



## **EFFECT OF SAWING PARAMETERS ON SAWBLADE LIFESPAN**

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Mechanical Engineering, Master's thesis

2023

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## ABSTRACT

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Mechanical Engineering

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Master's thesis

2023

72 pages, 25 figures and 5 tables

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Keywords: Steel sawing, Finite Element Analysis, Sawing parameters, Wear, Archard equation

In this thesis work, sawing of steel bar with a band saw is studied. Cutting process has two main parameters, cutting speed and feed rate, which affect the process. Depending on the parameter selection, the saw blades life cycle can be longer or shorter. This thesis focuses on the effects of different parameter selection on lifespan of saw blades.

Research is done by studying available literature, finding out current state of the process, simulating different parameter scenarios through finite element analysis and analysing the results. Current state of the operation was studied by interviewing the operators, monitoring operator behaviour and comparing results to literature review. Finite element analysis was carried out with Ansys software using explicit dynamic and static structural modules with Archard wear extension.

Results of this research show that in most cases, operators choose suitable parameters for optimal operation. In some cases, chosen parameters result in increased or decreased feed per tooth values. Finite element analysis stress results used with Archard equation calculations showed that these deviations can cause up to 21% increase in wear volume accumulation with either lower or higher feed per tooth values.

## TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Konetekniikka

Petri Sucksdorff

### **Sahausparametrien vaikutus sahaterän elinkaareen**

Konetekniikan Diplomityö

2023

72 sivua, 25 kuvaa ja 5 taulukkoa

Tarkastajat: Apulaisprofessori Ph.D. Hemantha Yeddu, Nuorempi tutkija M.Phil. Jiayi Chen

Avainsanat: Teräksen sahaus, Finite Element analyysi, Sahaus parametrit, Kuluminen, Archard-yhtälö.

Tässä opinnäytetyössä tutkitaan pyöröteräs kangen sahaamista vannesahalla. Sahauksessa on kaksi keskeistä parametria, leikkuunopeus ja syöttönopeus, jotka vaikuttavat prosessiin. Riippuen parametrien valinnasta, sahan terän elinikä voi olla pidempi tai lyhyempi. Tämä opinnäytetyö keskittyy parametrien valinnan vaikutukseen sahan terän elinikään.

Tutkimus on toteutettu tutkimalla saatavilla olevaa kirjallisuutta, selvittämällä nykyisen toiminnan tila, simuloimalla erilaisten parametrien käyttöä finite element analyysillä ja analysoimalla tuloksia. Nykyisen toiminnan tila tutkittiin haastattelemalla operaattoreita, valvomalla operaattoreiden toimintaa ja vertaamalla tuloksia kirjallisuuskatsaukseen. Finite element analyysi toteutettiin Ansys-ohjelmalla käyttämällä explicit dynamics ja static structural moduuleja Archard kuluma lisäosalla.

Tämän tutkimuksen tulokset osoittivat, että operaattorit valitsevat useimmissa tapauksissa sopivia parametreja optimaalista käyttöä varten. Joissakin tapauksissa valitut arvot johtivat kasvaneisiin tai alentuneisiin hammaskohtaisiin syöttöihin. Finite element analyysin kuormitus tulokset käytettynä Archard yhtälön laskennassa osoitti, että poikkeamat voivat johtaa 21% kuluma tilavuuden kertymiseen sekä pienemmillä, että suuremmilla hammaskohtaisilla syötöillä.

## ACKNOWLEDGEMENTS

I would like to thank my supervisor from the company Mika Eskelinen for giving me an opportunity to carry out this research as my thesis and providing support throughout the process. Special thanks also to my examiners Hemantha Yeddu and Jiayi Chen giving me guidance and encouragement to go forward.

Also, I would like to thank my wife Mia for supporting me throughout my studies and motivating me to go forward when the workload tough.

Petri Sucksdorff

Vantaa 3.9.2023

## SYMBOLS AND ABBREVIATIONS

### Roman characters

$A$	yield stress	[GPa]
$B$	strain hardening constant	[GPa]
$C$	strain rate strengthening constant	
$H$	hardness	
$K$	wear coefficient	
$L$	length of slide	[mm]
$m$	thermal softening coefficient	
$n$	strain hardening constant	
$Q$	load	
$T$	temperature	[K]
$V$	volume	[mm <sup>3</sup> ]

### Greek characters

$\alpha$	rake angle	[°]
$\varepsilon$	effective plastic strain	
$\dot{\varepsilon}$	effective strain rate	
$\theta$	relief angle	[°]
$\sigma$	flow stress	
$\varphi$	shear angle	[°]

## Abbreviations

CAD	Computer Aided Design
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
FEM	Finite Element Method
RCF	Resultant Cutting force

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# 1 Introduction

Metal sawing can be done with a large band saw that similarly to machining, removes material in a form the work piece being cut. Result is that the work piece ends up being divided into two parts where one part is the product with desired dimensions and the other part is a scrap or remnant part. In this thesis work, the effects of using different sawing parameters are studied. Effects of interest are wear of the blade with optimal parameters and decrease in saw blade life span when parameters are sub-optimal. These parameters consist of feed rate and running speed of the saw blade as they are the main parameters that operators change. The studied saw is a band saw which is used in sawing large round steel bars that have a diameter of over 200mm. Materials vary between a few alloyed and general steel grades. The saw is in a steel service centre, where production is running constantly.

Studied production is running high volumes of products and the amount of time used sawing is significant compared to time used for setting the production up. Processes for setting up the work pieces and packing processes have been developed previously but the sawing parameters have not been contested as the saw blade manufacturers have provided suggested values that have been in use. Saw blade life span is also a significant point of interest as the large blades have a noticeable part in production costs. Possibility of increasing the blade life would also lower the amount of labour needed for blade change which reduces production time. For continuous improvement, this subject has been considered as a next development step that is expected to have the best increase in added value.

In general wear analysis of sawing has been done before for many different materials and sawing methods. In this work a specific application is analysed and in addition the effect of inconsistent and sub optimal parameter use is studied for the purpose of highlighting the importance of correct parameter usage. Results of this work aim to show a real-life scenario

of operator behaviour and its relationship to theoretically optimal parameter usage and possible complications that could be found in between.

## 1.1 Background

Need for this research is from a steel service centre which has high volumes of sawing operations. Company ordering this work specialises on steel wholesale on structural profiles, plates, sheets, alloyed bars and other categories as well. Materials are bought from several countries where price and quality are desired. Bought materials are stored in Finland in several warehouses and sold to Finnish customers around the country. Large warehouses make it possible to provide customers with short delivery times for relatively large amounts by handling the stock amounts based on estimates of sales. Delivery times from steel mills can be long and minimum amounts for order might be too large for steel work businesses. This is where a service centre can handle high volumes and help customers with these issues. Customers can purchase materials the way they arrive from steel factories, or they can get additional processing for the material. This processing can be shot blasting, painting, laser or plasma cutting and sawing. Cutting by sawing is done to a customer's requested length and can be done straight or at an angle with structural steels and straight cuts with alloyed steel bars.

On the service centres production line saw blade life was noticed to be inconsistent and considered to be a potential next step for production development. Reason for variable life span has been suspected by the operators to be caused from non-uniform material or faulty saw blades. Suggested sawing parameters are provided from the saw blade manufacturer. These parameters are believed by the foremen to be the most efficient with a new saw blade but possibly not for the whole life span of the saw blade. It is suspected that the cutting speed and feed rate are changed to lower values when the saw blade is not performing well. This could cause a situation where the operator does not change the parameters collectively, and the feed per saw tooth could change. Exact habits are not known, and results of possible actions and their magnitude are also unknown.

## 1.2 Scope

The production area contains several saws with different methods of cutting several different materials and profiles. This work is limited to orthogonal cutting with a band saw for over 200mm diameter round bars. For practical studies a single saw from production is used. Some elements that affect the results significantly are taken into account, but in general the focus is on saw blade wear in normal process with different cutting parameters.

For work piece material, most common materials are used. Saw blade is narrowed for only one type of blade. The blade has three options for the number of teeth per blade: fine, medium, and coarse. The saw blade is a 9400mm long band that consists of either 432, 508, or 610 teeth per band. Image of the saw blade is shown in figure 1. The band is made from spring steel and the teeth have a welded tip of an unknown material that could probably be tungsten carbide.



Figure 9. Band saw blade (Wikus 2023).

Lubrication for the sawing process is done with Oemeta's product Novamet 900 A. The lubrication fluid is water-miscible and is diluted to 4-10%. Novamet 900 A is a boron-free lubrication fluid.

### 1.3 Research questions

During the planning of this research, several elements raised questions. The most essential subjects to cover were the following questions.

- What is the current state of operation?
- What is the optimal way to operate?
- How important is it to have specific values for sawing?

Current state of the operation is vital information as it is hard to solve problems that are not clear. Solving this question leaves out speculation on how things are done and verifies the experiences operators are having to be exact or misleading. Next question is what the optimal way is to operate. This forces literature to the research and verifies if the current habits are correct in theory. Answering this question also forces finding the reasons for suboptimal behavior if everything is done correctly with correct values. Third question is how important it is to have specific values for sawing. This answers how much harm can be done by incorrect operation. For the company, it is important to know how much cost and labor can be saved and if this subject is relevant for business. Results of this question is also important information for the operators as it can motivate them to use given parameters if they know they can do a more profitable job.

### 1.4 Structure of research

This research is carried out by conducting a literature review, interviewing the operators, recording sawing parameters, simulating sawing process with finite element analysis, and analysing the results. Literature review is conducted by studying literature available for subjects that affect this research such as sawing, wear, and finite element method. Interview of the operators is carried out by formulating a list of questions of answers that would serve the purpose of this research. Interviews are conducted to operators of the saw being studied

and supervisor of the operators. Recording of sawing parameters is done randomly throughout the research by taking notes from operation panel of the saw. All relevant data is gathered such as cutting speed and feed rate are gathered. In addition, secondary data that can help the research is gathered such as saw blade age. Based on results, three different cutting scenarios are simulated in finite element analysis to produce stress values and monitor chip behaviour. In finite element analysis a wear volume analysis is done based on stress values with an Archard extension of the software. After the studies have been conducted, results are presented by summarizing the operator interviews, analysing key findings on the process, and displaying the finite element analysis results. In the results, suggested next steps to improve the process are introduced. After the results, a discussion part is carried out regarding the findings of this research.

### 1.5 Expectations and goal

Theory of sawing and subtractive manufacturing is relatively common knowledge in engineering. After this research, it is expected that the orthogonal cutting process is studied in-depth and all the properties for it are understood specifically regarding the subject application. This includes subjects such as chip formations, understanding wear mechanisms and effects of lubrication. Previous studies are expected to enrich the theory and potentially add new knowledge that has been acquired in different research.

It is expected that during study of present actions, some information gathered from operators could be misleading. This can be caused by humane reasons such as when problems occur, the reason could be the current material or some external factors. When in fact the reason could be increased wear during a longer period and failure occurs later. Measurement of parameters and additional information combined with interviewing several operators is expected to narrow down misleading information.

Finite element analysis is expected to demonstrate the theoretical life span of the saw blade. It is also expected that optimal parameters for sawing change throughout the life of the blade and new knowledge is added in this regard. In addition, severe increase in wear could be found on different stages on saw blade life with certain parameters.

Goal for the results is to have reliable data to show what the current way of working is and how saw blade life could be extended. It is expected that difference between how parameters should be chosen and how they are chosen occurs. Concrete material as a result can be a set of guidelines for foremen and operators to implement in their working process. A clearer instruction on choosing correct parameters and options for different scenarios to take guess work out of the process to achieve standardized habits between operators and ensure best parameters for saw blade life would be an ideal solution from the company point of view. When the results are obtained, it is also planned to reflect the solutions on other sawing operations. Even though the results cannot be directly implemented with other materials and other saw blades, the importance of correct parameters could be unknown elsewhere and improvement could be achieved by looking into these machines.

