aluminium has high ductility which makes it easy to form [8]. Because of the high ductility and softness, aluminium can be forged into complex shapes without particular problems. A steel component is not as ductile as aluminium, and cannot be forged into a complex shape within a reasonable cost. This is because the ductility is much lower, so the forging process has to be performed in several steps [1].

2.4.2 Die material

When selecting the die material in hot die forging some factors must be considered, such as wear and creep resistance, hot hardness, toughness, and overall structural integrity [6]. The die in hot forging is most often made of steel. Raufoss Technology is using a tool steel alloy called Uddeholm Dievar. It is a high performance chromium-molybdenum-vanadium alloyed hot work tool steel, which has a good resistance to heat checking, gross cracking, hot wear and plastic deformation [9].

2.5 Products made by forging

The advantages of the forging process are that it produces little waste material and can generate the desired shape quickly, in one or a few strokes. The products often get better metallurgical and mechanical properties than products made by casting or machining [6]. This is especially true for closed-die forging where the material flow results in a homogenous material due to the high level of deformation throughout the complete part [1].

Typical products made by closed-die forging are parts for automobiles, aircraft, mechanical industry, milling and railroad equipment [6].

2.6 Challenges

2.6.1 Challenges with friction

Friction is present when two surfaces are in contact and move relative to each other, causing resistance against movement [3]. The friction in metal forming is important because forming loads and wear of dies depend on friction, and can be reduced with lubricants. Another reason is that the surface quality of the workpiece is dependent on the lubricant used [1].

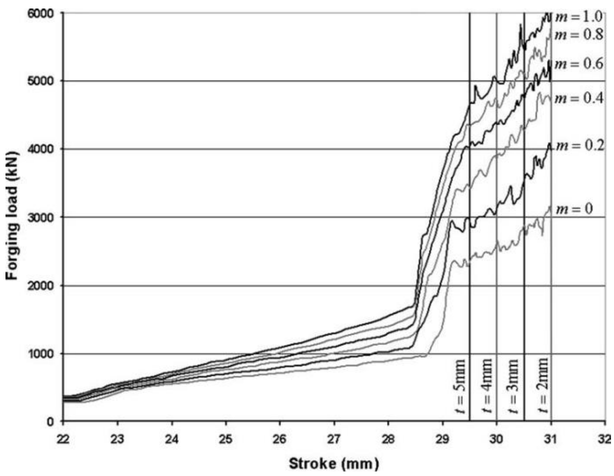

Figure 7: Required forging load for different friction factors [3]

A lubricant should give low and stable friction during the forging operation to reduce the required forging load and die wear. To prevent the workpiece to weld onto the die, the lubricant should minimize the contact between the workpiece and die [1]. This is also called galling, and happens when the tool and the workpiece come in direct contact, and the workpiece sticks to the tool so the tool shape changes [3].

2.6.2 Thermal conditions in hot forging

The energy consumed in forging is mainly transformed into heat, which causes the temperature to rise in the die and workpiece. To estimate the temperature in a workpiece during hot forging of aluminium Equation 2.1 can be used. Cooling to the surroundings and radiation effect are neglected [1].

$$T_1 = T_0 + \Delta T_D + \Delta T_F - \Delta T_T \qquad (2.1)$$

Here, the following symbols are used [1]:

T_0 is the initial temperature of the workpiece.

T_D is the temperature increase in the workpiece due to dissipated deformation energy during forming.

T_F is the temperature increase due to friction in the interface between die and workpiece.

T_T is the temperature decrease in the workpiece because of cooling by colder dies.

Around 5% of the energy consumed is placed in the microstructure of the deforming workpiece due to formation of vacancies or dislocations. The rest of the energy from the deformation goes to heating the workpiece. Shear stresses caused by friction appear in forging, and this sliding movement produces energy, which is transformed into heat in the die and workpiece [1].

If the die is colder than the workpiece there will be a cooling effect from the tool to the workpiece. In hot forging the dies are often much colder than the workpiece, and the die experiences a thermal shock when it comes in contact with the hot workpiece. Therefore the temperature increase a lot and fast at this point, when the workpiece comes in contact with the die [1]. However, this is not the case in Raufoss Technology, where the dies are heated.

2.6.3 Metal flow in forging

To obtain the desired properties of the component it is necessary to control the metal flow. The mechanics of plastic deformation determines how the metal flow in different forming operations. Plastic deformation makes the metal flow into the desired geometry of the forming tool. The mechanical and physical properties of the metal produced are dependent on the mechanics of plastic deformation. The metal flows plastically when the stress reaches the value of flow stress limit. This limit is usually determined by uniaxial testing [10].

How the metal flows inside the dies and fills the die cavity in closed die forging can be visualized by FEA. The book [1] by Valberg describes the steps of metal flow and load distribution in the forging process.

Stage 1: In the beginning of the forging process the workpiece is side-pressed between the two flat areas in the middle of the tooling. The load rises steeply from zero and then remains approximately constant throughout more than half of the whole stroke of the forging process. This is caused by the deformation. After some time the metal flow is changed, but this does not affect the forging load significantly. The metal flows downwards into the die cavity in addition to the side pressing of the workpiece. Figure 9 shows the degree of filling of the die cavity for the different steps.

Stage 2: When the flow in front of the material reaches the outer die edge, at the entrance of the flash gap, there is a sudden steep rise in the forging load. The contact grows in size as the forging continues. There is a second change in the metal flow when contact is established. One front starts to flow into the die cavity and the other front flows into the flash gap.

Stage 3: At this stage the deepest recession of the die has been completely filled with workpiece material. The complete filling occurs first in the middle of the die, and spreads out in both lateral directions inside the deepest cavity of the die. The load rises even more steeply than at stage 2. Figure 8 shows the load-stroke curve of the different stages.

Stage 4: When the die is completely filled there is a change in the metal flow. Since the volume of the workpiece material remains constant, the only possibility for the material to outflow is through the flash gap. Since the required forging load is dependent on the degree of filling of the die cavity, the force is highest at the end of the forging. Here, the metal flows only in one direction out of the flash gap. The forging continues until the specimen has the right dimensions in the direction of the forging [1].

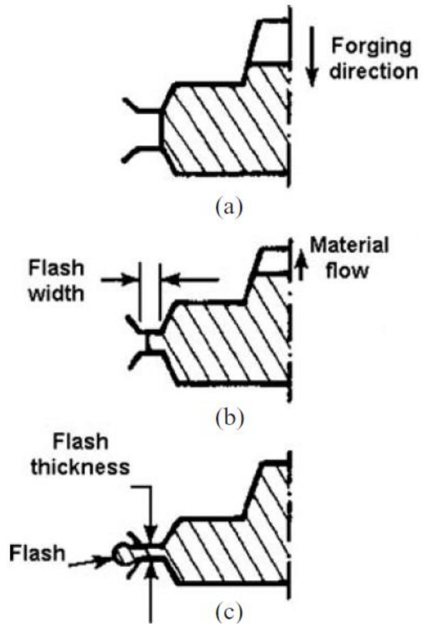

Figure 9: The filling of the die cavity, a) shows the degree of filling for step 1, b) is for step 2 and c) is for step 3 [1].

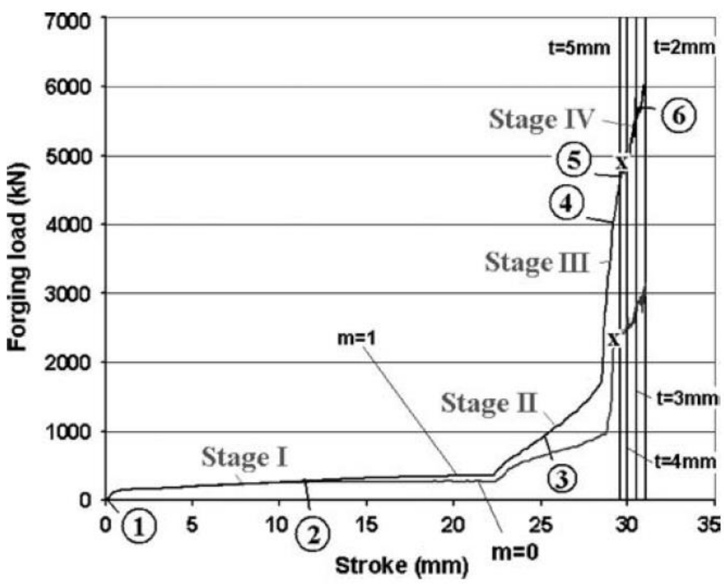

Figure 8: Stroke-load curve, showing the forging load required at each stage of the forging process [1].

Parameters influencing the metal flow are friction, temperature, fastening of the material and the speed of the forming tool. Modifications of the friction conditions can contribute to change the metal flow, the volume of the flash, the die cavity filling and the surface appearance [4]. The direction of the metal flow is dependent on friction.

The ring compression test is a common way to measure friction in metal forming. A ring of the workpiece material is placed in between two dies, with lubricant. At low friction between the ring and dies, both the inner and outer diameter of the ring will expand. In the case of high friction the metal flow will go in the opposite direction and the hole in the ring will decrease.

2.7 Mechanisms

2.7.1 Parameters influencing friction

The metal flow in forging is a result of the pressure transmitted from the dies to the deforming workpiece. Because of this, the friction conditions at the interface between the workpiece and the die influence the metal flow, stresses acting on the die, formation of surface and internal defects and load and energy requirements [6].

The surface roughness of the dies influences the friction conditions in forging. With a high surface roughness there is high friction present, because of the need to lift one surface over the asperities on the other [11]. Higher surface roughness means a higher proportion of friction and adhesion, and therefore the shear connection between the surfaces increases [12]. However, for very smooth surfaces the real area of contact increases and so does the friction. So there is an improvement in friction conditions with decreased roughness until a certain point. Figure 10 shows the variation of friction coefficient as a function of surface roughness [11].

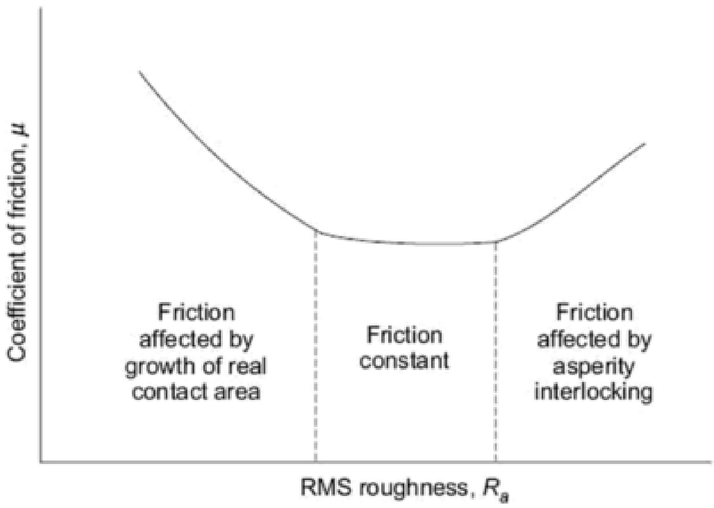

Figure 10: The variation of friction as a function of surface roughness [11].

2.7.2 Friction models

To describe the friction condition in metal forming, there are three friction models which are commonly used. It is the Coulomb friction model, the Tresca friction model and the Wanheim and Bay friction model.

The Coulomb friction model

The Coulomb friction model describes the friction condition when two contacting surfaces glide relative to each other. It is used when the contact pressure is low, and the mean normal stress component is less than the flow stress of the material. Equation 2.2 shows the Coulomb friction model:

$$\tau = \mu\sigma_n \qquad (2.3)$$

τ is the frictional shear stress, σ_n is the normal stress transferred between the two surfaces and μ is the coefficient of friction

The Tresca friction model

In closed die forging the contact pressure is high because the metal is deformed between two dies, where the contact pressure from the workpiece will act as normal forces on the die surface. The contact pressure can be much higher than the flow stress of the material. Since the Coulomb friction model is not well suited for high contact pressure, a different model called the Tresca friction model can be used. When the contact pressure exceeds the flow stress of the workpiece material, plastic deformation of the workpiece will occur. The friction stress must not exceed the shear flow stress k of the workpiece material. If this happens, the workpiece material will stick to the surface of the tool. Equation 2.4 describes Tresca's friction model.

$$\tau = \tau_i = mk \qquad (2.4)$$

τ is the frictional shear stress. The parameter m is called the friction factor, and varies between 0 and 1. When there is sticking between the workpiece and the tool, m is equal to 1. With lubricant the friction factor will decrease, until a frictionless case where m will be 0 [1]. In hot forging of steel, copper and aluminium alloys with graphite-based lubricants, the friction factor m varies from 0.2 to 0.4 [6].

Wanheim and Bay friction model

Orowan developed a friction model more suited for metal working processes, which describes friction at high normal pressures. He suggested the friction model shown in Figure 11, which says the friction stress at low pressures is proportional to the normal pressure and at high pressures is equal to the yield stress in pure shear [13].

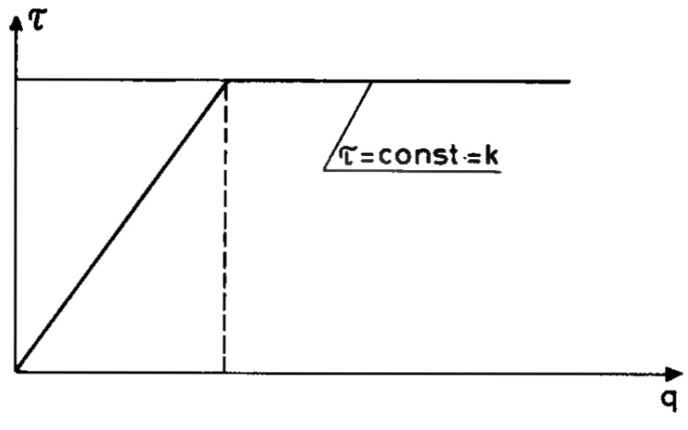

Figure 11: Orowan's friction model [13]

Shaw, Ber and Mamin gave a more precise explanation and improved Orowan's friction model. They said the ratio between the real area of contact and the apparent area increases with increasing pressure. The ratio will approach 1 asymptotically, since the last phase requires very high pressure. According to adhesion theory the friction stress is proportional to the area of contact. The connection between friction stress and normal pressure is shown in Figure 12. Wanheim has proven this model theoretically and experimentally [13]. He used a slip-line theory to model friction and plastic deformation beneath and ahead of sliding hard wedge-shaped asperity. The model can predict trends in friction as a function of asperity angle, normal pressure and yield strength [14].

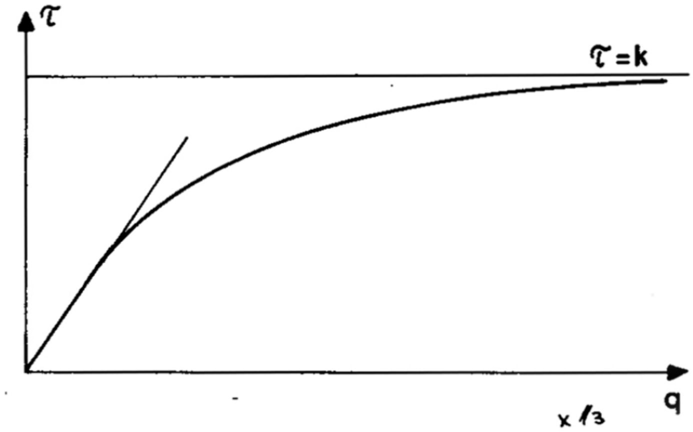

Figure 12: Shaw's friction model [13]

2.7.3 Wear

As a result of two contacting surfaces moving relative to each other, some material from one of the solid surfaces may detach from its surface, which is a type of wear. Friction and wear are not directly correlated. High friction does not necessarily mean high wear [2], but very often this is the case. This master's thesis focused on abrasive and adhesive wear.

Abrasive wear

Abrasive wear can occur when one of the contacting surfaces is considerably harder than the other, or if particles are introduced into the contact. When the harder surface asperities press into the softer surface, it results in plastic flow of the softer material around the hard one. When the harder material moves it removes the softer material which causes scratches or grooves in the surface [2].

Adhesive wear

Adhesive wear can happen when one of the contacting surfaces comes in contact with the roughness of the counter surface. A piece of the softer material is removed and attached to the stronger material, which is called adhesion [2].

Galling is a type of adhesive wear. Galling occurs in areas where the forming conditions are most severe. Metal to metal contact, caused by starved lubrication, can happen in forming when there are high stresses and high degrees of plastic deformation. This contact can result in transfer of work material to tool, which is called galling. The transferred material becomes hardened and causes the tool to change shape. When the tool changes shape it can lead to damaging the surface finish of the product and in the worst case the produced part might not be within the tolerance limit anymore. Then, it is necessary to remove the transferred material from the tool, by adding some chemicals which will attack the transferred material and not the tool material. To prevent galling it is important that the surface of the tool is smooth without defects because defects lead to high local contact stresses and high deformation [3].

Fatigue

When a material is exposed to repetitive loading, fatigue might occur. Fatigue is a wear mechanism which happens at a stress level the material could sustain once, but not when the material is subjected to repetitive loading. This can lead to cracking where the crack will grow for each load cycle [2].

2.8 Lubricants

2.8.1 Lubricants in metal forming operations

To control the friction conditions in a forging process it is common to use a lubricant. There are four types of lubrications: boundary lubrication, full-film lubrication, hydrodynamic lubrication and mixed-layer lubrication. Boundary lubrication exists when a thin layer is chemically or physically adhered to the metal surface. Under these conditions the friction is high. Full-film lubrication is when a thick layer of solid lubricant or dry coating is separating the die and the workpiece. Here, the friction conditions are dependent on the strength of the lubricant film.

Hydrodynamic conditions are present when there is a layer of liquid lubricant in between the dies and the workpiece. In metal forming operations with high speed, it is difficult to maintain hydrodynamic conditions because the viscosity of most lubricants decreases with the temperature [6]. Hydrodynamic friction conditions are not wanted in bulk metal forming operations because the total separation of workpiece against the tool material allows the grains in the workpiece to deform freely. This results in a poor surface quality [1].

Mixed-layer lubrication is most common in metal forming. It is a mixture of hydrodynamic conditions and boundary lubrication. It is hard to maintain a hydrodynamic condition because of the low sliding velocity and high pressure during forging. Therefore, the peaks in the metal experience boundary conditions and the valleys become filled with lubricants. If there is enough lubricant present in the pockets of the material, it can act as a hydrostatic medium and prevent metal-to-metal contact. The friction condition in mixed-state is moderate. Figure 13 shows the Stribeck curve where the coefficient of friction in the different types of lubricants is a function of the Hersey number, which is the viscosity multiplied with the velocity divided by the average pressure [6]. The bottom curve shows the thickness of the lubricant film of the different lubrication types. Figure 13 also contains an illustration of each of the lubrication types.

