



# New design and construction of high temperature tribology testing equipment

in the context of hard coatings

---

Ny design och konstruktion av högttemperaturtribologisk testutrustning i kontexten av hårda beläggningar

---

Atle Andersson Nykvist

Faculty of Health, Natural and Technical Sciences Materials Technology

---

Master of Science in Mechanical Engineering, Karlstad University

---

Degree Project for Master of Science in Mechanical Engineering, 30 hp

---

Supervisor: Mikael Fallqvist

---

Examiner: Mikael Grehk

---

Date: 2023-10-23

---





# Abstract

There are two main goals of this thesis. Firstly, to improve and develop an existing hot wear tester at Karlstad University so that it may test more samples of different sizes. Secondly, to test previously impossible samples and investigate their tribological properties and measure the coefficient of friction with high reproducibility. The development work on the tribometer was done by a prestudy including; Investigating the hot wear tester, idea generation in CAD and collecting information from the creator and prior users of it. After a few rounds of concept generation and discussion with the supervisor and workshop staff, a new sample holder with different sample adapters was created. Five tests of four different materials were conducted and their friction was measured. The new sample holder was able to solve the main concerns with the old design and showed great promise in producing reproducible results, better than any previous versions. The friction of the different TiAlN samples, at room temperature, seemed to indicate that there is a certain amount of Al% that maximizes friction and that there is no simple linear relationship between Al% and coefficient of friction. Finally it can be concluded that the initial goals of the thesis have been met, and that a new scientific instrument has been created to aid in the further understanding of tribology.

# Sammanfattning

Det finns två huvudsakliga mål med detta examensarbete. För det första, att förbättra och utveckla en existerande varmnötare på Karlstad Universitet så att den kan testa fler prover av olika storlekar. För det andra, att testa tidigare omöjliga prov och undersöka deras tribologiska egenskaper och mäta friktionskoefficienten med hög reproducerbarhet. Utvecklingsarbetet av tribometern skedde via en förstudie som innehöll följande: Undersökning av varmnötaren, idégenerering i CAD och samling av information från varmnötarens skapare, samt tidigare användare. Efter några iterationer av konceptgenerering och diskussioner med handledare och verkstadspersonal så skapades en ny provhållare med flera olika adaptrar. Fem tester med fyra olika material utfördes och deras friktion mättes. Den nya provhållaren löste de huvudsakliga problemen med den gamla designen och påvisade goda förhoppningar angående att producera tester med hög reproducerbarhet. Markant bättre än tidigare versioner. Friktionsmätningarna från de olika TiAlN-proverna, vid rumstemperatur, indikerade att det finns en viss mängd Al% som maximerar friktionen och att det inte finns något linjärt samband mellan Al% och friktionskoefficient. Slutligen kan det konstateras att de initiala målen för examensarbetet har blivit uppnådda, och att ett nytt vetenskapligt instrument har blivit skapat för att hjälpa utöka förståelse inom tribologi.

# Table of Contents

<b>Abstract</b>	<b>3</b>
<b>1 Introduction</b>	<b>8</b>
<b>2 Theory</b>	<b>9</b>
2.1 Machining	9
2.1.1 Metal cutting	10
2.1.1.1 The cutting process	10
2.1.1.2 Chip formation	11
2.2 Tribology	12
2.2.1 Characterization of surfaces	12
2.2.2 Friction	15
2.2.2.1 The laws of friction	15
2.2.2.2 Components of Friction	16
2.2.2.3 Friction and heat	17
2.2.3 Wear	18
2.2.3.1 Wear classes	18
2.2.3.2 Wear map	19
2.2.3.3 Wear in cutting tribology	20
2.3 Materials	21
2.3.1 Cemented Carbides	21
2.3.1.1 Composition of cemented carbides	21
2.3.1.2 Wear mechanisms	21
2.3.1.3 Mechanical properties	22
2.3.2 Hard Coatings	22
2.3.2.1 Types of hard coatings	22
2.3.2.2 Coating microstructure and composition - TiAlN	23
2.3.2.3 Preparation techniques	23
2.3.3 Nickel based alloys - Inconel	24
2.3.3.1 Properties	24
2.3.3.2 Composition	24
2.3.3.3 Classification	24
2.4 Tribological testing	25
2.4.1 Classification of tribotests	25
2.4.2 Classification system 1	26
2.4.3 Classification system 2	26
2.4.4 Choice of wear test	27
2.4.5 Tribo-test geometries for model tests	28
2.4.6 Experiment design	30
2.4.6.1 The experiment parameters	30
2.4.6.2 Choosing correct parameters	31
2.4.6.3 Initial testing	31
2.4.6.4 Minimize test spread	32
2.4.7 Experiment evaluation	32

<b>3 Method</b>	<b>33</b>
3.1 Investigating tribology in metal machining	33
3.2 Hot Wear Tester	33
3.2.1 CAD hot wear tester	33
3.2.2 Real hot wear tester	33
3.2.3 Real samples	35
3.2.4 Tribological setup	35
3.2.5 Goal definition	35
3.3 Idea generation and production	36
3.4 Testing and interpretation	36
<b>4 Results</b>	<b>37</b>
4.1 Information yield	37
4.2 Fixture for different geometries	38
4.2.1 Construction for two geometries	38
4.2.2 Construction for three geometries	39
4.3 Adapter development	39
4.4 Fitting into hole and alignment	40
4.5 Final design	42
4.6 Production and fitting	44
4.6.1 Screws and nuts	44
4.6.2 Sample holder base	45
4.6.3 Adapters	46
4.6.4 Guide	46
4.6.5 Fitting	47
4.7 Testing	49
4.7.1 TiN	50
4.7.2 Machine Steel	50
4.7.3 TiAlN 75/25	51
4.7.3.1 TiAlN 75/25 (1)	51
4.7.3.2 TiAlN 75/25 (2)	51
4.7.4 TiAlN 45/55	52
<b>5 Discussion</b>	<b>53</b>
5.1 Interpretations of results	53
5.1.1 Production	53
5.1.2 Testing	55
5.1.2.1 Testing temperature	55
5.1.2.2 Surfaces interactions	55
5.1.2.3 Analysis of friction	55
5.1.2.4 Wear of samples	56
5.2 Compare sample holders	57
5.3 Limitations	58
5.3.1 Limitations in design and construction	58
5.3.2 Limitations in testing	58

5.4 Challenges	59
5.4.1 Alignment of surfaces	59
5.4.1.1 Loading angle	59
5.4.1.2 Tolerances	59
5.4.1.3 Surfaces	59
5.4.2 Differences in theoretical geometry and reality	60
5.4.3 Mounting the sample holder	60
5.5 Future	61
5.5.1 Future use	61
5.5.2 Future breaking	61
5.5.3 Future development	61
5.5.4 Future testing	62
<b>6 Conclusion</b>	<b>63</b>
<b>References</b>	<b>64</b>
<b>Acknowledgements</b>	<b>69</b>
<b>Appendices</b>	<b>70</b>



# 1 Introduction

Metal machining is one of the most common ways to change the shape of materials into a desired shape. This is very useful in engineering applications. While machining steels in particular, which is one of the most common metal alloys in engineering, cemented carbides are often used as the cutting tool inserts. Even though cemented carbides are excellent for these applications, they are coated with TiAlN to improve longevity of the cutting insert, commonly via a method called physical vapor deposition (PVD), or chemical vapor deposition (CVD). TiAlN is appropriate to use in machining because of its chemical stability and high hardness. These materials are known to have excellent wear resistance in high temperature applications [1], but there are still many things left to discover.

A hot wear tester (HWT), at Karlstad University, is used to study the wear of cemented carbides with PVD TiAlN coating. This can be done at different temperatures, during different time durations, for different wear rates as well as for samples of different compositions. However, the current HWT has a sample holder designed for one specific sample geometry.

The first objective of this thesis is to solve the problem with the sample holder, so that more sample geometries can be tested in the current HWT, as well as improving the accuracy. Initially, the HWT can handle one, and will be increased to three. The second objective is to use the redesigned sample holder to test new samples with previously impossible geometries, to investigate if the properties of the new sampleholder have improved or not.

## 2 Theory

### 2.1 Machining

Ever since the industrial revolution[2] in the late 1800-hundreds people have used different tools and methods to shape hard metals. It is here that the start of metal machining and metal cutting started. This dawned the beginning for humankind to create skyscrapers, locomotives, airplanes and suspension bridges. It has contributed greatly to the industry and technology of today in uncountable ways.

As many people intuitively know, metal is hard to form, for example with one's bare hands. In order to facilitate the shaping of metals, processes like cutting, milling and turning were invented [3]. These all have their own applicable areas with advantages and disadvantages, even though they are all machining processes. It is true for all of them that a piece of metal is gradually loaded locally beyond its yield strength and breaks, either intermittently or continuously.

Metal machining puts the workpiece, and the tool, under tough conditions. During metal cutting the tool temperature is typically between 300-900 degrees[4] Celsius. This puts high demands on the material in the cutting tool.

A cutting tool looks different for different machining methods, but even though their parts may differ, their purposes are generally the same. Let's look closer at a face milling tool for a concrete example in Figure 2.1. The milling tool consists of a tool body, which is the larger part of the entire tool in Figure 2.1, a tip/insert, seen as gold color in Figure 2.1, and some sort of way of keeping these two attached. That could include some sort of housing[5] but in this case the inserts are just attached using a screw, to attach the insert directly to the tool body.



**Face Milling Cutter**

*Figure 2.1: Milling cutting tool [6]*



In Figure 2.2a one can take a closer look at a typical cutting tool insert. Since this is the part that interacts with the workpiece and is doing the actual machining, the insert has much higher demands on its properties. The cutting tool insert consists of; Substrate, coating, as well as the adhesion between the substrate and coating. And the hardness, ductility and strength highly depend on each of these. In Figure 2.2b there are two cutting tool inserts, but with an altered simpler geometry. This geometry is designed to make it simpler to investigate the material properties and test the insert while the inserts in Figure 2.2a's geometry are optimized for the best cutting properties.



Figure 2.2a: Cutting tool insert [7]

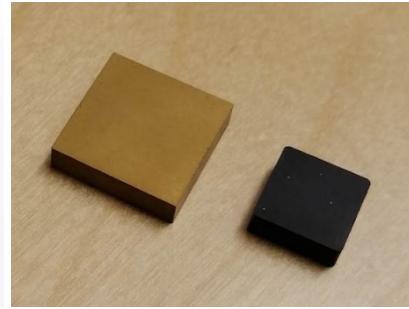


Figure 2.2b: Cutting tool insert (test samples)

## 2.1.1 Metal cutting

### 2.1.1.1 The cutting process

Compared to more normal tribological interactions like; the sole of a shoe and the ground, metal cutting is a much more extreme tribological interaction. With much higher pressure and temperature the demands in the cutting tool increases many times over. There are a few reasons for why one would want to have good cutting tools. Decreasing the friction and therefore saving energy costs and reducing the environment impact, or perhaps to decrease wear on the tooling, so that the material cost is reduced. Improving the surface finish is also a goal to strive towards.

Metal cutting is defined as a manufacturing method where larger pieces of metal change shape by removing smaller pieces of metal[8]. This can be done in a number of ways. For example with saw-cutting, lasering, water-jet or shearing. But this text only deals with the saw-cutting type, which consists of turning, milling and drilling. Here the cutting is done with hard teeth that get in contact with the material and remove chips from it.

There are a few parameters that one can control during the cutting process. Figure 2.3a displays a profile view of a turning setup with a tool underneath.  $v_c$  represents the velocity of the tool relative to the workpiece in the right direction. It also shows which surface that has been cut and which will be cut. Figure 2.3b shows a more zoomed in picture of the left setup with some notes for the different cutting tool geometry.  $f$  represents the feed, and is the distance the cutting tool moves along the surface over one revolution of the workpiece.  $r$  is the radius of the cutting tool tip.  $h_1$  is the theoretical chip thickness.  $a_p$  is the cutting depth. And finally  $b_1$  represents the width of the chip. [1]

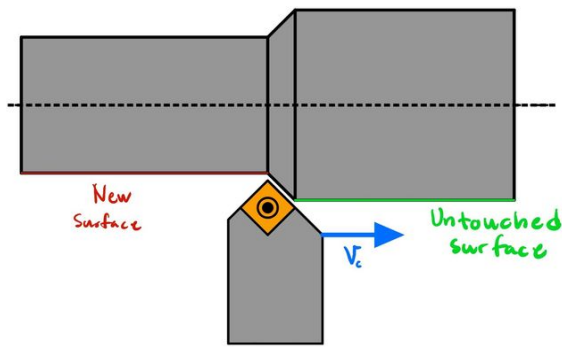


Figure 2.3a: Turing setup

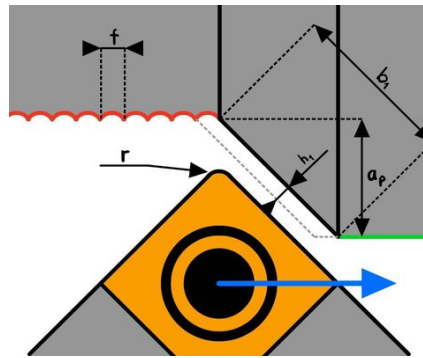


Figure 2.3b: Zoomed in turing setup with parameters

If the feed is increased more material gets worn off per revolution. This decreases the amount of time needed to complete the work at hand, which is positive. However this also increases the pressures experienced and worsens the surface roughness. So both of these can not be maximized at the same time and a compromise needs to be made.  $A_p$ ,  $f$  and  $v_c$  together with geometrical relations give the rest of the parameters.

#### 2.1.1.2 Chip formation

During the formation of a chip during the cutting process, there are three zones that have different characteristic behaviors. In figure 2.4 one can see them. Depending on the material the properties like shear hardening, hardness and ductility may vary greatly. The shape can be fragmented for more brittle materials, like cast iron. And for more ductile materials like wrought iron, the chips become continuous.

The primary shearing zone is where the chip is being created and the shearing stress in the workpiece exceeds the plastic limit of the material, and the deformation rate is greatest in this zone. During cutting this is where about 80% of the heat is being created and 75% of it disappears with the chip.

In the secondary shear zone it is where both the pressure and temperature reaches their maximum. The temperature can reach up to 1000 degrees Celsius and the stress 3 Gpa. About 18% of the heat is generated here.

In the leftmost part of the rubbing zone in figure 2.4, lies the tertiary shear zone. Compared to the other two zones the temperature and pressures are quite low. But still reaching around 500 degrees Celsius.[1]

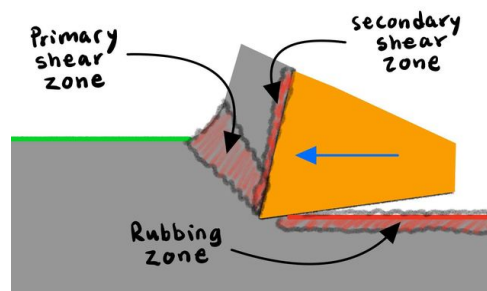


Figure 2.4: Chip formation and associated zones

## 2.2 Tribology

Tribology is defined as: A study that deals with the friction, wear, design and lubrication of interacting surfaces in relative motion[9]. Tribology has been used as a tool since 3000 B.C [10] for simpler types of contact mechanics but got its name in 1966 by H.P Jost, and has since developed into more complex ways of describing surfaces and the interactions between them. Today it is used in areas such as the medical industry for prosthetics, aerospace engineering and, of course, metal machining. In order to create a cutting process with adequate parameters these areas need to be well mapped out and investigated.

There are some general rules in tribology about how friction and wear works. But one can even more generally say that everything depends on the circumstances. Often the friction decreases when applying lubrication. But in some cases it raises it. This makes tribology into a mostly empirical science. This means that it is troublesome, if not impossible, to predict how two surfaces will interact by only knowing properties of each surface by themselves. This leads to a science that is in high demand of testing, increasing the empirical data to better understand these surface interactions.

### 2.2.1 Characterization of surfaces

Since tribology is centered around surfaces (and how they interact with each other) one could start to describe what a surface is and how they can be described. A surface is the outermost layer or boundary of an object and can be characterized in a number of ways. A surface can generally be described by its color, shape and composition.

The **color** is usually the least important of these three aspects but can influence the properties of the surface. For example a change in color can be an indicator of sustained damage on the surface. This could be because of loss of paint or change in morphology. And a darker surface can increase heat absorption[11] and thereby increase friction[12].

The **composition** of a surface is what material or materials the surface is made of. In many applications the composition of an object usually changes with depth. Even though a material is underneath the surface, it still affects how the surface behaves in various ways. The composition of a surface affects the mechanical, physical and chemical properties[13] of a surface. A few mechanical properties are; Strength, hardness, toughness and elasticity. The physical characteristics associated with composition are; Color, texture, reflectivity and conductivity. While the chemical properties affect the reactivity, corrosion resistance and chemical stability. Of course the color and texture are things in themselves that affect the properties of the surface. But, it's important to understand that there can be correlation between the composition and these characteristics.

The **shape** of a surface can be described and divided in a few different ways. How the shape of the surface changes is generally described in different scales[14], or magnitudes. Figure 2.5 shows the different magnitudes.

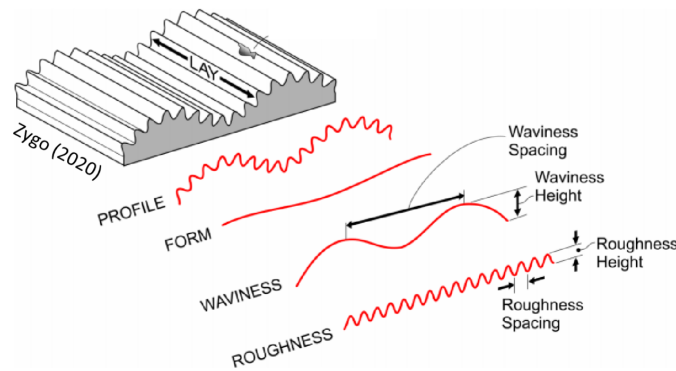


Figure 2.5: Form, waviness and roughness on a tribological shape [10]

Firstly form, which is the largest in magnitude. This describes the overall contour and is described by parameters like cylindricity, parallelism and flatness. These describe how similar the surface is to an exact cylinder, plane or planes etc.

Secondly waviness, which describes smaller deviations than form and can be quantified with a few different parameters. Wt is total deviation, Wp is peak-to-valley height and Ws is the spacing of the waves.

Lastly, Surface roughness. This quantifies small scale deviations like scratches and bumps, and can be described with parameters much like the waviness. Surface roughness is most commonly used to describe a surface in tribology and there are different parameters that describe different phenomena with varying accuracy. But to understand a surface one needs more than one parameter to paint the entire picture. In figure 2.6 one can see a few of the most common R-values.

Value	Description	Graphical
$R_{max}$	Difference in height between the highest peak and the lowest valley [ $\mu\text{m}$ ]	
$R_z$	Difference in height between the mean value of the five highest peaks and the mean value of the five lowest valleys [ $\mu\text{m}$ ] $R_z = \frac{(S_1 + S_2 + S_3 \dots) - (S_2 + S_4 + S_6 \dots)}{5}$	
$R_a$	The area above and under the mean value line divided by the length [ $\mu\text{m}$ ] $R_a = \frac{A_1 + A_2 + A_3 \dots}{l} = \frac{1}{l} \int_0^l  z(x)  dx$	

Figure 2.6: R-values, their description and geometrical interpretation [10]

The R-values give information about the shape of a profile. A two-dimensional object.  $R_{max}$  is one of them and gives the difference in height between the highest top and lowest valley, in the selected area of the profile. And  $R_a$  takes the absolute area above and below the mean value and divides it by the distance over which the area was taken. But in order to describe a surface and not a profile, this average needs to be taken over an area and not a distance. That would be a description of  $S_a$ . And if the  $R_{max}$  value would not be examined over a distance but over an area it would give  $S_{max}$ . These S-values are arguably more useful for describing surfaces since they represent a larger part of the object one wants to describe.

Here are a few of the values used in the description of surfaces.