## 1.6 Hypothesis

Hypothesis before the research is that parameters used for sawing are lower and slower than the saw blade manufacturer suggests. This could be because the saw blade manufacturer probably wants to give the fastest and most efficient values for sales purposes to make the saw blade seem more valuable. It could be possible that these parameters are good on a fresh new blade. However, the blade should degrade along the production and ability to achieve these values can weaken. If the parameters suggested for a new saw blade is used for example halfway of the life cycle, degradation of the blade could be higher than with a better suiting parameters. This could lead to chronic decrease of parameters as operators experience lower quality at some stage of the saw blade life cycle. Then the operator chooses lower feed values and slower speeds to achieve acceptable quality and stick to them to avoid issues. These issues could be coarse surface quality, vibrations, noise, or unwanted angle on the cut. It is also suspected that the operators do not consider the relation between feed rate and cutting speed when changing one or the other value. The parameters chosen for feed are millimetres per second and saw blade speed is meters per minute. If only one is changed, the feed per saw blade tooth is changed. It is expected that the finite element analysis will show the magnitude on change of behaviour when cutting speed and feed rate are changed disproportionately in relation to each other. Also, the lower sawing parameters might not increase saw blade life as operators intended if the chip formation is not the way the manufacturer has designed it to be.

## 2 Literature review

Sawing process and finite element method was studied for this research. In this chapter, the key findings from literature are presented. Sawing is defined in general and specifics regarding this research are shown such as chip forming and wear. Next part of this chapter handles finite element method and models used to improve the analysis. Last part consists of previous studies found that have similarities to this research and that can help validate the results obtained in this research.

### 2.1 Sawing

Machining is a general term for subtractive forming of parts. There are several different ways to remove material from a work piece such as milling and turning. Sawing is technically machining where a tool or commonly known, saw tooth is driven to a surface of a work piece. In sawing this is generally done by fixing the work piece to be stationary and moving a set of saw teeth. The teeth are generally in a continuous loop such as a band or a circular disc so that they can be driven through the material continuously in the same direction. During this operation, a chip of metal is sliced from the surface of the work piece and carried away. One tooth removes one chip and second removes another. Example is shown in figure 2

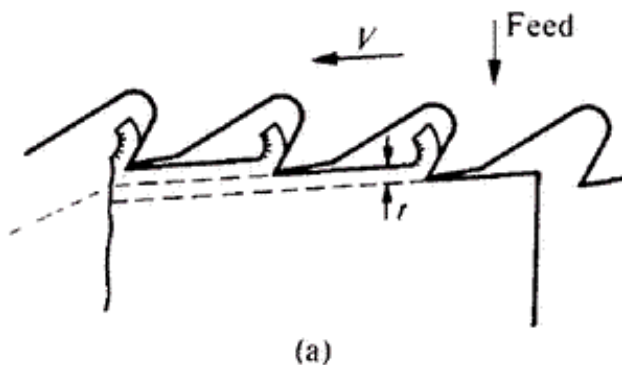


Figure 10. Sawing (Shaw 2005, p. 13).

A chip curls inside a cavity between the teeth as it has no other place to go. In sawing, the thickness of the chips is generally between 0,025 to 2,5mm. It is therefore necessary that there is enough space for the chip in height and width. This operation results in a kerf that has the width that is close to the width of the saw blade. In figure 3 a singular saw tooth is shown in detail as a “tool”. Sawing can be simplified as orthogonal cutting. (Shaw 2005, p. 13-14; Gapiński & Ciszak & Ivanov 2022, p. 124-137; Boljanovic 2010, p. 359-363)

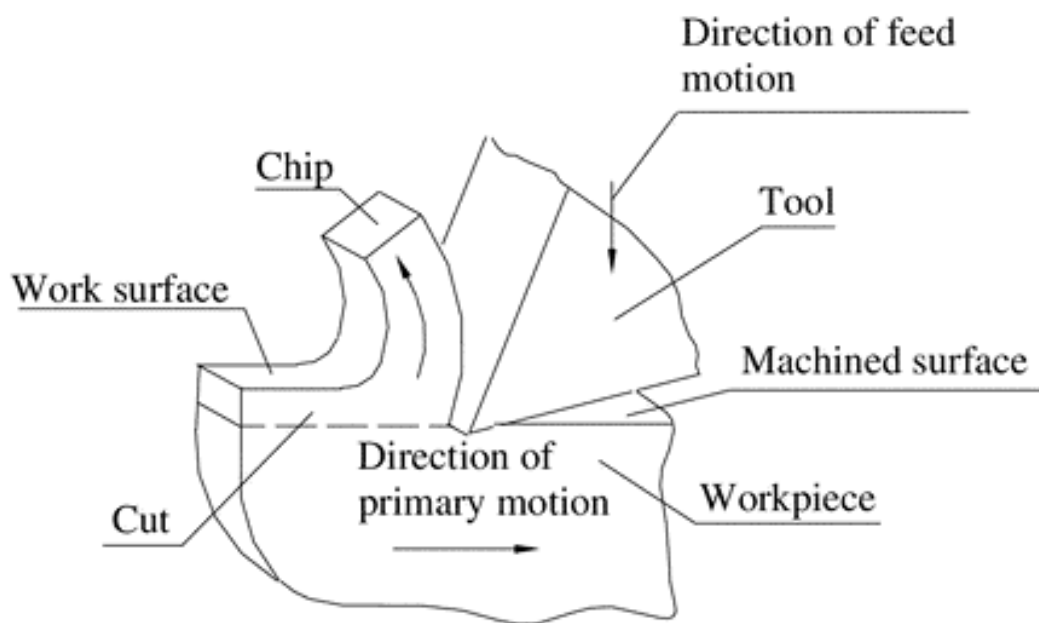


Figure 11. Metal cutting process (Boljanovic 2010, p. 276).

### 2.1.1 Chip forming and forces

Tool geometry affects the way the cut chip forms. In figure 4 a side view of a tool cutting a chip is shown. Surface between points A and C is called a rake face which is the surface of the tool that is facing the uncut material during the cut. Rake angle is the angle between the direction of travel and the rake face. This angle can be positive, negative or zero. In figure 4 rake angle is demonstrated as  $\alpha$  and it is positive. Surface between points A and B is a shear

surface. Above this surface, is the chip that is deformed from the work piece. Below this surface is the undeformed material on the work piece. Angle between the shear surface and direction of travel is called a shear angle and it is demonstrated with a symbol  $\phi$ . Angle between the bottom of the tool and direction of travel is called a relief angle and it is shown as symbol  $\theta$ . These values combined with the depth of cut, velocity, and both tool and work piece material properties form the general dynamics of the chip. Chips can be wavy, discontinuous or saw tooth like. As seen on the side view, the chip forms as a thicker part compared to the depth of cut. Because of this, the chip is also shorter as the amount of material does not increase. The rake face is subjected to a large amount of wear. This can be reduced by increasing cutting speed, adding lubrication, or ensuring a smooth surface on the rake face. When the friction between the formed chip and rake face is lowered, the chip flows away from the tool more easily resulting in a higher shear angle and therefore thinner chip. (Shaw 2005, p. 479-497)

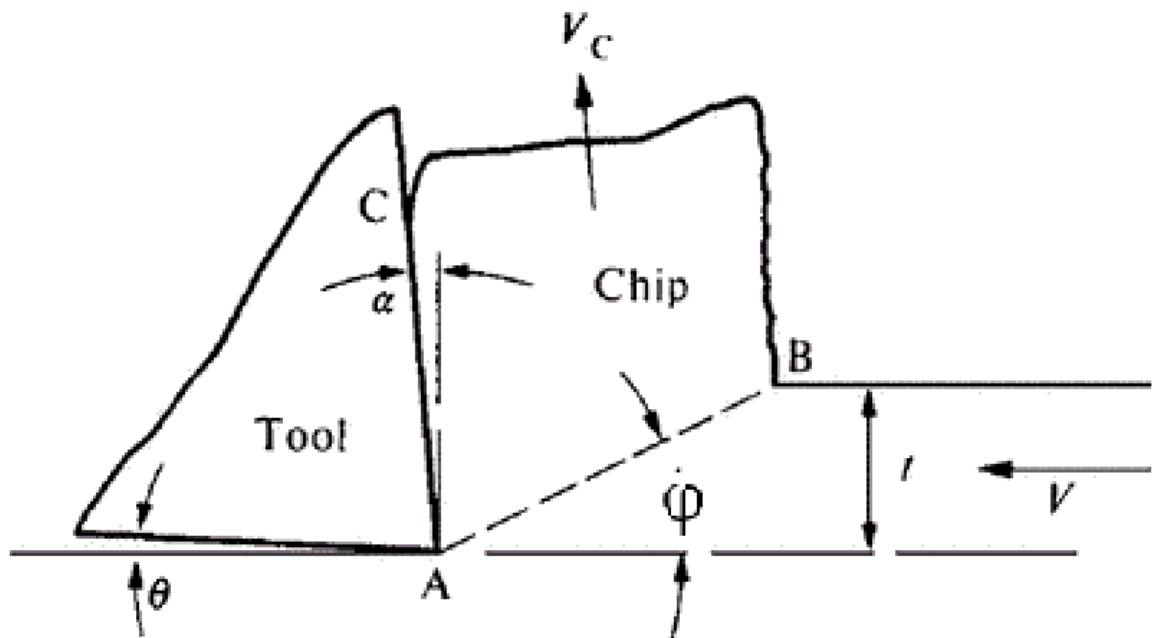


Figure 12. Side view of a cutting process (Shaw 2005, p. 13).

In figure 5, the effect of cut depth, feed rate and cutting speed on resultant cutting force (RCF) is shown in a graph. Depth of cut increases the RCF linearly as the surface of the chip gets bigger. Specific cutting pressure is reduced when feed rate increases. This results in nonlinear RCF increase with higher feed rates. During steel cutting in slower speeds, a built-up edge (BUE) can occur. In this case, material builds up on the cutting tool rake face. Accumulation on BUE is reduced in steel cutting when cutting speed is increased. This is illustrated on the cutting speed graph. (Grzesik 2008, p. 85-114)

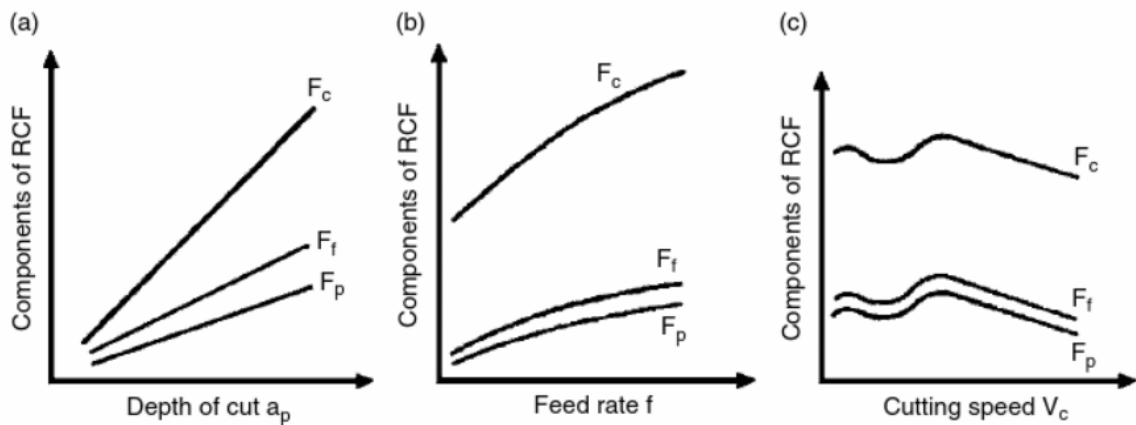


Figure 13. Effect of parameters in resultant cutting force (Grzesik 2008, p. 74).