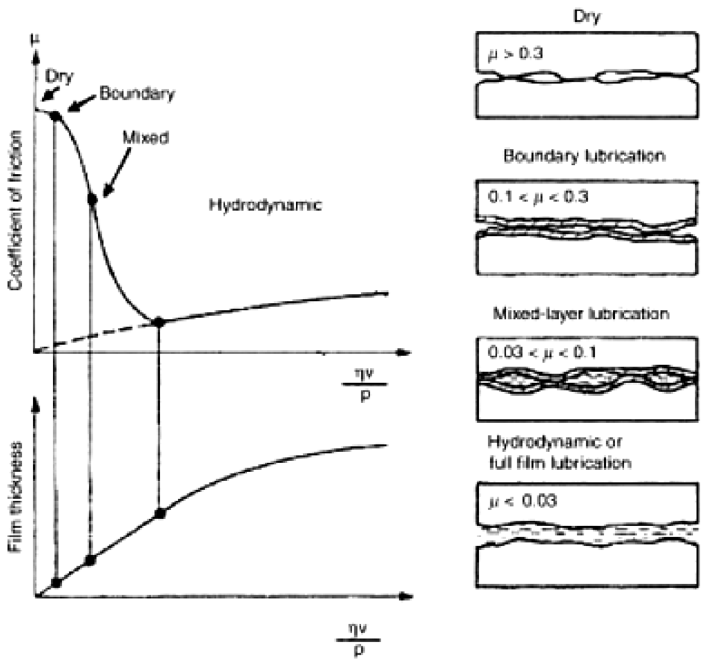

Figure 13: The Stribeck curve and an illustration of each of the lubrication types *[6]*

There are many parameters influencing friction and lubrication at the die workpiece interface in forging. The geometry of the die and the properties of the workpiece material influence how the material flows and deforms and how the lubricant must flow. The surface finish of the die and workpiece affects the formation of the hydrostatic pockets. The composition of the lubricant influences the viscosity and how it changes when it is subjected to extreme heat and pressure. The viscosity of the lubricant controls the flow of the lubricant and the deformation of the workpiece. During the deformation of the workpiece the lubricant is spread out and hydrostatic lubricant pockets form. This is dependent of the amount of lubricant [6].

The parameters of the forging process also influence the friction and lubrication. The pressure between the die and the workpiece has an effect on the viscosity of the lubricant and the forming of hydrostatic lubricant pockets. The velocity when the die slides across the workpiece affects the heat generation at the interface between the die and workpiece. The sliding length when the die moves over the workpiece influences the heat generation at the interface between the die and workpiece. It also influences how much the lubricant will spread out and when it will break down. Also, the amount of surface expansion affects how the lubricant will spread out. The deformation process generates heat which influences the properties of the workpiece and the die material and the viscosity of the lubricant [6].

A lubricant should fulfil the following functions [6]:

- Reduce the sliding friction between the die and workpiece
- Avoid metal-to-metal contact to prevent galling
- Have good insulation properties to reduce heat loss from the workpiece to the die
- Be inert to minimize reactions which can harm the die and workpiece at the actual forming temperature
- Be non abrasive
- Be free of polluting and poisonous components and not produce unpleasant or dangerous gases
- Have no risk of the lubricant setting on fire at temperatures up to 550 ^{o}C
- Be easily applicable to and removable from dies and workpiece
- Be commercially available at a reasonable cost
- Preferably not generate smoke. If so, there is a need for good ventilation
- Transfer of the work material to tools has to be minimal

Lubricants for hot forging

In hot forging the lubricant must function at high temperatures. A lubricant should reduce the heat transfer from the workpiece to the dies and the shear stresses at the interface between the tool and workpiece to prevent wear, heat checking and plastic deformation of the dies. The forging cycle is short, only a few seconds, which means the lubricant has to be applied quickly. It is not possible to use organic based lubricants because the lubricant will burn, nor soap based lubricants because they will melt at high temperatures. The most common lubrication in hot forging of aluminium is graphite in mineral oil. There are concerns over the environmental friendliness of graphite and the accumulation of graphite within the dies, which has led to development of water-based synthetic lubricants [6].

Cost evaluation of lubricants

The cost of lubricants is not very high compared to raw material, equipment and labour. Therefore, it might seem like the cost saving for changing lubricant is not that significant. Lubricant breakdown results in excessive die wear or die failure. This will reduce the production because of press downtime and part rejection. Therefore it is important to evaluate the lubricant in use and compare them with alternative lubricants to get optimal performance.

2.8.2 Current use of lubricants

The most common lubrication in hot forging is graphite based, and this is what Raufoss Technology uses today. There are two main types of graphite lubricants, water-based and oil-based. The next paragraph described the properties of the water-based graphite lubricant [15].

Graphite is very lubricious, because graphite has a hexagonal lattice structure. [15] The layers of the lattice are bound to each other by weak van der Waals bonds, making it easy for the layers to slide over one another. The softness and slipperiness of graphite make it an excellent solid lubricant. Graphite degrades slowly into carbon dioxide when the workpiece comes in contact with the graphite film. When the graphite moves, it allows the metal to flow across the surface of the die [15].

This section was based on information gathered from Raufoss Technology by personal communication.

In the new production line called L05, Raufoss technology uses a water-based graphite lubricant called Lubrodal F 33 AL. This water-based graphite lubricant tends to not stick to the tool surface when the tool temperature exceeds 260 - 280 ^{0}C. The lubricant is over sprayed to cool the tools, since diluted lubricant contains 92 % water. Therefore, a lot of lubricant is used, 0,5 litre per component with diluted lubricant. Typical tool temperature in L05 is 260 – 280 ^{0}C. The water in the process is carrying the graphite [16].

At high tool temperatures a phenomenon called Leidenfrost effect occurs for water-based lubricants. The Leidenfrost effect occurs when a drop of liquid comes in contact with a surface that is much warmer than the boiling point of the liquid. The drop will levitate above its own vapour, and the evaporation is slower because of insulating properties of the film [17]. The formation of a damp barrier between the tool and the lubricant results in the graphite in the lubricant not attaching to the surface.

In the old production line called L01, Raufoss Technology uses an oil-based graphite lubricant called GO8400 delivered by Hydro-Texaco. The amount of lubricant used for each component is about 0,03 litre. The oil-based graphite lubricant often ignites during the forging, so there is a need for an employee to continuously watch the process. Previously there has been an accident with a forging station setting on fire. The other main problem is that the oil is not environmentally friendly, and there is a need for a good ventilation system to gather the smoke [16].

Since the forging process at Raufoss Technology requires a large amount of lubricants, it is desirable if the amount can be reduced. The car industry is very competitive so all savings are appreciated. Raufoss Technology has a problem with the forging press where they have to stop the production because of starved lubrication resulting in galling of aluminium onto tools. This is also the reason for finding an alternative to the current use of lubricants.

2.9 Coatings

2.9.1 Requirements for a coating

Coatings are a surface treatment used in many metal forming applications, to improve the tribological behaviour of the tools. The purpose of coatings is to improve the surface properties of a material without influencing the bulk material properties. Coatings are mainly used for improving the lifetime and performance of products or tools, by reducing wear and friction by adding hardness to the surface or decreasing interaction forces [3].

Coatings have not been so commonly used in forging yet because the complexity and size of these tools make it complicated and expensive to apply coatings [2]. It is also a problem with a tendency for the work material to stick to the coated tool because of the high friction in metal forming [18].

Requirements for the tool material used for forming applications are that it must have a low tendency to adhere to the workpiece to avoid adhesive tool wear, and high hardness and sufficient toughness to avoid abrasive wear [2]. One alternative to obtaining both high hardness and high fracture toughness is to use multi-layered coatings [19].

Requirements of a coating [2]*:*

- It must withstand tool temperatures up to 500^0C
- The bulk material must tolerate the processing steps necessary to apply the coating.
- The coating must not damage the properties of the bulk material.
- It must be possible to cover the whole component with coating in terms of size and shape.
- The coating must be commercially available and cost-effective, but an increased cost can be justified if it increases the bulk material lifetime or quality of the product.
- It should be resistant against wear
- It should be possible to make at least 500 000 components before the tool needs to be changed. If not some necessary maintenance earlier can be accepted.

2.9.2 Deposition methods

There are several ways to deposit coatings, but the most actual for tools are Physical Vapour Deposition (PVD), and Chemical Vapour Deposition (CVD) [3]. In the CVD process gases containing the material to be deposited are placed into a reaction chamber together with the component to be coated. The gasses condense on the substrate and form a coating [2]. The process is normally performed at temperatures between 800 and 1200 ^{0}C, but the temperature can be lowered by using plasma assisted CVD (PACVD), or plasma-enhanced CVD (PECVD) [3].

PVD is a process where a material from a solid source is deposited by atomisation or vaporisation in a vacuum chamber to form a coating [2]. The coating consists of the material of either the solid itself, the solid reacts with gases in the chamber forming a coating or a mixture of solid sources and gases [3]. PVD requires lower temperatures than CVD, usually up to 600^0C. Deposition methods of PVD are often divided into evaporation and sputtering. Evaporation is when the deposition material evaporates thermally on the surface. Sputtering is when the source material is made cathodic and bombarded with ions, normally of an inert gas. The result is a transfer of momentum to atoms in the target where the coating atoms are ejected [2].

3 Coatings and lubricants

3.1 Alternative lubricants

3.1.1 Literature study of lubricants

Ngaile [21] tested four types of lubricants for warm forging of aluminium in a ring compression test. The lubricants were tested at two temperatures, 260 °C and 370 °C. A water-based graphite lubricant, a silicone oil, a boron nitride silicone 1 lubricant and a boron nitride silicone 2 lubricant were tested. Boron-nitride-silicone based lubricant combines the wanted properties of boron nitride and silicone oil resulting in a lubricant that is expected to behave better than graphite lubricants. Boron nitride has higher thermal stability and oxidation resistance than graphite.

In the boron-nitride-silicone 1 lubricant the weight percent of boron nitride was 1% and the viscosity of the silicone oil was 50 cS at 25 °C. In the boron-nitride-silicone 2 lubricant the weight percent of boron nitride was 8% and the viscosity of silicone oil was 350 cS at 25 °C. Lubricant 1 is supposed to have a better high temperature performance because of the higher viscosity formulation.

The lubricants were tested using a ring compression test. The ring was made of 6061 aluminium and the dies were made of steel. The specimen was heated to 430 °C and the dies were tested at two temperatures, 260 °C and 370 °C. The graphite lubricant behaved well at 260 °C, but at 370 °C the hole in the ring was drastically reduced implying severe friction and an increase in temperature. Figure 14 shows how the ring diameter varies after each test. For the silicone oil the opposite happened. The lubricant behaved better at 370 °C than 260 °C, implying that lubricity increased with temperature. The friction factor of boron-nitride-silicone 1 and boron-nitride-silicone 2 slightly decreased when the temperature increased from 260 °C to 370 °C. The boron-nitride-silicone2 behaved slightly better than boron-nitride-silicone 1.

Figure 15 shows the friction factor of each lubricant tested at two temperatures. The best performance at 260 °C among all lubricants was the boron-nitride-silicon-2 with an average shear friction factor of 0,3. Silicone oil had the worst performance at 260 °C with a shear friction factor of 0,48. At 370 °C the silicone oil had the lowest shear frictional factor of m= 0,23. The reason why the silicone oil performed better at the highest temperature could be that at higher temperatures the depolymerisation of silicone oil was enchanced by thermo-oxidation, which led to formation of tiny white flakes of silica. These flakes have shown to improve the lubrication. These flakes were also made in boron-nitride-silicone-1 and boron-nitride-silicone-2 at high temperatures.

The graphite lubricant behaved the worst among the lubricants at 370 °C with a shear friction factor of 0,92 while at 260 °C it behaved quite well with a shear friction factor of 0,36. Boron-nitride-silicone-1 and boron-nitride-silicone-2 did not vary significantly in performance when the temperature increased from 260 °C to 370 °C. At 260 °C the polydimethyl siloxane facilitated hydrostatic/hydrodynamic lubrication with boron acting as a barrier film, which resulted in low friction. At 370 °C the formation of silica together with boron nitride acted as a film barrier with low shear strength. This dual lubrication mechanism makes boron-nitride-silicone based lubricants suitable for a wide range of aluminium forging temperatures.

Figure 14: Deformed samples with graphite, silicone oil, boron-nitride-silicon-1 and boron-nitride-silicone 2 *[21]*.

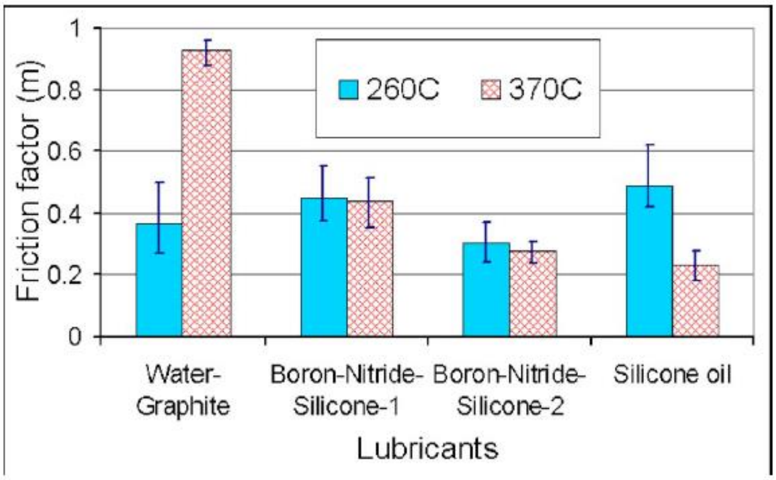

Figure 15: Friction factor at 260 °C and 370 °C for water graphite, boron-nitride-silicone-1, boron-nitride-silicone-2 and silicone oil [21].

Article [22] by Nishimura evaluated the frictional condition of different lubricant using an injection-upsetting test that was combined with backward extrusion. Five different lubricants were tested, as shown in Table 1.

Table 1: Kinds of lubricant *[22]*

Lubricant	Substance	Diluation	Method of application
Dag	Oil-based graphite	0	Brush
Deltaforge	Water-based	2	Spray
JF	Water-based BN	0 or 15	Brush or spray
MoS2			Aerosol spray
Dry			

Dag is an oil-based graphite lubricant. Deltaforge is a water-based graphite lubricant including glass, and is recommended for hot forging of aluminium. JF is a water-based BN lubricant. MoS_2 is a commercial aerosol spray. The billet was an aluminium cylinder and the die cavity for injection upsetting was composed of an upper and lower tool made of various tool material. The tool materials were made of coated tools ceramics, a cemented carbide and a conventional tool steel. The tests were done at room temperature, 200 °C and 400 °C.

All over the Dag and the JF lubricant had the lowest frictional shear factor regardless of the tool material. The TiCN coated tool steel with the water-based lubricant, JF, had the lowest frictional factor among all the combinations. The second best was the WC tool material together with Dag, and the SiAlON tool material together with JF. When the MoS_2 was used as lubricant there was a significant difference in shear frictional factor among the tool materials. The best result for MoS_2 was with the CrN coated tool steel. Figure 16 shows the frictional shear factor of the different combinations [22].

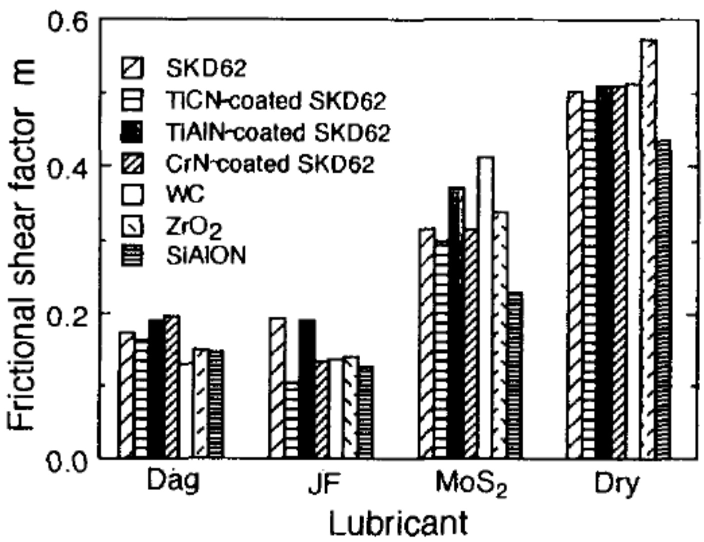

Figure 16: Comparison of the frictional shear factor for various tool materials at room temperature *[22]*.

Figure 17 shows the changes in the frictional shear factor as a function of test temperature. The test was done at room temperature, 200 °C (473K) and 400 °C (673K). Deltaforge and dry tests did not have much change in friction factor for the different temperatures. The frictional factor increased with temperature when MoS_2 was used as lubricant. This was because MoS_2 oxide at elevated temperatures weakened the lubricating performance, causing the frictional shear factor to rise [22].

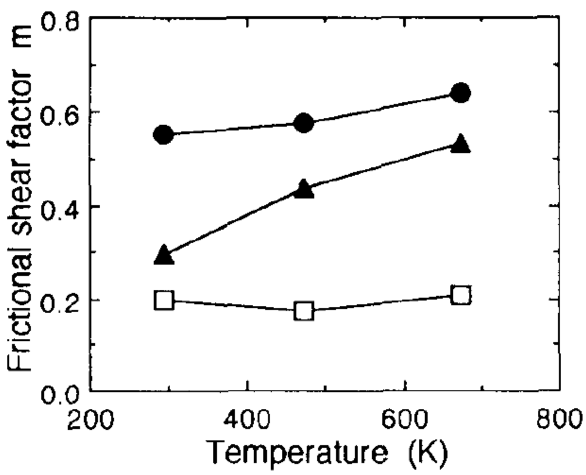

Figure 17: Change in the frictional shear factor as a function of the forging temperature for TiCN coated SKD62 tool steel. □ Deltaforge, ● dry, ▲ MoS_2 *[22]*.

No adhesion was observed after the test at the lower tool surface except for the water-based graphite lubricant, JF. There was most adhesion with the TiAlN coated tool which could be connected with the high frictional coefficient of TiAlN under JF lubricant [22].

3.2 New lubricants for metal forming operations

3.2.1 Alternative commercially available lubricants

Alternatives to the currently used lubricants in Raufoss Technology are to use a new type of lubricant or to apply a thin film of solid lubricant on the workpiece. Different lubricants have been developed which were claimed to be able to compete with the traditional graphite lubricants. To be able to find a new lubricant for Raufoss Technology, it is necessary to contact a company which is specialised in this topic. Klüber is a company which has developed new solutions for lubrication in many industries. A representative from Klüber was contacted. They had some suggestions for which lubricants may work for hot forging of aluminium. These lubricants could be tested in the tribology lab at NTNU. The lubricants were tested against the traditional tool steel and the coated tool steel.