- $R_{max}$
- $R_z$
- $R_a$
- $R_q$
- $R_{sk}$
- $R_{ku}$
- $S_a$
- $S_z$
- $S_{sk}$
- $S_{ku}$
- $S_{mr}$

#### **\*Measuring surfaces\***

In order to describe surfaces, R-values and S-values can be used. When these values are calculated, measurements from the sample are used. These measurements come from a machine that typically measures the surface with a light, like a profilometer, or a tip that scans over the surface, like an atomic force microscope (AFM). In the latter case, the shape and size of the scanning tip affect the measurement of the surface, see figure 2.7. If the tip is large or has a wide radius at the end, valleys will be registered as too shallow and not wide enough, and peaks will be registered as less pointy and wider. So it's important to understand that the given data of a surface is only as good as the machines that characterized its properties.[15]

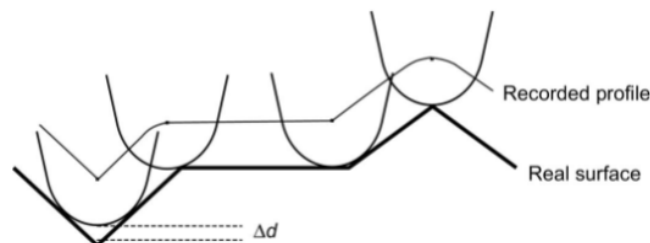


Figure 2.7: Tip scanning over surface

## 2.2.2 Friction

Friction is resistance against motion[16]. Friction plays an important and often unnoticed part in our lives. Walking on asphalt, putting on a shirt, gripping a door handle, brushing our teeth, wearing glasses, frying food, playing with a fidget spinner, driving a car and so on. **An appropriate amount of friction** is the goal. In some cases this means to maximize the friction. Like for the interaction between car wheels and the asphalt, where the wheel should grip the surface so that the car doesn't slide around and you can have control. In other cases, like when a person goes ice skating, you would want the lowest amount of friction to keep on sliding along the ice. There are also circumstances where the friction needs to be something in between. For example the interaction between a fork and a potato. The fork should be able to easily slide into the potato, having quite low friction, and still the fork should be able to stick in the potato if lifted, having a high enough friction. This example illustrates that sometimes the friction shouldn't be maximized or minimized, but rather, optimized.

Friction is not a material property, but a **system property**. This means that, lets say, copper (with a certain Ra-value and so on) does not have friction. However, copper against copper has friction. This is because the friction between two surfaces is decided by the interaction between the two. Some materials tend to "hook" onto each other, while other pairs tend to slide along each other quite nicely.

### 2.2.2.1 The laws of friction

There are three general laws[17] of friction which dictates how friction changes.

1. Amonton's 1st law dictates: The force of friction is directly proportional to the applied load.
2. Amonton's 2nd law dictates: The force of friction is independent of the apparent area of contact.
3. Coulomb's law dictates: The kinetic friction is independent of sliding velocity.

These laws came into existence in the late 1800-hundreds and since then progress in understanding friction has been made. Particularly in the 1880s where lubrication changed the way friction was treated.

The friction also changes depending on if the surfaces are in rest or in relative motion. The force that needs to overcome for a stationary object to move is called static friction. And the moving counterpart is called dynamic friction. The static friction is generally higher than the dynamic friction.

### 2.2.2.2 Components of Friction

Friction is composed of three parts. All of them contribute to the overall friction. In figure 2.8 one can see the components and what they relate to.

- Adhesive component
- Plowing component
- Topographic component

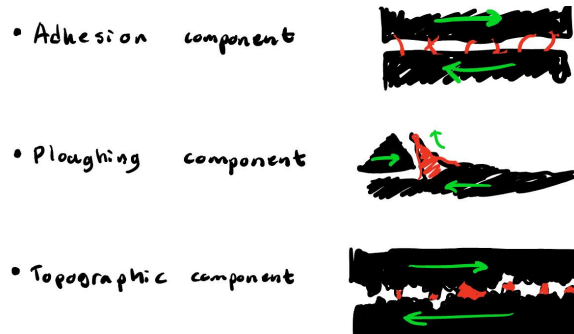


Figure 2.8: Friction components and their active areas

The **adhesive component** is related to the chemisorption and physisorption between the two surfaces. Physisorption is molecular interactions and Van Der Waals forces. Chemisorption[18] is the process of the two surfaces chemically bonding with each other, having their valence electrons interacting with each other. So both physisorption and chemisorption contribute to the adhesion of the “sticking” and hinders their relative motion. The adhesive component ( $\mu_a$ ) can be estimated using the following formula:

$$\mu_a = \frac{F_f}{F_n} = \frac{\tau_y A_r}{HA_r} = \frac{\tau_y}{H}$$

$F_f$  is the friction force  
 $F_n$  is the normal force  
 $\tau_y$  is the yield stress in shear  
 $H$  is the hardness  
 $A_r$  is the real area of contact

The **plowing component** comes from the resistance during the plastic deformation of, at least one, of the surfaces. The plowing component ( $\mu_p$ ) can be estimated using the following formula[19]:

$$\mu_p = \frac{F_f}{F_n} = \frac{HA_p}{HA_l} = \frac{A_p}{A_l}$$

$A_p$  is the plowing area  
 $A_l$  is the load bearing area

The **topographic component** of friction is due to the deformation of the asperities, and is a sub-part of the plowing component. The asperities are the protruding top peaks of the surface. One can think of it like surfaces containing mountains and when the tops of these mountains get squished or flattened a bit, then the relative motion of the surfaces are hindered.

These components form the entirety of friction and is calculated like the following:

$$\mu = \mu_a + \mu_p$$

#### 2.2.2.3 Friction and heat

Friction produces heat. One can intuitively feel this when rubbing their hands together. The friction increases the energy of the surface molecules causing their temperature to rise[20]. This can be felt in the entire hand when rubbing them together. But this is also true on a much smaller scale as well. In the case of when a hand is slowly placed on a table. It looks like the entire hand is in contact with the table although there are just a few microscopical bumps. It is here on these small asperities where the temperature reaches several hundred degrees. But, because of the very small volume that is affected by the temperature the surface is barely affected and not even felt at all by the person.

The temperatures that affect the surface for a short time and small volume are called flash temperatures. The flash temperatures are always present during tribological interactions. What affects how the overall interactions get is where and how often these interactions occur. If an aggressive, high load and frequent, tribological interaction takes place there are more asperities interacting, raising the temperature. And the more frequent, the less time the heat has to dissipate into the bulk of the material.



## 2.2.3 Wear

Wear is defined as the removal of material[21], and is usually a product of a sliding contact. Wear is typically undesirable, raising friction, and is often the first step in component failure. There are a few ways in which wear can occur on a surface but it always involves material loaded beyond its plastic limit and then gets removed.

### 2.2.3.1 Wear classes

The different types of wear that can occur can be classified depending on the interaction of the surfaces. If the surface gets worn down by hard particles, then it's either abrasion or erosion, and if it's a sliding interaction between two surfaces, then it's adhesion wear.

**Abrasion** is when a hard surface with sharp parts digs into a softer and more malleable surface. Abrasion itself can be divided even further into low stress, high stress, gouging and polishing. And depending on how many parts are involved, there can either be 2-body abrasion or 3-body abrasion. If two surfaces slide against each other, then it's 2-body abrasion. If some particles get between them, then it's 3-body abrasion.

**Erosion** is wear by hard particles and involves fluid. Erosion can be divided into solid impingement, fluid impingement, cavitation or slurry erosion. Depending on if the attacked surface is more ductile or brittle, different attack angles are better or worse. If a surface is more brittle, then an attacking angle of 90 degrees is the worst. And if it's ductile an attacking angle of 20-30 degrees will cause the most damage to the surface. The wear is affected mainly by the hardness, shape and size of the involved particles. The same is true for abrasion.

**Adhesion** is when conforming surfaces slide relative to each other. This can happen in a number of ways, via fretting, adhesion, seizure/galling or oxidative wear. Adhesive wear is the most common wear class encountered in metal cutting. Fretting is caused by small oscillatory movements between 1-100  $\mu\text{m}$  and material failure is caused by fatigue. Adhesive wear can be either ductile in shearing or brittle in cracking/chipping and fatigue can be detected if delamination is observed. Seizure (or galling) is simply severe sliding wear. Finally there is oxidative wear. Oxidative wear is always brittle due to the brittleness of the oxide. It starts with flash temperatures causing oxides to form which then gets removed. Depending on the stability of the oxide, it can be worn off in two ways. Oxidative wear or high oxidative wear. Their differences can be seen in figure 2.9.

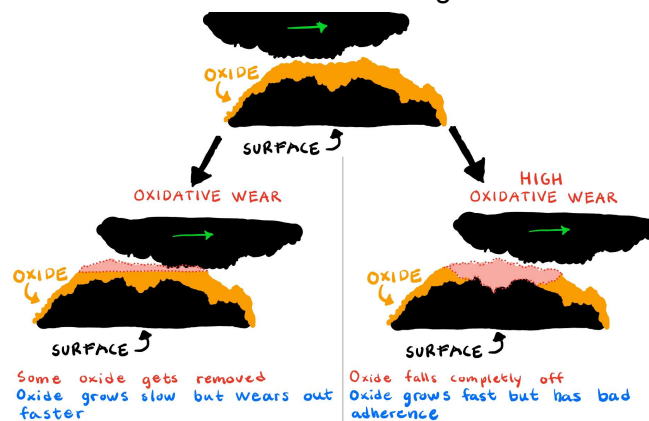


Figure 2.9: Oxidative wear vs high oxidative wear

### 2.2.3.2 Wear map

The wear map can be a useful tool in understanding wear. A wear map is a diagram that describes the type of wear in a certain situation, depending on the sliding speed and the normal force applied to the contact. In figure 2.10a one can see that the higher up to the right the more wear is caused. This is achieved by raising speed or load, or both. Figure 2.10b shows the wear map but indicates at which parameters certain wear mechanisms are achieved.

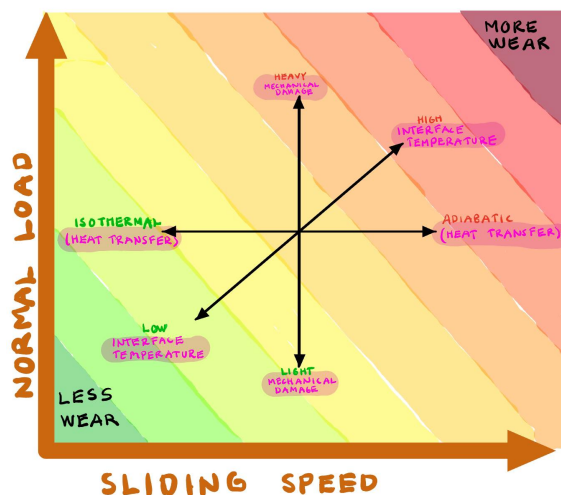


Figure 2.10a: Wear map and behavior

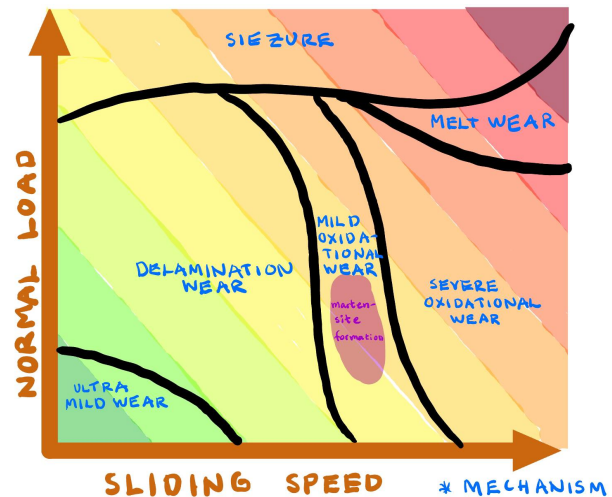


Figure 2.10b: Wear map and wear mechanism

As mentioned in chapter 2.2.3.3 Friction, the contacts in friction cause temperatures to rise. When temperatures rise to a high degree, meaning  $\frac{1}{3}$  of a material's melting temperature, it causes the wear mechanisms to change. This is called high temperature wear and is located in the upper right corner of the wear map, which can be seen in figure 2.11. This can happen in a ductile or brittle manner. High temperature often causes materials to act more ductile but in certain cases to cause oxide growth, which then makes the material more brittle and thereby increases oxidative wear.

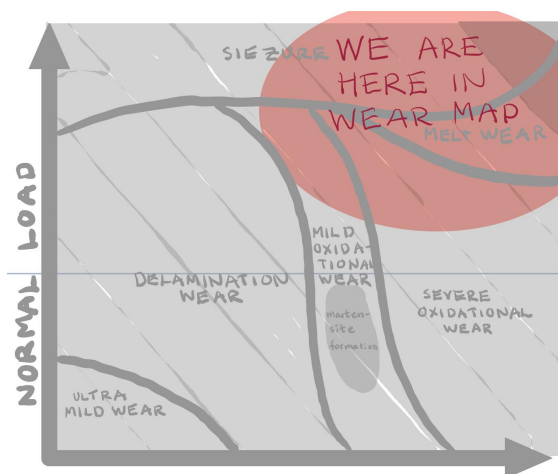


Figure 2.11: High temperature wear in wear map

### 2.2.3.3 Wear in cutting tribology

The tribological conditions during cutting are extreme in the contact between tool and workpiece. Even though the area of contact is small, the wear mechanisms can vary widely over the surface. The cutting contact is divided into three areas, called contact subzones. These subzones can be seen in figure 2.12. In the upper leftmost corner of figure 2.12 one can see the cutting tool with the created chip just above it, moving in the right direction. In subzone A there is only sticking and no sliding. The real area here is exactly or very close to the apparent area because this is where the stress and temperature is the highest. One can see this in the subzone A in figure 2.12. Subzone C is only sliding with a lower stress and temperature. Subzone B is a combination of both of these, with some sticking and some sliding. When calculating and analyzing the contact conditions one usually focuses on subzone C, sometimes subzone A, and even more rarely subzone B. But in B's case there is a decided relation of A's and C's properties when doing the calculations. [1]

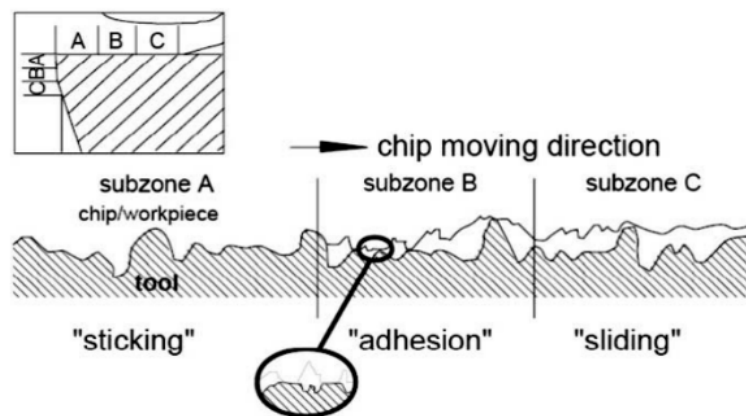


Figure 2.12: Subzones and their contact area

## 2.3 Materials

There are a few important components of the cutting process, and they are composed of a few different materials depending on their location in the cutting process. Some are used as the base cutting tool, called the substrate. Some are used as the coating on the substrate. And other involved parts also need to be considered even though they are not in the same extreme tribological conditions.

### 2.3.1 Cemented Carbides

Cemented carbides are the most widely used material for the substrate in cutting tools today. Cemented carbides are composed of very hard carbides, about 80-95 wt%, and a tough binder phase. The microstructure is a lot like a brick and mortar structure. With the carbides laying very close to each other and the binder phase seeping into the cracks, providing stability and toughness. The strength and high toughness depends on the cohesion between the binder and carbides as well as the ductility, fracture toughness and hardness[22] of the binder.

#### 2.3.1.1 Composition of cemented carbides

Tungsten (W) and Carbon (C) can bond together creating Tungsten carbide (WC). WC is one of the most widely used carbides in cemented carbides, but TiC and TaC are also common. WC is excellent mainly because of its great hardness and high melting point. There are a few common binders like; Ni, Fe, Co, Fe-Ni, and Fe-Ni-Co[23]. Where cobalt is the most used, in part because of its wettability, and of course because of its great mechanical properties. Wettability meaning that it can seep into the small spaces between the carbides during the sintering process. There can be small amounts of other additives like Cr<sub>3</sub>C<sub>2</sub> or VC which act as grain growth inhibitors, ensuring good microstructure and controlling carbides size.

#### 2.3.1.2 Wear mechanisms

The dominating wear mechanisms[24] in cemented carbides depends on the size of the carbide particles. The smaller the grain size the higher dry sliding wear is. Microabrasion is maximized at about 0.8  $\mu\text{m}$  and at that size is the dominating wear mechanism. The switch seems to be around 1.4  $\mu\text{m}$ . Although the wear mechanism changes with particle size the cemented carbide is quite brittle, and will most probably act in a brittle manner upon failure.

### 2.3.1.3 Mechanical properties

Usually when measuring the mechanical properties of materials yield strength and ultimate tensile strength are common use. However cemented carbides are seldom loaded in pure tensile, so these measurements are not very telling of its true properties. Instead TRS is used, standing for Transverse Rupture Strength[25]. TRS measures the bending stress of a material upon breaking, and is usually around  $2700 \text{ MPa}^{-2}$ . Compressive strength is also a common mechanical property worth noting in cemented carbides, and is typically around  $4900 \text{ MPa}^{-2}$ . The hardness is typically between 900-1900 HV vickers.

High hardness in combination with great fracture toughness makes the cemented carbides highly suitable for its use as a substrate in metal cutting tools.

## 2.3.2 Hard Coatings

Hard coatings are widely used in engineering applications due to their ability to reduce mechanical and corrosive wear in tools and other components[26]. They often have a thickness of a few microns.

### 2.3.2.1 Types of hard coatings

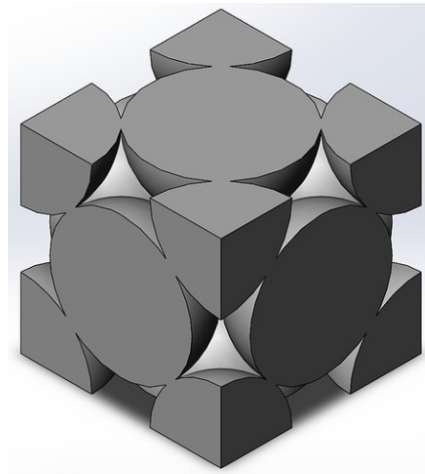
There are a few types of hard coatings, usually they are classified depending on their composition[27].

Boron Nitride (BN) has great lubricity and high thermal stability, making it applicable in high temperature situations where lubrication is needed. Chromium Carbide (CrC) with its superb hardness, good thermal stability and wear resistance is a good choice for machining applications. Zirconium nitride (ZnN) is a coating with high hardness, wear resistance and adhesion, with a gold like appearance, and is widely used in cutting, decorative coatings and space applications. Diamond-Like carbon (DLC) have similar properties as natural diamond, except instead of one “diamond shaped” crystal, there is a flat surface of the same material. DLC have superb hardness, low friction and high wear resistance. Chromium nitride (CrN) has high hardness, good adhesion and corrosion resistance, and is used in decorative applications, molds and cutting applications.

Titanium nitride (TiN) is a widely used coating for its exceptional hardness, wear resistance and low friction, and is widely used in cutting applications. If Al is added it becomes either Titanium aluminum nitride (TiAlN) or Aluminum titanium nitride (AlTiN) which both have higher thermal stability and higher thermal hardness[28] than their aluminum lacking counterpart. If the coating contains more Ti, it is called TiAlN, and if it contains more Al, it is called AlTiN. TiAlN has high oxidation resistance, while AlTiN is a little better when it comes to wear resistance. Since TiAlN is one of the most widely used hard coatings it will be in focus in this chapter going forward.

### 2.3.2.2 Coating microstructure and composition - TiAlN

TiAlN has a FCC crystal structure which means that the atoms are arranged with an atom in each corner and in the middle of the faces on each side of a cube, seen in figure 2.13. [29]



*Figure 2.13: FCC crystal structure, one unit cell*

The grain size of TiAlN varies depending on several factors, such as deposition method and manufacturing parameters. About 10.5 nm when using cathodic arc ion plating[30], between 50-90 nm when using triode magnetron sputtering[31], and 17-20 nm with PVD[32].

The TiAlN coating is about 1-4 micrometers[33] thick and is mostly composed of a solid solution of TiN and AlN to increase and improve some properties[34]. The proportions of these depend on the manufacturing method and its parameters but is usually in the range of 50:50 to 30:70.

### 2.3.2.3 Preparation techniques

PVD and CVD are the most common manufacturing methods for creating the hard coatings. New technologies are emerging like atomic layer deposition (ALD) but especially PVD stays widely used as newer techniques are developed.

PVD, short for physical vapor deposition, is a material coating method used to increase hardness, wear resistance and corrosion resistance. The coating material and substrate are placed in a vacuum chamber. Then the coating material is heated by various means until it vaporizes. The vapor is transported to the substrate where it loses energy and adheres to the surface, creating a thin film[35]. Sometimes during this process macro particles, often called droplets, are formed. These have a detrimental effect on the tribological properties. This phenomenon is known to increase in frequency when raising the amount of Al in the coating[1].

### 2.3.3 Nickel based alloys - Inconel

Nickel based alloys (NBAs) are widely used in engineering, aerospace and commercial applications. This is in part because of their great mechanical, but also physical properties.

#### 2.3.3.1 Properties

NBAs have great mechanical properties with a yield strength of 900-1200 MPa[36], compared to low carbon steel is 200-400 MPa[37].

At elevated temperatures NBAs create a thick passivating oxide layer, meaning chemically stable and unreactive. This protects the surface from further reaction and deterioration, increasing corrosion resistance[38].