### 2.1.2 Blade materials

There was no actual information on what the tip of the saw blade tooth is made of. Some unconfirmed information suggested that the tip would be similar to tungsten carbide tools used in other machining operations, but the exact contents and mixtures are kept secret by the manufacturer of the blade. For finite element analysis, it was considered that the blade is similar to that of a mixed carbide tip.

The most common carbide tool in turning is a mixture of tungsten carbide, titanium carbide, tantalum or niobium carbide and cobalt. This mixture is referred to as WC-TiC-(Ta/Nb) C-Co. Generally, the tool consists of approximately 5-10% of cobalt, 4-25% of titanium carbide, and up to 25% of tantalum and or niobium carbides combined. Titanium carbides benefit is

to reduce the amount of tungsten carbide being diffused to the work piece material. Tantalum and niobium carbides increase strength and reduce the amount of cratering on the tools surface. Amount of cobalt has a significant influence on the hardness of the tool surface. In figure 6 the effect of cobalt mixture on Vickers hardness can be seen. Amount of different materials in the mixture varies for different applications. Compressive strength of these tools vary between 3450 MPa and 6900 MPa. Temperature on the tool reduces the hardness and compressive strength. (Isakov 2009, p. 104-111)

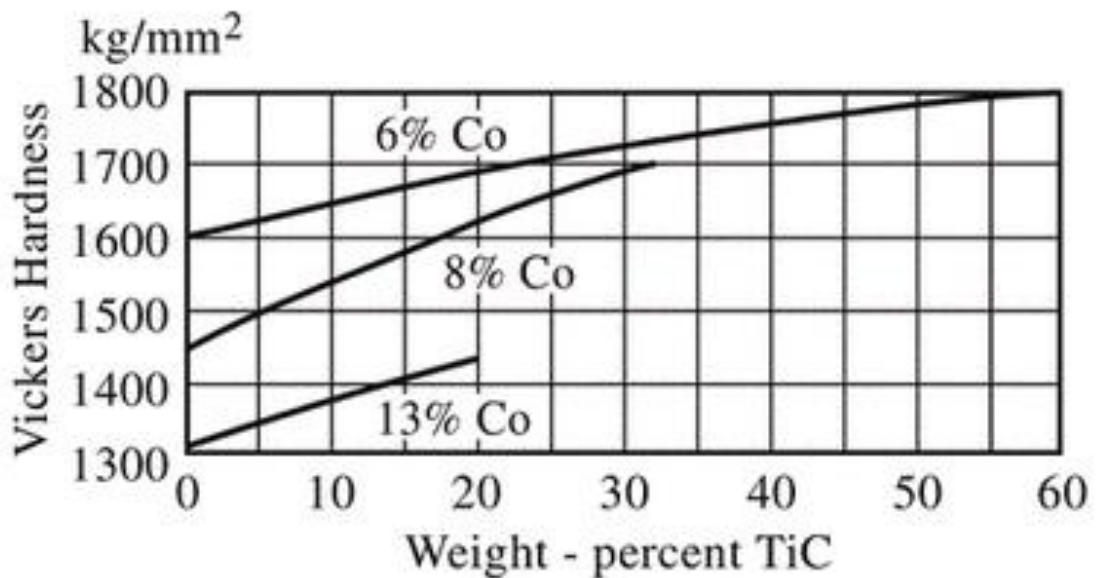


Figure 14. Cobalt mixture effect on hardness (Isakov 2009, p. 108).

### 2.1.3 Work piece materials

Materials used on the saw were known and narrowed down to most used ones. Three materials in various dimensions were S355J2, 18 CrNiMo 7-6 and 34 CrNiMo 6. Both CrNiMo alloyed steels are quenched and tempered. Some other materials are in use, but they were ruled out of this research.

S355J2 is a common steel used in several applications such as machine frames or support structures. The letter S stands for structural steel. Number 355 refers to materials minimum

yield strength which is 355 MPa. According to specification this material has 0,2% carbon, 1,6% manganese, 0,55% silicon, and 0,55% of copper. (The World Material 2023.)

18 CrNiMo 7-6 is a case hardening steel that is similar to AISI4820 grade of steel. Requirements of cleanliness vary but generally 18 CrNiMo 7-6 has a high level of oxidic cleanliness. This material is used in big parts that require high pressures and speeds such as shafts, gears and bearings. 18 CrNiMo 7-6 has 1,5-1,8% of chromium, 1,4-1,7% of nickel and 0,25-0,35% of molybdenum. (Ovako 2023.)

34 CrNiMo 6 is a similar steel than AISI 8620 that is generally used for machine components such as large axels or high strength fasteners. It has a high toughness, hardenability and strength. Amount of chromium is 1,3-1,7%. Nickel content is 1,3-1,7% and molybdenum amount is 0,15-0,3%. 34 CrNiMo 6 is not the best material for welding as it has temper brittleness. When welding, it needs to be heated to avoid stress. For machining this material is better when it is annealed or normalized as well as tempered. All traditional methods for machining work well. (ASTM Steel 2023.)

#### 2.1.4 Lubrication

Tribology is considered to be a combination of lubrication, wear, and friction. Wear happens mostly when surfaces slide between each other. This is caused by the friction that happens when force is present during the sliding motion. To reduce this friction, a lubrication film is introduced between these surfaces. As materials and efficiency has evolved, it is crucial to have optimal lubrication to reach the full potential of the tool material. Absence or breaking the lubrication film can cause significant wear and therefore material loss or failure of the tool (Pramanik 2021, p. 15-16).

Depending on the machining process, the lubrication can have different benefits. In slower cutting processes the lubrication's main purpose is to reduce friction as temperatures do not rise extremely high. In faster processes, the temperature of the tool or work piece can get higher or even be a limiting factor for efficiency. In this case the lubrication serves as a coolant to reduce the temperature in the process. In faster processes the lubrication fluid might not be able to reach the cutting surface and therefore the only purpose can be cooling. Too much lubrication can be unwanted as temperature gradient can cause the chip to curve.

This results in a situation where lower amount of contact between the rake face and chip are in contact and the energy gets concentrated closer to the tip. This increases friction and therefore wear of the tip. (Shaw 2005, p. 265-304)

## 2.2 Wear

Mechanical force and temperature subjected to the saw blade cause wear to the saw blades teeth. Tooth geometry, saw blade pressure, feed rate, and saw blade speed have an effect on these forces. In slower speeds, mechanical wear is more significant. In faster speeds, temperature is more significant due to oxidation and diffusion. Usually, abrasive friction is subjected between the rake face and chip and thermal issues subjected to the flank face of the tooth. (Gapiński et al., 2022, p. 124-137)

According to Budinski (2013) wear is” Progressive loss or damage of a solid surface caused by forcible sliding contact with another solid.” Material loss happens in different ways for different reasons, and they might need different ways to solve possible issues. In figure 7 different types of wear modes are specified. Wear modes can be divided into abrasion, nonabrasive wear, rolling contact fatigue, and impact. (Budinski 2014, p. 1-4)

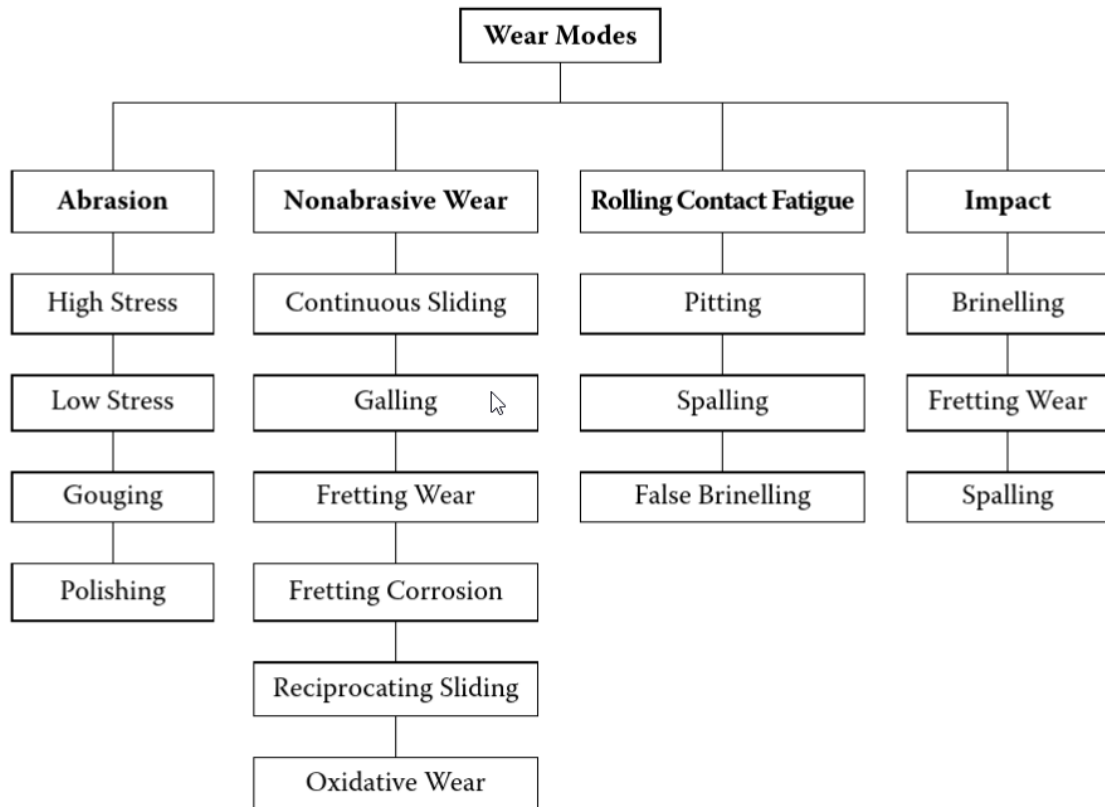


Figure 15. Different types of wear modes (Budinski 2014, p. 6).