3.2.2 Liquid lubricant

One of the commercially available lubricants at Klüber is called Wolfraco WF 51 W. It is a water-miscible liquid lubricant which can be used for hot forming of nonferrous metals. It is pigment-free, graphite free and based on mineral oil. It can be used for pressing of copper alloys, hot forming of aluminium and pressure die casting applications. Klüber claims that Wolfraco WF 51 W will reduce friction between the die and the formed part at die temperatures up to 260-280^{0}C. Even if the water evaporates the lubricant should attach to the die as a thin film. The lubricant film improves the metal flow properties under extreme conditions, which ensures a smooth surface finish of the formed part [23].

Wolfraco WF 51 W can be applied to the die by spraying or by a brush. It does not ignite under normal die temperatures, and it generates very little smoke and residue formation at the die. Therefore, the press contamination is reduced to a minimum. The chemical composition of the lubricant is confidential, but Klüber can reveal that it is made of a silicone copolymer.

3.2.3 Solid lubricant

Another alternative is to apply a thin film of lubricant which acts as a coating on the workpiece. Klüberplus S 08-107 is a high temperature bonded coating with excellent lubricating and separating properties. It contains graphite and MoS_2. It adheres well to the workpiece's surface, prevents abrasive wear and has great sliding properties. It is water-based with an inorganic binder. The coating must dry and burn immediately after its application prior to the forming process. The lubrication is completely dry, so normally there is no residues building up at the forging die because the bounded coating is removed with the formed component [24].

Klüberplus S 08-107 is meant for use in hot forming processes with a minor surface increase. It improves hot forming processes which involve long sliding distances. It can be used in upsetting and hot forging of aluminium. The advantages of Klüberplus S 08-107 is that it can be applied before it enters the press, so the time in the press can be reduced and this allows higher capacity of the press.

Another advantage is that it has better sliding properties compared to conventional liquid lubricants. So it gives a better form filling, which leads to reduced material costs and reject rates. It also requires much less quantity of the lubricant compared to conventional liquid lubricants. It has no fire risk at 550^0C, less contamination of the pressure, and significant less pollution of the outlet purification systems and the waste water. This lubricant could work well in the forging process in Raufoss Technology [24].

3.2.4 Powder lubricant

Klüberpress HF 2- 804 is a powder lubricant for hot forming processes. It is graphite free and gives therefore a clean machine environment. The product is a powder based on inorganic solid lubricants and a special wax which melts into the die to form a lubricant film. Klüberpress HF 2- 804 is applied to the die by a spray gun, and adhesion can improve by electrostatic charging. The product can be applied manually, semi-automatically or automatically. The advantage is that it is precise and enables low consumption. There is little residue build-up in the die, which reduces the need for cleaning. It does not generate much smoke which leads to a better working environment. The disadvantage is that it requires special equipment for applying the lubricant. It is an interesting solution which can be further investigated, but it was too difficult to test it on a small scale in this project because of the required special equipment [25].

3.2.5 Lubricants decided to be tested and why

Wolfraco WF 51 W is a graphite free water-based lubricant, which contains a silicone copolymer. A lubricant made of boron-nitride-silicone was tested by Ngaile [21] and gave good results at 370 ^{0}C regarding friction. Since the chemical composition of Wolfraco WF 51 W is unknown, it might behave very different from the boron-nitride-silicone.

Klüber has recommended to test the Wolfraco WF 51 W lubricant because it is claimed to be suitable for hot forming of non-ferrous metals at temperatures above 300 ^{0}C. Since Raufoss wants to use less graphite and oil-based lubricants it was worth to test if Wolfraco WF 51 W could be a good alternative.

Klüberplus S 08-107 is a solid lubricant. It contains graphite, but not oil. It is applied to the workpiece before it enters the press, which can save time used in the press for each component. Klüberplus S 08-107 contains MoS_2, which is also the case for the lubricant tested by Nishimura [22] which is an aerosol spray containing MoS_2. The test done by Nishimura showed that the frictional factor was very dependent on temperature. It was not the best lubricant tested, the other lubricants had a lower frictional factor.

Klüberplus S 08-107 had previously been planned to be tested at Raufoss Technology, but they did not have time for it, so this was a good opportunity to test it. Klüber was willing to coat some of the samples which could be used in the tribological test.

The current water-based graphite lubricant used in the new production line L05 in Raufoss Technology, Lubrodal F 33 Al, was also tested as a reference.

3.3 Coating of tools

3.3.1 Literature study of coatings

The next sections compared different coatings tested by others, regarding mechanical properties, friction, and galling.

The article [26] written by Kumar et al. compared TiAlN and AlCrN PVD coatings. TiAlN and AlCrN coatings had better mechanical properties such as better oxidation resistance and wear resistance than TiN coatings. The TiAlN gradient coatings had high bonding strength and no pores and cracks. TiAlN was a successful coating for cutting tools because of its improved oxidation resistance and hardness compared to TiN coatings. AlCrN coatings had higher oxidation resistance because both chromium and aluminium could form protective oxides which suppress the diffusion of oxygen.

Friction conditions after applying a coating

After applying coatings, the surface conditions were different and the friction might increase or decrease. New deposition methods as CVD and PVD made it possible to produce surfaces with extremely low friction. The low friction was dependent on the grain size, the crystal orientation effects and the lack of contaminants in the coating. [2]

The article [18] by Pellizzari described the tribological contact between an 6082 aluminium alloy and a hot work tool steel. A block on disk test was used to simulate an extrusion process. The block was made of steel and the disk was made of aluminium. The tool steel underwent three different surface treatments, nitriding, duplex-PVD (CrN, TiAlN, TiCN) and CVD coated (TiC + TiN). The mass of the block was measured after the test to quantify the aluminium pick up on the die material.

The friction was measured continuously throughout the test. The test was stopped when a transition of the friction coefficient occurred, characterized by strong oscillation of this parameter and unstable contact. The duplex PVD coated samples performed better, with a higher transition time than the nitrided samples, except for one coating, the duplex PVD TiCN coating, which had a lower transition time than the nitrided samples. The surface roughness highly influenced the transition time, resulting in a lower time before an increase of roughness. This was especially relevant for the PVD coatings, where the roughness caused increased oscillations of friction, with less stable contact between the die and billet. This effect was less significant for the CVD coating. For the single coated systems the CVD TiC + TiN and PVD TiAlN had the most promising performance regarding friction. The worst results were the duplex PVD TiCN and rough electron beam sputtering PVD CrN coating, which both behaved worse than the nitrided sample [18].

The article [27] written by Huang was about a ball on disk test with TiN, CrN and (TiAl)N coatings against steel. It studied the friction conditions. This is important because higher friction influences the mechanical efficiency, it increases the frictional heating and the distribution of contact stresses in the surface region. A higher friction coefficient of the contacting pair would increase the shear stress while moving it towards the surface. The resultant shear stress at interface between the coating and the substrate would most likely be increased as a result of increased friction coefficient. The study of the friction behaviour of different coatings is important to find ways to reduce the friction of the contact pairs [27].

Friction is a result of adhesion, ploughing and asperity deformation. During the ball on disk test the steel slider was ploughed by the hard asperities of the coating surface, making many ploughing grooves on the worn area. The slider material was gradually transferred to the coating surface forming discontinuous layers, and at the steady state the friction behaviour of the contacting surfaces was characterised by the sliding between the slider and the transferred slider materials. The TiAlN coating had the highest hardness and roughness values and had the highest friction coefficient. The CrN coating, which had the lowest hardness and roughness values, had the lowest friction coefficient [27].

Birol [28] wrote about the sliding wear of three different coatings, CrN, AlCrN and AlTiN and used a block on cylinder test. The aluminium cylinder reacted chemically with the coating and progressive oxidation happened at the test temperature. Aluminium diffused along the grain boundaries interconnecting the coating and the aluminium counterface. This led to a high state of friction. The friction coefficient was 1,83, 1,68 and 1,41 for CrN, AlCrN and AlTiN coatings respectively for the sliding contact conditions. The high friction conditions led to sticking of aluminium to the coating, forming an aluminium-aluminium tribo-layer, and increasing the friction further. The frictional forces caused considerable shear stresses at the surface. The aluminium penetration along the grain boundaries reduced the cohesive strength of the coating and its adhesion to the substrate. Under these circumstances fracturing and delamination of the coatings were unavoidable, this could be seen from the surface and section micrographs of the wear tested samples.

The test with CrN had the highest friction coefficient and the largest wear damage. This was because it reacted chemically with aluminium resulting in aluminium transfer, and it had the lowest hardness. The coatings containing aluminium had higher hardness, lower friction coefficient and higher oxidation resistance, which resulted in less wear. The AlTiN had the lowest coefficient of friction and a smooth wear track because of the high chemical resistance against aluminium of the Al-rich AlTiN coating.

Coatings to reduce abrasive wear

Article [28] by Birol was about the sliding wear of CrN, AlCrN and AlTiN coated hot work tool steels in aluminium extrusion. A wear test with block on cylinder configuration inside a heating chamber was used. The test was performed at 550 ^{o}C and a normal force of 60 N was applied to the coated steel test sample establishing dry sliding contact with the rotating aluminium cylinder. The wear track on the aluminium cylinder was studied for each coating. The CrN coated sample experienced the deepest wear track with a rough topology implying a more extensive interaction of the aluminium alloy with the CrN coating. The wear track with the AlCrN behaved slightly better. The AlTiN coated sample gave a wear track with significantly smoother topography with more uniform features. Figure 18 shows the wear track on the aluminium cylinder after the test with the different coated samples.

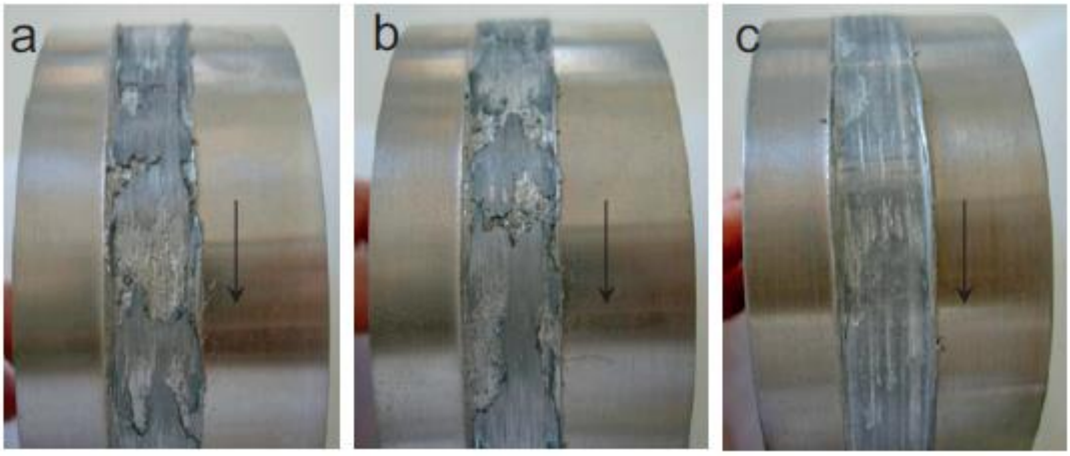

Figure 18: Macrographs of the aluminium cylinders rotated against CAPVD (a) CrN, (b) AlCrN and (c) AlTiN coated hot work tool steel after the sliding wear test. The sliding direction is indicated with an arrow *[28]*.

The PVD coated hot work tool steel surfaces were gradually covered with aluminium transferred from the cylinder after the wear test had started. The aluminium had an increased thermoplastic behaviour at 550 ^{o}C which promoted aluminium transfer. The aluminium transfer on the CrN coated sample was extensive. The contacting interface was completely covered with an aluminium layer with a rough topography. The AlCrN coated surface was covered with a thin and uniform layer of aluminium with only occasional patches of aluminium on the sliding track. The AlTiN coated sample was much smoother and hardly exhibits any wear damage. There were only very small and shallow patch-wise wear sites randomly dispersed over the surface.

Duplex treatment for hot forging tools was discussed in article [19] by Panjan. Steel plates which were preheated to 1050 ^{o}C were used as workpiece together with a graphite lubricant. The duplex coating was made of multilayers of TiN/TiAlN. After forging, the wear of the tools were studied in a Scanning electron microscope (SEM). The duplex coating had no visible wear after 300 forgings. After 1100 forgings, there was no damage on the upper part of the tool, but there was observed partial delamination of hard coating in the area of largest sliding lengths. The coating was partially damaged in the roundings of the tool, but undamaged on the front side. The roughness was measured after 100 strokes, and the duplex coatings roughness remained unchanged. The test stated that the duplex coating reduced abrasive wear, no cracks were observed on the surface of the tool. From this research it was found that a duplex coating can reduce wear in hot forging of steel, but it is not known yet if it possible to apply for hot forging of aluminium of a complex shape.

In the study [18] by Pellizzari the damage mechanisms in the simulated test of extrusion of aluminium were discussed. At the surface of the nitrided steel sample there was a damage caused by irregular morphology of the wear track. Wear was localized at an earlier state by the presence of delamination pits. A formation of subsurface cracks propagated because of high tangential stresses, which caused delamination. Then hard nitrided wear debris particles became captured in the soft Al alloy. This resulted in abrasion of the steel surface because of the ploughing action of these particles. Less damage was observed by the coated samples at the end of the test. Most of the sample was still covered by the coating according to the Energy dispersive x-ray spectroscopy (EDS) analysis. The TiAlN PVD coating was almost undamaged. In the areas where the coating was thinner it was observed a thin aluminium oxide film on the tool, which could not be removed. Where the coating was completely removed some pits could be detected. In areas where the coating was still present, measurements of the CrN coated system showed that no Al could be detected after the test.

Article [29] by Behrens et al. described a full scale forging test of a TiN/TiB_2 multilayered coating in hot forging of steel. The result was a reduction of abrasive wear, where the coated dies showed much less abrasive wear than the nitrided dies. The nitrided dies showed severe spreading of abrasion, in contrast to the coated dies which stayed in good shape. The best layup of the TiN/TiB_2 coating gave a reduction of abrasion by 78% compared to the nitrided die.

The study [30] by Mo et al. investigated the difference between CrN, AlCrN and AlTiN PVD coatings regarding wear evaluated by a cyclic impact wear test and a micro-scale abrasion test.

The abrasion test was done in a TE66 microscale abrasion testing machine where a ball made of hardened steel slid in an abrasive slurry with a suspension of SiC particles in distilled water. The CrN coating had the worst abrasive wear resistance compared to the aluminium containing coatings, this can be because of the hardness of CrN was softer than the SiC abrasive media. The abrasive wear of the CrN coating was made from plastic deformation, fine micro-cracking and micro-spallation processes. AlTiN and AlCrN are much harder than the SiC particles and had much less abrasive wear. AlCrN had the best abrasive wear resistance. The reason why AlTiN had a lower abrasion resistance than AlCrN could be because the higher friction coefficient of AlTiN. This might result in a more severe multiple indentation from the abrasive particles [30]

Coatings to reduce adhesive wear

Continuing with the article [30] by Mo et al. the abrasive wear of the CrN, AlTiN and the AlCrN coatings was studied. An impact test was performed on a proprietary pneumatically actuated cyclic impact tester. The specimen surface was repetitively stressed at a defined contact point by impacts from a hard sphere. The sphere was made of tungsten carbide, used as the impacting body. Under normal loads of 150 and 300 N there was no significant pick-up and transfer of the ball material observed. For increasing impact cycles there was no significant change of the wear morphologies, except some very minor transfer of the ball material on the worn surface.

The wear debris hardly adhered to the worn surface of the AlCrN coating which avoided adhesive wear and detachment or delamination of coating by the cyclic loading [30].

The AlTiN coating behaved differently than the AlCrN coating. There were large areas of pick-up and ball material transfer observed at a lower number of impact cycles inside the wear scar of the AlTiN coating. From the impact test the AlCrN coating had much less adhesive wear than the AlTiN coating. This could be because AlTiN coating had a higher friction coefficient between the coated surface and the ball. Another reason was that the titanium in the AlTiN coating had a stronger affinity to the ball counterface elements [30].

Kolbe [31] described a test of different PVD coatings in hot forging of steel. The result showed that a $CrSi_2$ coating increased the occurred friction during forging. The crystalline structure of this coating may be the reason of the increased friction. As a result about 70% of the steel parts continued to adhere to the tool, which was even more than the uncoated tool. The TiAlN coating had about 20% of adherence to the tools. The best result was a TMS coating, the TMS coating was made of tetramethylisan. There was almost no friction where all parts separated easily even without lubricants. The reason for this was the carbon partially bounded in the coating which worked like graphite. Article [31] also described a test with CVD coating of TiC/TiCN/TiN which gave good results in reducing adhesive wear. This shows that PVD and CVD coatings can reduce galling in hot forging of steel. Therefore, it was worth to find out if it can work in hot forging of aluminium. To use the CVD coating, the tool steel must withstand the high temperatures in the CVD coating process. For the PVD coating to work the shape of the tool cannot be too complex to make a uniform layer of the coating at the tool surface [31].

The study [18] by Pellizzari contained a simulated test of extruded aluminium against a tool steel with different coatings. Immediately after the test started it was observed a thin layer of Al on the block surface. After a transient period of about 5 minutes, the aluminium pickup continued almost linearly, but with a much lower transfer to the coated surfaces than the base steel and nitrided ones. Figure 20 shows the mass gain of the sample as a function of time, (NCL= nitrided sample with compound layer and NDL= nitrided sample with diffusion layer only). An increasing transition time indicates low tendency to adherence of aluminium to the tools, as shown in Figure 19. The heat treated and nitrided steels performed much worse than the coated samples because of the abrasion where Al oxide particles were formed. The hard particles can cause stop in the production if they stick to the die surface because then the product’s surface get damaged. The best coating for avoiding sticking of aluminium was the PVD coating TiAlN, and the CVD coating TiC + TiN.

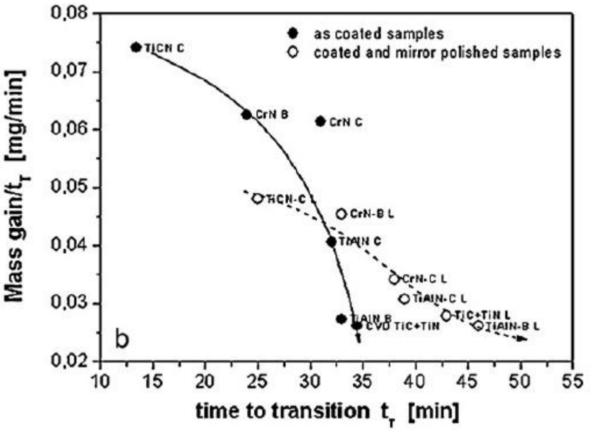

Figure 19: Mass gain curve vs. transition time of duplex PVD and CVD coated samples [18].