NBAs are attractive for usage at high temperatures due to their ability to retain strength when temperature is increased. High temperature strength is attained in two ways, depending on the specific alloy. Either by solid solution hardening or by precipitation hardening. The precipitation hardening is attained by adding small amounts of Niobium. The Niobium together with the Nickel creates an intermetallic phase, called the gamma phase. The gamma phase takes the form of small cubic crystals that inhibit creep and slip at elevated temperatures, but also worsens the machinability of the NBAs.

#### 2.3.3.2 Composition

The composition varies from the different alloys but there are commonalities. Of course NBAs contain Nickel, and makes up about 23-100%[39] of the weight. Cr is added for corrosion resistance, oxidation resistance and high temperature strength. Fe is added to increase overall strength. Mo is sometimes included for high temperature strength and creep resistance. Co is added in superalloys to increase creep resistance and high temperature strength. Cu is commonly added for NBAs in corrosive environments and increases thermal and electrical conductivity[40]. Ti is sometimes added to increase precipitation hardening and promote creep resistance. Al is often added to enhance oxidation resistance, high temperature strength and corrosion resistance. Finally W is sometimes added to alloys in high temperature applications to improve strength, creep resistance and thermal stability.

#### 2.3.3.3 Classification

There are many different types of NBAs. And most of them can be classified into types. **Hastelloy** alloys are nickel-molybdenum-chromium-based alloys with excellent corrosion resistance for high corrosive environments[40]. Hastelloy C-276, Hastelloy C-22 and Hastelloy X are the most common in this type. **Nickel-based Superalloys** are high performance superalloys used in extreme temperatures and high stress situations, like turbines. The Rene series, Waspalloy and Udimet alloys are used most frequently of the Nickel-based superalloys. **Inconel alloys** are nickel-chromium based alloys with high temperature strength and good corrosion resistance. Inconel 600, Inconel 625 and Inconel 718 are the most common in the Inconel family.

## 2.4 Tribological testing

There are many applications where the tribological properties of materials are important. Materials can be ranked generally from great to worst, but it is better to individually investigate what materials are most suited for a certain conditions or application. And there are many reasons for choosing a certain material in tribological contexts. To lower the cost, friction or wear of an existing construction, choosing optimal material for a new construction, or to predict the tribological behavior of a given application. And in order to know which materials to use, information about these materials are needed. This information is gathered via tribological tests. And in order to get the desired information there are a few things to consider. Like the testing method, parameters, planning and interpretation of results.

### 2.4.1 Classification of tribotests

Tribological tests (or tribotests for short) come in many shapes and sizes, and they can be grouped into two main ways, two classification systems. Quite conveniently called; classification system 1 and classification system 2. The different tiers of the classification systems relative to each other can be seen in Table 2.1. The complexity of the tests are tabulated in descending order, meaning that the top most elements in the tables are most reality-like, and the lower down on the list is more simple. [41]

Table 2.1: The two different classification systems

<b>Classification system 1</b>	<b>Classification system 2</b>
Field test	Complete tribo-pair test
Bench test	
System part	
Component test	
Simplified component test	Half tribo-pair test
Model test	Model test



### 2.4.2 Classification system 1

Classification system 1 is the most commonly used of the two. In order to more easily understand these different levels, let's use a car and its piston/cylinder interaction.[41]

**Field test** is the most realistic, testing the entire object in the field or in its real applicable area. It would be equivalent to a car riding around being used normally.

**Bench test** is quite close to reality but not quite. Here the entire object is used in the test, but not in its usual environment, like in some sort of laboratory. It would be equivalent to a car used on a type of treadmill.

**System part test** is when a system inside the object is tested in the lab. Like taking out the engine of a car and letting it run.

**Component test** is taking out a component of the object and testing it in the lab. For example in a car, taking out and testing just the cylinder and piston.

**Simplified component test** is a lot like the component test. The main difference is that the components geometry is somewhat simplified. In the car example it would mean that the piston and cylinder would have a less complicated geometry.

The **Model Test** is the most simplified, not looking anything like the real tribosystem. The main part of the model test is to simulate the correct mechanism in the contact. This is the test where the steerability is the highest and the cost is the lowest. In the car case it could be done in many ways. But one example could be a pin sliding back and forwards over a metal sheet.

### 2.4.3 Classification system 2

**Complete tribo-pair test** includes the two correct surfaces interacting with each other. Other parameters like shape, speed and temperature may differ from the actual contact.

**Half tribo-pair test** includes one of the correct surfaces from reality while the other is a type of model.

**Model test** in classification system 2 does not differ from Model test in classification system 1.

#### 2.4.4 Choice of wear test

The goal of most tests is to understand the properties of components in the application where they are supposed to be used. So one might imagine that one would always do the most **realistic** tests. But, this is in fact not the case. Because there are other factors that come into play. [41]

**Controllability** is crucial in choosing a wear test. The most important thing during a tribological test is that the parameters are as close to reality as possible. And if one cannot control the parameters like wear mechanism, temperature and speed, then the test is investigating a case that one is not interested in.

The **speed** is one parameter that needs to be taken into consideration. A test could include the correct wear mechanisms, materials and temperature, but if it takes too long to complete the test is then unfortunately unviable. Some wear tests can only be set to a certain speed or not to a great enough to make it viable. So the timeframe needs to be taken into account.

In some cases it is important to **continually measure** quantities like friction, wear and temperature. For example, during a closed contact tribotest (where the same surfaces keep interacting with each other) there can be interactions between the surfaces that change over time. That some particles are worn off and start scratching between the surfaces, changing the overall behavior in the contact. During some cases it is of high importance to investigate how these properties change over time.

The **cost** is unfortunately an obstacle that needs to be taken into consideration. Sometimes it's not economically viable to do the most realistic test. Either because the testing setup is too expensive, or because in order to have enough data to make adequate statistical analysis a great number of tests needs to be made.

### 2.4.5 Tribo-test geometries for model tests

There are different kinds of tribometers, and various ways of classifying them. One way is by their geometry. In figure 2.14 6 common wear test geometries are displayed, where the straight line shows where a normal force is applied and the curved arrow shows the motion of the other part. It is also common to measure the friction force. This is the force needed to make the block stay in the same place, in the case of the block-on-ring geometry for example.

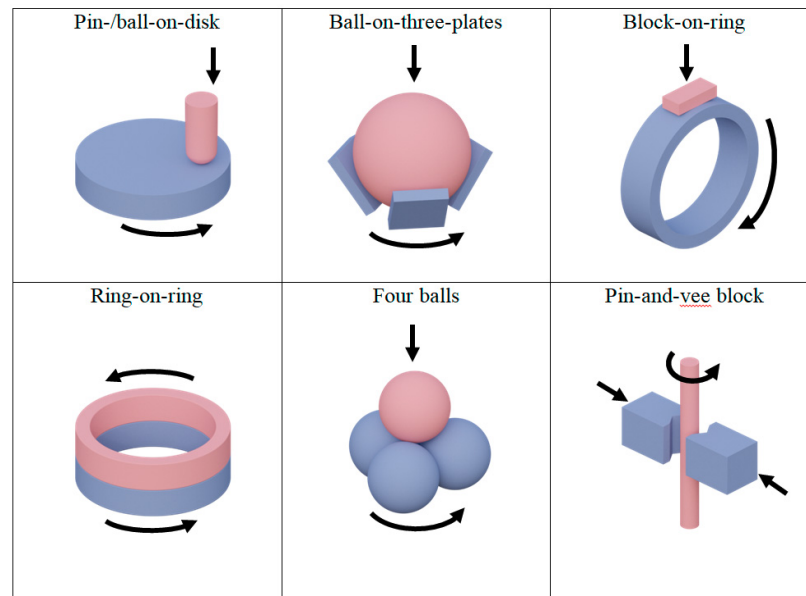


Figure 2.14: Different wear test and their geometries [42]

It's not only the type of test that matters but also the orientation of it. This decides what happens to the wear particles. In the first image in figure 2.15 the particles stay on the surface more easily than in the other two orientations. One wants to mimic the way the particles would go in the real situation and choose the orientation that most closely resembles that.

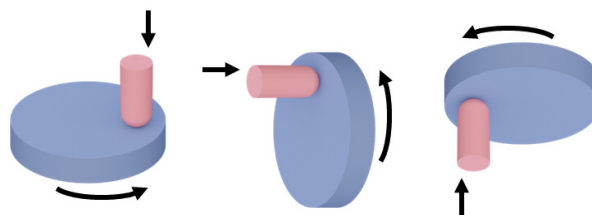


Figure 2.15: Different orientations of the pin on disc wear test [42]

There are a few more subdivisions of the models test. Like with open/closed contact. Open contact means that new material is constantly being exposed and worn down. And a closed contact, which is the more common of the two, would be where the same surface gets worn again and again. One could compare it to a person walking in a straight line in a field, or in a circle in a field. One might imagine that the person walking in a circle would eventually wear down the grass, turning it into mud, and therefore change the surface interaction between sole and ground. Perhaps making it more muddy and slippery.

Another way to classify the contact of two surfaces is by their relative motion. Unidirectional sliding is sliding in one direction, like going down a slide or walking in a circle. Reciprocal sliding is sliding that is changing direction. Like when someone is brushing their teeth. And finally there is shock contact. Like when a person is jumping on a trampoline or balls being shot on a wall.

There is also wear dependent and wear independent surface contacts. Wear dependent contacts change their contact area during loading. Like a metal pike inserted into the ground, dragging across, plowing the ground. After the plowing, more ground surface is exposed than before the contact. And wear independent contact does not change their area during loading. Like in the case of shaving cheese. After shaving the cheese, the same amount of cheese surface is still exposed.

Contacts can also be divided into their relative time of contact. Continual contact and intermittent contact. Continual contact means that the contacts are always touching each other, like a snowboard sliding across snow. And in intermittent contact, the surfaces are sometimes touching each other. Like a pen writing on a piece of paper. Then that pen is sometimes sliding across the surface and is sometimes traveling in the air.[41]

## 2.4.6 Experiment design

After the type of test has been decided the parameters in that test need to be settled, which is essentially the last layer of design before the experiment takes place.[41]

### 2.4.6.1 The experiment parameters

The **speed** of the surfaces relative to each other can determine or influence many behaviors in the contact. Like the wear mechanisms and the temperature, which both also influence each other.

The force and area (that the surfaces are in contact with each other) influences the pressure in the contact. The **pressure** is what mainly affects the stress in the material. Depending on what angle the force is applied, with what the geometry of the surface are by themselves, but also importantly, relative to each other. In many tribotests it is important to align surfaces relative to each other properly. For example, if two samples are to be examined, one would want to isolate and test one main difference of these samples. Let's say their composition. All other parameters would be preferably kept constant, so that a difference in wear or friction could be attributed to the composition. But, if some other parameter would change between them, for example a slight angle change during loading. That would increase the pressure at one place and decrease the pressure at another. This could possibly change the wear mechanism entirely and make it impossible to draw a conclusion if the change in damage is because of the composition or the change in pressure caused by the slight angle misalignment.

The **contact frequency** can also be of importance. There are two, or three, cases if the frequency of contact can make a difference, depending on how one looks at it. The first is if the experiment time is kept constant and the frequency is changed. This would increase the number of loading cycles that the materials are experiencing, and would in turn damage the samples faster. The other case is if the contact frequency is the same as the resonance frequency of one of the components involved. This could cause a greater amplitude in oscillation and therefore increase the stress that the object is experiencing. Finally if the frequency is changed to zero, then there would either be no contact or constant contact. These contacts are fundamentally different from a shock contact, which is what happens if the contact frequency is greater than zero.

The **temperature** in the contact of the surfaces changes their behavior. This could happen linearly with a temperature increase or more drastically at a certain temperature. The stiffness of materials are dependent on their temperature, so as they grow hotter they grow softer and more pliable. This is the general truth over most spans of temperatures for all materials. But, there are temperatures, or temperature ranges, called transition temperatures where the properties of materials change rapidly. This can be a change in stiffness, conductivity or magnetism. All these can affect the results of the tribotest. The temperature also plays a crucial component in determining the wear mechanism in the contact.

The **atmosphere** inside of a tribological testing chamber can affect the interaction between the surfaces. The most common case is with air. The air contains oxygen that can chemically interact with any of the surfaces and create oxides. These oxides can either be chemically stable, like for titanium oxide, or be chemically unstable, like for rust. It can also happen that the oxide created behaves in the same way as the unoxidised material. Depending on its stability and new friction coefficient the surface interaction changes. In order to decrease or entirely halt the oxidation process a gas other than oxygen can be pumped into the tribosystem, if the tribosystem is contained or if the gas is continually added onto and around the affected area.

**Lubrication** is something that is well known to decrease the amount of friction in many scenarios. However it is important to use the right lubricant in the right location. Some lubricants work very well with one surface and increase the friction in another case. It is also important to use the right amount of lubrication. Too little and no effect of the lubrication can be detected, and if too much is used then extra friction will be experienced due to the extra force required to shear the lubricant.

#### 2.4.6.2 Choosing correct parameters

When choosing parameters one should aim to have the same parameters as the real situation that one wants to know more about. Because if everything was the same, everything would act in the same way. This is often not feasible to actually achieve, but can be a good guiding point to reach for. Even if not all parameters can be the same as in the real case, the most important part is that the correct wear mechanisms dominate. This is the essential part of the tribological test and decides the overall behavior of the contact.

#### 2.4.6.3 Initial testing

If one hopes to have a good statistical analysis, one needs to test many samples. The number of samples that needs to be tested should be estimated. But before doing large batches of tests one should ensure that the testing parameters are consistent over a few samples before committing to a larger batch, as not to waste samples unnecessarily. Also take into consideration before doing the testing how long one sample will take to test. Is the wear quantifiable during a reasonable time, and then calculate how long all of them will take. If the time is reasonable then one can continue the testing.

It can also be of great use to have a reference of a similar material, but optimally the same material. This is in order to compare if the results of the test seem plausible. After a reference has been selected a few practice runs can take place and compare to the reference.

#### 2.4.6.4 Minimize test spread

To produce viable statistical results the tests output should be reasonably close to each other in output data. Like similar wear and friction. To ensure this the samples should be as close to each other in properties as possible. Same shape and material. Different materials act in different matters chemically and tribologically. The shape can change the way the surface interacts and if the Ra-values of the surface are different they will also interact differently.

After a run of the machine it will be different from before the machine was used. There can be wear particles left, either on surfaces or in the lubrication. The machine can have a higher temperature due to the friction. So let the machine cool down and change dirty lubrication.

#### 2.4.6.5 Accelerated testing

During some cases it takes too long to do a test, or a series of tests. In this case it seems very attractive to accelerate the testing process. However, if there are two surfaces in relative sliding motion, and their relative speed is increased, it would lead to a change in tribological behavior. Starting with a higher temperature. This is generally not acceptable during testing. Although, there are two cases where accelerated testing is viable. The first one is where there is an intermittent contact of two surfaces. Here one can decrease the time in between the contacts. The other one is where a surface is loaded in small spots all over a surface. Like during erosion.

### 2.4.7 Experiment evaluation

In order to tell if an experiment yielded useful results the experiment needs to be evaluated. The main ways to tell if the results of an experiment is relevant is to investigate if;

- The experiment produces real case wear mechanism
- The experiment produces real case temperature in the contact area

In order to investigate the wear of a part there are two main ways. The easiest way is to weigh the sample before and after the test. However there are some difficulties with the weighing option. Small weight losses relative to the sample are hard to detect. It is difficult to measure a local weight decrease. Smearing of other materials on the sample will affect the weight. Chemisorption, absorption and adsorption will also increase the weight. The other way of measuring wear is by investigating the change in geometry. This can be done with a LVDT (linear voltage displacement transducer) for example, which has an accuracy of  $\sim 0,1 \mu\text{m}$ . When the change in volume is known the change in mass can simply be calculated together with the density of the sample material.[41]

## 3 Method

### 3.1 Investigating tribology in metal machining

In order to reach the desired goal during this thesis. A path and a method is needed to complete the necessary tasks along the way. The hot wear tester tests cutting tool inserts used in metal machining. And to design and construct an instrument that meets the requirements a few areas need to be researched. The inserts themselves, with their substrate of cemented carbides and coating of mostly TiAlN. Also the cutting operation itself needs to be investigated, to understand what the cutting tool inserts requirements are, and how they can be tested. Tribological tests are used to investigate the wear and friction properties. These matters were investigated using literature from Karlstad university's Tribology literature and search on the internet, partially on google scholar, metal machining websites, tribology websites and Chat GPT open AI was used. The answers from Chat GPT were used only initially to get an overview of some areas and later verified on more trusted sites or documents. Tribology was also discussed continually with the supervisor, which is also a tribology lecturer.

### 3.2 Hot Wear Tester

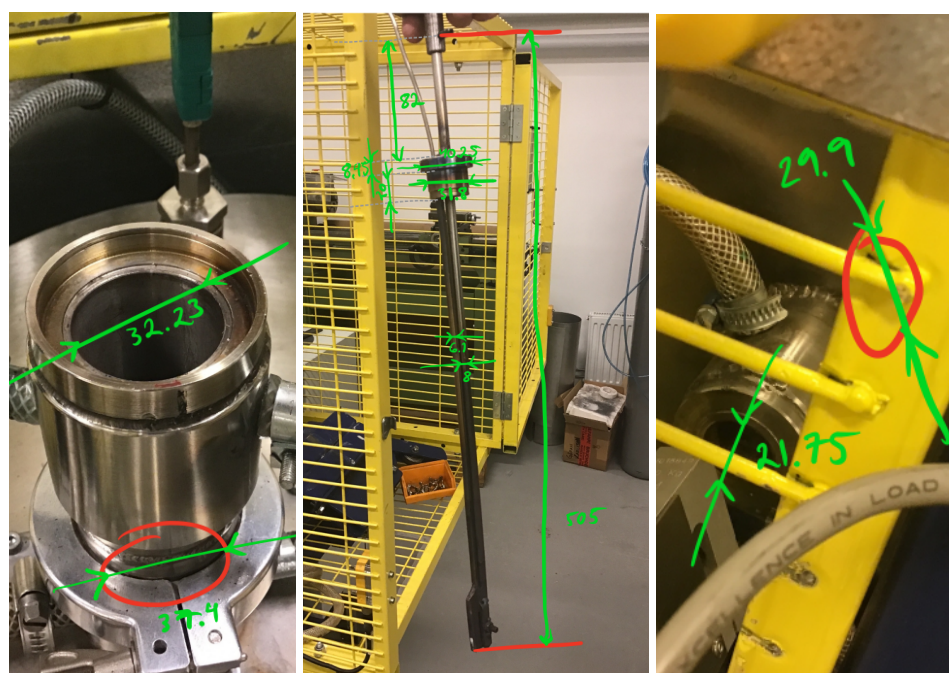
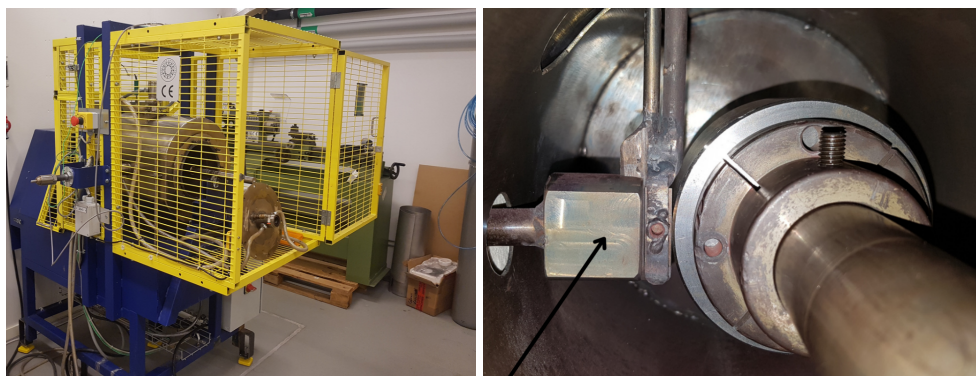
#### 3.2.1 CAD hot wear tester

A CAD-file of the hot wear tester at Karlstad University was acquired from the supervisor and was investigated. The main parts like the wear cylinder, guide, sample holder and sample were investigated more closely. The relative position of these components are of high importance, as well as anchoring points, meaning positions where the guide and sample holder is attached. This was useful, in part, because of a small model of a machine that needs to be investigated, but also with the extra benefit of very easily making objects transparent and looking at individual components to investigate them.

#### 3.2.2 Real hot wear tester

After the virtual hot wear tester was inspected the actual one was interacted with. In figure 3.1 one can see the outside and inside of the machine. In part with the supervisor, and the constructor of the machine. It was partially disassembled and opened to look closer at key components, like: The sample holder, the guide and the test cylinder. These were discussed with the members involved, about their shapes and purposes. They were also measured and notes were taken in order to compare with the CAD equivalent. In figure 3.2 one can see a few of the key components and their measurements.