In abrasion, material is lost progressively. Abrasion wear mode can be divided into high stress, low stress, gouging and polishing. In high stress abrasion, during two surfaces sliding, fractures occur with hard metals. In low stress abrasion the compressive strength is lower than the materials capability to handle compression strength. Gouging is a wear model where impacts and sliding are combined for example in crushing stones. This causes plastic deformations such as cratering. In polishing, compliant small hard parts on a flat surface cause wear. (Budinski 2014, p. 37-60)

Non-abrasive wear is generally same thing as adhesive wear. It can be divided into continuous sliding, galling, fretting wear and corrosion, reciprocating sliding, and oxidative wear. In adhesive wear, surfaces obtain solid state bonding during contact with one and other. Galling is a mode where material gets picked up from surface and gets attached to another surface after bonding. Fretting is a situation where small amplitude movement between surfaces happen. The amount of amplitude is between 10 to 300 micrometers. Fretting corrosion is a case where the movement of surfaces leads to oxidation or chemical

reaction. Oxidative wear appears similar to corrosion but is material loss due to oxygen reaction turning material to debris. (Budinski 2014, p. 17-36)

In rolling contact fatigue, two surfaces are pressed against each other in a rolling motion. This motion is typical in bearings. Rolling contact fatigue can be divided into pitting spalling and false brinelling. In pitting, the pressure subjected to the material is greater than the materials ability to withstand pressure. Spalling is a phenomenon where particles detach from the material due to cracks beneath the material surface. (Budinski 2014, p. 61-72)

Impact wear is caused by impacts that are perpendicular to the wearing surface. Impact wear consists of brinelling, fretting wear and spalling. In brinelling, round surfaces are subjected to forces that cause plastic deformation. False brinelling appears similar but the reason for the wear is fretting and not force as in normal brinelling. (Budinski 2014, p. 73-82)

## 2.3 Finite element method

In finite element method also known as FEM, a part is divided into nodes in a form of a mesh. An example can be seen in figure 8. This is because a complex shape can be hard to analyze and dividing the part into smaller pieces, the calculation for the part gets simpler. Finite element method is used to solve for example stress, forces, vibrations or thermal effects subjected to a part through algebraic equations. For example, stress can be calculated from displacement between nodes. The number of these equations is usually high when acceptable results are calculated, and this is why powerful computers are needed to solve numerous of calculations. This also poses limitations on the complexity and timeframe of the model as high number of nodes and long analyze period increase the amount of equations significantly. Normally higher number of nodes result in a better quality analysis. For the equations, a set of boundary conditions are needed. These conditions are limits for the node movement. For example, if a work piece is clamped to a table, this can be assigned in finite element analysis, also known as FEA, by restricting the movement of the nodes on the location of the clamping. Other example is to fix nodes of a drill bit to rotate around a given axis. The nodes in finite element analysis can in different shapes such as triangles or rectangles. The shape and size of the nodes needs to be suited for the application. Some settings can work in some cases and some in others. Normally, a part or parts are designed in a computer aided design software also known as CAD and then imported to a software

that can do a finite element analysis. In a finite element analysis software, a set of parameters need to be assigned. These parameters represent a theoretical situation that can be made to simulate reality relatively well. However, the parameters cannot be made to simulate reality exactly, they can still give useable results. (Markopoulos 2013, p. 29-57)

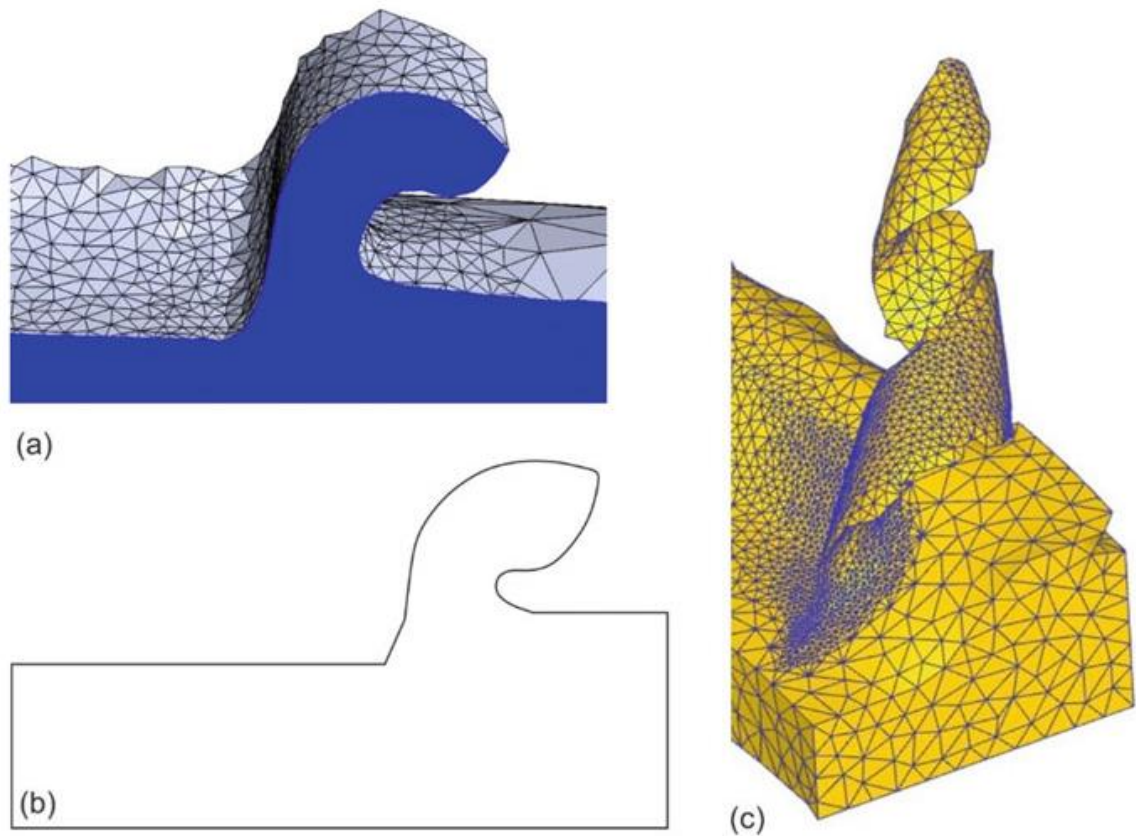


Figure 16. Finite Element Method examples (Kyratsis & Tzotzis & Davim 2023, p 6.).

Finite element method is a modern and valuable method of simulating different scenarios of machining. It reduces the amount of field testing as incorrect operating parameters can be seen in simulation and real parts and tools do not need to be wasted. Finite element method is widely studied method and it is proved that it can be made reliable enough. Simulation can be done in two or three dimensions. Simulating in two dimensions can be practical in certain cases and it is less demanding for computing. Three dimensions are needed in other cases, such as micro grooves where two dimensions are not enough, where the analysis provides more complex results. This leads to an increased need for computational power.

Finite element analysis is typically done with a computer aided engineering, also known as CAE, software which has the possibility to solve modelling with finite element method. Complex shapes, different materials, and complicated boundary conditions require a software designed especially for these kinds of problems for complex calculations. This method can be implemented in machining, drilling, turning and especially in this case, sawing. (Kyratsis & Tzotzis & Davim 2023, p. 1-12)

Good properties for finite element method are that need for experiments decrease. This leads to decreased costs as time and money spent on tests decrease. Also manufacturing defects can be more predictable. Wear of parts can also be estimated through this analysis. This applies especially in this research when wear is of interest. Downside of finite element method is that complex models need lots of computational power and the amount of nodes need to be reasonable. After all the simulation and results are theoretical scenarios with the given parameters and therefore cannot be considered an exact result in real life. (Kyratsis et al., 2023, p. 1-12)

### 2.3.1 Johnson-Cook plasticity model

$$\sigma = [A + B(\varepsilon)^n] * \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] * \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (1)$$

For high strain rates and temperatures, a Johnson-Cook model has been developed by G.R. Johnson and W.H. Cook. This model is applied in dynamic failures for example in a bullet impact or crash displayed by Jankowiak & Rusinek & Wood (2013) and solves flow stress of the material. The equation is presented below. Here the parameter A stands for yield stress of the material. B stands for strain hardening constant. n stands for strain hardening coefficient and C stands for strain rate strengthening coefficient. m stands for thermal softening coefficient.  $\varepsilon$  represents effective plastic strain,  $\dot{\varepsilon}$  represents effective strain rate. T takes into account the temperature effect with initial temperature and melting temperature. (Jankowiak et al., 2013, p.39-49)

Johnson-Cook model is used in several research. Common software's that have the possibility to calculate Johnson-Cook parameters are Abaqus and Ansys. Downside of the model is that it calculates the coefficients separately and not collectively. (An & Ganlin & Hailong & Xitao 2013, p. 677-685)

### 2.3.2 Johnson-Cook damage model

$$Failure = (D_1 + D_2 \exp D_3 \sigma) [1 + D_4 \ln(\dot{\epsilon}')] [1 + D_5 T] \quad (2)$$

In a Johnson-Cook damage model, a damage is considered as material detaches from a work piece. When plastic strain gets high enough for failure in a certain point, for example swarf from sawing, breaks away. This is formulated in an equation presented below where there are five constants. First three constants represent the relation between strain, failure and stress triaxiality. Two of the last constants represent strain rate and temperature. Constant  $\sigma$  represents hydrostatic stress divided by equivalent stress ratio. (Kadkhodapor & Motazerian & Darabi & Anaraki & Ahmadi & Zadpoor & Schmauder 2015, p.180-191)

### 2.3.3 Archard wear

$$V = K \frac{QL}{H} \quad (3)$$

In Archard wear model, it is assumed that loss of material volume is proportional to work being subjected by friction to the material. It is also assumed that the material loss is inversely proportional to the hardness of the softer material. In this model, plastic deformation happens between two points on the surface. Archard wear model is usable for long wear happening in long duration with sliding contacts. This model is used for example from wind turbines to prosthetic joints. Equation for the wear model is shown below. In this equation, V is the volume being lost due to wear, K is a wear coefficient, Q is normal load

to surface,  $L$  is sliding distance, and  $H$  is hardness of the material. (Yu & Xia & Song & Wu & Wang & Yao 2018; Varenberg 2022, p. 4)

## 2.4 Previous studies

Two different studies were found with relevant results regarding this research. Both studies used similar methods for results that are used in this research. Materials on these studies were also similar to this research but manufacturing methods were alternative.

### 2.4.1 Analysis on titanium turning

Sahli & Abid & Barrière & Mamen (2023) investigated turning of Ti-6Al-4V alloy on turning process. Investigation was conducted by measuring the cutting forces with different cutting speeds and lubrication amounts. In addition, finite element analysis was conducted with Johnson-cook parameters implemented. On the finite element analysis, a thermos coupler was used to obtain temperature data on the simulation.

It was found that higher cutting speed resulted in lower amounts of friction and that the amount of lubrication did not have a significant effect on it. Increased speed and lower friction resulted in a lower amount of cutting force. Higher speed was simulated to increase 5-7% of plastic deformation and chip formation resulted to become wavier. Chip segregation was also increased with higher speed and lower speed resulted in continuous chipping. Chip segregation was found to reduce the temperature on the cutting zone. Lowering feed rate on the process reduced temperature on the cutting area. Increased amount of lubrication was found to thicken the chips, but the amount of friction did not have a significant effect on cutting force. For stress distribution analysis, the stress was found to be highest on the shear plane.

### 2.4.2 AISI 316 machining analysis

Maranhão & Paulo Davim (2010) studied AISI 316 stainless steel machining with a cemented carbide tool. Analysis was done with a software called Advantage. Focus on the study was cutting forces, plastic strain and strain rate, and shear stress on different feed rate

settings. Point of interest was the friction between the chip and the tool. Johnson-Cook parameters were implemented in this research.

Studies showed that friction between the chip and the tool were a significant factor on the values of interest. Feed rate was not found to have a significant effect on feed force, but increased feed resulted in an elevated cutting force. Due to the materials relatively poor heat conduction, the temperature increased significantly when feed rate was increased. Most of the heat was found to be conducted to the chip and the tool instead of the work piece. Plastic strain was focused on the outer curve of the chip instead of the inner curve on all feed rates equally. In conclusion the cutting force, process temperature and stress was found to be significant for good quality of the overall process.

### 3 Methods

In this chapter, the methods of this research are described in detail. Research methods for literature review were studying of books, scientific articles, and reports of previous studies. Results of literature review were shown in chapter 2. New discoveries were done by finite element analysis and several ways of discovering present actions.

#### 3.1 Discovering present actions

Present actions refer to chosen parameters and habits by the operators. Better knowledge on what is happening during production is gathered by two methods. First one is the interview of the operators and second is measuring of the parameters used. These methods are expected to give reliable results combined as feelings of the operators are noted and verified separately.