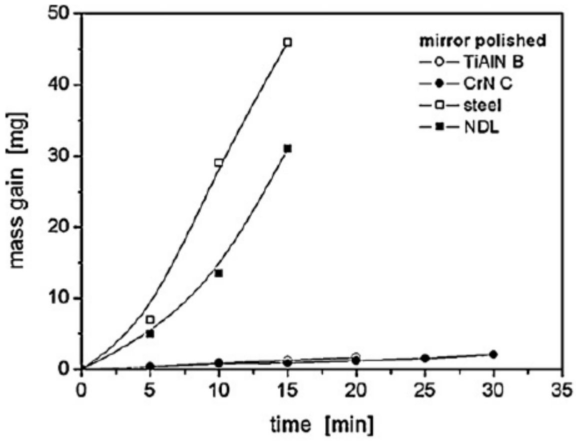

Figure 20: Mass gain curve of different samples due to Al- pickup measured during interrupted test [18].

The article [28] by Birol was about the testing of three different coatings, CrN, AlCrN and AlTiN. The damage of the coating was investigated. Most of the coating was retained during the test. The CrN coating had some wear craters, caused by surface irregularities connected with the droplets typical for the PVD coating. The detachment of these droplets led to formation of pits at the surface during the wear sliding test. These pits promoted the formation of large craters and entrapment of aluminium at the coated surface, which led to accelerated aluminium pick up. For the AlCrN coating the wear scars remained as small pits which were less in number and smaller in size. This means less aluminium pickup on the AlCrN coated surface. For the AlTiN coating there was no sign of delamination of the coating that seems to be intact after the wear test. This can explain that the AlTiN coated surface had the least aluminium pickup.

Article [29] by Behrens et al. which was a test of a TiN/TiB_2 coating in hot forging of steel, showed improved results for the coated die regarding less adhesion of the work material to the tool. For the nitrided die it was adhesion at the top of the die, while the coated die had almost no sign of adhesion. The best layup of the TiN/TiB_2 coating gave an improvement of 22% reduction of adhesion compared to the nitrided die.

3.3.2 Cost analysis from literature

The article [32] by Bayramoglu et al. described a cost analysis of three different coatings used for forging dies, and compared them with the untreated forging dies.

The AlTiN coated dies performed much better than the untreated dies. The polishing life before first polishing was 234% better than for the untreated dies. For the further polishing it was improved by 57% compared to the untreated dies, this is because the AlTiN layer is thin, and most of the coating got polished off. Nitrided dies lost less of their advantages after polishing since the nitrid layer is thicker. Only nitrided dies performed 175% better than the untreated dies.

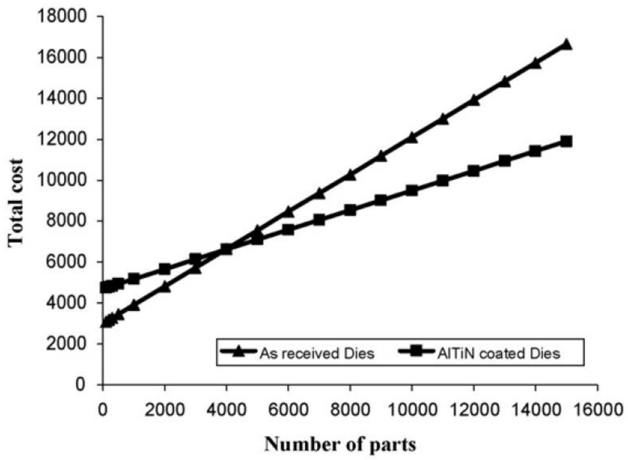

Figure 21: Break even points for costs versus number of parts of the experimented dies [32].

Figure 1 shows the number of parts which needs to be produced before the surface treatment pays off, for the AlTiN coated dies this is around 4000 parts. In total the costs were reduced by 47% for the AlTiN coated dies compared to the untreated dies.

3.3.3 Other types of surface treatments

Diamond-like carbon – DLC

This section discussed if Diamond-like carbon can reduce galling in forming operations, and if it can be used in hot forging. Diamond-like carbon (DLC) coatings are a group of amorphous carbon based coatings with similar properties to natural diamond, but without the crystalline lattice structure [2]. A DLC coating consist of a mixture of sp^2 (graphite like) and sp^3 (diamond-like) hybridised carbon atoms in different relative proportions, where the ratio between the two structures determines the properties [3]. DLC coatings give great wear resistance and low friction properties and can be used in for example: cutting tools, automotive sliding components, gears, mechanical seals, textile industry parts and much more [2].

Heinrichs [33] has done tests of different coatings and concluded that DLC coatings were effective to reduce galling of aluminium to tools in cold forming. Heinrichs has written another article about how DLC is successful in reducing galling in cold forming [34]. It describes a test consisting of a sharp tip of work material which came in contact with a tool material under a controlled load. The load was high enough to plastically deform the work material as in forming. The two surfaces slide relative to each other, and the sliding was observed in a Scanning Electron Microscope (SEM). The work material was made of 6082 aluminium and the tool was made of steel (Vancron 40). The tool material was coated with a sputtered DLC coating with thickness of 2 μm and hardness 1500 $HV_{0,5}$. This coating gave good result for reducing galling proven in Henrichs paper [33].

In the test [34] by Heinrichs the friction between the tip and the tool material was relatively low and stable even in unlubricated state, with a polished DLC coating. The contact interface was also very stable, after the tip was flattened by plastic deformation, no further deformation was noted, and almost no transfer of aluminium to the DLC coated tool steel was found. This amount of transfer of aluminium is negligible, consisting of scattered micrometre-sized surface defects. Figure 22 shows a SEM image of one of the small particles transferred at a rough spot. In comparison with uncoated polished tool steel, the galling happened already in the beginning of the test, and more aluminium adhered throughout the test resulting in an increase of friction factor by 2,5. In contrast, at the DLC coated surface the galling marginally changed the friction conditions [34].

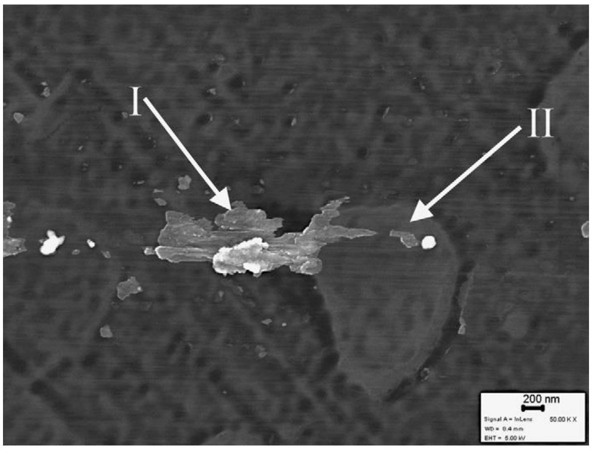

Figure 22: SEM picture of one of the rare very small particles (I) that has become transferred at a local rough spot (II) on the polished DLC surface [34]

The article by Heinrichs [34] described that DLC is a coating which could reduce galling. The next question is: "Can it be used in hot forming?" Raufoss Technology has done a test of a Diamond-like Carbon (DLC) coating on the support rollers in their cross wedge rolling machine. The test was performed to reduce a problem with galling of aluminium. The support rollers are not under high pressure or pre-heated, but are heated indirectly from the warm aluminium rods and by radiation heat from the hot rollers, the maximum temperature goes up to 300^0C.

The DLC coating gave immediately positive effect by reducing the galling, but the effect decreased along with the number of produced parts. The coating withstood production of around 10 000 parts, the desired lifetime is around 500 000 parts. The reason for the short lifetime may be that the temperature was on the limit of what the coating tolerates. This showed that DLC coatings are probably not well suited for hot forging when the temperatures are even higher.

Nitriding

Nitriding is the most commonly used surface treatment for hot forging dies. Nitriding has a much lower relative cost than PVD or CVD coatings. Nitriding can reduce the wear up to 50% [35]. Nitriding is not in use in Raufoss Technology on the forging tools. Article [19] by Panjan et al. compares plasma nitriding coating vs. duplex treatment. The result from the test shows that nitriding is not as effective to reduce wear as a duplex treatment, which is a type of PVD coating.

3.3.4 The coatings decided to be tested and why

In the literature study different coatings were studied. From the literature study it was found that a coating will reduce friction and galling between tool and workpiece for hot forging of steel. The coatings also reduced the friction and wear in extrusion of aluminium. The question is, will it work to coat the tools for hot forging of aluminium? Forging of aluminium occurs at a lower temperature. Therefore, the coating used for forging of steel will tolerate the temperature in hot forging of aluminium. The tool steel must tolerate the high temperature needed to apply the coating without damaging the mechanical properties of the tool. To apply a CVD coating it requires temperatures of around 800-1200 $^{\circ}$C, the tool steel used in Raufoss Technology will be damaged at these high temperatures. Therefore, a CVD coating cannot be used. PVD coatings requires a lower deposition temperature of around 500 $^{\circ}$C, which is much better for the tool steel. Therefore, two PVD coatings were tested.

Primateria is a company that is working to reduce friction in production by optimising the tool surface conditions. They have recommended two coatings for the tools in hot forging of aluminium. It is an AlTiN and an AlCrN coating.

The AlCrN and AlTiN coatings can provide better wear protection than aluminium-free nitride coatings, such as TiN and CrN. This is because the aluminium causes higher hot hardness, oxidation resistance and a lower thermal conductivity [36].

From the literature study the TiAlN coating has proven to give good results regarding reducing friction and galling. Primateria has suggested to test an AlTiN coating. AlTiN has similar properties to TiAlN, but AlTiN has a higher surface hardness and higher percentage of aluminium [37].

Article [28] by Birol contains a block on cylinder test with steel and aluminium, where a CrN, an AlCrN and an AlTiN coating were tested. The AlTiN had the smoothest wear track indicating the lowest coefficient of friction. The study by Mo [30] also compared CrN, AlCrN and AlTiN PVD coatings. The AlCrN gave the best results regarding abrasive and adhesive wear, and had the lowest friction coefficient in this test.

Since the AlTiN and AlCrN coatings have been successful in most of the tests done in the literature and have also been recommended by Primateria, these coatings were selected to test.

AlTiN stands for aluminium titanium nitrid. It performs well in cutting operations with high speed, high temperature drilling and milling because of the high amount of aluminium present. The aluminium acts as a protection against heat. A layer of aluminium oxide is produced and protects the tool during cutting. However, too much aluminium present can make the crystal structure of the AlTiN coating change from cubic to hexagonal lattice. This will change the material towards less favourable properties. [38]

AlCrN stands for aluminium chromium nitride. It is an alternative to the AlTiN coating, it is here possible to add more aluminium without changing the structure. More aluminium gives the coating even better properties in many high speed metal cutting operations. The application of AlCrN coating is broad. It performs well in gray and ductile irons, hard and mild alloyed steel and aerospace metals [38].

The PVD coatings used in this project was made by Primateria, and was applied to the pins by reactive arc evaporation at 450 ^{o}C. The metal the coatings was made of, went from solid phase through an electric arc, making the coating condense on the surface resulting in a thin film. The metal melted locally and atoms detached from the melt to a gaseous state. If too much material had melted, it could boil over, making small droplets of the metal come out in the reaction chamber, resulting in an uneven coating. The material sources were placed in the chamber walls and the items which was to be coated are mounted on a rotating holder in the middle of the chamber. In the ionising gas mixture in the chamber, also called plasma, a reactive gas was added. The ions in the plasma were attached to the items surface and reacted into the coating [20].

3.4 Research questions

From the literature study there were studied different types of lubricants and coatings tested in tribological tests or metal forming operations. From this study it was possible to find some lubricants and coatings which gave good results in the literature for different metal forming processes. Since there was not much found in the literature regarding new lubricants and coatings for hot forging of aluminium, there is a knowledge gap in the literature.

The following chapter will describe a test method used to compare the selected lubricants and coatings, to answer the following research questions:

- Which lubricant and coating combination gives the lowest frictional factor?
- Determine the maximum temperature limits for different lubricants, as assessed by wear and friction of specimens.
- Is there any significant difference regarding galling of aluminium for the lubricants and coatings?

4 Test methods

4.1 Test preparations

4.1.1 Test setup

A simplified tribological test can give an indication if the selected coatings and lubricants can be used in hot forging of aluminium. A reciprocating pin on plate test was performed in a TE88 machine at the TriboLab at NTNU.

The pins were made of Uddeholm Dievar steel, representing the forging tool, which is the die material used on the forging tools in Raufoss Technology. Four different pin configurations were made:

- Uncoated pins
- Polished pins
- AlTiN coated pins
- AlCrN coated pins

The uncoated pins had the same surface roughness as the tools used in Raufoss Technology today. The plates were made of EN-AW 6082 aluminium, the same material as the workpiece used in the forging process.

Three different lubricants were tested together with each coating:

- Lubrodal F 33 Al – a water-based graphite lubricant
- Wolfraco WF 51 W – a water-based graphite free lubricant
- Klüberplus S 08-107 – a solid graphite lubricant applied to the workpiece

Lubrodal F 33 Al is the lubricant Raufoss Technlogy uses today. Table 2 shows the combinations of coatings and lubricants that were tested.

Table 2: Test matrix showing how many pins that were tested with each combination

Surface treatment	Without lubricant	Lubrodal F 33 Al	Wolfraco WF 51 W	Klüberplus S 08-107
Only heat treated	X 1	X 3	X 3	X 3
AlTiN coating		X 4	X 4	X 4
AlCrN coating		X 4	X 4	X 4
Polished, no coating		X 3		

After the pin on plate test was finished, the steel pins were studied in a Scanning electron microscopy (SEM), to see the material contrast, which will indicate if there is any galling of aluminium at the pin surface. A SEM-EDS was also used, a scanning electron microscopy with Energy-dispersive X-ray spectroscopy. This is to see which materials that are present at the pin surface and the amount of each material.

4.1.2 Testing equipment

For the experiments a TE 88 multi-station friction and wear test machine was used. The machine is designed for wear testing under high contact pressures. There are three different types of wear test modes; pin on disc, block on ring and reciprocating pin on plate. The test performed in this study was a reciprocating pin on plate test. Figure 24 shows the test machine. The plate is flat and mounted in a reservoir to maintain the lubricant.

The station is equipped with electrical heating for temperatures up to 300 ^{0}C and a thermocouple. The reservoirs are fastened on a common plate, which is placed by ball bushings on a linear bearing assembly. The plate is moved back and forth by a variable throw crank. The pin is held stationary by a static arm. A pneumatic bellow is used to apply the loading of the pin and is placed at the end of the arm [39].

Figure 23 illustrates how the plate moves relative to the pin and where the load is applied. To secure no horizontal movement of the arm, it is localised between two pads. The machine records the velocity, the frictional load and the load at the pin. The possible stroke length configuration is up to 25mm at 2 Hz or 50mm at 1 Hz [39].

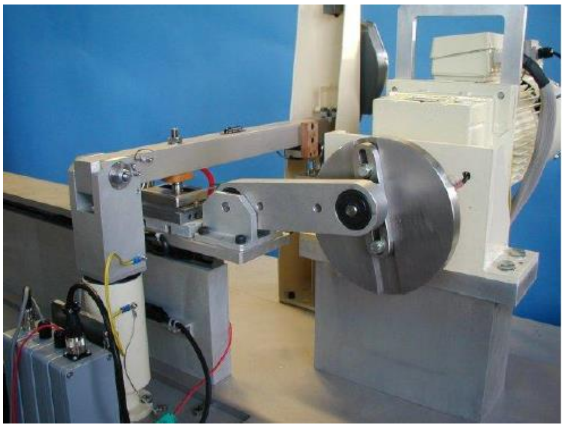

Figure 24: TE 88 test machine configured in pin on plate mode [39]

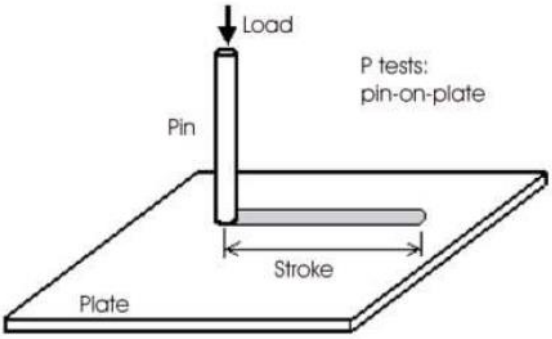

Figure 23: Pin on plate test illustration [40]

The parameters needed for setting up the test:

- Pin size
- Load
- Stroke length
- Speed
- Temperature

SEM and EDS

A scanning electron microscopy (SEM) was used to produce a scan image at a high spatial resolution. It scans a focused electron beam over a surface to create an image. Information of the topography and composition are detected by signals from the electrons in the beam when it interacts with the sample [41].

Energy dispersive x-ray spectroscopy (EDS) was used to detect which materials that were present at the pin surface. EDS is a chemical microanalysis technique used in conjunction with SEM. EDS can characterise the elemental composition of the analysed volume by detecting x-rays emitted from the sample during bombardment by an electron beam [42].

4.1.3 Evaluation parameters

There are several evaluation parameters which should be measured from the test:

- Friction coefficient – is it higher or lower than the standard setup with uncoated pin and water-based graphite lubricant?
- Spallation of the coating, is the coating maintained during the process?
- Adhesive wear and galling, has the work material adhered to the pin?
- Abrasive wear – has the pin maintained it's original geometry?
- Amount of needed lubricant

4.1.4 Test preparations

Test materials

For the tests there were 25 aluminium plates and 46 steel pins available. The pins and the plates were provided by Raufoss Technology. The pins had a diameter of 3 mm and a length of 15 mm. The plate size was 38 x 58 x 6 mm. A new pin holder was made at a workshop at NTNU to fit the pin because 3 mm in pin diameter was not a standard pin size. The aluminium plates were grinded to get an even surface with a 220 SiC-paper. 8 of the plates were sent to Klüber in München for application of a solid lubricant called Klüberplus S 08-107.

Surface preparation of pins

The pins were grinded at NTNU and sent to Primateria for surface treatment. Raufoss Technology grinds their tools with a P 220-240, the pins grinded with P 220 SiC-paper represented the current tool steel without surface treatment. The other pins were grinded with a P 500 SiC-paper and polished and/or coated. The coated pins went through polishing and pre-treatment, coating and post-treatment. Table 3 shows the surface treatment for the different pins. The polished uncoated pins were tested to get a reference to the coated pins, since the roughness affects the friction test results. The polished pins were tested with the lubricant which gave the best result with the coated pins.

Table 3: Surface treatment of pins

Number of pins	Grinding paper	Coating
9	P220	No
3	P220	No, but polished
15	P500	AlTiN
16	P500	AlCrN

4.1.5 Test procedure

Preparing the samples

An ultrasonic bath with ethanol was used to clean the pin and plate prior to each test. Before each test the weight of the pin was measured.