A closer inspection was made of the sample holder. Figure 3.3a shows the sample holder in profile and figure 3.3b shows the sample holder from the perspective of the cylinder, with the surface of a sample exposed.



### 3.2.3 Real samples

The samples were investigated also. Their geometry was also measured and recorded. Figure 3.4 shows the old sample that the holder was designed for to the most left in the figure, as well as two additional sample sizes.

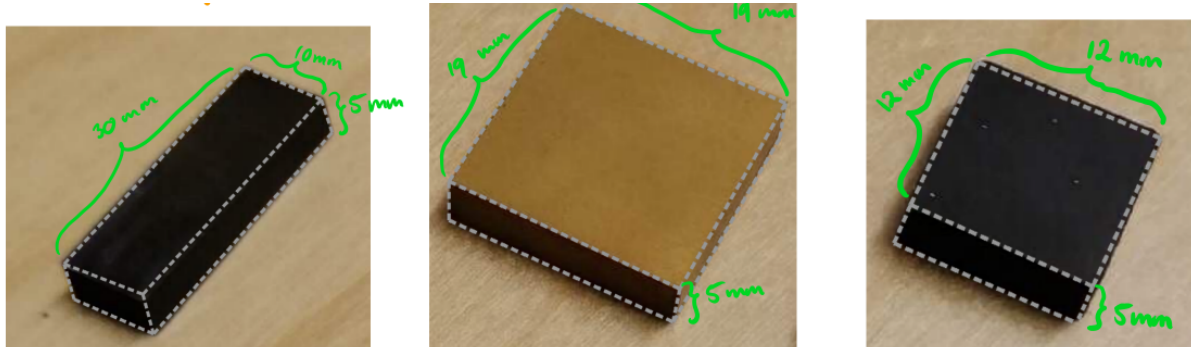


Figure 3.4: New sample geometries and their measurements

### 3.2.4 Tribological setup

The hot wear tester is a wear and friction testing machine with a block-and-ring setup. This also means that it is a closed contact, with unidirectional movement pattern, and that the contact area is wear dependent. The contact is oriented vertically, meaning that the sample's surface touching the cylinder is oriented vertically.

### 3.2.5 Goal definition

In order to construct a new working design, a few things need to be in order. The sample needs to be held in the correct location and aligned correctly. The problem of location was solved by investigating the relative position of the real components that had been recorded. The relative location of these components were sketched out in order to more easily interpret the entire setup. As well as knowing the size of the new samples that the holder is designed for. The alignment was discussed during several meetings with the workshop staff, investigating other tribological testing setups online and generating own ideas.

### 3.3 Idea generation and production

Sketches were made mostly on a digital tablet using an Apple pen and the program Notability. This made the sketches easy to tweak, duplicate and create clean pictures for recording the process. Some sketches then turned into 3d models using the CAD-program Creo Parametric. This made the concepts even more understandable and more easy to grasp when presenting.

After some ideas turned into CAD-files they were presented to the supervisor and workshop staff. This was usually done via PowerPoint presentations and later discussed between the present members. Problems that had been solved were presented and problems that were still present were discussed more thoroughly.

With the input from the meetings, new sketches were made and sometimes just alterations to existing CAD-files, but mostly entirely new concepts. This process was iterated through for a few weeks until a design that everybody thought was adequate.

Before the production started the last concept was presented with 3D renditions and drawings. After these had been approved by the workshop staff the drawings were sent over to one of the staff members. The drawings in themselves were observed and tolerances were looked over to ensure that they were sufficient and realistic.

After the drawings were looked over the workshop staff members produced the sample holder at the workshop at Karlstad University.

### 3.4 Testing and interpretation

To begin the testing a few things need to be in order. If the sample holder is already mounted, it should be removed together with its loading cell and put on a table for easier handling. Next one needs to choose the correct adapter for the given sample. The outer screws are tightened a bit but not entirely to ensure that some play is present. The same is true for the sample and middle screw. The sample holder is then lowered into the testing chamber. Two people are needed. One at the top and one with their hands in the chamber to put the back of the adapter in the gap of the guide. The person at the top can then move over to the loading cell for the guide to apply a load as the person in the chamber ensures correct contact between the sample and cylinder. Then the software can be started on the computer. How the software works is outside the scope of this thesis, but parameters like rotation speed can be chosen here. Then the test can run for a chosen duration. After the test is finished, the sample holder is removed. If a test is conducted at elevated temperatures it is allowed to cool off. The sample can either then be looked at either just by eye, like in this thesis, or in an SEM or alike. The friction and temperature is recorded during the test and can be further interpreted after the test is finished.



## 4.2 Fixture for different geometries

After the initial mapping was done, some ideas started to take form. An outline of the 30\*10 and 19\*19 was used as the baseline of the sample holder, with the idea that both of them could be slotted into a cavity and could be fastened from above with a screw. Figure 4.4a shows the relative size of the samples and figure 4.4b show how they fit into the design. However the 12\*12 sized sample could not be fitted securely in the same outline as the other. The solution was to indent the outline of the 12\*12 into the holder, so that they theoretically could be fitted simultaneously parallel to each other, even if that would not be suitable during a real test.

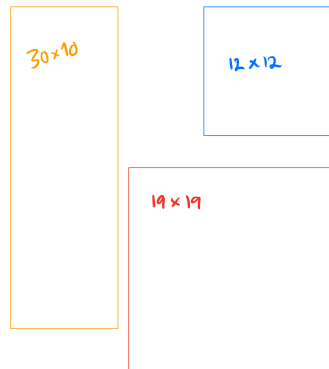


Figure 4.4a: The relative size of the samples

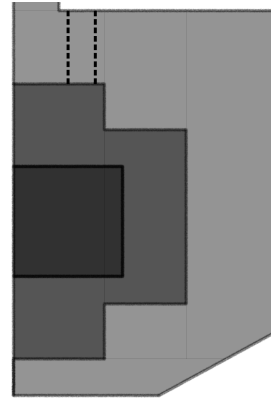


Figure 4.4b: Sample holder idea

### 4.2.1 Construction for two geometries

Further development of this idea first created a variation for the 30\*10 and 19\*19. Figure 4.5a shows a sketch of the idea, figure 4.5b shows the CAD-file of the design with a removed guiding plate to see the inside better, and figure 4.5c shows the CAD-file as it is.

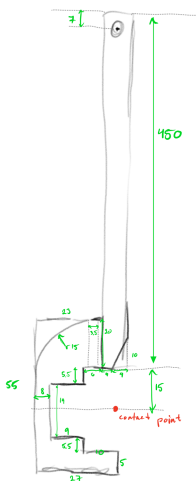


Figure 4.5a: Sketch

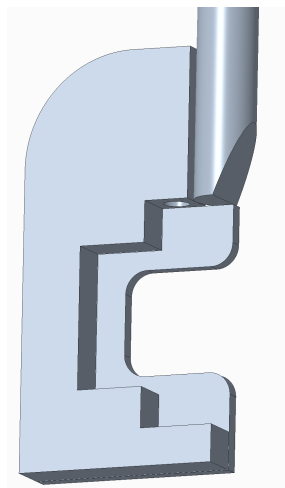


Figure 4.5b: Removed guide plate

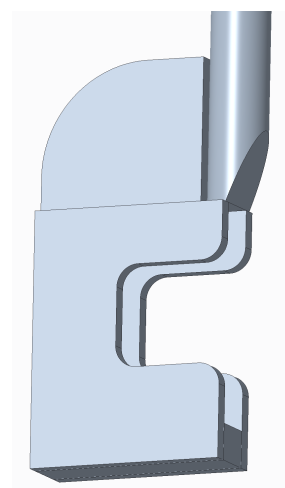


Figure 4.5c: Unaltered

### 4.2.2 Construction for three geometries

The design was then altered to accommodate the 12\*12 sample as well, figure 4.5. This made the design 5mm thicker and increased the number of fastening holes for the screw, from one to two.

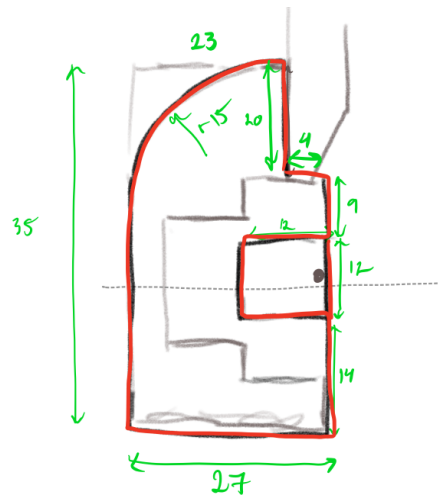


Figure 4.5a: Sketch

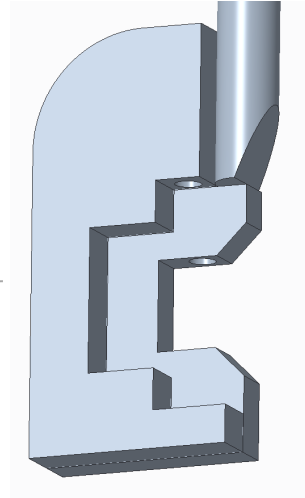


Figure 4.5b: Removed guide plates

Although this solved the problem of accommodating all the geometries and fastening them in their right location, it did have some challenges that needed to be solved. The main problem here is that the guide that is loading the sample holder, from the back, does not load the sample in the middle of its plane. This will be explained in more detail later.

### 4.3 Adapter development

In order to make the design easier to produce and to handle, as well as solve the problem of loading angle, the different sample sizes were split up. Making a general sample holder that fits three distinct adapters. With each adapter fitting into the general holder and each adapter fitting one specific sample geometry each, the general first idea is shown in figure 4.6a. A few of the involved components are shown in figure 4.6b. And in figure 4.6c one can see more of the general shape of the new holder.

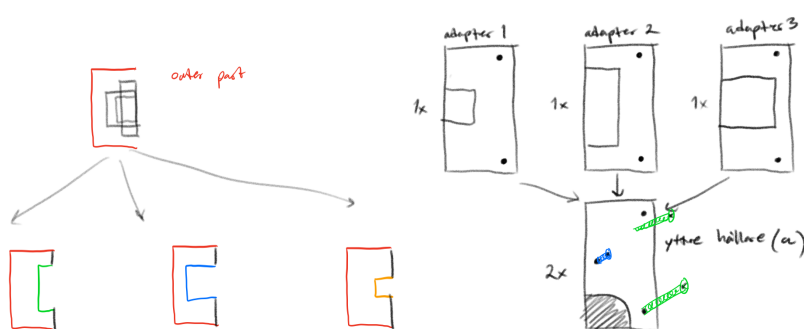


Figure 4.6a: Idea

Figure 4.6b: Components

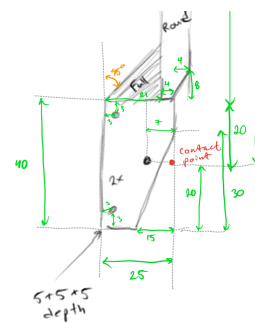


Figure 4.6c: General shape



The design was later developed in CREO and in figure 4.7a one can see how the general adapter base can be used together with the three adapters. Figure 4.7b shows the guide that was created to accommodate the change in thickness of the new sample holder. Drawings can be seen in the appendix.

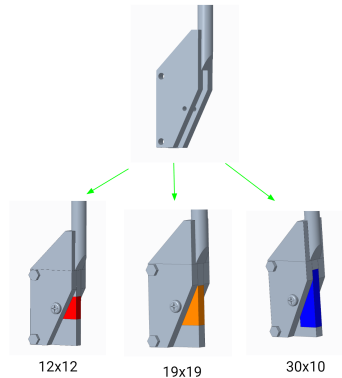


Figure 4.7a: Base and adapters

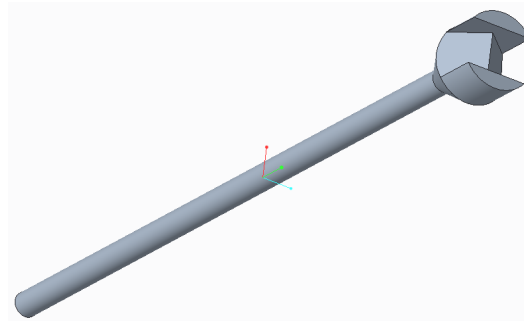


Figure 4.7b: Guide V2

## 4.4 Fitting into hole and alignment

After closer inspection of the holes of the *actual* hot wear tester the geometry of the newly constructed sample holder needed to be changed. In figure 4.8a the upper hole of the hot wear tester is shown. This is where the sample holder is meant to be inserted into the testing chamber. Figure 4.8b shows the relative size of the sample holder and the hole. Here one can see that the sample holder does not fit into the upper hole. And figure 4.8c shows their relative size from side perspective, as well as a possible alteration to move a screw inwards and change the shape of the adapter. This would make it easier to curve it slightly in order to make it fit into the hole.

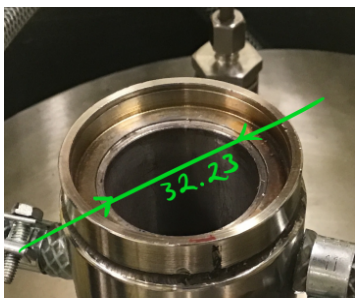


Figure 4.8a: Hole with diameter

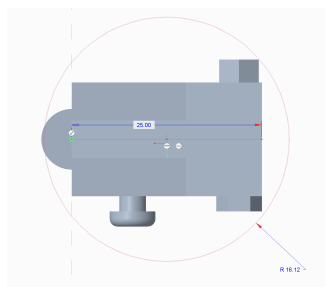


Figure 4.8b: Relative size

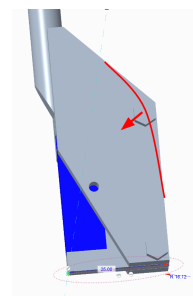


Figure 4.8c: Possible alteration

This design solved the problem with the alignment of the force though the axis of the guide and straight through the sample. However, the exposed front side of the sample needs to be highly aligned with the wear cylinder. In order to achieve the parallelity of these surfaces the design needs to be tweaked. Figure 4.9 shows how the surface of the sample and wear cylinder should be parallel to each other.

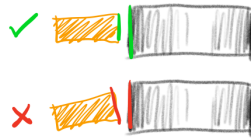


Figure 4.9: Sample and wear cylinder

There are a few crucial matters to consider to align the aforementioned surfaces. The rod that the sample holder hangs in needs to have a correct angle relative to the wear cylinder. The adapter needs to be highly parallel relative to the rod. And the sample needs to be highly parallel to the sample holder. These components are, supposed to be, welded together or tightly fastened with screws. The guide in the back very tightly fits around the holder and loads the holder, that then applies a load on the adapter, that then applies a load on the sample. All of these relative small rotations add up and it is highly difficult to control the final relative position of the sample and wear cylinder.

An alternative solution was created to better solve the problem of the alignment. The main idea is to have the sample self-aligned against the surface of the wear cylinder. In order to achieve this the fastening between the sample holder and sample cannot be too tight. It needs to allow some wiggle room. The same is true for the guide and sample holder. It should fit less tightly around it, and should directly load the adapter instead of the holder itself, Figure 4.10a. In order to lessen the number of relative movements that add to the inconsistency in angle. The interaction between the guide and adapter should also be “unstable” or loose so that interaction of the sample and wear cylinder decides the angle. This can be done by loading them via a single line instead of two straight surfaces. The guide has a flat loading surface and the back of the adapter has a sharp angle, Figure 4.10b.

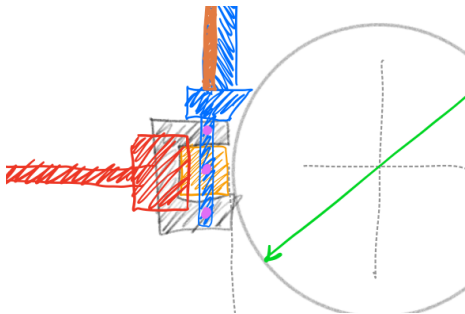


Figure 4.10a: Guide(red) adapter(gray), from side

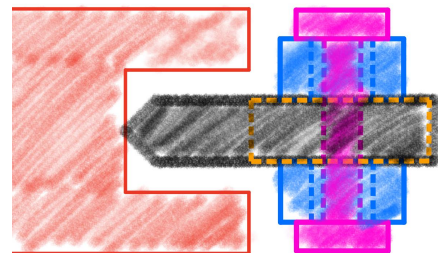
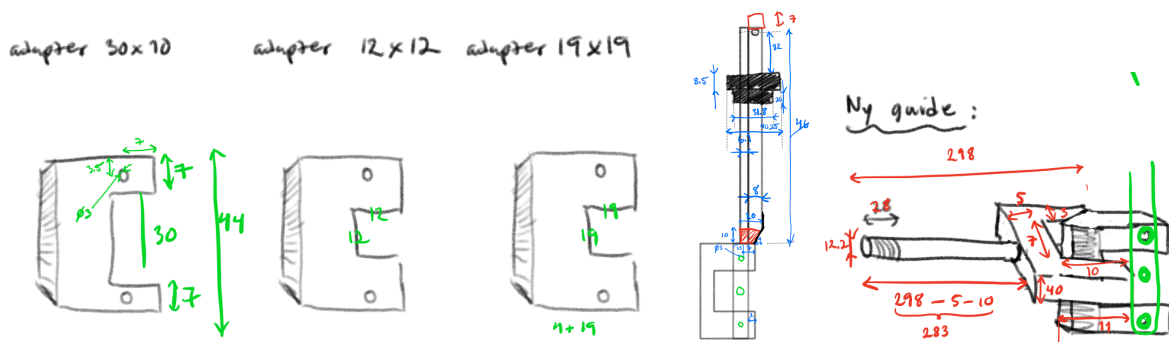


Figure 4.10b: Guide and sharp edge of adapter, from top

The new guide and sample holder, with corresponding adapters, were then created, as well as a cap on the rod to hinder gas in the chamber to get out, and a hole in the rod-cap to fit the thermoelement (and the thermoelement itself). Figure 4.11 shows sketches of the sample holder with cap and thermoelement, adapters and guide.





## 4.5 Final design

Figure 4.12 shows the last design of the sample holder without any inserts (rotated to fit page). The blue part is the holder itself and the brown/copper colored rod is the thermoelement. Figure 4.13 shows the last design of the guide.

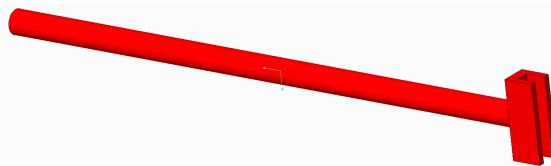
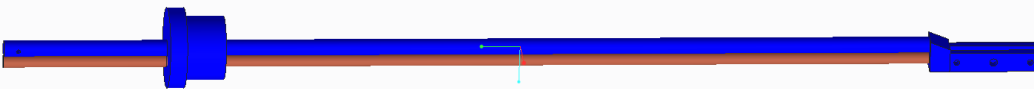


Figure 4.14a shows a closer look at the lower part of the sample holder. It is partly composed of two tiles/rectangles. The closer one has three holes, and the further one has two. The closer one is not attached, while the further is attached via welding. This is because one wants to allow for wiggle room and a less snug fit. Figure 4.14b is the holder with a 19\*19 adapter attached with two bolts. Figure 4.14c shows the holder with adapter and sample fastened with a small screw.

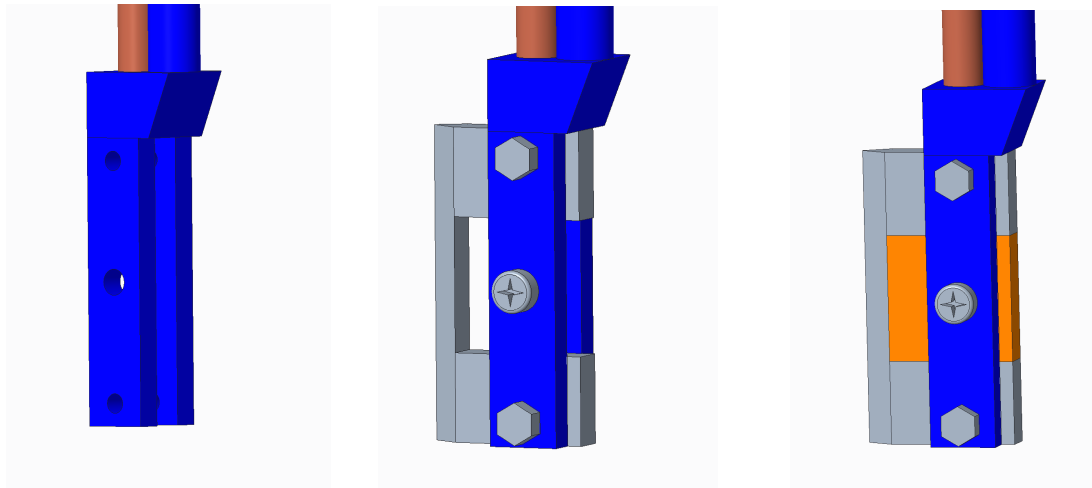


Figure 4.14a: sample holder (SH), Figure 4.14b: SH + adapter(A) Figure 4.14c: SH + A + sample

This design can also be shown to fit in the upper hole of the hot wear tester, figure 4.15.