##### 3.1.1 Interview of operators

All operators working on the studied saw are interviewed with the following questions. One supervisor is also interviewed. First three questions are about parameter selection. These questions aim to get a sense on how parameters are chosen and if there is a reason for deviating from instructions. A follow up question is asked about parameter change throughout the life span of the saw blade to make sure if this is one of the reasons for parameter change. Next four questions are aimed to find out reasons for saw blade change and if relevant reasons for concern are found regarding the life cycle of the saw blade. Next two questions are about ambient temperatures and lubrication's effect on the process. Rest of the questions consist of abnormal scenarios, habits with different saw blades and swarf quality.

- How do you choose sawing parameters
- Do you follow the guideline for parameters
- If not, why

- Do you change the parameters throughout the lifespan of the blade
- When do you change the saw blade
- What causes the blade change
- What causes premature blade change
- Does the time of year affect parameters
- Does lubrication have inconsistencies
- How do you change practices with different saw blades
- Do you check swarf quality
- Where do you get most of the problems
- Are surprises or abnormal situations common

### 3.1.2 Measurement of parameters

Cutting parameters were obtained by making spot checks randomly during production. During these checks a set of values such as sawing parameters are written down to produce data over time. Only way of finding the used parameters was to check the parameters from the control board of the machine. This way there is also a possibility to check swarf quality. Physical appearance on the machine also gives the possibility to ask the operator for recent behaviour of the process. In general, the aim is to make most of the spot checks when the operator is not present at the machine to avoid the temptation for the operator to change the parameters during cutting. It can be possible that the operator uses different parameters as answered on the interview, so this way brings up that behaviour. Data gathered from the spot checks are listed below.

- Time
- Material
- Diameter
- Cast number

- Saw blade
- Cutting hours
- Cutting speed
- Feed rate
- Saw blade pressure
- Cut angle deviation
- Swarf

Time of the record is noted first on every spot check. Then the properties of the cut material are recorded. These properties are material alloy and diameter. There are several different alloys used that have different instructions for sawing parameters. This is why alloy material record is important. Diameter affects the sawing parameter instructions also. Cast number is recorded as it provides additional data from the specific batch manufactured from steel mills. This data is for example hardness measurements which can affect the saw blade wear. After material information, the state of the saw blade is obtained. Used saw blade is recorded as it is possible that different teeth distributions are used between different diameters of material. This affects on choosing sawing parameters. Cutting hours of the current saw blade is recorded to gather knowledge in differences on sawing parameters between separate phases of the saw blade life cycle. Next when the basic information is obtained, information of the ongoing process is recorded. Cutting speed and feed rate are the most important parameters for the research as they form the core of the process. In addition, the saw blade pressure and cut angle deviation are also noted. Saw blade pressure is measured from the saw blade and shown in the operation panel. Cut angle deviation is a feature on the saw but it is an estimate and not precise, but it was decided to be followed just in case it provides valuable data. Lastly, a visual inspection of the swarf produced is done. Pictures from swarf are taken and some comments recorded for further analysis.

Results of the parameter data will be collected to a table and analysed. The possible inconsistencies will be noted and reasons for those deviations will be speculated in the discussion chapter. To visualize the magnitude of the deviations, graphs will be made and displayed. Results will also be compared to manufacturers suggestions and the possible deviations between them will be noted. If the results are close to the manufacturer's

instructions, then it can be noted that the deviations of chosen parameters do not disturb the process and that production is running as planned and inconsistencies in blade life are resulted in something else than differing parameter use.

Key part of the hypothesis is that the saw blade speed and feed rate are not changed correctly relative to each other. Magnitude of this situation is shown by calculating the feed per saw tooth on each recorded parameter use. Benchmark for desired feed per tooth is determined by blade manufacturer's instructions. Results will be shown in a graph and percentage of deviations will be displayed clearly. Effects of deviations will be evaluated with finite element analysis.

### 3.1.3 Manufacturer's directions

Saw blade manufacturer provides suggestions on parameters that should be used on a given material and dimension. The information is searched from the internet, primarily on the manufacturer's website. In addition, information is asked from the manufacturer by email and from the manufacturer's local representative. Same information is available on the working station by the saw, but directions is asked also from the blade representatives to ensure, that the displayed parameters in the production line is up to date. This way the possibility of wrong or outdated information is ruled out. The saw blade manufacturer also has a portal service, where different saw blades can be compared to each other on a given scenario. This takes into account the machine the blade is being used on, work piece material and profile. From this data, a specific saw blade can be used, and the scenario can be changed. The optimal sawing parameters are provided and this way a set of parameters for varied materials and work piece dimensions can be obtained. This information will be gathered and compared to the parameters given from the manufacturers' representatives and parameters used by the operators.

The gathered data will be analysed and contested for inconsistencies. The parameters from the manufacturers' representatives are probably not specific for every single dimension, but for dimension ranges. If for example a drop off in certain parameters occurs in larger dimensions, this is noted in the results. Similarly in the parameter measuring phase, the feed per tooth is looked at closely to see inconsistencies.

### 3.2 Finite element analysis (FEA)

Analysis of the cutting process was carried out with Ansys R1 software. In Ansys, Explicit Dynamics and Static Structural modules were used. Explicit dynamics was used to model the cutting process with material data and parameters that were expected to be closest to normal operation. Results for the explicit dynamics analysis were stresses subjected to the saw tooth. Stress was evaluated but in addition, the maximum stress was used in another analysis made with Static Structural module. In Static Structural module, Archard wear add-on was used to calculate material loss on the tip of the saw blade tooth. This was done by applying same amount of pressure to the saw tooth that was found on the Explicit Dynamics analysis and sliding the tooth along the work piece surface. Result is a material loss for the duration of the analysis. This result is then calculated for a longer duration to get wear estimates for longer cutting spans. Three sets of analyses were done with three different feed per tooth rates to find wear rate differences between feed parameters.

Model for the saw blade tooth and work piece were designed in Fusion 360 CAD software. A digital picture from the blade was obtained from the saw blade manufacturers website. Work piece is a block material matching the saw blade tooth thickness.

#### 3.2.1 Model shapes

Saw blade tooth was modelled based on a digital model of the actual saw blade being used. To get shorter analysis times, the parts were made small to focus on the places where stress is applied and reduce the number of nodes that are not affected severely. Shape of the saw blade tooth is shown in figure 9. Length of the saw blade tooth was approximately 0,01mm. Thickness of the tooth was 0,001mm. The tooth had a rake angle of 15 degrees, and relief angle of 18,2 degrees. Work piece was a material block that has a length of 0,04mm and height of 0,018mm. Height was chosen due to desire of modelling three different feed per tooth cuts with 0,0025mm intervals. As the material is fixed from the bottom, there was still material between the cut and the bottom. Length was chosen to have good enough visual ratio with respect to height and to have the possibility to detect chip forming. Number of nodes and calculation time also kept the length as short as reasonable.

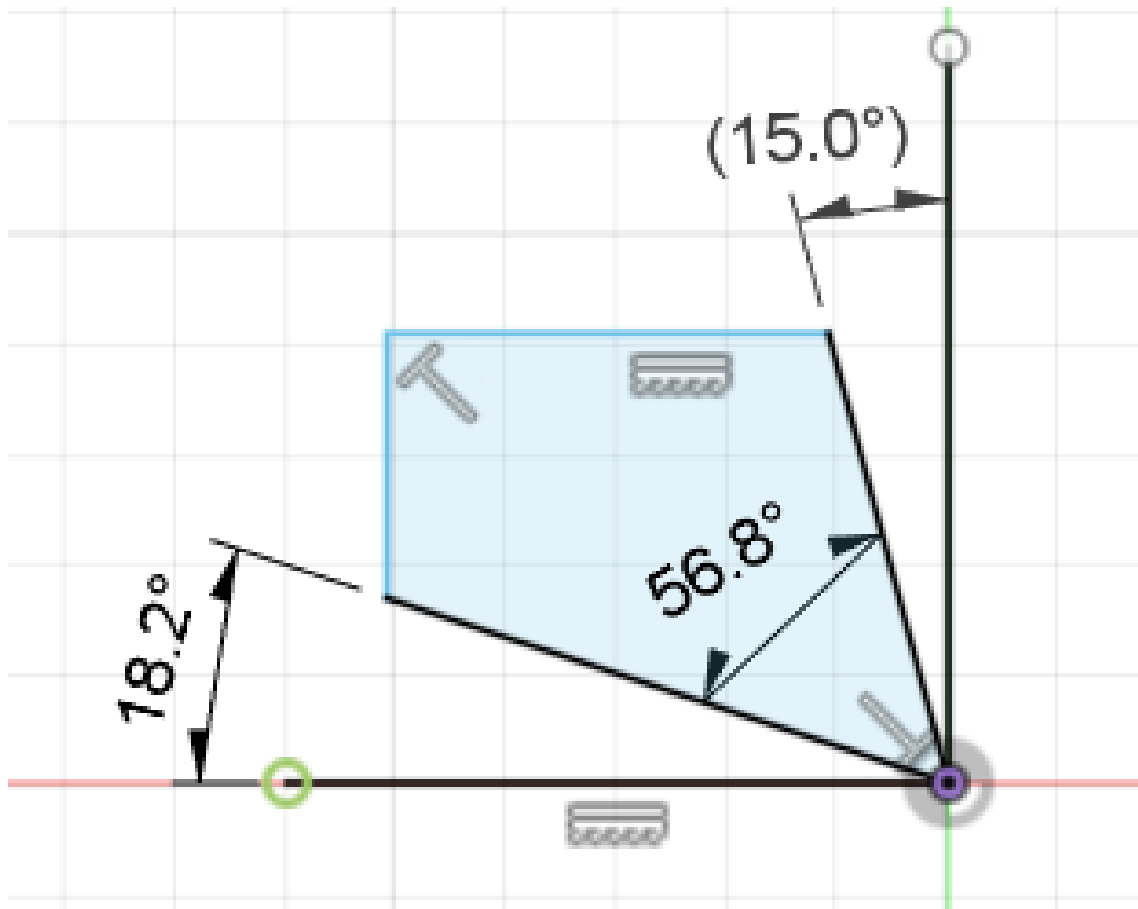


Figure 17. Saw blade tooth geometry

### 3.2.2 Boundary conditions

Cutting process was simulated by setting boundary conditions for the tool and work piece as best as possible. Work piece was fixed from the bottom to anchor the work piece. Work piece movement perpendicular to cutting direction was restricted as the material cannot move in this direction as the work piece extends on both directions and is clamped in the sawing process. Without this boundary, the work piece would buckle, and the simulation would not produce realistic results.

Saw blade tooth movement was also restricted perpendicular to cutting direction for similar reason than the work piece. The tooth would slip from the work piece and break due to buckling. Travel of the tooth was restricted by forcing it to move on a given track. This results in a restriction on other movement than given so the tooth cannot move undesirably.

For the boundaries of tooth travel, only surfaces that were not subjected to force were chosen. This enables wearing parts of the tooth to receive stress while still being forced to travel with the rest of the tooth body. Travel was divided into displacement on height and velocity on length. Displacement boundary enabled easier change of feed rate within the same setup for the analysis.

Wear analysis on static structural module were done with a modified model. Work piece was much thinner as the need for excess material was not needed due to the saw blade tooth being slid on the surface of the work piece. Also, the tooth's rake face was made much smaller, as it did not need to receive stress from the chip. These alterations were made to reduce nodes and therefore calculation time.