Test process

The test process was the same for all the lubricants and pins. The parameters from Table 18 were set in the program of the TE 88 machine. When the plate was heated the liquid lubricants were applied with a pipette.

Table 4: Test parameters used in the TE 88 machine

	Test parameters used
Pressure	70 MPa
Load	500 N
Speed	100 mm/s
Temperature	200 ^{o}C
Testing time	1 cycle
Stroke length	30 mm at 1.25 Hz

The load was applied on the pin. The program was started and made the plate move one cycle. The plate moved horizontally while the pin was in contact with the plate with a constant pressure set by the load. After the test stopped, the load was removed and the wear track on the plate was studied. The weight of the pin was measured and compared with the weight before the test, to check if there was severe galling of aluminium onto the pin.

All the lubricants were tested with the uncoated pins, and pins coated with AlTiN and AlCrN. There was tested enough pins to get two successful results with each combination of coating and lubricant.

Testing of Lubrodal F 33 Al

The first lubricant tested was Lubrodal F 33 Al. It is a water-based graphite lubricant used in Raufoss Technology today. Lubrodal F 33 Al started to boil when it came in contact with the hot plate, as shown in Figure 26. The water in the lubricant evaporated, and left a thick solid graphite layer on the plate, see Figure 25.

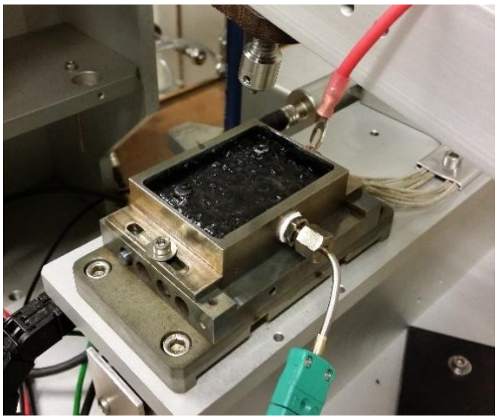

Figure 26: Right after Lubrodal F 33 Al was applied

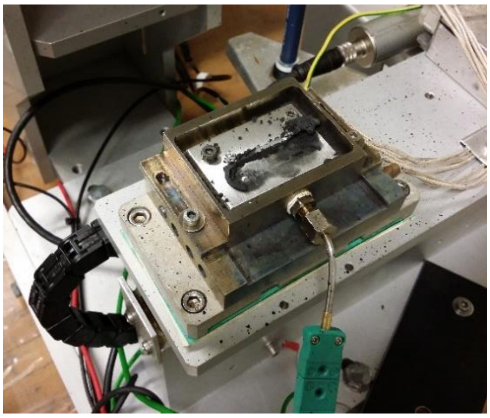

Figure 25: The plate with solidified Lubrodal F 33 Al, after the test

Testing of Wolfraco WF 51 W

The next lubricant tested was Wolfraco WF 51 W. The lubricant was diluted 1:1 with water. When the lubricant was applied to the hot plate it started to boil, and a lot of lubricant had to be applied to get a thick enough layer of lubricant sticking to the plate.

Testing of Klüberplus S 08-107

The third lubricant tested was a lubricant called Klüberplus S 08-107. It is a solid lubricant containing graphite, which is applied to the workpiece, in this case the aluminium plate. A company called Klüber lubrication coated the aluminium plates. The coated plates were mounted in the sample holder, and the same procedure was done as with the other lubricants, but there was no additional lubricant added when the plate was heated.

Surface investigation with SEM and EDS

The pins were studied in a Scanning electron microscopy (SEM) and pictures were taken of the surface to see the material contrast. Figure 27 shows the pins placed in the SEM before the analysis. An EDS, Energy-dispersive X-ray spectroscopy, was used to find the materials present at each pin after the test. Figure 28 shows the pins placed in the EDS before the analysis.

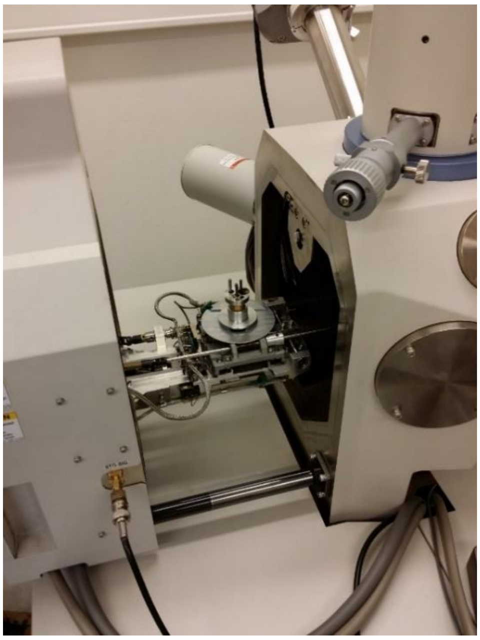

Figure 28: The samples mounted in the energy dispersive x-ray spectroscopy (EDS)

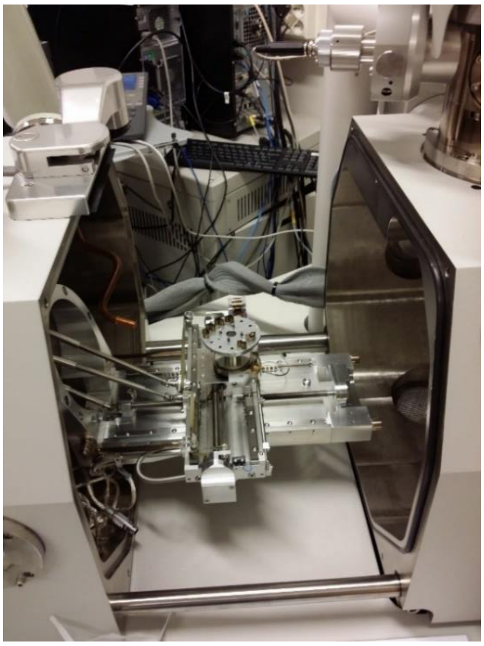

Figure 27: The samples mounted in the scanning electron microscopy (SEM)

5 Test results

The following sections presented the results from the friction and wear tests.

5.1.1 Comparison of lubricants

The first test was performed without lubricant, a deep wear track occurred and the friction coefficient was very high.

Lubrodal F 33 Al was the first lubricant tested, it is a water-based graphite lubricant. When it was applied to the hot sample, the water vaporised and left a solid layer containing graphite on the surface. This layer prevented the aluminium plate and the pin to get in direct contact. Sometimes the lubricant did not behave like expected and a large wear track appeared, similar to the wear track obtained at the test without lubricant. Figure 29 shows the wear track with successful and failed lubricant.

Figure 29: The wear track on top is where the lubricant failed, and the wear track on the bottom is when the lubricant worked successfully

Also with the other lubricants some of the test failed due to the lubricant not working properly. It was clearly visible from the wear track, as the steel pin plowed a deep wear track in the aluminium plate. From the coefficient of friction it was possible to see which tests failed. At the successful tests, the maximum coefficient of friction was 0,16, while the tests where the lubricant failed the coefficient of friction was over 1.

Figure 30 shows a successful test with the aluminium plate coated with Klüberplus S 08-107.

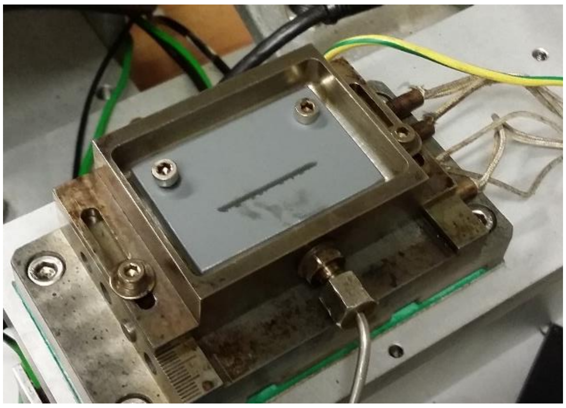

Figure 30: Successful test with Klüberplus S 08-107, a solid lubricant coated to the workpiece

Figure 31 shows the average maximum coefficient of friction for the different coatings and lubricants. It looks like the tests with Lubrodal F 33 Al, which is the lubricant Raufoss Technology uses today, had the lowest coefficient of friction. The coated and polished pins contributed to a lower coefficient of friction than the uncoated pins for the tests with each of the lubricants. It was not a large difference between the tests done with Wolfraco WF 51 W and Klüberplus S 08-107 for the coated samples, regarding the maximum coefficient of friction shown in Figure 31, the difference is neglect able.

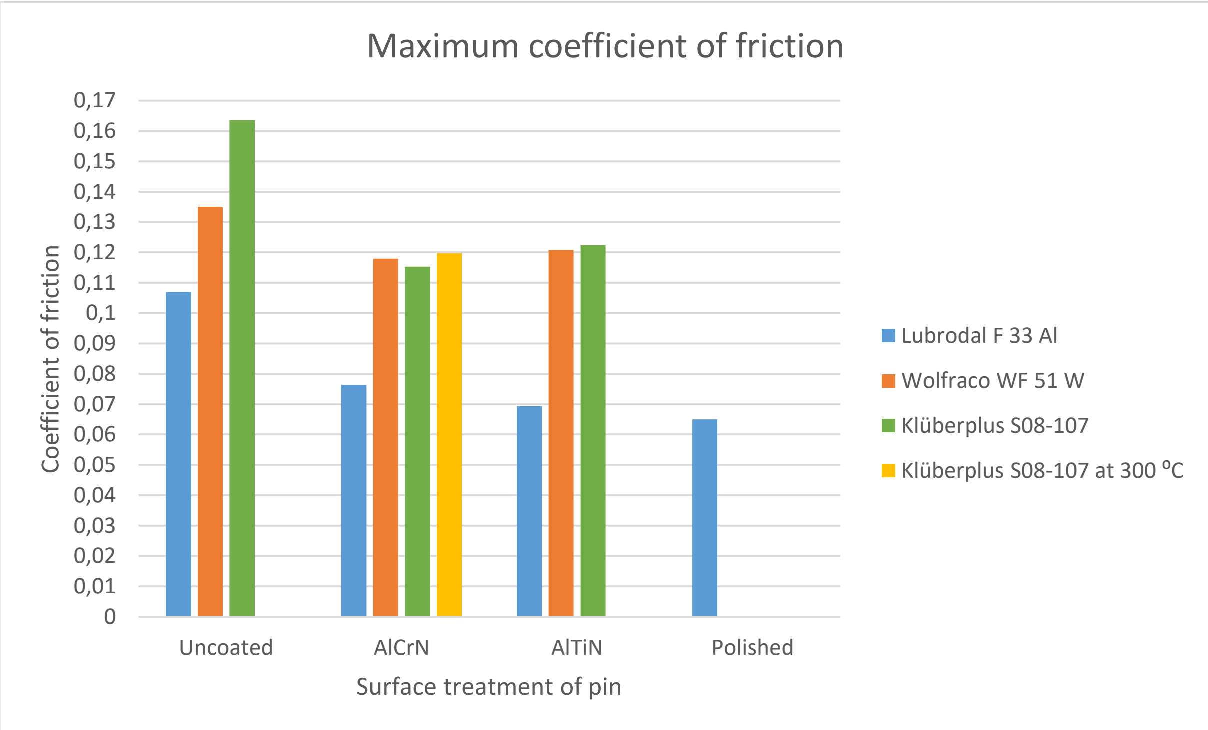

Figure 31: The maximum coefficient of friction with the different combinations of lubricants and coatings for the successful tests.

Table 5 shows all the frictional coefficient values of all the successful tests.

Table 5: Maximum coefficient of friction values for all the successful tests

Test	Lubricant	Coating	Maximum coefficient of	Degrees
3	Lubrodal F 33 Al	Uncoated	0.107	250
5	Lubrodal F 33 Al	AlCrN	0.07044	230
6	Lubrodal F 33 Al	AlCrN	0.08231	235
10	Lubrodal F 33 Al	AlTiN	0.05474	195
33	Lubrodal F 33 Al	AlTiN	0.05185	200
11	Lubrodal F 33 Al	AlTiN	0.10133	200
34	Lubrodal F 33 Al	Polished	0.06041	206
35	Lubrodal F 33 Al	Polished	0.06955	204
24	Wolfraco WF 51 W	Uncoated	0.13502	143
28	Wolfraco WF 51 W	AlCrN	0.08116	182
32	Wolfraco WF 51 W	AlCrN	0.10733	194
27	Wolfraco WF 51 W	AlCrN	0.16523	223
15	Wolfraco WF 51 W	AlTiN	0.11767	210
31	Wolfraco WF 51 W	AlTiN	0.12384	163
23	Klüberplus S 08-107	Uncoated	0.16362	200
20	Klüberplus S 08-107	AlCrN	0.12893	200
21	Klüberplus S 08-107	AlCrN	0.10164	200
16	Klüberplus S 08-107	AlTiN	0.12152	203
17	Klüberplus S 08-107	AlTiN	0.12316	200
18	Klüberplus S 08-107	AlCrN	0.13095	300
39	Klüberplus S 08-107	AlCrN	0.10846	294
38	Klüberplus S 08-107	AlCrN	0.15887	288

There were several tests that failed because of breakthrough of the lubricant film, causing metal to metal contact. Figure 32 illustrates the number of failed and successful tests of each lubricant. Wolfraco WF 51 W was the lubricant which was most difficult to work with resulting in an equal number of successful and unsuccessful tests. The high temperature makes it difficult to apply a lubricant containing a lot of water, because of the Leidenfrost effect.

There were also many tests which failed with Lubrodal F 33 Al, only 62% of the tests were successful. Lubrodal F 33 Al was the first lubricant tested, which caused some start-up problems, as finding the right testing temperature. Klüberplus S 08-107 had the highest success rate with 73% successful tests.

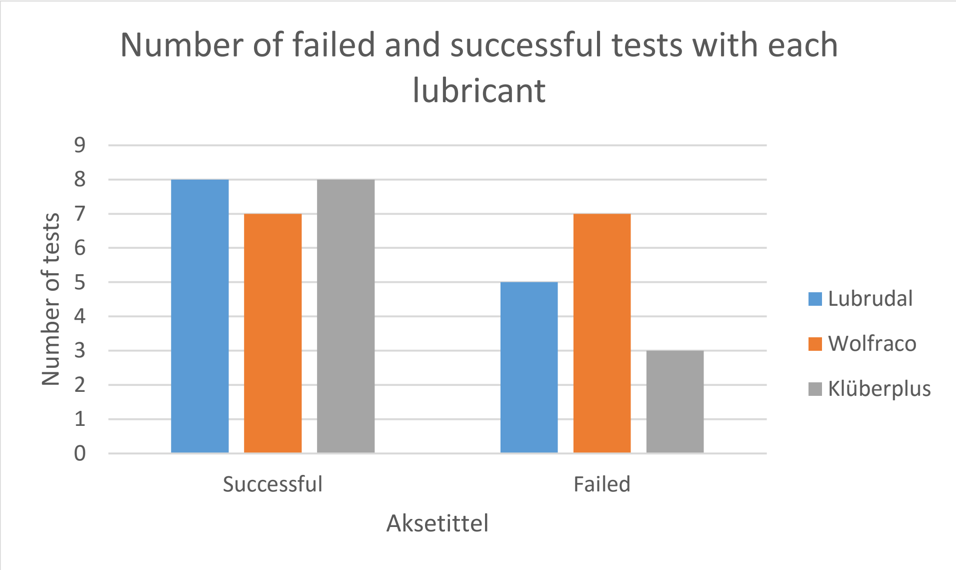

Figure 32: Number of successful and unsuccessful tests with each lubricant

Figure 33 shows the coefficient of friction as a function of the displacement for a successful test with Lubrodal F 33 Al and an AlCrN coating. The test underwent one cycle, where the pin moved three times across the same track. The displacement values were negative because of the start position of the throw crank, but the values are relative so it had no significance. From Figure 33 it can be seen that the friction was highest at the ends of the tracks, right before the plate changed direction. Here the velocity was the lowest, it can be seen from Figure 34. This pattern was seen for all the successful tests.

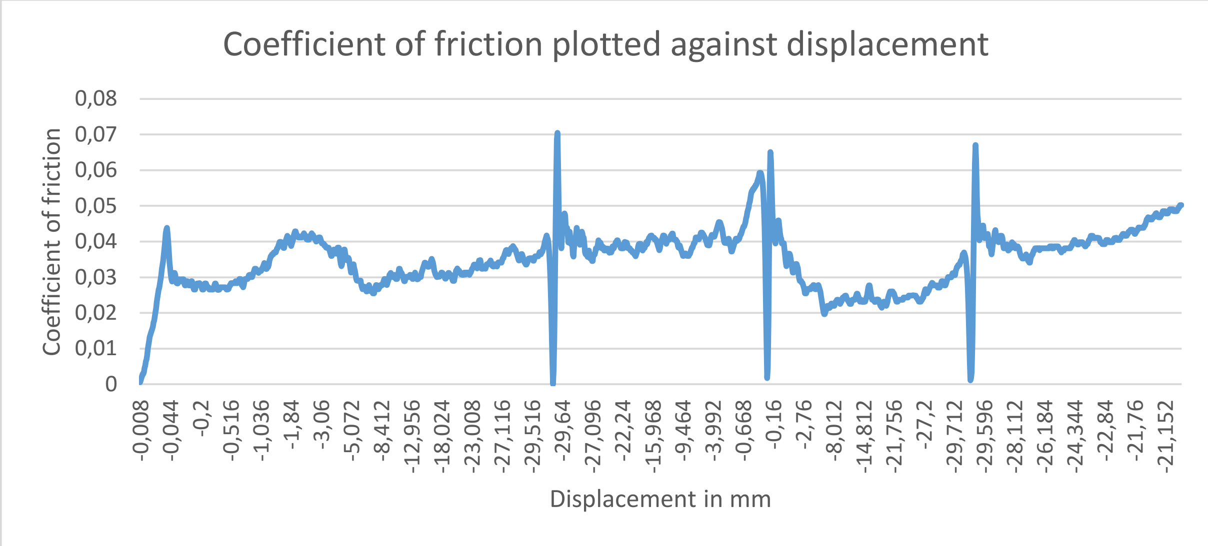

Figure 33: Coefficient of friction plotted against displacement for a test with Lubrodal F 33 Al and an AlCrN coated pin

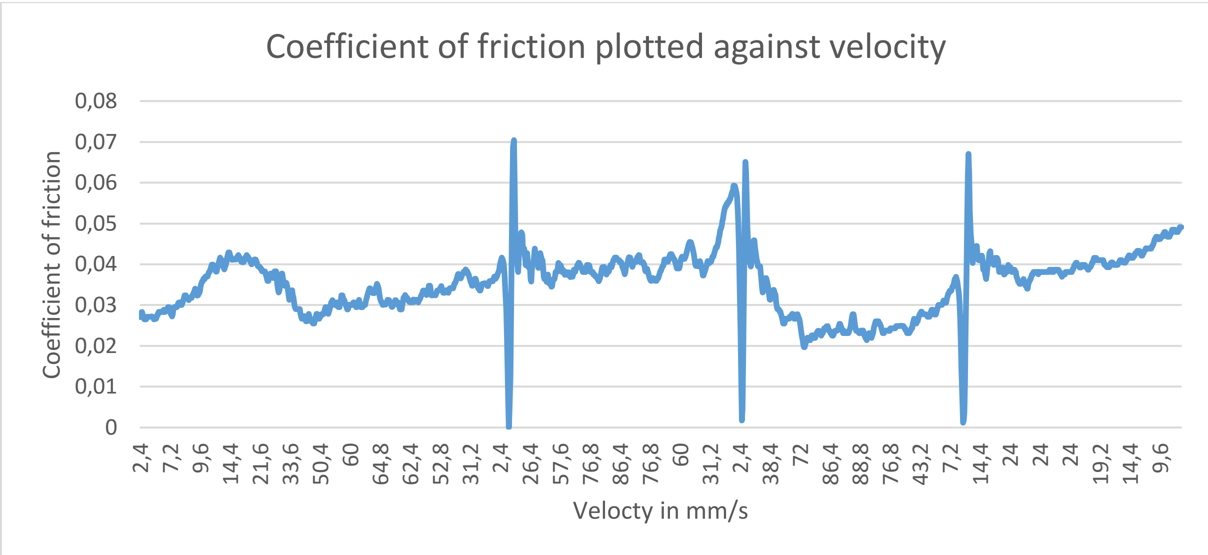

Figure 34: Coefficient of friction as a function of velocity for a test with Lubrodal F 33 Al and an AlCrN coated pin

5.1.2 Comparison of surface treatment of pins

Roughness

A pin grinded with 220 SiC paper were investigated regarding the topography and surface roughness by Primateria, using a surface profilometer that utilise white light interference to analyse the studied surface. The analysed surface area was approximately 90x120 µm and 3 independent measurements were made on each sample. An image from the surface profilometer of the grinded surface is presented in Figure 35. The gray-scale bar on the right hand side in the figure indicates the height (bright spots) and the depth (dark spots) of each area in the image compared to the zero level. The maximum height to depth difference in the ground image is approximately 2 µm. The surface roughness from the analysed surface was measured in the profilometer and presented in Table 6. The arithmetic average of the roughness profile, Ra, was found. The Ra value was approximately 0,22 µm, and the Rz value was approximately 1,76 µm [43].