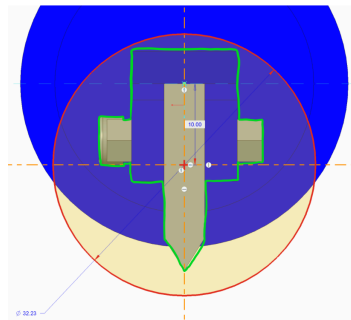


Figure 4.15: sample holder relative to upper hole on hot wear tester

Figure 4.16a shows the setup of the crucial components and how the sample is the only part touching the wear cylinder. Figure 4.16b shows that there is room between the back of the sample holder and the front of the guide. This provides the opportunity for relative motion in the form of a slight rotation. Figure 4.16c shows the room between the sides of the adapter and guide. This also provides the opportunity for relative motion.

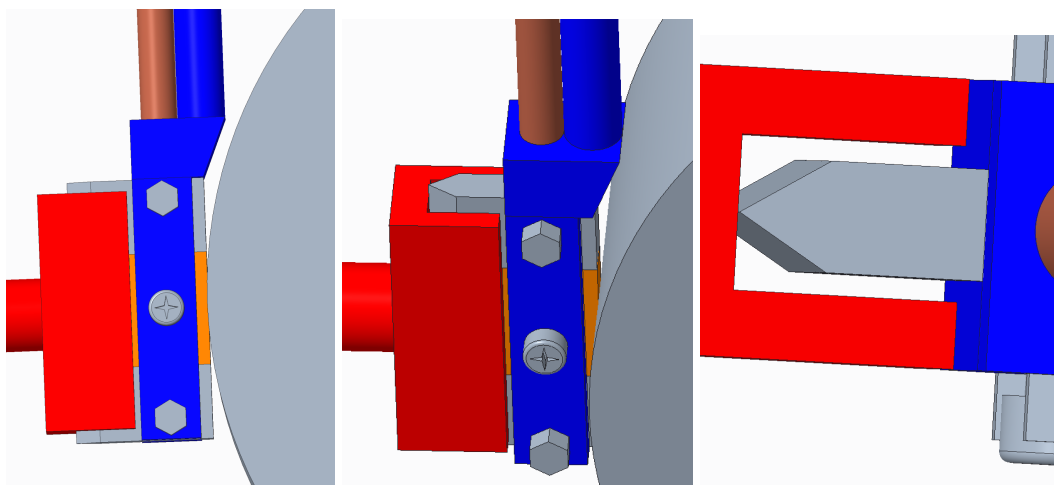


Figure 4.16a:

Figure 4.16b:

Figure 4.16c:

## 4.6 Production and fitting

Due to several factors, like time limitations and delays in material and tooling deliveries, some alterations to the design have been made. Figure 4.17 displays all of the new components for the hot wear tester. One might take note that the guide is missing. That is because no new guide was produced.



*Figure 4.17: Produced components*

### 4.6.1 Screws and nuts

The screws and nuts, seen in figure 4.18, are bought in and not produced at the university, as opposed to all the other new components. They are made of acid proof and 316 stainless steel with a strength grade of 8.8 and have a scaling temperature of 850 degrees Celsius. The remainder of the components are made of Inconel 718, which is a Nickel base alloy.



*Figure 4.18: Screws and nuts*

#### 4.6.2 Sample holder base

One of the last minute changes done to the sample holder, is that the old hanging rod and pipe for the thermoelement was reused. A welding line indicates this in figure 19, which also shows the sample holder base in its assembled and disassembled state. One of the supporting sides of the base is shown to be attached here. This is developed further later in the discussion chapter. Figure 4.20 shows the sample holder base attached to the upper loading cell from the side and figure 4.21 shows the sample holder base from the front, meaning the side that faces the test cylinder.



*Figure 4.19a: Sample holder base (disassembled)    Figure 4.19b: Sample holder base (assembled)*



*Figure 4.20: Sample holder base and loading cell in profile*



*Figure 4.21: Sample holder base from the front*

### 4.6.3 Adapters

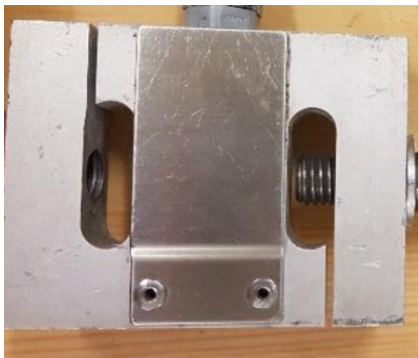
All the new adapters are shown in figure 4.22. From left to right there is the, 12\*12 adapter, 19x19 adapter and 10\*30 adapter. There are a set of extra holes on the 12\*12 adapter, this is not a design choice, but simply an error in manufacturing.



*Figure 4.22: 12x12 adapter, 19x19 adapter, 10x30 adapter*

### 4.6.4 Guide

With only a slight change in attachment, the old guide can be reused. The guide is screwed into place inside the loading cell on the side. This allows some slight difference in displacement relative to the old version. The old guide is shown in figure 4.23b together with its loading cell in figure 4.23a.



*Figure 4.23a: Loading cell*

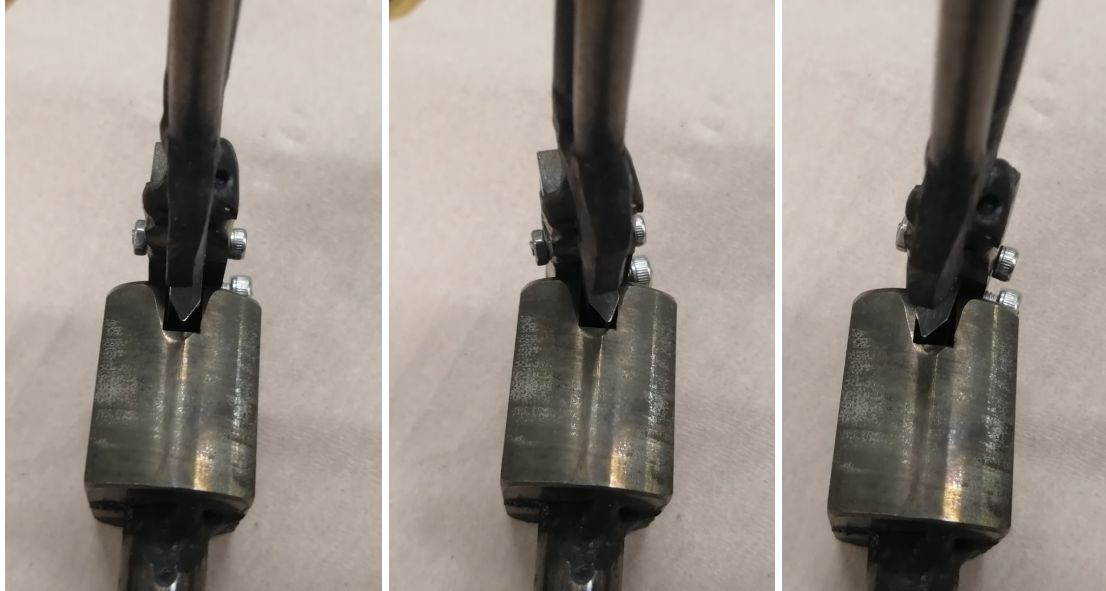


*Figure 4.23b: The guide*



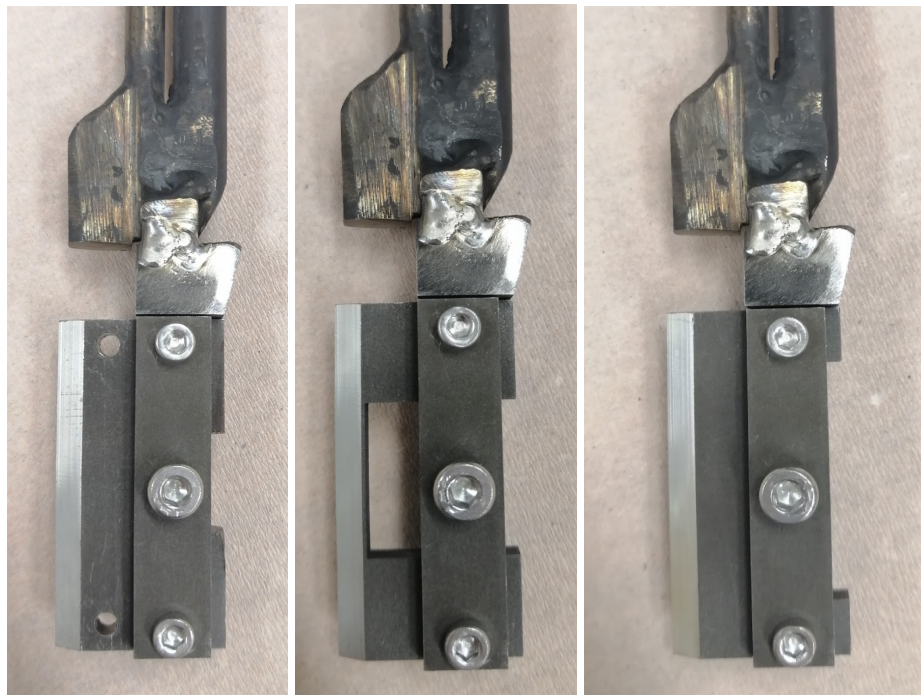
#### 4.6.5 Fitting

Figure 4.24 shows the back of the sample holder and how it fits into the guide. The different images show how the sample holder is allowed to rotate in the insert of the guide. In reality it should not rotate this much, but is exaggerated for viewing purposes.



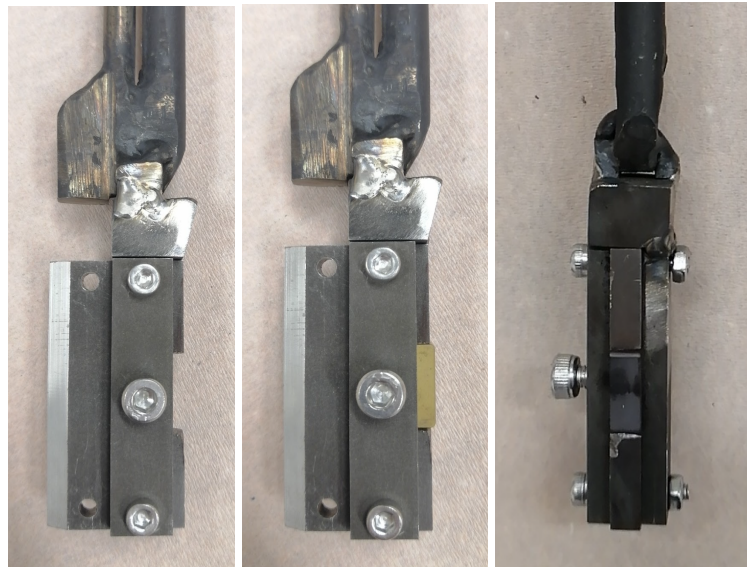
*Figure 4.24: Sample holder and guide*

Figure 4.25 shows how the different adapters are mounted inside the sample holder base. On the left is the 12x12 adapter, the middle displays the 19x19 adapter and the right is the 10x30 adapter.



*Figure 4.25: Sample holder base with the different adapters mounted*

Figure 4.26 displays the mounted 12x12 adapter without a sample in profile, with a sample in profile, and with a sample from the front. Note that there are two different samples but with the same geometry.



*Figure 4.26: 12x12 adapter in sample holder with (and without) samples*

The fully mounted sample holder is seen in figure 4.27. The guide is seen on the left, applying a normal load on the back of the sample holder, which is transferred over so that the sample is loaded onto the surface of the test cylinder, which is to the right in the image. Fitting the sample holder in from the top was difficult and required multiple attempts but was made easier with one person lowering it from the top and another person guiding it in from within the testing chamber.



*Figure 4.27: sample holder inside testing chamber*

## 4.7 Testing

The testing phase is primarily a test to observe the capability of the sample holder, seeing how well it fits in the hot wear tester and if the alignment works. Secondly, a goal is to test different materials and draw conclusions on how the material affects the tribological properties of the samples.

The sample holder was put into the hot wear tester and a few experiments were conducted. All tests were conducted at room temperature, approximately 22°C for a period of 3 minutes. The test cylinder, which is made of low carbon alloyed steel, rotated at 100 rpm and the guide loaded the samples with ~50N.

The coefficient of friction is calculated from measuring the friction force in the upper loading cell (attached to the sample holder top) as well as the applied normal load in the left loading cell (attached to the guide). The loading cells are measuring the load 100 times per second. From these values the friction is calculated and plotted over time. By inspecting the worn surfaces after the test it can be possible to draw conclusions about the wear on the samples.

During testing four different samples were investigated. Three 12x12 samples and one 10x30 sample. The 12x12 samples were obtained from Seco tools and were composed of TiN, TiAlN (75/25), and TiAlN (55/45). The TiN is 50% Ti and 50% N. In the different TiAlN samples the N stands for 50% of the weight content, and (75/25) means that the remaining 50% of the material is 75% Ti and 25% Al. The 10x30 sample is made of machine steel.



### 4.7.1 TiN

TiN was the 1st tested sample. Figure 4.28 shows the TiN sample before and after testing. It seems to have a rectangular loading area.



Figure 4.28a: TiN sample before testing

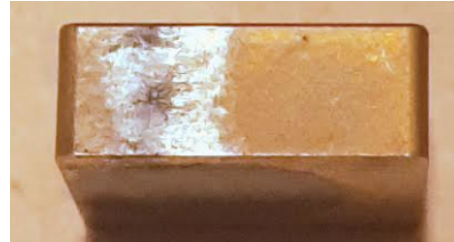


Figure 4.28b: TiN sample after testing

Data from the loading cells was used to calculate and plot the friction of the TiN over time, seen in figure 4.29. The average friction coefficient over the three minutes was 0.63 for TiN.

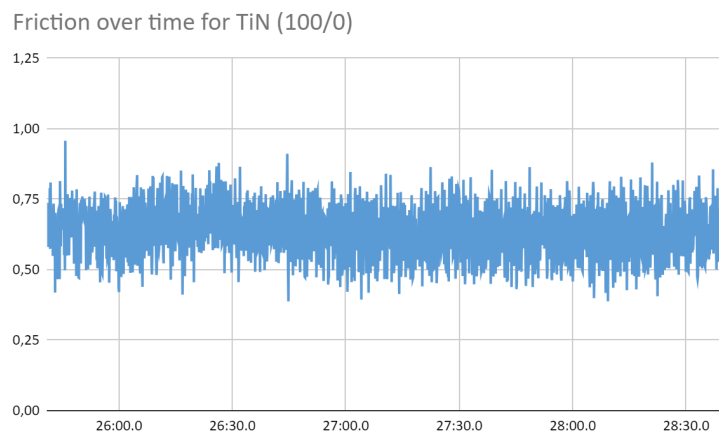


Figure 4.29: Friction over time for TiN

### 4.7.2 Machine Steel

Tool steel was the 2nd tested sample. Figure 4.29 shows the machine steel sample before and after testing. It has a very poor loading area on the corner.



Figure 4.29a: Machine steel sample before testing



Figure 4.29b: Machine steel sample after testing

No friction data is displayed because it is only the TiAlN samples that are of interest.

### 4.7.3 TiAlN 75/25

#### 4.7.3.1 TiAlN 75/25 (1)

TiAlN 75/25 was the 3rd tested sample. It was tested in the same place on the test cylinder as the machine steel sample. Figure 4.30 shows the TiAlN 75/25 sample before and after testing. There is no clear loaded area, but also no clear signs of misalignment.



Figure 4.30a: TiAlN 75/25 sample before 1st testing Figure 4.30a: TiAlN 75/25 sample after 1st testing

#### 4.7.3.2 TiAlN 75/25 (2)

A second test was performed for TiAlN 75/25, now on a fresh (non-loaded) part of the test cylinder, making it the 4th test. Figure 4.31 shows the TiAlN 75/25 sample before and after testing. It seems to have a rectangular loading area.



Figure 4.31a: TiAlN 75/25 sample before 2nd testing Figure 4.31b: TiAlN 75/25 sample after 2nd testing

Data from the loading cells was used to calculate and plot the friction of the TiAlN 75/25 over time, seen in figure 4.32. The average friction coefficient over the three minutes was 0.69 for TiAlN 75/25.

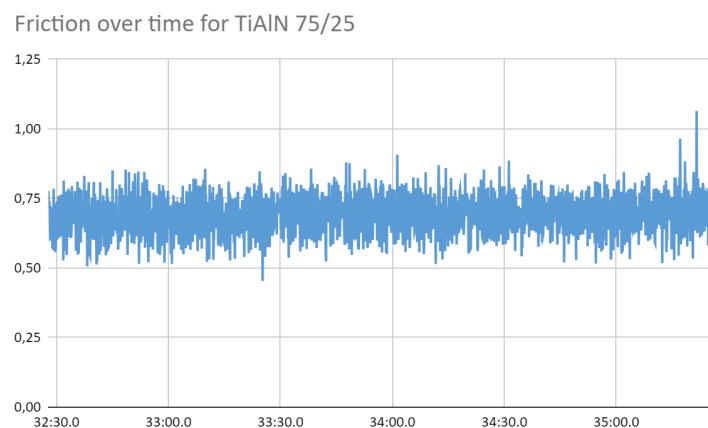


Figure 4.32: Friction over time for TiAlN 75/25 (2)

#### 4.7.4 TiAlN 45/55

TiAlN 45/55 was the 5th tested sample. Figure 4.33 shows the TiAlN 45/55 sample before and after testing. It seems to have a rectangular loading area.

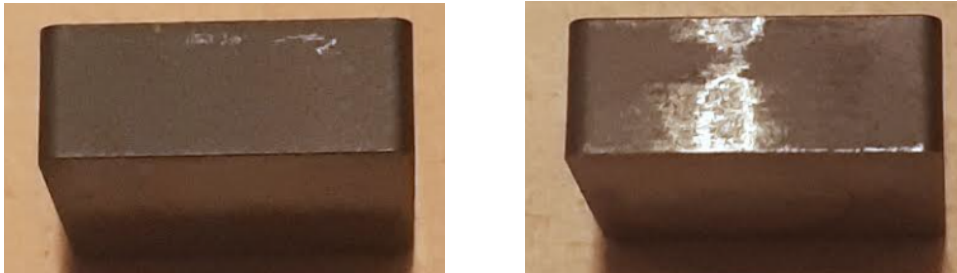


Figure 4.33a: TiAlN 45/55 sample before testing Figure 4.33b: TiAlN 45/55 sample after testing

Data from the loading cells was used to calculate and plot the friction of the TiAlN 45/55 over time, seen in figure 4.34. The average friction coefficient over the three minutes was 0.6 for TiAlN 45/55.

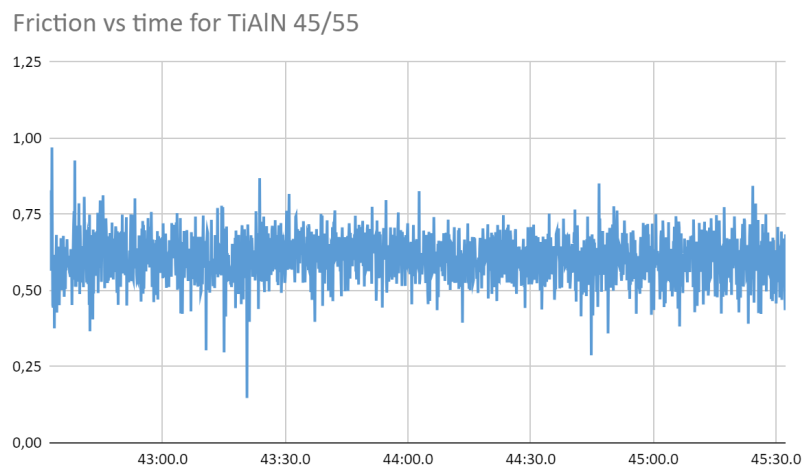


Figure 4.34: Friction over time for TiAlN 45/55

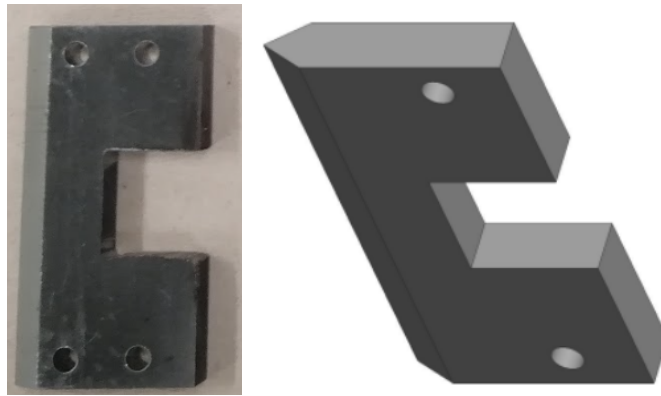
## 5 Discussion

### 5.1 Interpretations of results

#### 5.1.1 Production

Even though the final product turned out well there were some parts of the production that did not go to plan.