### 3.2.3 Settings

The analysis was done with three different feeds. 0,005, 0,0075, and 0,01 mm. These values were chosen based on the most common feed per tooth rates discovered on the actions of the operators. They were also expected to be values that would serve the research best. Cutting speed was chosen to be 100 meters per minute as it was common for the operators to use. In the analysis this was converted to 1666 mm/s. All feed rates were run with the same cutting speed.

In explicit dynamics module, Johnson-Cook parameters were used for plasticity and damage models. Zhao & Yang & Khan & He & Zhang (2019) verified Johnson-Cook plasticity

parameters for cemented carbide machining tool WC 17,5 Co. Parameters are shown in table 1

Table 1. Johnson-Cook plasticity parameters.

Initial yield stress	3,4 GPa
Hardening constant	0,83 GPa
Hardening exponent	0,24 GPa
Strain rate constant	0,011
Thermal softening exponent	1,1

For Johnson-Cook damage model, Moxnes & Teland & Skriudalen & Bergsrud & Sundem-Eriksen & Fykse (2010) found values for similar cutting tool material. Values for Johnson-Cook damage model are shown in table 2. Work piece material parameters were obtained from Ansys library for structural steel with same grade as of S355 steel that is used in the cutting process.

Table 2. Johnson-Cook damage model parameters.

D1	0
D2	1,072
D3	1,669
D4	0
D5	0

For the analysis, a friction coefficient of 0,15 was used. Pottirayil & Kailas & Biswas (2010) studied friction on metal cutting process and as one of the results, a graph in figure 10 was produced. Friction coefficient in fully lubricated scenario is close to 0,1. In slower cutting speeds there is slight increase in friction coefficient compared to faster speeds. In this research the cutting speeds are on the slower end of this scale, so friction coefficient was chosen to be on the higher end of this graph. Also, sawing of large diameter work piece could

be harder to lubricate as the kerf of sawing can be a hard-to-reach place for the lubrication oil.

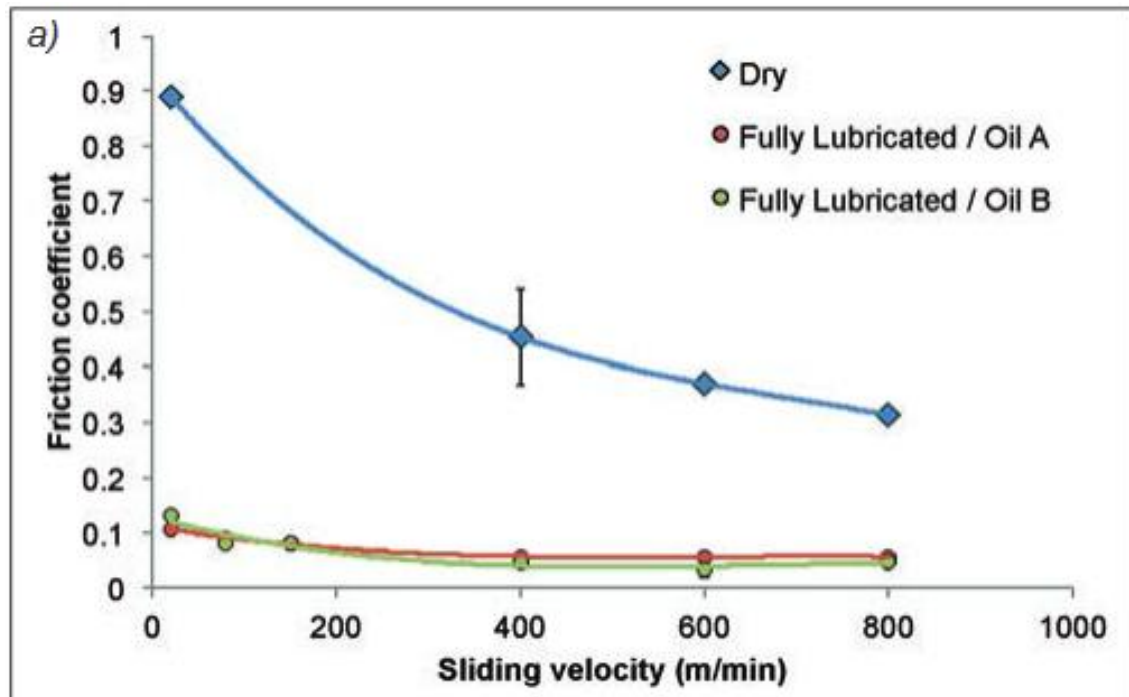


Figure 18. Friction coefficient in steel machining (Grzesik 2008, p. 243).

## 4 Results

In this chapter, the results of this research are explained in detail in the order in which research was conducted. First part is the interview of operators and foremen. Interview was conducted as planned and answers are summed up. Second step was to analyse manufacturer's directions on saw blade use. Values are analysed and key factors for this research are explained. After this, the operator's used parameters are displayed and analysed with respect to the manufacturer's directions. Next, the results of the finite element analysis are shown, and findings explained. Last part of this chapter is about suggested solutions based on the results of this research.

### 4.1 Interview

Three operators and one supervisor were interviewed according to plan. First phase of the questions resulted in slightly conflicting answers. Everyone answered that the sawing parameters are chosen from a list that is provided by the manufacturer. The list is located on the side of the saw. Three different list are provided for three different saw blades with varying teeth per inch values. There seemed to be minor confusion on which list is used for each blade. Later operators stated that the values from the lists are directive, and that usually they alter the values according to their preference. Most troubling phenomena was a loud squeaking noise, that was expected to decrease the life of the saw blade. Solution for this was to decrease the saw blade speed until the noise is reduced enough. Second phenomena were ridges on the cutting surface. This was not suspected by the operators to decrease the saw blade life, but instead to be a cosmetic issue for the customers. The operators noted that they generally do not alter the parameters during production. Overall, the material and blade life cycle were seen as a cause for altering the parameters in addition to trying to preserve the saw blade. Regarding material, everyone interviewed noted that S355 steel has a higher tendency to produce noise and therefore require slower saw blade speeds. Other materials causing issues was pipes, where the swarf accumulates on the inner hole and is not carried out normally away from the cutting process. Last question on the first phase of questions was about saw blades life cycle affecting sawing parameters. One of the operators did not

feel that the deterioration of the saw blade affected the selected parameters. Others including the supervisor disagreed and claimed that lower speeds and feed rates are used at the end of the saw blades life cycle. This could be caused by the fact that the parameters should be compared to manufacturer's instructions and if the comparison is not done, then it might seem that nothing has significantly changed.

Next phase of the interview was to focus on saw blade changing. First question was about the timing of the blade change. Everyone answered similarly to this question. The machine has a sensor that measures the deviation of the saw blade from its desired position. This value is shown on the control board of the saw. If this value is above 0,02mm then the operators start to pay attention to the process. The deviation has not caused rejected parts generally but a concern for the process to fail such as saw blade breakage or rapid wear increase arises. Other indication for saw blade wear is increased blade pressure. The machine has a pressure sensor above the saw blade from which the force applied to the work piece material can be displayed on the machines control board. These values are usually much under 200 newtons but when they increase, it is considered to indicate saw blade wear. Operators also noted that they are aware of the blade life that is displayed on the control panel. When the cutting hours reach higher values, operators start to look for the signs on decreased saw blade performance. Cutting hours on saw blade change vary between 10 to 50 hours. If the blade needs to be changed at 10 hours, then something is wrong. This could be a saw blade manufacturing defect, inconsistent alloys in work piece material, or long sets on problematic materials. If the cutting hour reach 50 hours, then the operators prepare for the blade change to avoid sudden lapses in saw blade performance. Operators noted that increased noise and poor cut quality are symptoms of worn out saw blade.

Last phase of the interview consisted of questions that were considered to lead to reasons of possible issues on the process. Everyone did not consider the time of the year a relevant factor in the cutting process. This was considered irrelevant as the temperature does not change significantly between winter and summer. Also, the operators did not recall any changes in their behaviour between seasons. Next question was about lubrication. Everyone was aware of the mixtures between the fluid and water. One of the operators was more aware of the lubrication mixture status and claimed that he checks the mixture daily with a mixture gauge. Other operators agreed that this happens. Everyone claimed that the mixture has not been an issue on the process even though the mixtures have had higher ratios occasionally.

Mixture values vary between four to eight percent. After lubrication questions, the operators were asked about habits between different saw blades. Different saw blades have been used in the past, but one saw blade had proven to be a best choice on all ranges of diameters that have been cut on this saw. The operators said that habits between the blades do not vary and that they similarly choose the values from a list and alter the values based on noise and surface roughness. Quality of swarf was discussed next. Only one operator said that the form of the chips is monitored. If the swarf had short chips, it was considered that the saw blade speed was too low compared to the feed of the saw blade. Others did not monitor the swarf formation. The supervisor claimed that all operators have had training from the saw blade manufacturer's representative where optimal chip formation has been introduced. Still supervisor did not expect that this education is implemented during production. Lastly on the interview, the operators were asked about situations where most problems arise and if sudden issues come up regularly. No one felt that sudden abnormalities happen and claimed that the process runs smoothly, and deterioration happens relatively as expected. Operators reminded that S355 steel and pipes cause most of the trouble for them. The supervisor suspected that blade change, adjustment of swarf brush and blade guidance rollers assembly have a significant impact on saw blade wear if not done correctly.

#### 4.2 Manufacturer's directions

Parameters for optimal use was mainly obtained by the saw blade manufacturers representative. This information was available before the research, and it was in use before. Additional information from the manufacturers portal from their website was not found valuable as the parameters suggested were significantly lower than what were provided earlier by the manufacturer's representative. Therefore, a conclusion that parameters provided especially for this machine and process were used for this research. Parameters provided were saw blade speed and feed rate on a given material and work piece diameter.

In the past, three different saw blades have been in use. The difference between the saw blades is the number of teeth on the blade. Later the blades are referred with a number where blade number one has lowest number of teeth and blade number three has the greatest number of teeth. Blade number one has 432 teeth on the whole blade. Blade number two has 508 teeth and blade number three has 610 teeth. All saw blades have a length of 9400mm.

When the number of teeth, saw blade length, saw blade speed, and feed rate are known, the feed per tooth can be calculated with the following formula.

$$\frac{\text{Feed rate}}{\text{Blade speed} * \left( \frac{\text{Teeth per blade}}{\text{Blade length}} \right)} \quad (4)$$

Research was narrowed down to two materials 18 CrNiMo 6-7 and S355 steels because the parameter spot checks showed that most of the materials used consisted of these two materials. Some other materials were used but not enough data was collected on used parameters to draw valid conclusions. In figure 11 the feed per tooth values is calculated and shown in a graph for each work piece diameter for material 18 CrNiMo 6-7 steel. On the coarse saw blade number 1 the feed per tooth values is significantly higher with smaller work piece diameters compared to the two other saw blades. Values for saw blade 1 are double compared to the other blades on the lower diameter range and values decrease steadily. The values get closer to each other when the work piece diameter increases. Deviation between saw blades 2 and 3 is much lower compared to saw blade 1 and values decrease more slowly when diameter range increases. Noticeable deviation between feed per tooth values between saw blade 2 and 3 appear in diameter ranges 200-300 and 500-600 where deviation is around 0,001 millimetres. Choosing the parameters from a wrong saw blades table can cause significant deviation on feed per tooth values especially on the smaller diameter work pieces.