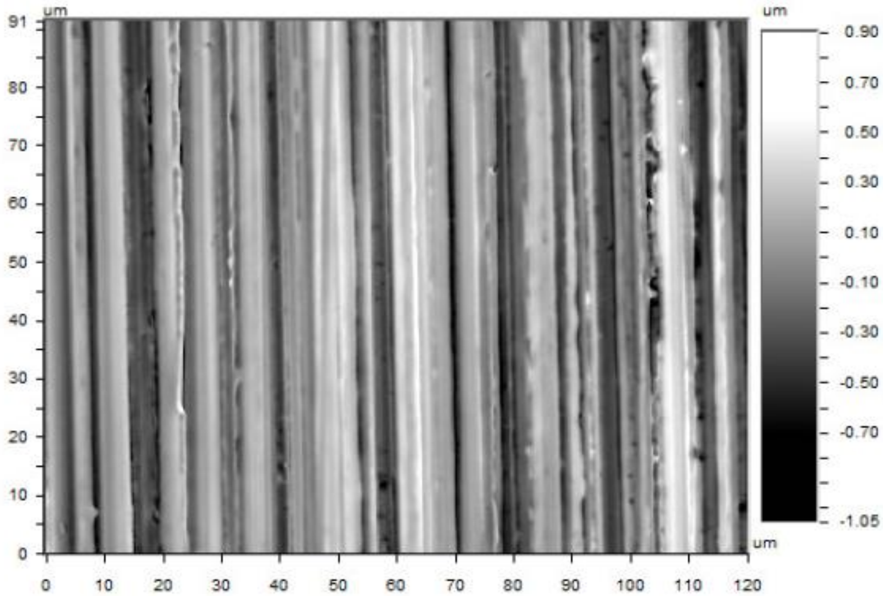

Figure 35: Surface of test pin grinded with P 220 SiC paper [43].

Table 6: Surface roughness values for the grinded test pins. Three measurements were performed on each sample and the mean value as well as standard deviation has been calculated [43].

	Ground surface	
	Ra [µm]	Rz [µm]
	0,235	1,77
	0,220	1,74
	0,202	1,78
mean	0,219	1,763
Standard deviation	0,017	0,021

A pin grinded with 500 SiC paper was polished by Primateria and the surface properties were analysed using a surface profilometer. Figure 36 shows a picture of the polished surface from the profilometer. The surface measurement was done in the same way as for the sample grinded with 220 SiC paper. The maximum height to depth difference was approximately 0,2 µm. The roughness was much lower for the polished pin than the unpolished pin. The Ra value was reduced from approximately 0,22 µm to approximately 0,01 µm. The Rz value was reduced from approximately 1,76 µm to approximately 0,15 µm. Table 7 shows the surface roughness values for the polished pins [43].

Table 7: Surface roughness values for polished pins [43].

	Polished surface	
	Ra [µm]	Rz [µm]
	0,011	0,151
	0,010	0,136
	0,011	0,149
mean	0,011	0,145
Standard deviation	0,001	0,008

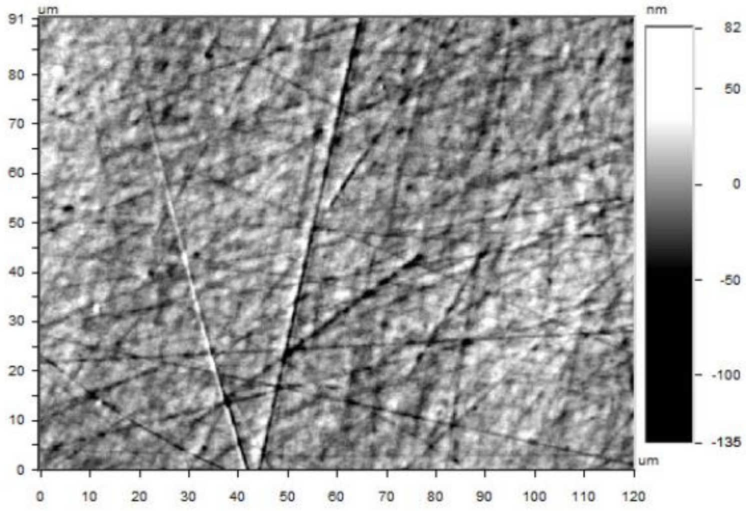

Figure 36: Surface of polished test pin [43]

Figure 35 and Figure 36 are images of the grinded and polished sample. The only grinded sample had unidirectional grinded marks which can be seen as the lines in Figure 35. The polished pin was randomly polished, this can be seen in Figure 36 were the lines are crossing each other in different directions.

Table 8 shows the surface roughness of the AlCrN coated pins. The Ra value was 0,03 µm which is a little higher than for the polished pins. This is because there were small pores or exfoliation formed in the coating. This mainly effected the Rz value, the Rz value was 0,816 which is much higher than the polished pins, but still much less than the untreated pins. Figure 37 shows a picture of the AlCrN coated surface taken with a profilometer. The largest black spot was the largest defect in the coating, this was also where the the highest Ra and Rz value occurred.

Table 8: Surface roughness values of the AlCrN coated pin [43].

AlCrN coated surface		
	Ra [µm]	Rz [µm]
	0,027	0,715
	0,027	0,653
	0,035	1,080
mean	0,030	0,816
Standard deviation	0,005	0,231

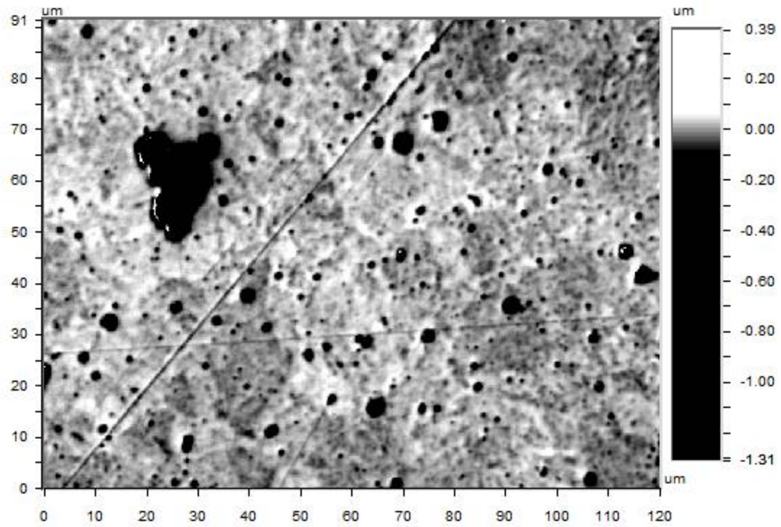

Figure 37: Picture of the AlCrN coated pin surface [43].

Table 9 shows the surface roughness values for the AlTiN coated pin surface. The Ra value was 0,03, which was the same value as at the AlCrN coated pin. The Rz value was 1,62, which is close to the Rz value in the untreated pins. Figure 38 is an image of the AlCrN coated pin surface. The black spots are defects in the coating, which could not be removed from the post-treatment with polishing after the coating. The defects caused the increase in surface roughness.

Table 9: Surface roughness values of the AlTiN coated pin surface [43].

AlTiN surface		
	Ra [µm]	Rz [µm]
	0,031	1,490
	0,030	1,770
	0,030	1,600
mean	0,030	1,620
standard deviation	0,001	0,141

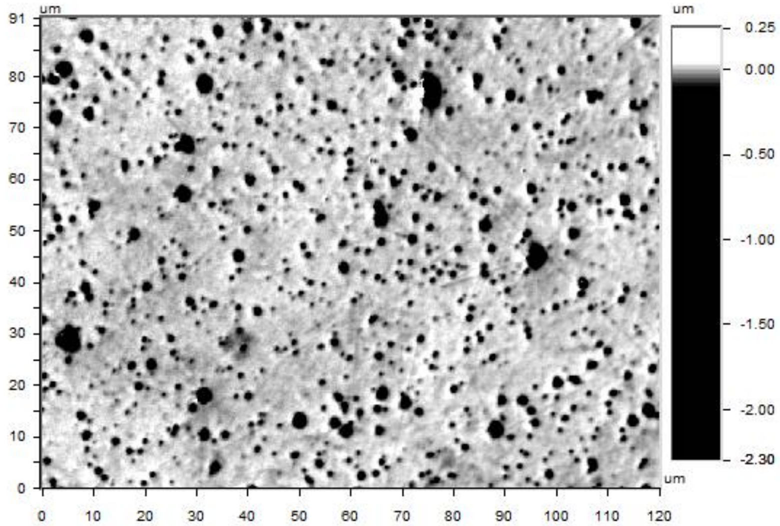

Figure 38: Picture of the AlTiN coated pin surface [43].

The polished pins had similar friction coefficients as the coated pins, it can be seen in Figure 31. The surface roughness of the coated pins have a Ra value much closer to the surface roughness of the polished pins, than the untreated pins. Figure 39 shows the Ra value of the pin surface for different surface treatments.

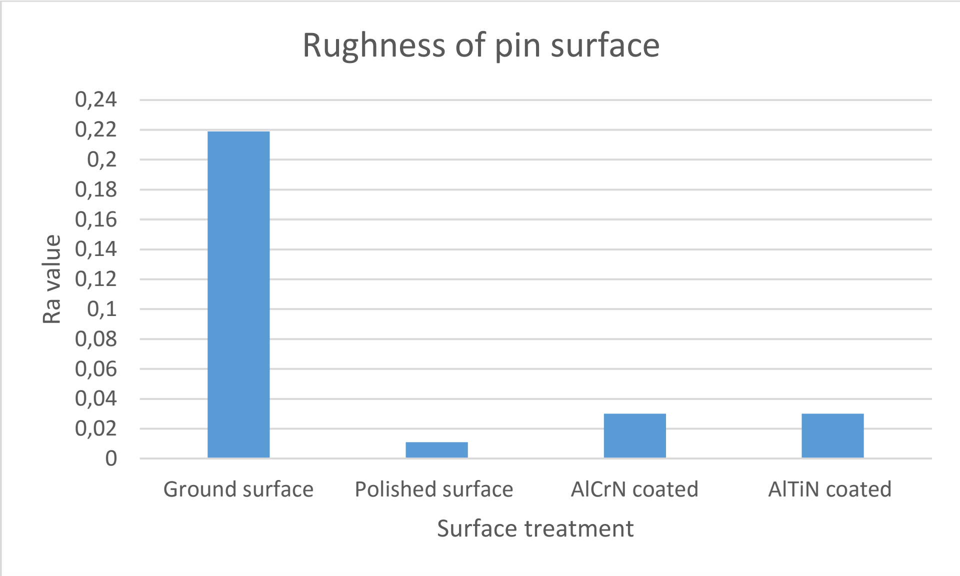

Figure 39: The Ra value of the surfaces with the different surface treatments

Surface treatment with Lubrodal F 33 Al

From Figure 31 it looks like the AlTiN coating behaved better than the AlCrN coating and the polished pins with Lubrodal F 33 Al. The polished pins behaved slightly better than the AlCrN coated pins, and a little worse than AlTiN coating. It was largest difference between the surface treated pins and the uncoated pins with Lubrodal F 33 Al compared to the other lubricants.

Surface treatment with Wolfraco WF 51 W

With Wolfraco WF 51 W, the AlCrN coated pins had the lowest maximum coefficient of friction and the uncoated pins had the highest. The AlTiN coated pins behaves slightly better than the uncoated pins, but the difference is not very large. Figure 31 shows the maximum coefficient of friction for each coating tested.

Surface treatment with Klüberplus S 08-107

With Klüberplus S 08-107 the coated pins behaved better than the uncoated pins. This can be seen in Figure 31. There is not much difference between the maximum coefficient of friction for AlCrN and AlTiN.

Galling of aluminium

The weight of the pins was measured to see if there was excessive galling of aluminium onto the pins. Where the lubricant worked well there was no weight change, with a maximum of difference of 0,0002g. There was a bigger weight change, where the lubricant did not work, up to 0,0812g for uncoated pin with failed Wolfraco WF 51 W. This is shown in Figure 40.

For most of the tests with failed lubricant there was not large amounts of aluminium stuck to the pin. Instead, on the plate there was aluminium ploughed to the ends of the wear track, this is shown in Figure 41. However, there could be some aluminium transfer at the pin surface without resulting in any weight change. This was checked in an Energy dispersive X-ray spectroscopy (EDS).

Figure 40: Pin in pin-holder, with aluminium sticking to the pin

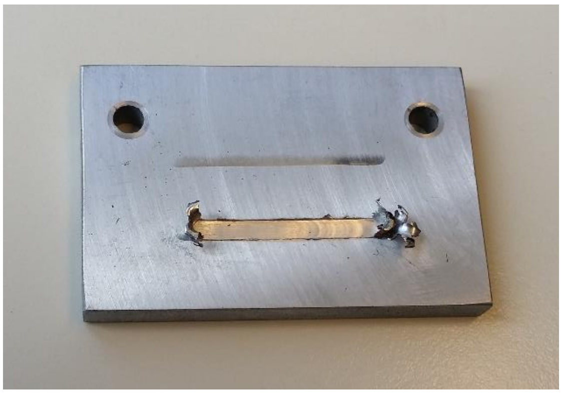

Figure 41: The wear track in the bottom is from a test of Wolfraco WF 51 W with failed lubricant. The wear track on the top is with working Wolfraco WF 51 W.

Aluminium transfer investigated in SEM and EDS

A scanning electron microscopy (SEM) was used to get images of the surface of the pins.

An energy dispersive x-ray spectroscopy (EDS) analysis was used to see how much of the different materials which were present at the pin surface.

Figure 42 shows the material contrast of an AlCrN coated pin tested with Wolfraco WF 51 W. This was a successful test where the lubricant worked well. Since there is only one colour at the surface it indicates that it was just one material present. This means no galling of aluminium to the pin.

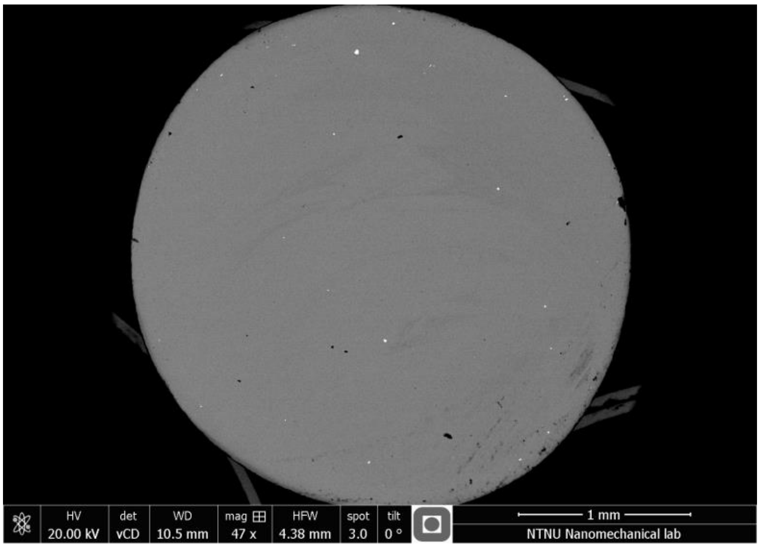

Figure 42: Test 32 Wolfraco WF 51 W AlCrN

Table 10 shows the percentage of each material present at the surface of the AlCrN coated pin tested with Wolfraco WF 51 W. Figure 43 shows the EDS spectrum of the surface. Since Al, Cr and N constitute almost all of the materials present the coating has not been damaged. If there was spallation of the coating there would be much more iron present at the surface from steel material underneath.

Table 10: Material content from the EDS analysis of test 32 with Wolfraco WF 51 W and AlCrN coating.