The 12x12 adapter had an extra set of holes drilled into it. This is merely an error in production. A comparison of the correct vs actual adapter can be seen in figure 5.1. Since this has no actual detrimental effect on the testing and fitting, it was still kept.



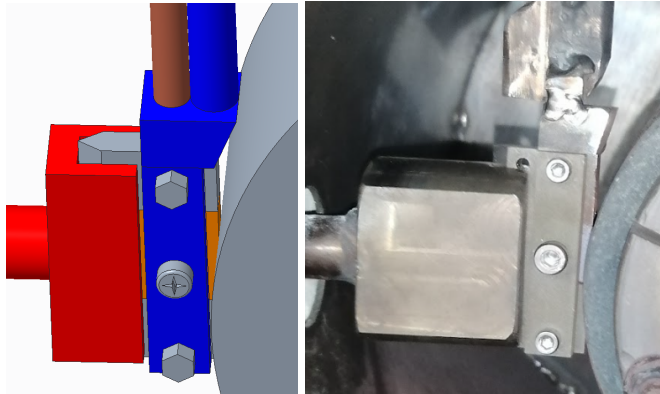
*Figure 5.1: actual 12x12 adapter vs correct 12x12 adapter*

For the first sample holder designs a new guide was needed to accommodate the extra width. When the last sample holder design was ready, a new guide was created for this one as well even though it was as wide at the back as the old version. Meaning it did not need an extra wide guide. This was not realized. However, due to limitations in time at the later stages of the project the guide was decided to be reused to save time, and did fortunately fit.

Also in the spirit of saving time the holding rod and pipe for the thermo element was reused. Since the new version is modeled after the old one in this particular area, this does not matter, except for that some material is saved. Which is economically and environmentally better[43].

Before the tests began, the adapters were investigated and tried to fit them together with their respective samples. When this was done it was realized that the 12x12 and 19x19 adapter holes had wrong measurements. But not due to a production error, due to design error. The given measurements of the samples were wrong. Not exactly 19x19 but 19,7x19,7. This was later corrected for the 12x12 sample, but in the writing moment the 19x19 adapter has still not been adjusted.

Figure 5.2 shows how the mounted sample holder looks relative to its CAD counterpart.



*Figure 5.2: CAD sample holder vs Real sample holder*

## 5.1.2 Testing

### 5.1.2.1 Testing temperature

All of the tests were made at room temperature. This was done as an initial test for three reasons. Firstly because it sets lower demands on the sample holder, which then later on can be thermally loaded more. Secondly, having the test made at room temperature allowed the testing chamber to be open during the test. This made it so that the alignment of the sample to cylinder could be investigated during the test, not only before and after. Lastly, it allowed a shorter time between the samples, because there was no need to wait for samples to heat up or cool down.

### 5.1.2.2 Surfaces interactions

As mentioned earlier, one of the adapters' insert areas are still too small, the 19x19 adapter. The 12x12 adapter works as intended in this regard. The 10x30 adapter can fit a sample inside but takes a few attempts and can be cumbersome, and oxide formation on the adapter surface will affect this. More on this in the Challenges chapter. The surfaces of both the adapter and samples are of importance. The surface roughness of these are recommended to be about Ra 100 nm to not affect the alignment in a negative manner[44].

### 5.1.2.3 Analysis of friction

The average friction from the tests can be plotted relative to the amount of Al, seen in figure 5.3. It can be seen to be low at first, then raised, then lowered again. A higher amount of Al is usually correlated with a higher amount of droplets formed during the PVD process, which is line line with the first two results. With a greater amount of droplets on the surface, there will be a higher surface roughness, and therefore raise the friction.  $Ti_xO_y$  [45] is also known to generally have a lower friction than  $Al_2O_3$  [46], which is created in TiAlN. However, something strange happens when increasing the Al% further. The coefficient of friction drops again. One possible explanation for this is; When the amount of Al% reaches a certain limit, it changes crystal structure from FCC to HCP[47], this is known to happen in PVD TiAlN coatings[48]. FCC is known to be of higher strength than HCP which can indicate that the coating is more easily sheared. This would show up as a lower friction and can be the explanation for the friction curve in figure 5.3.

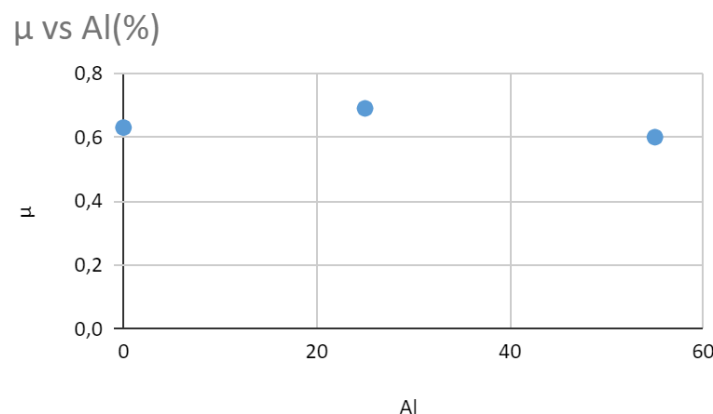


Figure 5.3: Average friction of samples vs amount of Al(%)

#### 5.1.2.4 Wear of samples

When investigating the three 12x12 samples, seen in figure 5.4, there was no clear indication of which was most worn down. Each of them seemed to have about the same amount of surface damage.



*Figure 5.4: Tested samples of TiN, TiAlN 75/25, and TiAlN 45/55*

The wear in these tests does not simulate real cutting conditions perfectly. The applied load is quite low, the sliding speed as well, and the test is done at room temperature instead of being several hundreds of degrees. All of these parameters can be shown in a wear map (like in figure 2.10b) to change the wear mechanisms. The temperature is the parameter that can be changed and have the greatest effect on the wear. The temperature can be raised several hundred degrees but the load cannot be much higher than 100N. The speed and load can however also be increased to further simulate cutting conditions better.

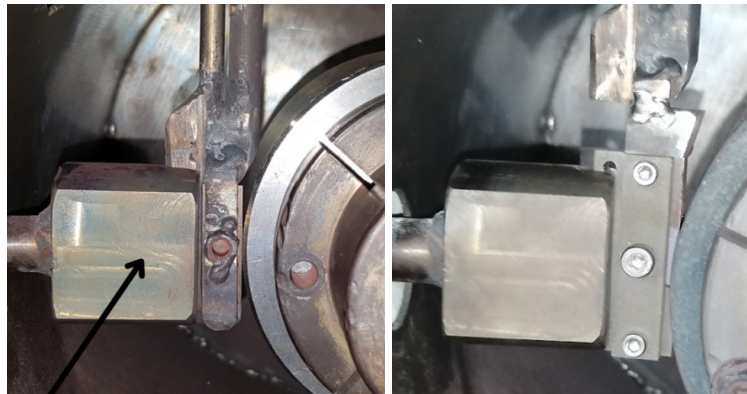
## 5.2 Compare sample holders

Figure 5.5 shows the old and new sample holder. Here one can see that the upper part of the images looks the same, due to the reusing of the top of the old sample holder.



*Figure 5.5: Old sample holder and new sample holder*

Figure 5.6 shows the old sample holder and the new sample holder mounted inside the hot wear tester. The guide can be seen to be the same, due to its reuse.



*Figure 5.6: Old sample holder and new sample holder in the hot wear tester*

Due to the several loose components in the new sample holder, it can seem more flimsy and less stable. Which is in a sense true. However, this allows the sample surface to more often cater to the cylinder surface, making alignment in present and future tests more frequent. The invention of the adapters has now made it possible to test more samples and makes it even easier in the future to expand the possibilities even further.



## 5.3 Limitations

When doing scientific work, or even work in general, there are always a finite amount of resources. Resources like time, money, workforce and knowledge are what enables and limits projects like these. Here are a few of the limitations during this master thesis.

### 5.3.1 Limitations in design and construction

One of the main goals of this thesis is to redesign the sample holder of an existing hot wear tester. This makes it easier in one sense, and more difficult in another. Only certain parts of the machine needed to be redesigned, mainly the sample holder but then eventually the guide needed to be redesigned as well. But due to the larger part of the machine being reused there comes some limitations. Limitations that hinder the ultimate goal, which is to increase the number of possible testable samples. One such limitation came in the form of the top hole of the hot wear tester. This caused one possible design to be discarded, because it did not fit into the hole. The size of the upper hole limits the design of the sample holder, but also hinders future possible adapters for larger samples to be designed. The current adapters cannot be made much larger before the previous problem is encountered again, being that the sample holder and attached components cannot be inserted into the testing chamber. The problem is not that the components have a hard time fitting inside the actual testing chamber, it is just the insertion that is the problem. Or rather, could be a future problem for future adapters.

If a larger part of the hot wear tester was to be redesigned. For example the testing chamber and mantle. Then it would free up more possibilities for even more adaptable constructions. The current design did achieve the desired result in adapting for the three specific sample geometries, but the decrease in geometric restrictions could free up space for an even better universal design. And would work for any general shape of a certain size, instead of having adapters for each version of sample.

Limitation in time made it so that only a few parts could be designed instead of the whole hot wear tester, and during the later stages of production some priorities had to change. The old guide was used as well as the top part of the sample holder. This decision was made in order to meet the deadline.

### 5.3.2 Limitations in testing

Due to the lack of time during the later stages of the project only four samples could be tested. This leads to a lousy statistical analysis and makes it so that the data and therefore the conclusions themselves are not as reliable.

## 5.4 Challenges

### 5.4.1 Alignment of surfaces

One crucial part of the testing setup from a tribological standpoint is the alignment of the surfaces. This was a point of interest during a majority of the project. This problem was encountered in three ways. Firstly was the direction in which the samples are loaded. Secondly are the tolerances. Lastly is the surfaces involved.

#### 5.4.1.1 Loading angle

During one of the earlier stages of designing, one of the solutions was discarded due to the problem of loading angle. In chapter 4.2.1 the parallel placement of the sample insertions can be seen. This design was discarded. This is because the guide would apply a force in the center of the back of the holder, meaning that the load would effectively go just to the side of the sample. This could cause the sample to be loaded more on one side than the other. And since that would increase the pressure on one side and decrease it on the other it would lead to a non uniform wear mechanism from side to side, and quite possibly from sample to sample. This would decrease the repeatability of tests and make them less reliable. In order to negate this a type of self aligning mechanism was developed, which can be useful in tribological testing[49].

#### 5.4.1.2 Tolerances

When a mechanism or machine has multiple components and is loaded in a way that transfers the load from component to component, it makes it much more difficult to control the exact location and angle of the last vs first part in the loading chain. This caused the design to change in a way so that fewer components were loaded in series. This does not remove insecurities in angle and location, but it decreases it. When deciding wear and friction geometric tolerances still need to be strict[50]. So even though the number of loaded components are decreased, the remaining still needs to have adequate tolerances.

#### 5.4.1.3 Surfaces

One more challenge during the creation of this component is making sure that the surfaces are good enough. That they have the correct shape mostly. There is one rigid plate that the sample lies against. And if the form, waviness or the roughness is really bad, that could be detrimental for the alignment of the sample vs test cylinder. The conditions of the samples are not controllable, but the surface of the side panels of the sample holder is however. Therefore ensuring that these surfaces are up to par are crucial for the testing[51].

### 5.4.2 Differences in theoretical geometry and reality

There was a difference in geometry of the CAD file of the real hot wear tester and its digital twin, which then obviously turned out not to be a digital twin. This caused delays in the production and second guessing about the information. Some components were easy to measure in the real design because they were accessible or could be disassembled and measured outside the hot wear tester. Other components are harder to measure and even more so the relative position of components, which is a crucial part in designing a fitting component.

The geometry of the samples was also not what was expected. The square samples were both larger than said to be. This was realized during production, just after the adapters were ready and before the sample holder base was ready. Because this was realized so early, it had no effect on the timeline of the project and could be solved quickly.

### 5.4.3 Mounting the sample holder

It was initially hard to fit the sample holder into the testing chamber. This was solved by using teamwork, like mentioned earlier. However, even though it fit, that was not the last problem. The alignment worked for the first test, but not the second. This could be because of two reasons. The second machine steel sample was convex, meaning not entirely rectangular. Also, when mounting the sample holder the second time, it was gently placed against the cylinder surface, then the test started, then the load was applied. In tests after this, the sample was loaded close to 50 N before the test started. This way it was possible to see directly if the sample was loaded correctly. This was partially confirmed by the later tests where the sample did not change angle after the cylinder started rotating. Just to clarify; If the sample was loaded close to fully before the cylinder started rotating the areas alignment seemed to be stable.

## 5.5 Future

Now when the project nears its end it can be fruitful to not only look back and reflect on what has happened and why, but also to look forward and reflect on what's to come.

### 5.5.1 Future use

The new construction of the sample holder enables some new possibilities in the future. From now on, a larger amount of sample geometries can be tested. With the additional adapters, the amount of possible geometries have tripled. Depending on the objective of the cutting insert, the geometry changes[52], and also the composition. It is also true that some companies only carry certain materials in certain shapes. This is also true for components with a simplified geometry. This means that with an increased amount of testable geometries that more materials can be tested.

### 5.5.2 Future breaking

In the case of catastrophic failure of the new sample holder, the old one can temporarily be used for some geometries. The 3D CAD-files and drawings have been sent to the workshop members so that a new one can be made. Or that the design can easily be tweaked to remove possible errors.

The adapters are made of Inconel. Inconel oxidizes at elevated temperatures[53]. This can be a problem especially for the 10x30 adapter that had a very snug fit. It will probably lead to an oxide forming over time, and will eventually lead to that the samples can no longer fit into the adapter. This can later on be resolved using an alkaline degreasing or rust removal[54] which removes the chromium oxide that has been formed. This could also be done with heat treatment above 1050 degrees celsius with dry  $H_2$ [55].

### 5.5.3 Future development

One of the great possibilities with an adapter design is that new adapters can be made. As long as the new sample geometry fits in a 19\*30 mm rectangle it is possible to only produce a new adapter without adjusting the sample holder itself. This is because the outer parts of the adapters are based on the maximum height and maximum width of the samples, leaving enough room for a load bearing back part and enough room for fastening holes. So the maximum height is 30mm (from the 30\*10 sample) and the maximum width is 19 (from the 19\*19 sample), making the maximum size 19\*30. The width can however not be too small. There is a screw placed 7mm in from the contact point and is 3 mm wide, reaching 8,5 mm in from the edge. In order for the screw to be able to fixate the sample in place a part of the sample needs to be in this location. Concerning the height of the sample insert section there are not many restrictions. Just that the sample needs to be high enough for the screw to fit on it (3mm).

In summary, new adapters are to be made for the sample holder, and if they are rectangular, the height should be between 3-30 mm and the width can be between 8,5-19 mm.

#### 5.5.4 Future testing

The testing with this new sample holder and its adapters have just started. It has opened many new possibilities for future testing with more materials, different geometries, other speeds, other temperatures and involved gasses. It should also be mentioned that more of the same samples should be tested, in order to give more data for statistical analysis to have a higher certainty that the results are correct.

## 6 Conclusion

In the end, a new sample holder was conceived. The base of the new sample holder is designed to have three different adapters mounted inside of it, one at the time. This allows the new sample holder to test two more possible geometries than before the project started. The sample holder was assembled and fit well into the hot wear tester. Tests were made with TiAlN samples with varying alloying elements. After some fidgeting with the loading of the sample, it seemed to produce aligned samples with near identical wear areas. Three out of five samples had near perfect alignment, which was previously unprecedented. The friction was measured during the test and it seemed to indicate that there is a certain amount of Al that maximizes friction. But more tests need to be made to be sure.

In conclusion, one can say that the initial goals of the project were met, and that a new scientific instrument can now be used to further increase the understanding of the field of tribology.

# References

- [1]. Fallqvist M. Microstructural, Mechanical and Tribological Characterisation of CVD and PVD Coatings for Metal Cutting Applications [pdf]. [Uppsala Universitet]; 2012.
- [2]. THE ART AND DESIGN OF THE MACHINE AGE. The New York Times [Internet]. 1986 Sep 21;
- [3]. Europe X. The Ultimate CNC Machining Guide [Internet]. Xometry Europe. 2019 [cited 2023 Jun 17]
- [4]. Rafi Ravoach. Turning ups the temperature [Internet]. Canadianmetalworking.com. Canadian Metalworking; 2020 [cited 2023 Jun 17].
- [5]. DPM02 PCD Face Milling cutter [Internet]. www.preziss.com. [cited 2023 Jun 17].
- [6]. Milling Cutter Tools Explained - Types and Selection Guide - WayKen [Internet]. Rapid Prototype Manufacturing in China - WayKen. 2022.
- [7]. Premium Photo | Inserts tool with hole coating titanium nitride for steel stainless cast iron cutting facing boring chamfered parts automotive isolated on white background [Internet]. Freepik. [cited 2023 Jun 17].
- [8]. Company AM. A Guide to Metal Cutting | Comparing Metal Cutting Methods [Internet]. AAA Metals Company Inc. 2021 [cited 2023 Jun 17].
- [9]. Definition of TRIBOLOGY [Internet]. Merriam-webster.com. 2019.
- [10]. Fallqvist M. First tribology lecture. 2022.
- [11]. Coakley J. REFLECTANCE AND ALBEDO, SURFACE [Internet]. 2003.
- [12]. Kauffman P, Vondracek M. The Effect Surface Temperature Has on Kinetic Friction [Internet]. Research gate. 2015.
- [13]. Tadao Ishibashi. Material Composition - an overview | ScienceDirect Topics [Internet]. www.sciencedirect.com. [cited 2023 Jun 17].
- [14]. Kogovšek J. Mitjan Kalin Surface roughness and its effects in tribology [Internet]. 2011 [cited 2023 Jun 17].
- [15]. 3D Surface Measurements [Internet]. www.bruker.com. [cited 2023 Jun 17]. Available from:
- [16]. The Editors of Encyclopedia Britannica. friction | Definition, Types, & Formula. In: Encyclopædia Britannica [Internet]. 2019.
- [17]. Introduction to Tribology Friction [Internet]. Washington.edu. 2023 [cited 2023 Jun 17].

- [18].D. Agboola O, U. Benson N. Physisorption and Chemisorption Mechanisms Influencing Micro (Nano) Plastics-Organic Chemical Contaminants Interactions: A Review [Internet]. Frontiers.org. Department of Chemistry, Covenant University, Ota, Nigeria; 2021.
- [19].Li J, Tian Y, Fang Q. 8 - Molecular dynamics simulation of friction, lubrication, and tool wear during nanometric machining [Internet]. Pramanik A, editor. ScienceDirect. Elsevier; 2022 [cited 2023 Jun 17]. p. 187–211.
- [20].CK-12. CK12-Foundation [Internet]. flexbooks.ck12.org. 2020.
- [21].Tribology Wear [Internet]. www.stle.org. [cited 2023 Jun 17].
- [22].García J, Ciprés VC, Blomqvist A, Kaplan B. Cemented carbide microstructures: a review. International Journal of Refractory Metals and Hard Materials. 2019 Apr 1;80:40-68.
- [23]. Liu C. Alternative binder phases for WC cemented carbides [Master's thesis]. KTH Royal Institute of Technology. 2014.
- [24].Wang H, Gee M, Qiu Q, Zhang H, Liu X, Nie H, Song X, Nie Z. Grain size effect on wear resistance of WC-Co cemented carbides under different tribological conditions. Journal of Materials Science & Technology. 2019 Nov 1;35(11):2435-46..
- [25]. Mari D, Miguel L, Nebel C, editors. Comprehensive hard materials. Newnes; 2014 Feb
- [26].Hard Coating - an overview | ScienceDirect Topics [Internet]. www.sciencedirect.com. [cited 2023 Jun 17].
- [27].DAN JP, BOVING HJ, HINTERMANN HE. Hard coatings. Le Journal de Physique IV [Internet]. 1993 Nov [cited 2023 Jun 17];03(C7):C7-933C7-941.
- [28].BryCoat Aluminum Titanium Nitride (AlTiN or TiAlN) Coatings [Internet]. brycoat.com. [cited 2023 Jun 17].
- [29].Niklas Norrby. Microstructural evolution of TiAlN hard coatings at elevated pressures and temperatures Niklas Norrby NANOSTRUCTURED MATERIALS DIVISION DEPARTMENT OF PHYSICS, CHEMISTRY AND BIOLOGY (IFM) [Internet]. [cited 2023 Jun 17].
- [30].Tai P, Pang L, Shen T, Wang Z, Jin P, Huang S, et al. Microstructure evolution and nanohardness of nanostructured TiAlN coating under N<sup>+</sup> ion irradiation. Surface and Coatings Technology. 2022 Jul;441:128494.
- [31].D.M.Devia, E. Restrepo-Parra, J.M.Velez-Restrepo. Structural and Morphological Properties of Titanium Aluminum Nitride Coatings Produced by Triode Magnetron Sputtering [Internet]. Research gate. 2014.
- [32].El-Awadi G, Waheed A, Samad S, Saleh Z, Sayed E, Rassoul. EG0800320 Phase Transition and Hardness of TiAlN Coatings Deposited on WC/Co by MSIP [Internet]. [cited 2023 Jun 17].