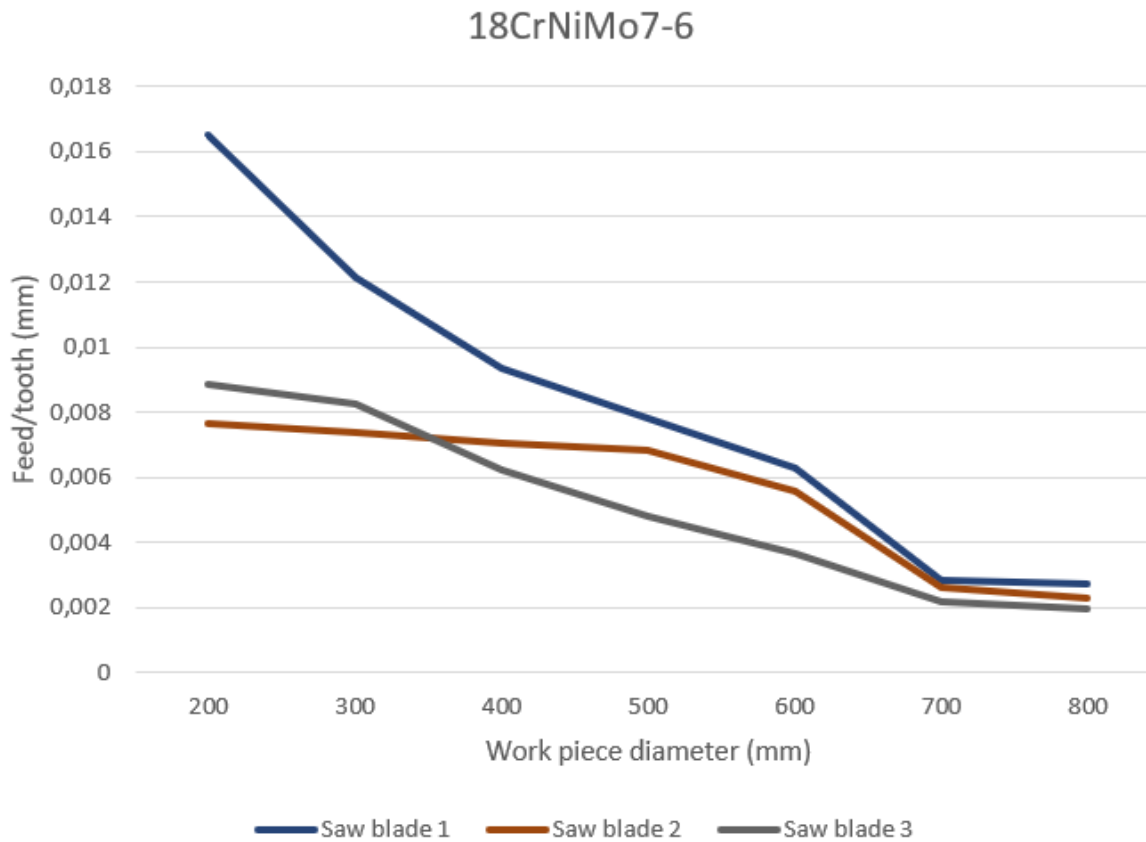


Figure 19. Feed per tooth values of three different saw blades for different work piece diameters for 18CrNiMo7-6

In figure 12, feed per tooth values between three saw blades is shown for S355 steel. For this material, the results are similar to those of 18CrNiMo7-6 but the decrease in feed per tooth seems more consistent with S355 steel. Saw blade number three has a noticeable drop in feed per tooth after diameter of 500. Similar situation happens with 18CrNiMo7-6 after diameter of 600 with all three saw blades. This can be caused by swarf accumulation between the teeth and need for lower volume of swarf forming. Similarly with both materials, the feed per tooth values have noticeable differences with different saw blades.



Figure 20. Feed per tooth values of three different saw blades for different work piece diameters for S355

#### 4.3 Measurement of parameters

Operator chosen parameters were obtained with spot checks randomly. 14 different sets of parameters were obtained during the measuring period. After the measurements, it was established that operators had only been using saw blade with 508 teeth earlier referred to as saw blade 2. Therefore, in this research, only saw blade 2 is used for investigation. Regarding material, only two materials, 18CrNiMo7-6 and S355 steel were measured as they were the only materials that were in production during the spot checks. 11 measurements were done on 18CrNiMo7-6 and 3 measurements were done on S355 steel. In figure 13, the feed per tooth values calculated from measured cutting speed, measured feed rate and saw blade teeth amount for 18CrNiMo7-6 are shown. Most of the measurements were in the diameter range between 250mm and 350mm. Results for feed per tooth in this range were all close to

0,007mm with only slight deviations. Manufacturer's instructions resulted in a little over than 0,007mm feed per tooth value. All measurements in this range were under the manufacturer's instruction but still very close. Singular measurements were obtained from higher diameters. Two measurements from diameter range 400-500mm were obtained which resulted to have feed per tooth values almost exact to manufacturer's instructions. Two measurements were also obtained from around 550mm diameter work pieces where feed per tooth values are significantly lower than instructed by the manufacturer. No significant reason for use of lower values was found.

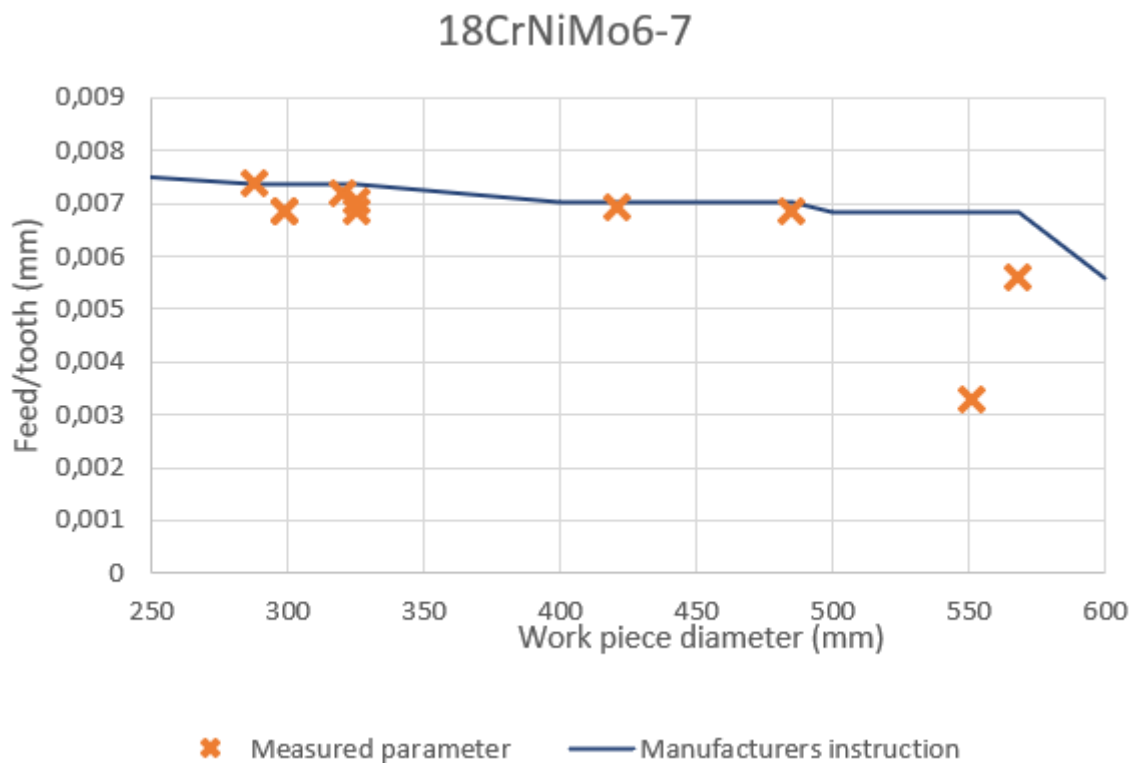


Figure 21. Feed per toot rates for used parameters with 18CrNiMo7-6

In figure 14, the feed per tooth values calculated from measured cutting speed, measured feed rate and saw blade teeth amount for S355 Steel are shown. Only three measurements were obtained in the range of 420mm and 450mm diameter. Two of the measurements resulted in an almost exact feed per tooth value than manufacturer's instructions direct. One of the measurements was resulted in a significantly higher feed per tooth value than

instructed by the manufacturer. Likely cause for this is that only cutting speed has been reduced due to increased noise of the cutting process, but feed rate for the blade has been left to instructed value. This would validate the operators answer on the interview regarding issues with S355 steel issues.

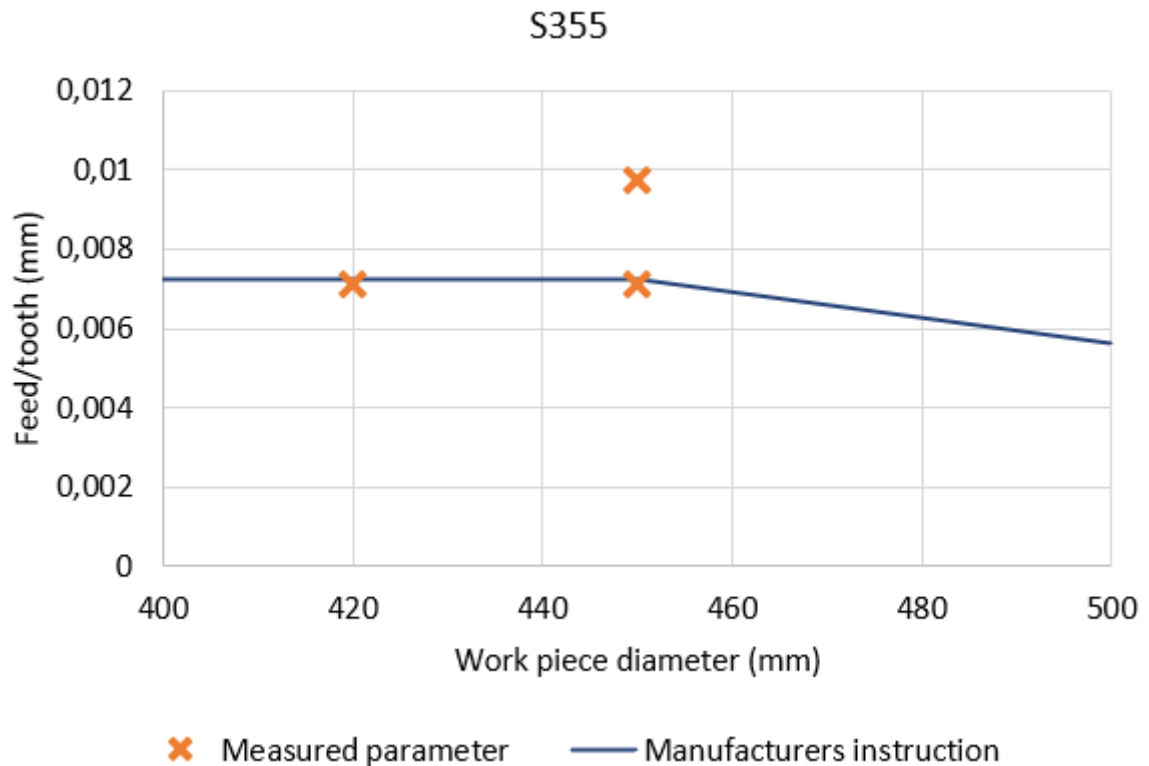


Figure 22. Feed per toot rates for used parameters with S355 steel

Results from the measurements can be seen in table 3. Overall, the measured data indicated that in 18CrNiMo7-6, the cutting speed was on average 8,5 meters per minute and 9% lower compared to the manufacturer's instructions. On S355 steel the cutting speed was 60 meters per minute and 101% lower on average compared to manufacturer's instructions. Feed rate was on 18CrNiMo7-6 6,95 millimeters per minute and 27% lower on average and on S355 steel 21,3 millimeters per minute and 85% lower on average. On average the feed per tooth values were 4% lower than what manufacturer instructs. Most extreme variations with 18CrNiMo7-6 was 52% less feed per tooth and with S355 steel 35% more feed per tooth

compared to manufacturer's instructions. Extreme values are singular and occur in larger diameter work pieces.