Element	Wt%
C	5.69
N	22.55
Al	31.86
Cr	38.83
Fe	1.07
Total:	100

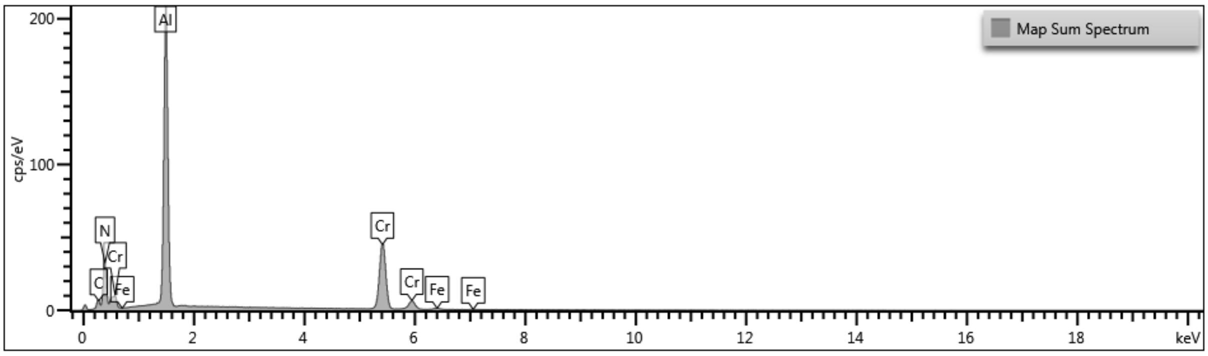

Figure 43: EDS Spectrum for the pin surface for test 32

Figure 44 shows the material contrast of an uncoated pin tested with Wolfraco WF 51 W. The lubricant failed and resulted in wear. The two colours imply that there are two different materials present. It must be aluminium transfer to the pin, since steel and aluminium were the only materials present in the test. The whiter areas are steel since it is a heavier material than aluminium, because in SEM the heaviest material will be whiter. The dark areas are aluminium.

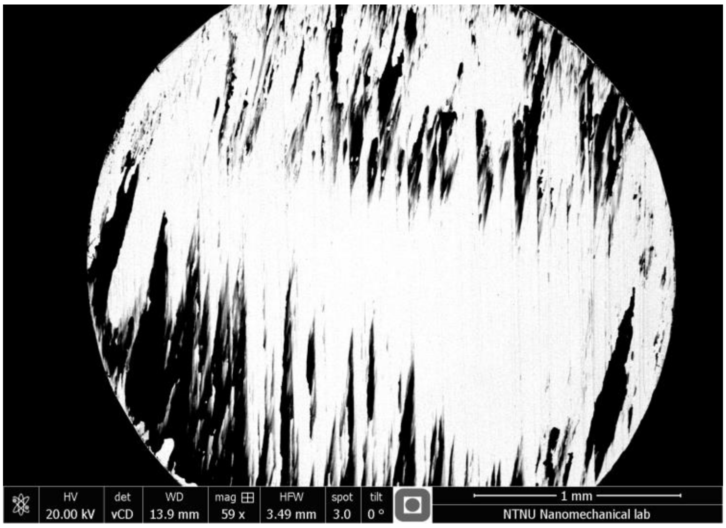

Figure 44: Test 36 of Wolfraco WF 51 W with uncoated pin

Table 11 shows the percentage of each of the materials present at the pin surface. Carbon, vanadium, chromium, manganese and molybdenum are present because it is parts in the Uddeholm dievar tool steel alloy the pins are made of. There is 29.41 % aluminium present which comes from aluminium transfer from the aluminium plate.

Table 11: Material content from the EDS analysis of test 36, an uncoated pin tested with Wolfraco WF 51 W

Element	Wt%
C	7.59
Al	29.41
V	0.34
Cr	3.52
Mn	0.43
Fe	57.16
Mo	1.55
Total:	100

Figure 45 shows the material contrast of an uncoated pin tested with Lubrodal F 33 Al. In this case, the lubricant failed and metal to metal contact occurred. There are two colours present which indicates two materials present. Most likely there is aluminium sticking to the pin, it could also be traces of lubricant since the lubricant is made of graphite.

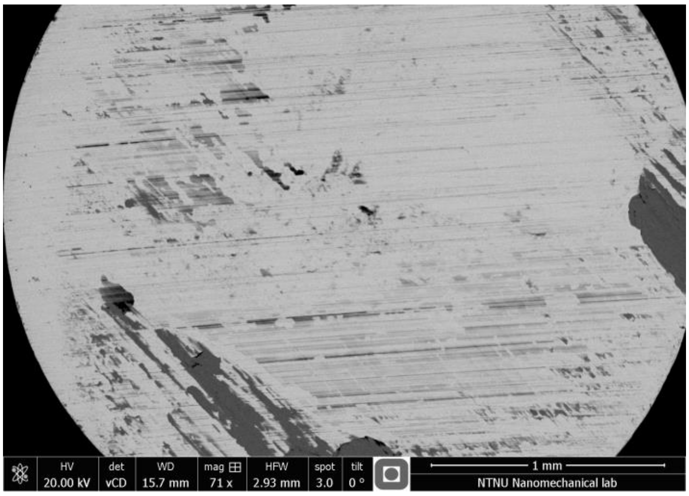

Figure 45: Test 8 uncoated pin with Lubrodal F 33 Al

Table 12 shows the percentage of materials present at the pin surface found from an EDS analysis. It was taken from an unsuccessful test where there was breakthrough of the lubricant. The pin was uncoated and tested with Lubrodal F 33 Al. There was 13 % aluminium present, this is significant aluminium transfer.

Table 12: Material content from the EDS analysis of test 8, an uncoated pin with Lubrodal F 33 Al

Element	Wt%
C	21.34
O	2.55
Na	0.25
Al	13.05
P	0.47
V	0.37
Cr	3.4
Mn	0.39
Fe	56.56
Mo	1.38
Ag	0.24
Total:	100

Figure 46 shows the material contrast of an AlCrN coated pin tested with Lubrodal F 33 Al, where the test was successful. There is only one colour at the surface which means there was only one material present.

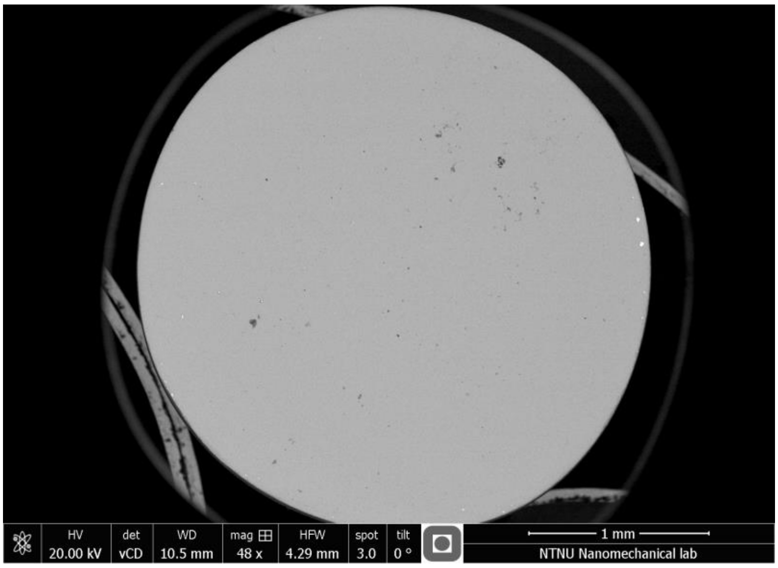

Figure 46: Test 6 AlCrN coated pin with Lubrodal F 33 Al

Table 13 shows the percentage of the materials present at the pin surface. Almost all the surface contains of Nitrogen, Aluminium and Chromium which comes from the AlCrN coating. Therefore, there is no spallation of the coating.

Table 13: Material content from the EDS analysis of test 6, an AlCrN coated pin with lubrodal

Element	Wt%
C	2.61
N	23.35
Al	33.08
Cr	39.9
Fe	1.06
Total:	100

Figure 47 shows the material contrast of an AlCrN coated pin tested with Klüberplus S 08-107. This was a successful test where the lubricant worked properly. There is only one colour present at the surface which means there was only one material present. Therefore, there was no galling of aluminium.

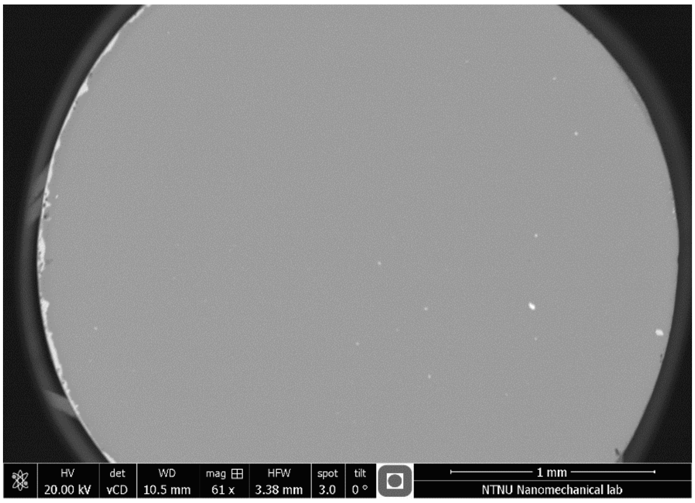

Figure 47: Test 20 material contrast of AlCrN coated pin with Klüberplus S 08-107

Table 14 shows the composition of the materials at the pin surface for an AlCrN coated pin tested with Klüberplus S 08-107. The coating was not damaged since there were almost no other materials present at the surface in addition to the chromium, aluminium and nitrogen the coating was made of.

Table 14: Material content from the EDS analysis of test 20, an AlCrN coated pin tested with Klüberplus S 08-107

Element	Wt%
C	2.43
N	20.47
O	3.07
Mg	0.24
Al	32.61
Si	0.45
P	0.27
S	0.26
Cr	38.64
Fe	1.31
Sr	0.25
Total:	100

Figure 48 shows the material contrast of an AlCrN coated pin tested with Klüberplus S 08-107, where the test failed. The two colours means there are two materials present, therefore it must be aluminium transfer on the steel pin.

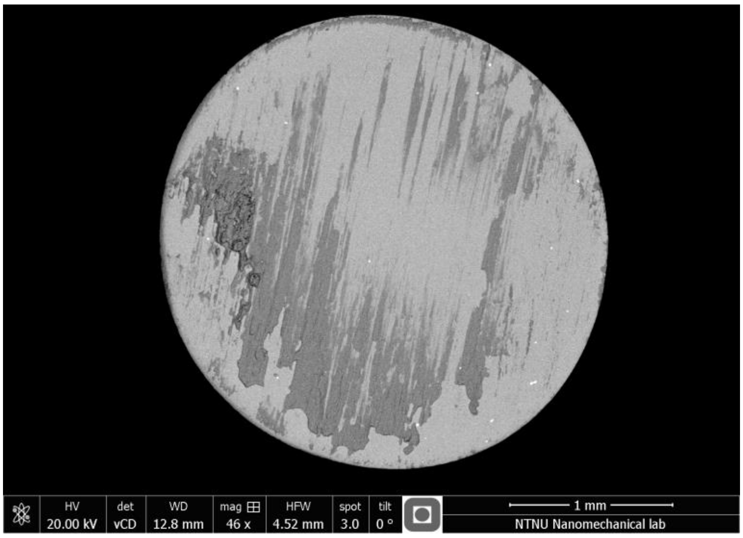

Figure 48: Test 19 Material contrast of AlCrN coated pin with Klüberplus S 08-107

Table 15 shows the percentage of the materials present on the surface of test 19, an AlCrN coated pin tested with Klüberplus S 08-107. There was a breakthrough of the lubricant film, causing metal to metal contact resulting in aluminium transfer. Test 20 was a successful test of also an AlCrN coated pin with Klüberplus S 08-107, there it was 33 % aluminium detected at the surface from the coating. In test 19 there was 58 % aluminium at the surface which is much more. This must be a result of the aluminium transfer from the plate to the pin in addition to the aluminium present from the coating.

Table 15: Material content from the EDS analysis of test 19, an AlCrN coated pin with tested with Klüberplus S 08-107

Element	Wt%
C	2.24
N	14.12
O	0.78
Mg	0.36
Al	57.87
Si	0.27
Ar	0.19
Cr	22.62
Fe	1.06
Ag	0.48
Total:	100

Figure 49 shows the material contrast of an uncoated pin tested with Klüberplus. There is mostly one colour at the surface, there is some very small darker spots which could be aluminium.

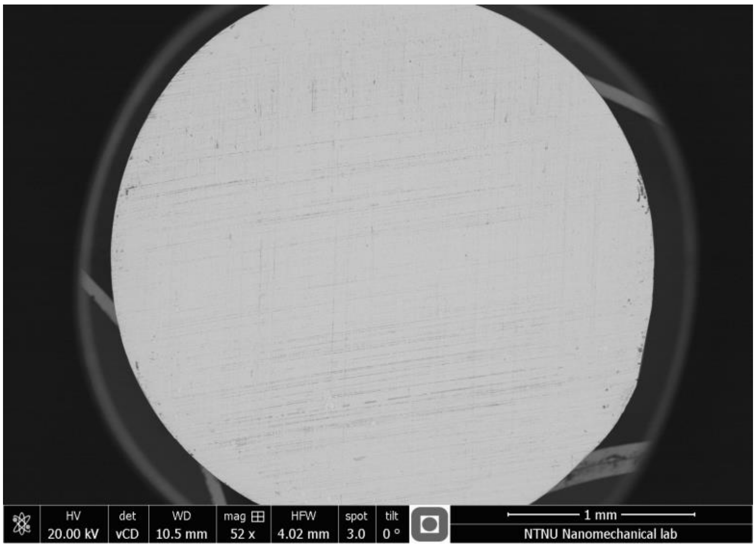

Figure 49: Material contrast of an uncoated pin tested with Klüberplus S08-107

The EDS analysis in Table 16 shows that there was 0.25 % aluminium at the surface which can be transfer from the aluminium plate. However, this amount is very small, so there is no significant amount of aluminium transfer to the pin.

Table 16: EDS analysis of test 23, an uncoated pin tested with Klüberplus S08-107

C	5.4
O	2.2
Mg	0.35
Al	0.25
Si	0.59
P	0.25
S	1.11
V	0.51
Cr	4.74
Mn	0.43
Fe	80.52
Mo	3.65
Total:	100

Figure 50 shows an uncoated pin tested without lubricant. Naturally the test failed and left a deep wear track due to the metal to metal contact. The two colours indicates two different materials. Since there was no lubricant or coating present, the materials must be steel and aluminium.

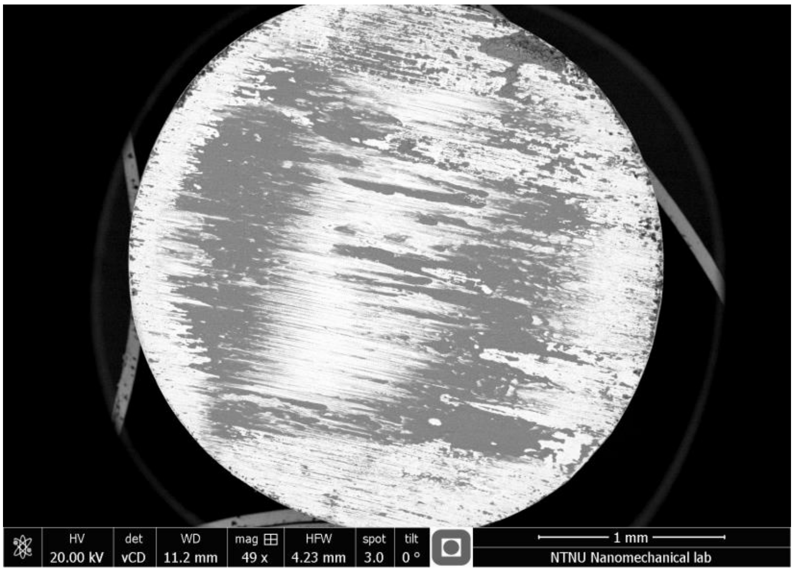

Figure 50: Test 7 Material contrast for pin without coating and without lubricant

Table 17 shows the percentage of the different materials present at the pin surface after a test of an uncoated pin without lubricant. There was 53 % aluminium at the surface, which means excessive galling of aluminium to the pin. This was the test with the most aluminium transfer.

Table 17: EDS analysis of test 7 an uncoated pin tested without lubricant

Element	Wt%
C	3.45
O	1.11
Mg	0.46
Al	52.84
Si	0.34
V	0.26
Cr	2.43
Mn	0.41
Fe	36.97
Mo	1.04
Ag	0.69
Total:	100

6 Discussion

6.1 The relevance of the test representing the forging process

How the input parameters used in the tests are selected

Simulations performed by Raufoss Technology showed where there is most relative movement between the tool and the workpiece, it is around 140 MPa. Here it is assumed to be the highest chance of galling. To get this load the pin size of 3 mm in diameter was selected. Equation 4.1 shows how to calculate the load.

$$Load = Contact\ pressure\ \times Cross\ section\ area \qquad (4.1)$$

Choosing a diameter of 3mm gives a cross section area of 7,07 mm^2, this makes it possible to vary the contact pressure by applying different loads. The range of possible loads which can be applied is from 100 N to 1000 N, which gives a range of possible contact pressure from 14 MPa to 140 MPa. To get 140 MPa it is required to apply a load of 1000 N.

There is a possibility that the pin could be damaged since it is only 3 mm in diameter and with the risk of the lubricant not working well resulting in very high friction. With this high friction and load the machine may be damaged. Therefore, a load of 500 N was selected, resulting in a pressure of 70 MPa. This is still more than 3 times the yield strength of aluminium at 500 ^oC, where it is a high chance of galling according to Raufoss Technology, so 70 MPa is assumed to be representable.

The sliding speed of the aluminium in the forging die where the galling is most severe, is the recommended speed and stroke length the machine setup should have. In forging process at Raufoss Technology the aluminium flows relative to the tool at a speed of maximum 200 mm/s. The sliding length was adjusted to match the sliding speed. The sliding speed in the test machine was set to 100 mm/s after guidance from the apparatus responsible.

The maximum temperature of the machine is 300 ^0C. There were some problems with getting the lubricant to adhere to the surface when a higher temperature than 200 ^oC was used in the test. Therefore, 200 ^oC was selected as the testing temperature. This is not that far from the actual temperature of the forging tools used with water-based lubricant, which is around 260 - 280 ^oC. The tools are cooled down by over spraying of the lubricant which contains water.

At Raufoss Technology the water-based graphite lubricant, Lubrodal F 33 Al, is diluted with water, resulting in the lubricant containing 92% water. At the experiments performed in this thesis the lubricant was not diluted with water. This is assumed to be representable since all of the water is supposed to evaporate and leave a solid graphite layer. One reason Raufoss

Technology is diluting the lubricant with water, is that the water in the lubricant cools the tools. In these tests the tools is already at a low enough temperature so there is no need for additional cooling.

Table 18: Input parameters for test setup

	Test parameters used	Values assumed to be most actual for the
Pressure	70 MPa	140 MPa
Load	500 N	1000 N
Speed	100 mm/s	200 mm/s
Temperature	200 ºC	260-280 ºC
Testing time	1 cycle	
Stroke length	30 mm at 1.25 Hz	

The parameters were selected based on a study of a simulation of the forging process made by Raufoss Technology regulated by the limitations of the test machine. The difference between friction and galling among the coatings and lubricants was studied. The values from Table 18 shows how the test values are compared to the values assumed to be the most relevant for the forging process. This shows the relevance of the test compared to the forging process. Even though the values did not match completely, the tests were still able to compare the different lubricants and surface treatments. The results from the test gave an indication of which combinations of lubricants and coatings that are worth testing further.