- [33].Titanium Aluminum Nitride (TiAlN) PVD Coating | Calico Coatings [Internet]. [www.calicocoatings.com](http://www.calicocoatings.com). [cited 2023 Jun 17].
- [34].Abrikosov IA, Knutsson A, Alling B, Tasnádi F, Lind H, Hultman L, et al. Phase Stability and Elasticity of TiAlN. *Materials* [Internet]. 2011 Sep 1 [cited 2023 Jun 17];4(9):1599–618.
- [35].Matthews A. Titanium Nitride PVD Coating Technology. *Surface Engineering*. 1985 Jan;1(2):93–104.
- [36].MatWeb - The Online Materials Information Resource [Internet]. Nickel base alloys. [www.matweb.com](http://www.matweb.com).
- [37].MatWeb - The Online Materials Information Resource [Internet]. Low carbon steel [www.matweb.com](http://www.matweb.com). [cited 2023 Jun 17].
- [38].Evans R. 2 - Selection and testing of metalworking fluids [Internet]. Astakhov VP, Joks S, editors. ScienceDirect. Woodhead Publishing; 2012. p. 23–78.
- [39].MatWeb - The Online Materials Information Resource [Internet]. Nickel alloys. [www.matweb.com](http://www.matweb.com). [cited 2023 Jun 17].
- [40].Types of Nickel Alloys and their Properties [Internet]. [www.thomasnet.com](http://www.thomasnet.com).
- [41].Jacobson S, Hogmark S. Tribologi, friktion smörjning nötning. 2018.
- [42].Basics of tribology :: Anton Paar Wiki [Internet]. Anton Paar.
- [43].EPA. Reducing and Reusing Basics | US EPA [Internet]. US EPA. 2023.
- [44].Harlin P, Carlsson P, Bexell U, Olsson M. Influence of surface roughness of PVD coatings on tribological performance in sliding contacts. *Surface and Coatings Technology*. 2006 Dec;201(7):4253–9.
- [45].Saideepak R. INSPECTION OF CP TITANIUM MATERIAL AND ITS COEFFICIENT OF FRICTION [Internet]. IRJET. International Research Journal of Engineering and Technology (IRJET); 2021.
- [46].Boz M, Kurt A. The effect of Al<sub>2</sub>O<sub>3</sub> on the friction performance of automotive brake friction materials. *Tribology International*. 2007 Jul;40(7):1161–9.
- [47].Qiu R. Electron Microscopy Investigation of Detailed Microstructures of CVD TiAlN and TiN Coatings - Effects of Gas Flow and Substrate on Coating Microstructure [Internet]. Research gate. Chalmers University of Technology; 2020.
- [48].Prengel HG, Santhanam AT, Penich RM, Jindal PC, Wendt KH. Advanced PVD-TiAlN coatings on carbide and cermet cutting tools. *Surface and Coatings Technology* [Internet]. 1997 Oct 1;94-95:597–602.
- [49].Nguyen PTM, Bhandari B, Prakash S. Tribological method to measure lubricating properties of dairy products. *Journal of Food Engineering*. 2016 Jan;168:27–34.

[50].Gil I, Mendiguren J, Galdos L, Mugarra E, Saenz de Argandoña E. Influence of the pressure dependent coefficient of friction on deep drawing springback predictions. Tribology International [Internet]. 2016 Nov 1 [cited 2023 Jun 17];103:266–73.

[51].Surface Roughness - an overview | ScienceDirect Topics [Internet].  
www.sciencedirect.com. [cited 2023 Jun 17].

[52].The Importance of Choosing the Right Insert Shape [Internet]. SCTools. [cited 2023 Jun 17].

[53].Kathiravan S, Kaliaraj GS, Kamalan Kirubaharan AM, Kumar RR. Study of oxide layer formation on Inconel 718 during isothermal oxidation between 800 °C to 1200 °C in hot air. Ceramics International [Internet]. 2022 Dec 15 [cited 2023 Jun 17];48(24):36012–20.

[54].Brooks WC. Chemical removal of a chromium oxide coating from an article [Internet]. [cited 2023 Jun 17].

[55].Dino S. What is the best solution to remove chromium oxides from chromium coating & to increase adhesion with other layer that is Palladium coating? [Internet]. Research gate. Beijing University of Chemical Technology;

# Acknowledgements

Det finns flera människor som har spelat en betydande roll under tiden som jag har skrivit detta examensarbete, både som har direkt med arbete att göra, men också i mitt liv. Här vill jag tacka några av dem.

Micke - Till en början var jag lite uppgiven att ett annat examensarbete inte gick att göra, och jag stod utan något projekt knappt en vecka innan allt skulle starta. Sen så råkade jag som ett bananskal halka in på ditt kontor och hamnade under dina vingar. Årets bästa olycka. Att ha dig att bolla idéer och tankar med har varit mycket betydande under den här tiden. Det är mycket möjligt att jag är den mest nöjda över sin handledare, av alla som gjort exjobb på Karlstad Universitet över de senaste 10 åren. Jag är mycket glad och tacksam att haft ynnesten att jobba inte bara under, utan med dig. Tack Micke, min nyaste favoritperson.

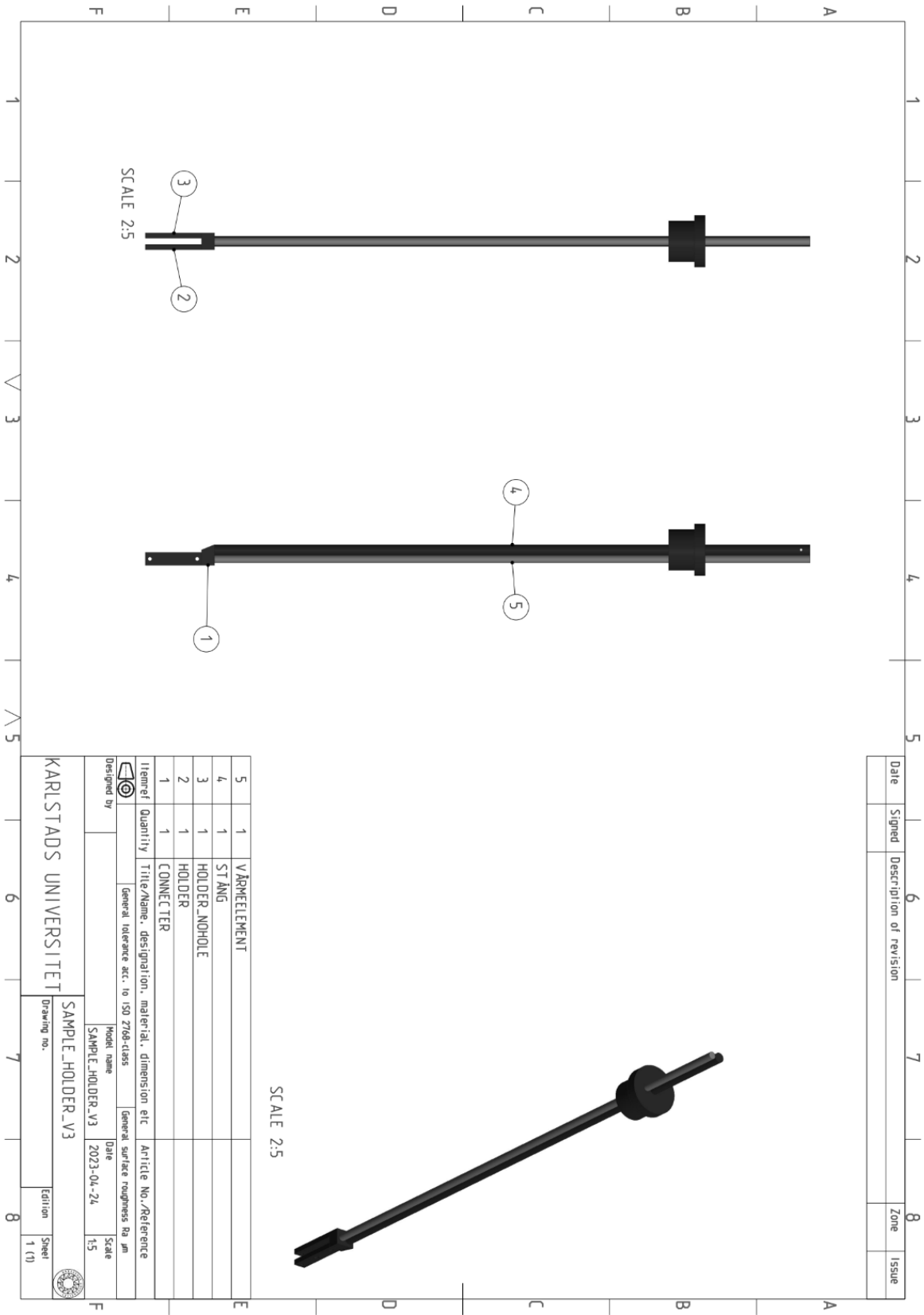
Lars - Att har haft dig med på mötena och fått insikt i flera delar av projektet har varit instrumentalt för mitt arbete. Utan dina visdomsord så hade inte den slutgiltiga hållaren inte varit hälften så bra. Tack Lars, för din tid och din visdom.

Helene - Jag kommer ihåg i 7an på högstadiet när du satt med mig i färjestugan och övade på spanskaglosor. Jag var väldigt trött och sa till dig i en suck att jag inte orkade mer. Då sa du snällt, men ännu mer bestämt, till mig att; "Jo Atle, nu tar du och anstränger dig här" ... eller något liknande. Det kan ha varit den första gången jag gjorde en akademisk ansträngning. Du har varit med sedan dess längs vägen och stöttat mig genom den resan, till där jag är nu. Tack, för ditt engagemang och din kärlek.

Martin - Jag pluggar för min egen skull, primärt. Många kollar mot sina fäder för att få någon typ av bekräftelse för sina bedrifter och arbeten. Jag har inte varit så mycket sån... Vi är båda egna individer med olika bra egenskaper och vi har under hela våra liv komplimenterat varandra väldigt bra. Du har varit, och är, den som alltid kan hypa upp mig över någon nice film, spel, låt eller händelse och förgyller mitt liv och gör mig exalterad, som ingen annan individ kan. Och ibland kan jag snöa in väldigt hårt på något ämne och sedan ge dig en inblick i vissa saker. Några av de gångerna när jag berättar vad jag jobbat med kan jag se en viss förundran, eller typ stolthet i dina ögon. Det är många tidiga mornar och sena kvällar som jag har tänkt på den blicken och den känslan som det bringar mig. Att vara någon som du kan vara stolt över har under längre perioder varit den största motivatorn att jag har kämpat på och gjort att jag rest mig igen, efter otaliga förluster. Tack Martin, för att du lånar din styrka till mig, när jag inte har den.

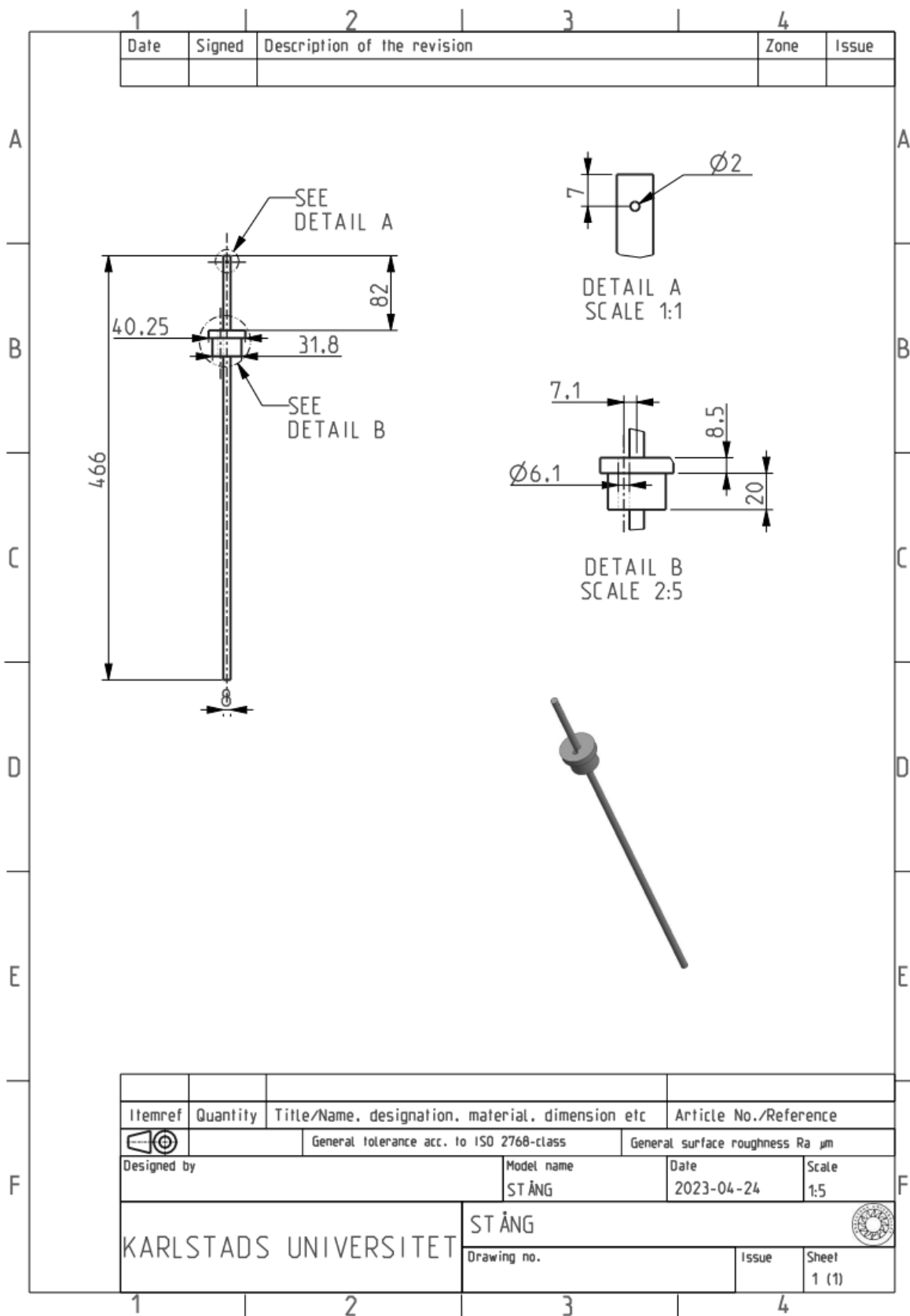
Erina - Du är utan tvekan den individen som har haft den mest intressanta karaktärsutvecklingen under den här tiden. Den har inte varit utan förvirring. Mot slutet av mitt examensarbete så har du spelat huvudrollen i mitt liv, och vem vet vad framtiden har att bringa. Men det jag vet är att du har gett mig mer mening och bidragit till mer personlig tillväxt än vad vissa har under en livstid, på mindre än 3 månader. Tack Erina, för ditt stöd, din kärlek och lyckan som har kommit med den.

Appendices

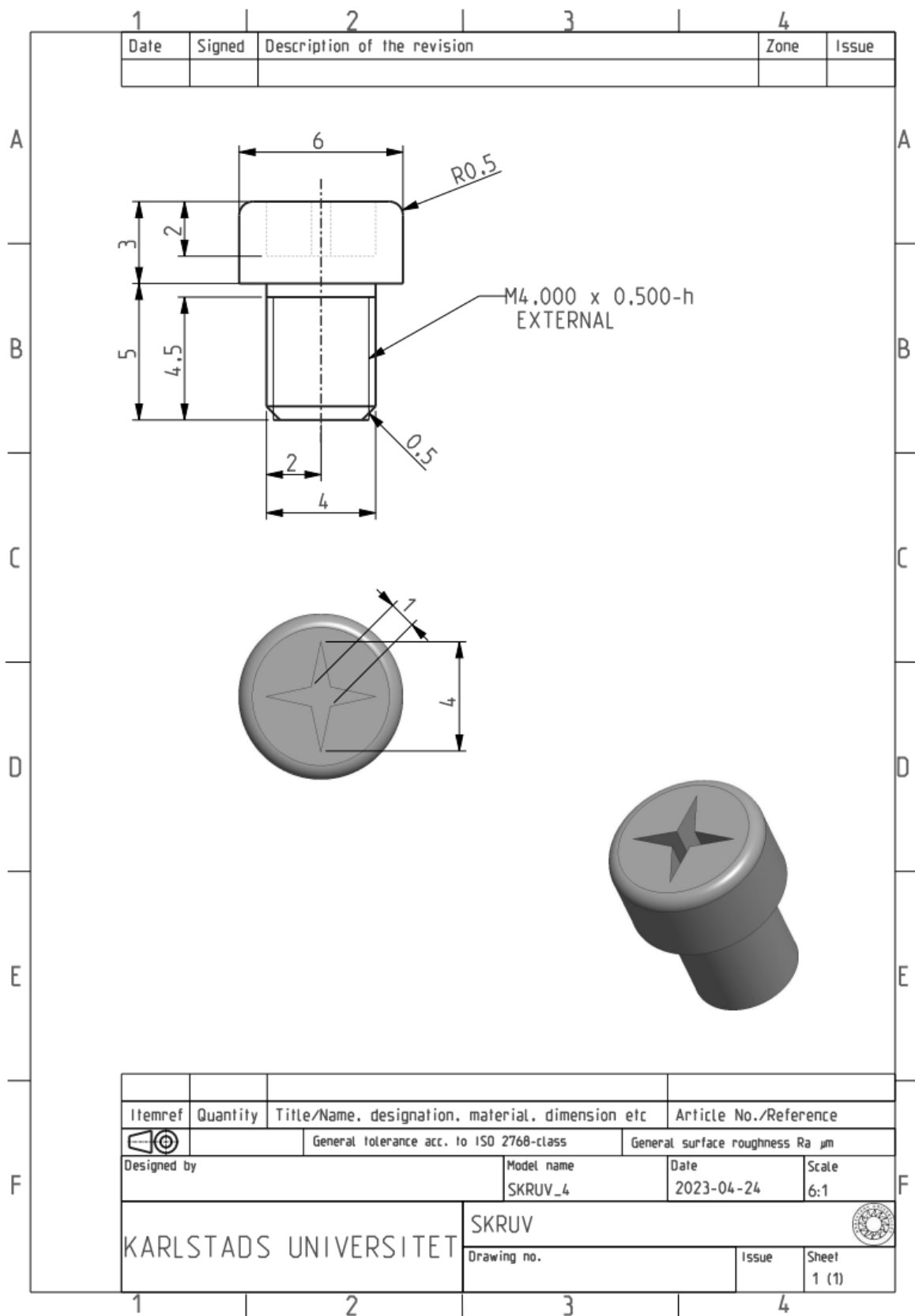


Sample holder





Rod for sample holder



Screw

1	2	3	4	
Date	Signed	Description of the revision	Zone	Issue

**Top View:**

6  
R1.5  
120°

**Side View:**

3

**Isometric View:**

Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
		General tolerance acc. to ISO 2768-class	General surface roughness Ra $\mu\text{m}$
Designed by		Model name	Date
		MUTTER_3	2023-04-24
			Scale
			9:1

KARLSTADS UNIVERSITET

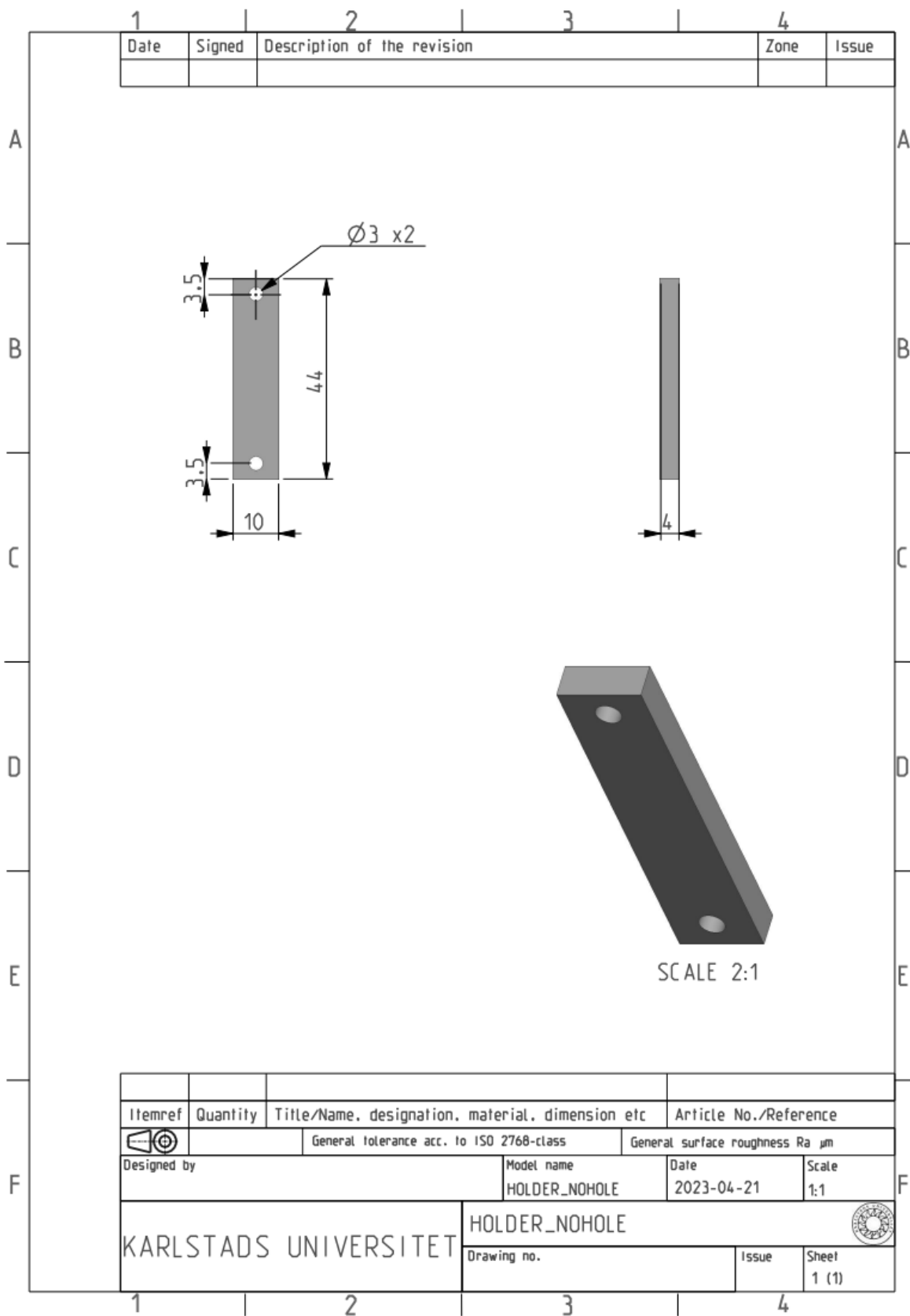
MUTTER

Drawing no.