6.2 Discussion of the test results

Frictional conditions

The results from the tests of the same combination of and lubricant coating were not identical. A possible explanation may be related to uncertainties of the test. For instance, there may be a different amount of lubricant present at each test, resulting in a different friction factor.

The lowest friction coefficient was found at the tests with Lubrodal F 33 Al. This can be because it formed a thick layer of graphite in the tests. In the actual forging process Raufoss Technology claim they use a thin layer of Lubrodal F 33 Al applied by spray. The thick layer used in the experiments can result in different frictional conditions than with a thin layer, but it was experienced that the tests were unsuccessful with a thin layer of Lubrodal F 33 Al. In the forging process there is a different movement between the workpiece and the forging tool than in the pin on plate test, where the pin slides three times across the same track at the plate.

On the pin on plate test the pin slides three times across the same track on the plate. It is a different movement than in the forging process where the metal is deformed and flows across the tool surface into the die cavities. This may explain why some of the tests were unsuccessful.

The tests with the combination of AlTiN coating and Lubrodal F 33 Al had the lowest coefficient of friction, which was 0,069. This is much less than the friction coefficient of uncoated pins tested with Lubrodal F 33 Al. The polished and the AlCrN coated pins gave also good results, this can indicate that a lower roughness decreases the friction coefficient. In Table 5 in section 5.1.1 the maximum coefficient of friction is listed for each combination of lubricant and coating.

Wolfraco WF 51 W had a lower coefficient of friction in the tests than Klüberplus S 08-107 with the uncoated pin. For the tests with the coated pins both the lubricants had almost equal frictional factor, 0.12, for both the coatings.

Overall the tests with the coated and polished pins had a lower coefficient of friction than the uncoated pins. The average maximum coefficient of friction for the coated and polished pins at 200 °C was 0,101 while the average coefficient of friction for the uncoated pins was 0,135. The friction is dependent on the surface roughness, as explained in section 2.7.1. The coated and polished pins had a lower surface roughness than the uncoated pins. The Ra values for the different surface treatments are shown in Figure 39. Article [18] by Pellizari described a test of different coatings. There was found a correlation between the surface roughness and the time until unstable contact in a block on disk test. A lower surface roughness resulted in a longer time before unstable contact.

When the pins tested with Klüberplus S 08-107 were polished or coated, the friction coefficient was reduced to a similar frictional coefficient as present at the tests with Lubrodal F 33 Al and uncoated pins. Lubrodal F 33 Al was tested with polished pins without coating and this gave similar results as with coating, most likely because of the similar roughness. Klüberplus S 08-107 was not tested with only polishing, but will probably give better results than unpolished pins because of the finer roughness. The cost of polishing the forging tool is less than half of the cost for coating the tools. Therefore, it can be worth to test with polishing tools before coating them.

The friction coefficient varied with the displacement and the velocity in the test as seen in Figure 33 and Figure 34. The reason why the friction was highest at the point where the plate changed direction was because this was where the velocity was lowest. From the Stribeck curve in Figure 13 it can be seen that the friction coefficient was highest where the speed was low, and here the lubricant film was thin.

Unsuccessful tests caused by starved lubrication

Quite many of the tests failed caused by starved lubrication. Figure 32 shows the number of successful and unsuccessful tests for each lubricant. The reason for the highest percentage of failed tests with Wolfraco WF 51 W, may be because it contained a lot of water. The water made it difficult to apply a thick layer of lubricant because it boiled and vaporised quickly. Klüber claims that it is possible to use Wolfraco WF 51 W at 260-280 ^{o}C, but in these tests there were problems with the lubricant not sticking to the surface at temperatures higher than 200 ^{o}C. Wolfraco WF 51 W was diluted 1:1 with water. Klüber claims that the recommended mixing ratio is 1:4, but with that amount of water the lubricant did not stick to the surface in the tribological tests.

Some of the tests with Lubrodal F 33 Al failed because of the Leidenfrost effect where the lubricant did not stick to the surface. This effect happens at temperatures above 260 -280 ^{o}C. However, some of the tests also failed at lower temperatures, where a breakthrough of the graphite layers caused metal to metal contact. The reason for this could be the way the lubricant was applied or the time the lubricant was applied before starting the test.

The highest percentage of successful tests was with Klüberplus S 08-107. This is a solid lubricant. There was no problem at 200 ^{0}C or 300 ^{0}C with boiling or evaporation since it does not contain water. Klüberplus S 08-107 was the only lubricant which worked more than once at a higher temperature than 240 ^{o}C. Four tests of Klüberplus S 08-107 were performed at 300 ^{o}C, where three of them gave successful results without a deep wear track. This indicates that Klüberplus S 08-107 can be interesting to try out in the forging process because it can handle a higher temperature than the current lubricant, Lubrodal F 33 Al. It needs to be further tested if it also can work with temperatures above 300 ^{o}C.

The reason some of the tests with Klüberplus S 08-107 failed can be because two tests were done at each plate. For the second test the plate had to be reheated, which can weaken the lubricant.

Surface properties

The orientation of the grinding marks can also influence the friction coefficient. The polished and coated pins had randomly oriented grinding marks, while the untreated pins had unidirectional grinding marks. Tests done by Menezes, described in article [44], showed that there was a large difference of friction coefficient with different textures. Randomly oriented grinding marks gave the lowest friction coefficient while unidirectional grinding marks gave the highest. The untreated pins had unidirectional grinding marks as showed in Figure 35. The grinding marks can be one reason for the polished and coated pins had lower friction coefficient than the untreated pins tests done in this thesis.

The pins were studied in a scanning electron microscopy (SEM) and pictures of the material contrast was taken. The successful tests had only one colour at the material contrast pictures, which means there was no aluminium transfer. The unsuccessful tests had two colours at the material contrast pictures, which means there were two materials present. The high friction present caused the pin to plow deeply into the aluminium plate. This could lead to material transfer and be the reason for the presence of two materials at the pin surface.

The Energy-dispersive X-ray spectroscopy (EDS) analysis showed which, and how much of the materials, that were present at the pin surface. There were not any signs of aluminium transfer on the pins which were tested with working lubricant, except for one test with an uncoated pin tested with Klüberplus S08-107. This was the combination which had the highest frictional factor. However, the aluminium present at the surface was only 0.25 %, which is very little, and can be neglected. From the EDS it was possible to see that there was no spallation of the coating for the successful tests.

There was most galling of aluminium with the test of the uncoated pin tested without lubricant, this was expected since direct metal to metal contact occurred. There was also excessive galling at the tests where there was a breakthrough of the lubricant film. This was a result of the water-based lubricants being difficult to get to stick to the hot surface. This proves that it is important to have a lubricant which can tolerate the high temperatures in hot forging of aluminium.

The EDS analysis showed the amount of aluminium present at the surface. Since the coatings contained aluminium it was difficult to identify how much of the aluminium at the surface was caused by galling and how much was from the coating. From the pictures from SEM it was possible to see the areas which was covered by aluminium, it was not detected a large difference between the coated and uncoated pins. Therefore it cannot be concluded that the coated samples behave better or worse than the uncoated samples regarding galling.

Adding a coating can increase the hardness and surface properties of the tools, which is assumed to have an influence of the tool life. The tests done in this thesis had a very short duration and can therefore not give any results about how the coating can affect the long term wear of the tools and if it can increase the tool life.

In article [32] by Bayramoglu different coatings were tested by evaluating the time the forging press could run before the tools needed to be polished. The coated dies performed much better than the dies without surface treatment and the costs for applying the coating was payed of after 4000 parts were made. This means it can be worth to further investigate if a coating can be applied to the tools in Raufoss Technology.

6.3 Costs

6.3.1 Costs in the forging process at Raufoss Technology and potential savings

Table 19 shows the distribution of costs for producing one forged component at Raufoss Technology.

Table 19: Distribution of costs for producing one component [16]

	Percentage of total cost
Aluminium bolt	58%
Depreciation	7.5%
Maintenance	6.1%
Energy	1.7%
Consumables (mostly lubricants)	3.2%
Labour	5.3%
Development cost and profit	18.2%

The largest expense is the aluminium bolt. The aluminium bolt is casted and then extruded before Raufoss Technology purchases it.

There is maintenance every day for one hour. In addition the tools need to be cleaned, which takes about one hour. With an hourly cost of about 5000 NOK, it costs 50 000 NOK per week for cleaning and maintaining the tools. It is desirable if the maintenance of the tools can be reduced.

The oil-based graphite lubricant costs 59,134 NOK per litre, and they use 0,03 l per part. The water-based graphite lubricant costs 2,65 NOK per litre after it is diluted with water, and they use 0,5 l per part. Lubricant cost per part for the oil-based lubricant is 1,774 NOK, and the lubricant cost for the water-based lubricant is 1,175 NOK per part.

The tool can be used to make around 500 000 parts before it needs to be replaced. The cost of the tool is 500 000 NOK. Raufoss Technology produce approximately 1 000 000 parts per year. If the tool life can be extended it is possible to save costs.

In line L05 where the water-based graphite lubricant is used, they use 20 seconds in the forging press for each part where 7 of these seconds are used to apply a lubricant onto the tools.

Klüberplus S 08-107 is an alternative to the water-based graphite lubricant. It is a solid lubricant that is applied to the workpiece before the forging process starts. This allows the forging press to make more parts since the time of applying lubricant to the tools before each press can be eliminated. Then, the cycle time could be reduced to 13 seconds. On 3 shifts it would be possible to produce around 500 000 parts more per year. This means 7500 hours can be saved to produce a given volume. With an hourly cost of 5000 NOK per hour, this reduces the yearly cost with 8 800 000 NOK. The difference of the costs of the lubricants and the cost of additional surface treatment has to be considered to find the actual savings [16].

6.3.2 Actual cost of changing lubricant and/or applying a surface treatment to the tools

Cost of surface treatment by Primateria

The cost for coating the forging tool with an AlTiN or an AlCrN PVD coating is 99 100 NOK. This includes polishing before applying the coating, nitriding, PVD coating and polishing after applying the coating for the upper and lower tool.

The cost for polishing the tools without coating, but with pre- and post-treatment is 41 100 NOK.

Cost of lubricants

The costs of the new types of lubricants are dependent on the volume ordered. However, an indication of the costs has been stated from Klüber lubrication [45]. The amount needed in the forging process has to be tested.

- Wolfraco costs 85 NOK per litre.
- Klüberplus S 08-107 costs 370 NOK per litre.

Klüberplus S 08-107 costs much more than Lubrodal F 33 Al per litre. But much less lubricant is needed. With a large saving for reducing the forging time, this can allow a higher cost of the lubricant. It must be tested how much lubricant which is needed with Klüberplus

S08-107, to find the costs of the lubricant per part, before it can be decided to change lubricant.

7 Conclusions and further work

7.1 Executive summary

In this study alternatives to the conventional lubricants used in hot forging of aluminium were investigated and tested. The outcomes of the experiments performed in this thesis resulted in a recommendation of some lubricants and coatings for further testing. The simplified tribological test which was executed compared the lubricants and coatings by finding the coefficient of friction and checking if there was any galling of aluminium present. The test parameters were not exactly the same as in forging, but as close as possible limited by the capacity of the machine.

Two alternatives to the water-based graphite lubricant Raufoss Technology uses today were tested:

- Wolfraco WF 51 W – a graphite free water-based lubricant
- Klüberplus S 08-107 – a solid lubricant containing graphite which is applied to the workpiece.

Wolfraco WF 51 W was the lubricant which was most difficult to apply to the hot test surface, resulting in half of the tests giving unsuccessful results. Therefore, this lubricant is not recommended.

The water-based graphite lubricant Raufoss Technology uses today is the lubricant which had the lowest friction coefficient, which was 0,11 for the uncoated tools. Klüberplus S 08-107 had a higher friction coefficient, up to 0,16. This friction coefficient can be reduced to 0,12 by applying a lubricant or polishing the tools.

Klüberplus S 08-107 was the lubricant which tolerated the highest temperatures, it did not have problems with the Leidenfrost effect which was seen in the tests with the water-based lubricants.

Another advantage with Klüberplus S 08-107 is that it is a solid lubricant that is applied to the workpiece before it enters the forging press. This means the time in the forging press can be reduced since the lubrication process can be eliminated. In Raufoss Technology a workpiece uses 20 seconds in the forging process including the lubrication, without the lubrication the press time can be reduced to 13 seconds. This allows the machine to produce more parts each day, which saves costs.

Overall the most promising combination of lubricants and coatings is Klüberplus S 08-107 combined with polished tools.

7.2 Conclusions

This thesis investigated the tribological issues in hot forging of aluminium and tried to improve these conditions by changing the lubricant and/or applying a coating to the tool. Through a literature study and by identifying the requirements of different lubricants and coatings, some were selected to be tested. A tribological test was performed to compare the different lubricants and coatings regarding friction conditions and wear.

From the tests following conclusions can be made:

The friction coefficient of the tests with Wolfraco WF 51 and Klüberplus S 08-107, was similar and higher than with Lubrodal F 33 Al, the lubricant Raufoss Technology uses today.

The frictional conditions were improved when the samples were coated and/or polished because a smoother surface reduces the friction. All coated and polished pins had a very similar coefficient of friction when tested with the same lubricant. The surface roughness had a much larger influence on the frictional conditions than the type of surface treatment.

There was not found any significant aluminium transfer from any of the tested lubricants and coating combinations when there was no breakthrough of the lubricant film. However, the water-based lubricants, Lubrodal F 33 Al and Wolfraco WF 51 W had problems in some of the tests, with the lubricant not sticking to the hot surface. This resulted in metal to metal contact and excessive wear and aluminium transfer. There was not found any significant difference of the aluminium transfer between the different surface treatments of the unsuccessful tests either.

It cannot be concluded that one surface treatment is better than the others from these tests. The positive effect of the coating is assumed to be largest in the long term and may contribute to an increased tool life. The experiments in this thesis had a short duration time and therefore it was not possible to investigate this effect.

Klüberplus S 08-107 had the most successful tests without lubricant breakthrough. This was also the lubricant that tolerated the maximum temperature of the testing equipment, 300 ^{o}C. The other lubricants did not tolerate higher temperatures than 200-230 ^{o}C. Klüberplus S 08-107 is a solid lubricant, which is applied to the workpiece before the forging process starts. This reduces the time in the forging press and thereby also the costs.

As a result of the thermostability, the application time and the reliability Klüberplus S 08-107 is the recommended lubricant for further testing. By combining Klüberplus S 08-107 with coating or polishing the tools the frictional conditions will be almost as good as with the lubricant Raufoss Technology uses today, Lubrodal F 33 Al with uncoated dies.

Klüberplus S 08-107 contains graphite, but since it is solid is less messy than water-based graphite lubricants. It is oil free, which is better for the environment than the oil-based lubricants. Klüberplus S 08-107 is a good alternative to the water-based graphite lubricant Raufoss Technology uses today since it does not have the problem with the lubricant not attaching to the hot surface.

7.3 Recommendations for further work

This thesis discussed and tested different alternative lubricants and coatings to improve the lubrication conditions in the forging process. To test and compare the lubricants a simplified tribological test was executed, this has some limitations.

The experiments could not be performed with exactly the same parameters as in the actual forging process. In the forging process the deformed workpiece material will flow across the die surface, while in these tests the tool steel pin slides horizontally over the aluminium surface. The author thereby suggests to perform a ring compression test to investigate how the lubricants performs in a test with plastic deformation.

From the experiments in this thesis it was not found a difference regarding galling among the different coatings. To find this, a test with longer duration has to be performed. It would be beneficial to find a method to test the different coatings regarding wear to compare the lifetime of the tools with and without coating.

A possibility is to test the recommended lubricant and surface treatment in the forging process. The recommended lubricant can be tested by a few forging strokes. A test with long duration has to be performed to see how a coating is affecting the tool life. If a tool is coated it is possible to compare it to an uncoated tool and compare the time before polishing is needed and the lifetime of the tools.

To contribute to fill the knowledge gap on tribology in hot forging of aluminium the author will write a paper with the results from this thesis.

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Enhet: **Institutt for produktutvikling og materialer** **Dato: 02.02.2016**

Linjeleder: Torgeir Welo

Deltakere ved kartleggingen (m/ funksjon)**: Carine Eggen (student), Torgeir Welo (veileder)**
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Lab forsøk på tribologilab **Masteroppgave** student: **Carine Eggen** Tittel på oppgaven. Tribologitesting av smøremiddel og overflatebehandling av verktøyoverflater i varmsmiing av aluminium

Er oppgaven rent teoretisk? (JA/NEI)**: NEI** *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder:* Torgeir Welo *Student:* Carine Eggen

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
01	Forsøkskjøring med pin-on-plate tribometer	Torgeir Welo				
02	Pussing av metallflater i manuell pussemaskin	Torgeir Welo				

NTNU HMS	Risikovurdering	Utarbeidet av HMS-avd.	Nummer HMSRV2601	Dato 22.03.2011
		Godkjent av Rektor		Erstatter 01.12.2006

Enhet: **Institutt for produktutvikling og materialer** **Dato: 02.02.2016**

Linjeleder: Torgeir Welo

Deltakere ved kartleggingen (m/ funksjon): Carine Eggen (student), Torgeir Welo (veileder)
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Labforsøk i tribologilab Masteroppgave student: Carine Eggen. Tittel på oppgaven: Tribologitesting av smøremiddel og overflatebehandling av verktøyoverflater i varmsmiing av aluminium

Signaturer: *Ansvarlig veileder:* Torgeir Welo *Student:* Carine Eggen

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
01A	Forsøkskjøring med pin-on-plate tribometer	Hvis prøven ødelegges under forsøkskjøring kan deler av den slenges ut i rommet når lokket ikke er dratt ned.	2	B	A	B	A	2B	Bruk vernebriller
01B	Forsøkskjøring med pin-on-plate tribometer	Mulig å søle varmt smøremiddel.	2	B	A	A	A	2B	Bruk vernebriller og hansker, lukk lokket når forsøk kjøres
01C	Forsøkskjøring med pin-on-plate tribometer	Utstyret har ingen nødbryter for å slå av i en nødsituasjon.	3	B	A	A	A	3B	Få grunding opplæring i bruk av maskinen
01D	Forsøkskjøring med pin-on-plate tribometer	Utvikling av røyk/gass under forsøkskjøring med varmeplate i drift.	3	B	A	A	A	3B	Lukk lokket når forsøk kjøres

02A	Pussing av metallflater i manuell pussemaskin	Hvis prøven slippes under pussingen kan den slenges ut i rommet	4	A	A	A	A	4A	Bruk vernebriller

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A Svært liten	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.