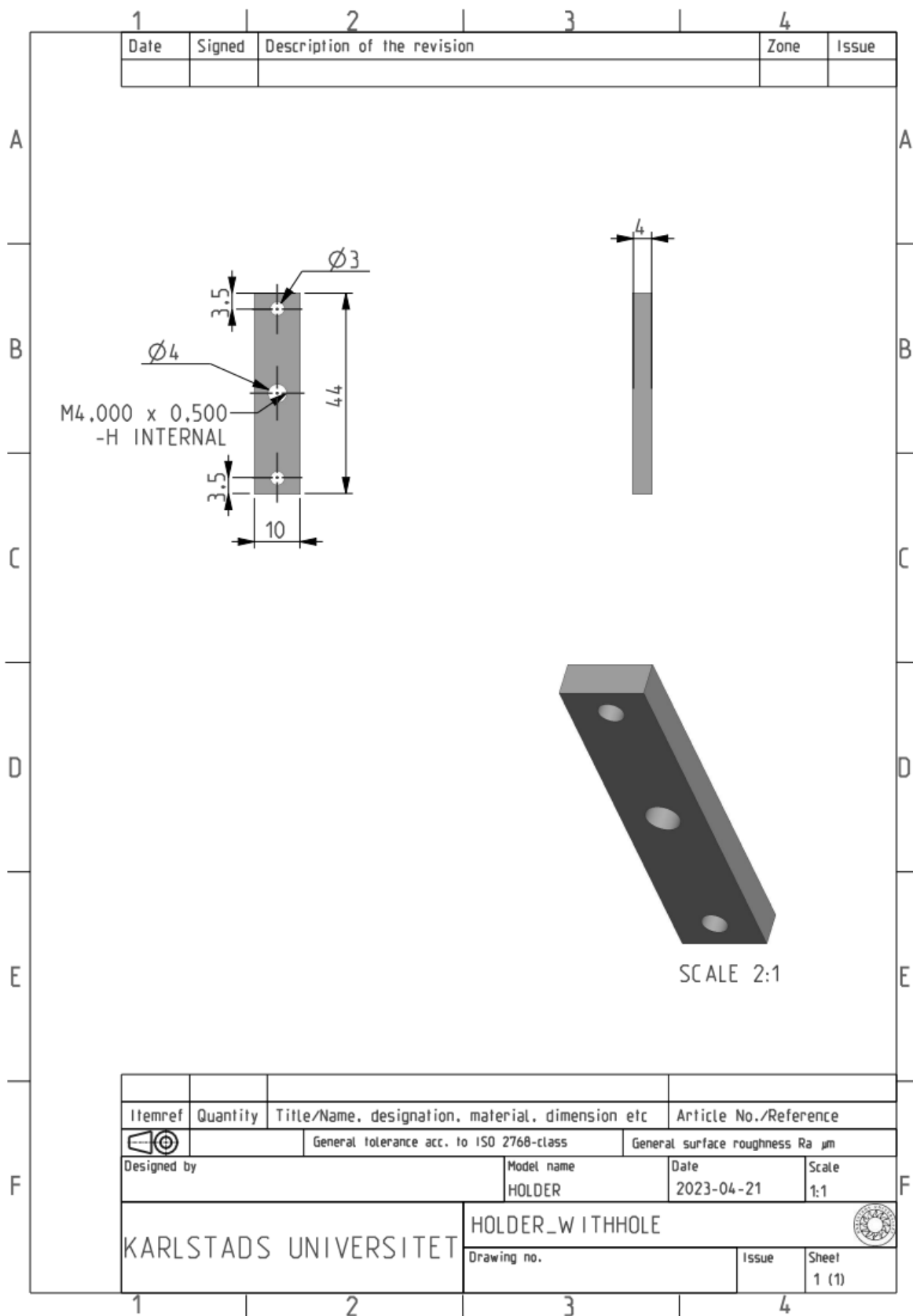
1	2	3	4	

Nut





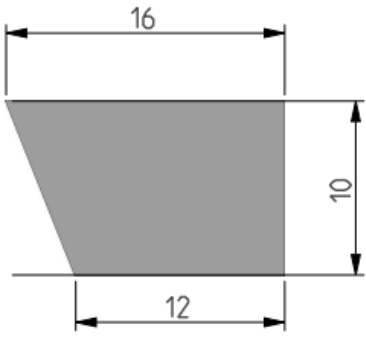
Holder - Side piece for fixating angle of sample



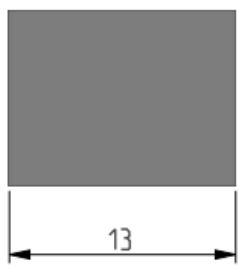
Holder with hole for screw



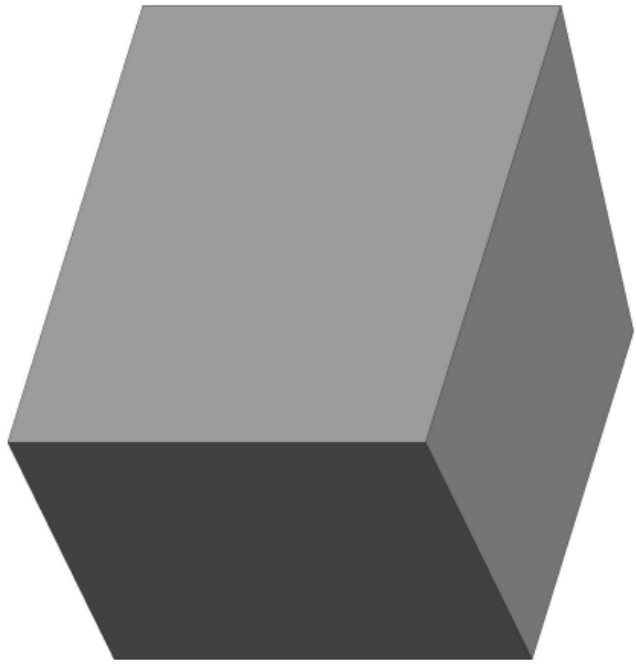
1		2		3		4	
Date	Signed	Description of the revision			Zone	Issue	



Top view dimensions: 16, 12, 10





Side view dimension: 13



Isometric view

SCALE 6:1

Itemref	Quantity	Title/Name, designation, material, dimension etc		Article No./Reference	
		General tolerance acc. to ISO 2768-class		General surface roughness Ra $\mu\text{m}$	
Designed by		Model name		Date	Scale
		CONNECTER		2023-04-21	3:1
KARLSTADS UNIVERSITET			CONNECTOR		
					
Drawing no.			Issue	Sheet	
				1 (1)	

Connector

1	2	3	4
Date	Signed	Description of the revision	Zone Issue

A
A

B
B

C
C

D
D

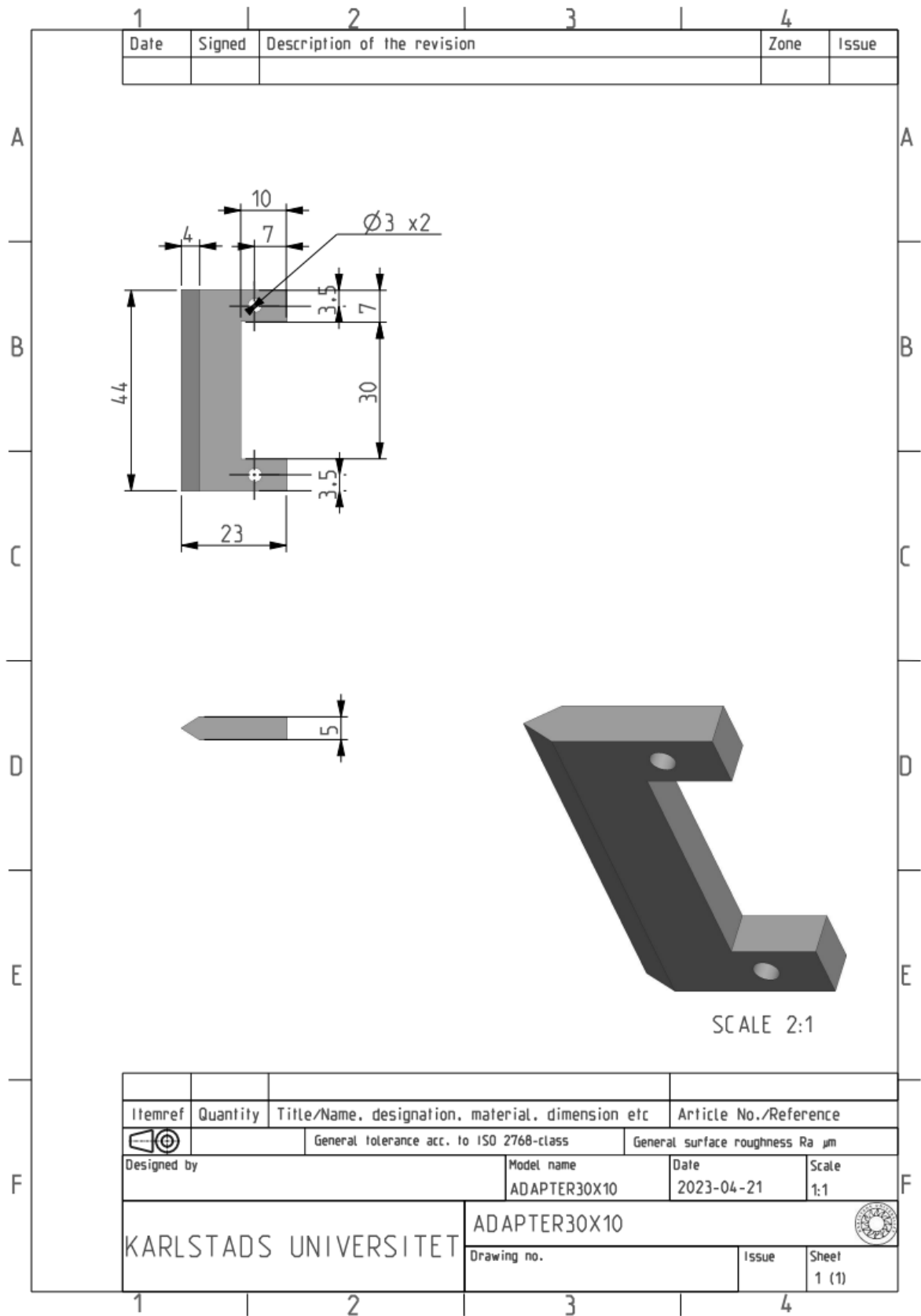
E
E

F
F

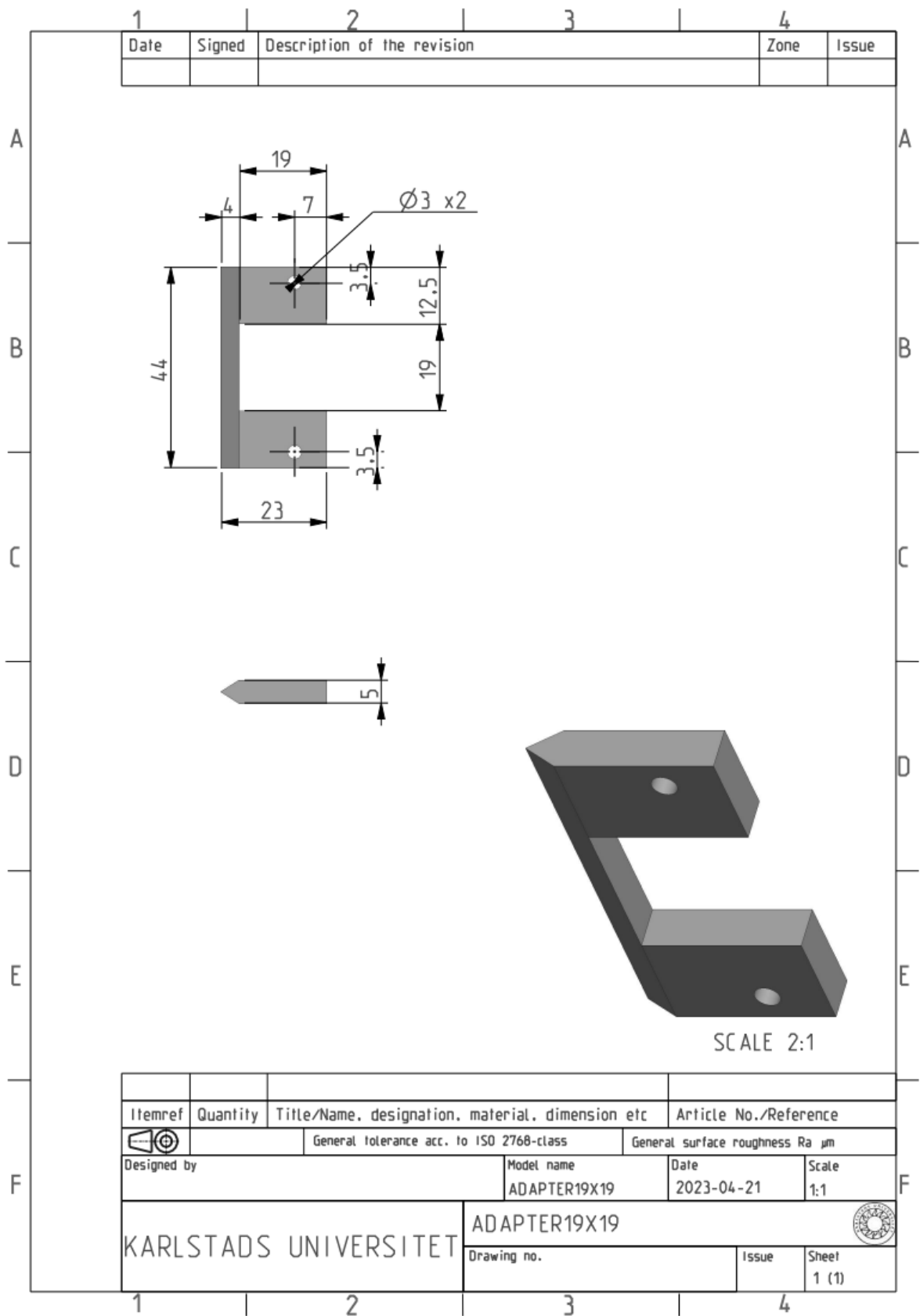
Itemref	Quantity	Title/Name, designation, material, dimension etc	Article No./Reference
		General tolerance acc. to ISO 2768-class	General surface roughness Ra $\mu\text{m}$
Designed by		Model name	Date
		BULT_3	2023-04-21
		Scale	3:1
KARLSTADS UNIVERSITET		BULT_3	
		Drawing no.	Issue
			Sheet
			1 (1)

1	2	3	4

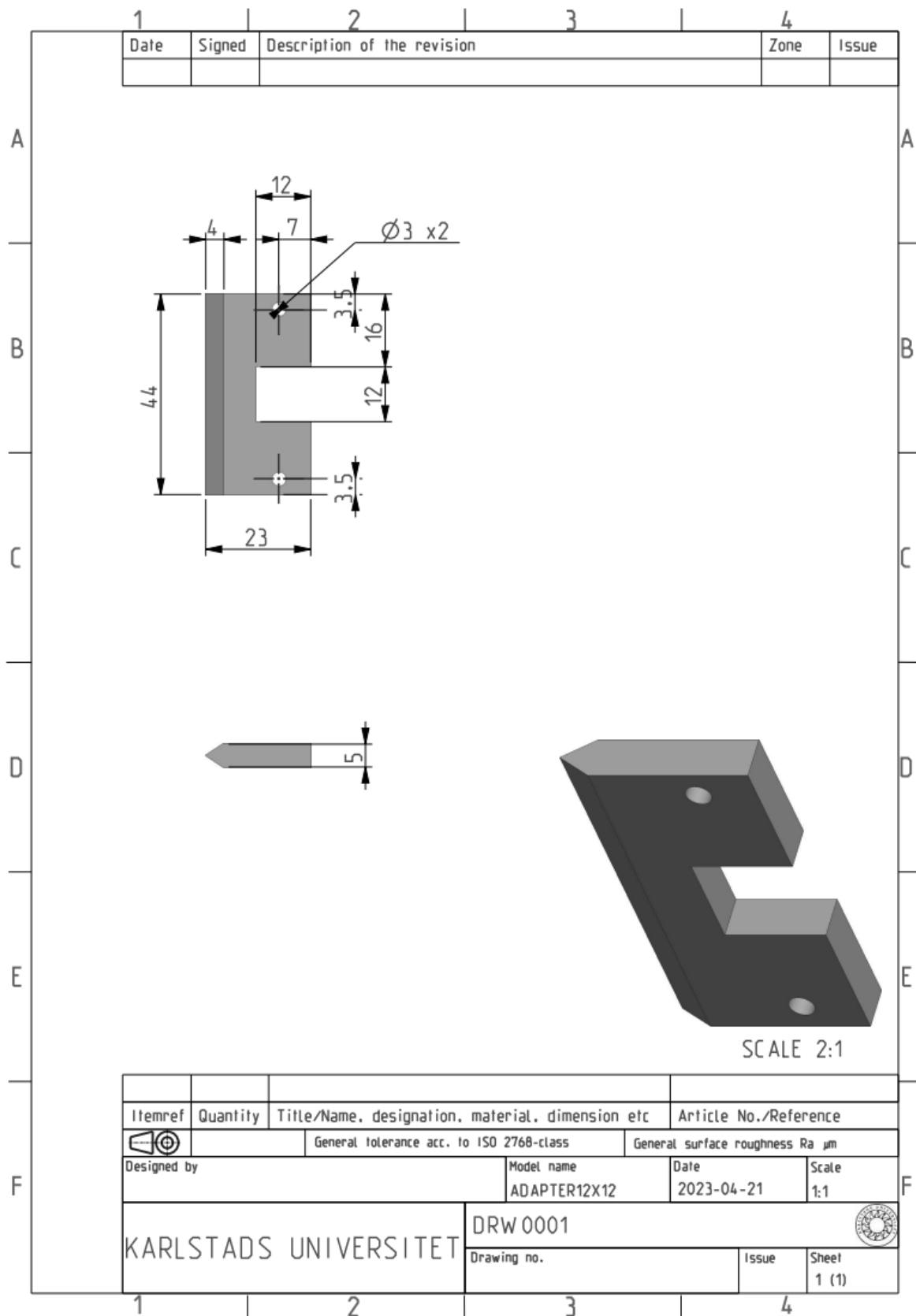
Bolt



30x10 Sample adapter



19x19 Sample adapter



12x12 Sample adapter





*Amazing author and the Sample holder in front of the hot wear tester at Kau*