Table 3. Measured parameters from sawing.

Material	Diameter	Cutting speed	Feed rate	Feed per tooth	Blade age
18cronimo 7-6	288	113	45	0,007368824	20h 21 min
18cronimo 7-6	299	100	37	0,006846457	17h 49 min
18cronimo 7-6	299	100	37	0,006846457	40h 45 min
18cronimo 7-6	320	100	38,8	0,007179528	11h 38 min
18cronimo 7-6	325	108	41	0,007024643	14h 02 min
18cronimo 7-6	325	100	37	0,006846457	18h 35 min
18cronimo 7-6	421	104	39	0,006938976	15h 50 min
18cronimo 7-6	485	100	37	0,006846457	28h 22 min
18cronimo 7-6	551	88	15,7	0,003301271	10h 27 min
18cronimo 7-6	568	96	29	0,005589731	27h 32 min
S355 Steel	420	60	23	0,007093176	41h 13 min
S355 Steel	450	65	25	0,007116899	3h 17 min
S355 Steel	450	55	29	0,009756621	4h 25 min

During the measurement, variations in saw blade pressure was noticed. The deviations were around 5 newtons in amplitude. It was decided that these values are not considered reliable as the variation on the operating panel screen changed quickly and might not be accurate. Similar variation was noticed in all measurements so deviations in the process was not expected.

Visual observations on the swarf was carried out as planned. During the observations it was noticed that some difference between chips was noticeable. After comparing the notes of the chips with feed per tooth calculations of the measurements, it was observed that longer chips were formed in cases where feed per tooth values were around 0,005mm. When the feed per tooth values were around 0,007mm, the chips tended to be shorter. This could be caused by chips being thicker and therefore not curling as easily and rather breaking compared to lower feed per tooth value.

#### 4.4 Finite Element Analysis

Simulation by finite element methods was carried out with three different parameters. Changing parameters were the height of the tool when contacting the work piece. The height

of the tool represented the feed per tooth value. All three different simulations were analysed for stress and strain. After the stress values for the simulations were obtained, the results were used for wear analysis. Time scope for the analysis was 0,00001 seconds. Mesh for the models were done with 0,0015mm sizing with triangular shapes. Tool was meshed progressively so that the tip had smaller nodes and rest of the body had bigger nodes.

#### 4.4.1 Stress analysis

In figure 15, a side view of result of analysis is shown for 0,005mm feed per tooth value. On the top of the figure is a visualisation of the simulation where the tool has cut the work piece. In this visualisation the von Mises equivalent stress experience by both the tool and the work piece is shown with different colours. Scale of the colouring is shown in the left side of the visualisation. On the bottom of the figure is a graph of the stress throughout the simulation. In this graph, the green line is the value of the maximum stress of the analysis at a given point. The blue line is the average stress of the simulation on the given point. On the bottom right is a table of the same values shown in the graph.

0,005mm feed produced expectedly the thinnest chip. The chip is clearly curling more compared to the higher feeds shown later. Even in this simulation, where the tools rake face does not extend as high as in reality, it seems that the chip does not run far along the rake face. This causes the stress to concentrate more on the tip. Tip stress is shown in detail later. On the work piece, the stress is concentrated on the chip and areas below the cut significantly. Concentration on the chip is likely caused due to lower volume of chip compared to other feed rates. Maximum stress on this simulation is 1674 MPa around after a third of the simulation period. Before the maximum stress, the stress is lower compared to other feed rates which would suggest that some more elastic behaviour happens before the plastic deformation begins. Fluctuations on maximum stress was highest on 0,005mm feed compared to the other feed rates. Average stress was highest around same time as the highest maximum stress but after that, few dips occur and average stress declines to the end of the simulation. Highest value on the average stress on the simulation is 390 MPa.

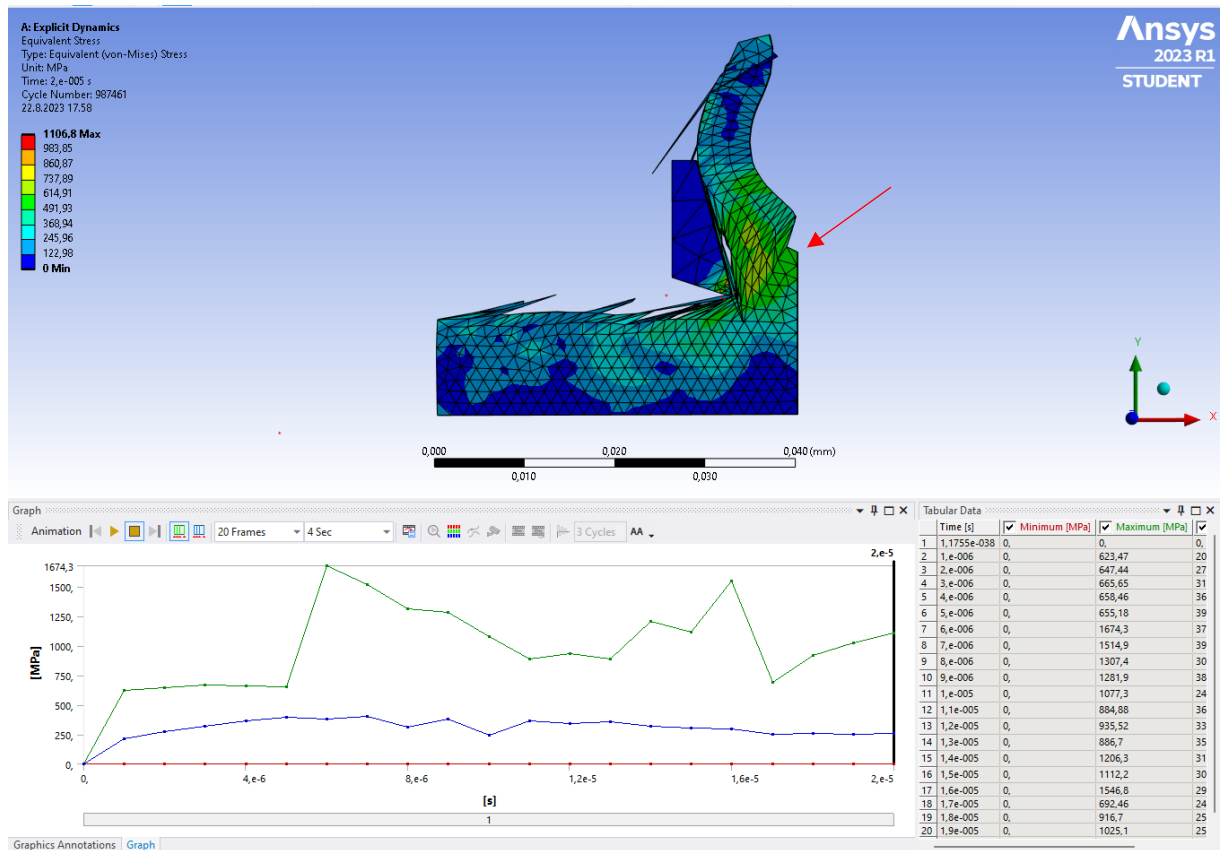


Figure 23. von Mises equivalent stress 0,005mm feed per tooth

In figure 16, a same view of the simulation is shown. In this figure the feed per tooth is 0,0075mm. As expected, the chip is thicker compared to 0,005 mm feed per tooth but chip also seems to be shorter. Curling of the chip is lower than in the 0,005 mm feed rate and seems to be almost straight and running along the rake face. Maximum von Mises stress value is 1532 MPa. The maximum values are distributed most evenly for the duration of the analysis compared to other feed rates. Some variation can be seen on the maximum stress but amplitudes are relatively low. Similarly in average stress of the simulation, the stress seems consistent from start to finish. Compared to 0,005 mm feed per tooth analysis, the stress seems to concentrate more clearly around the shear plane indicated with a red arrow in figure 15 and stress on the chip is getting lower more quickly. Also, on the work piece the stress seems to be less concentrated below the cutting surface.

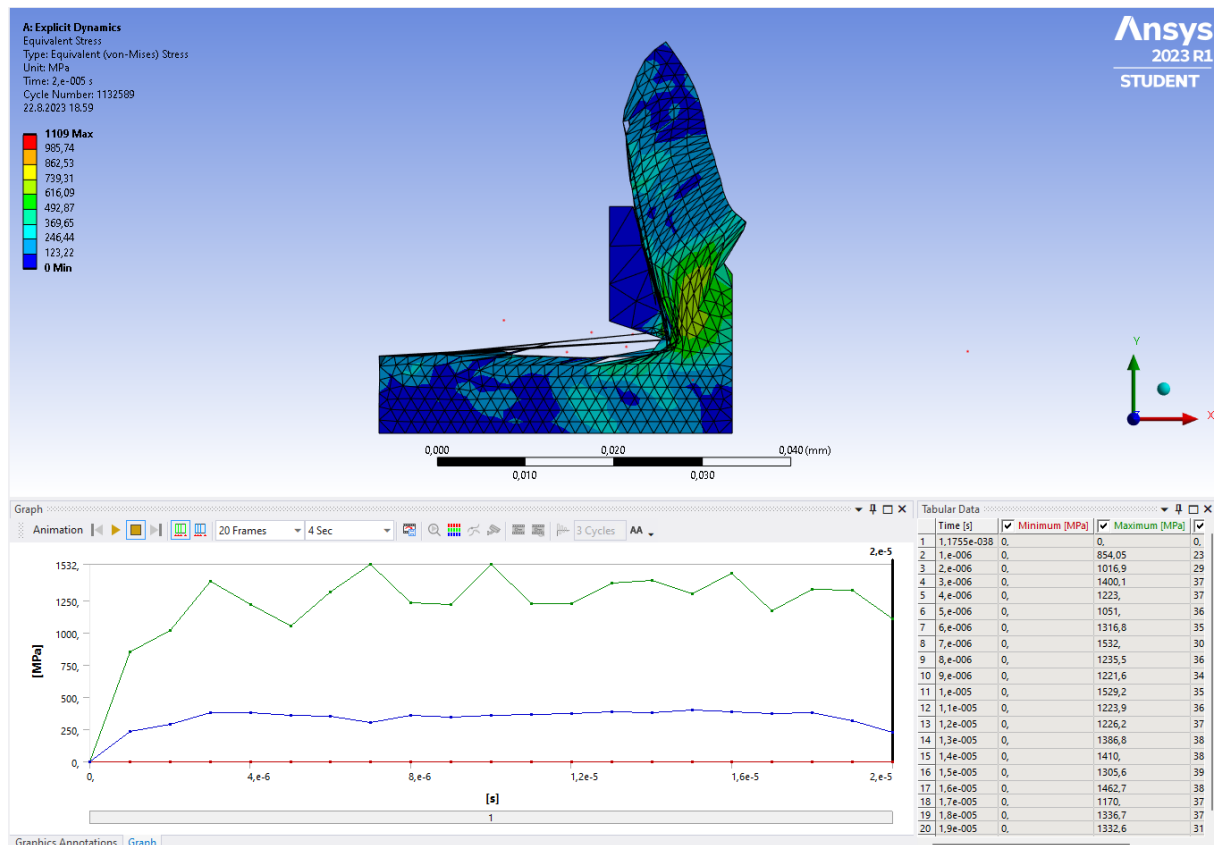


Figure 24. von Mises equivalent stress 0,0075mm feed per tooth

In figure 17, the simulation of 0,01 feed per tooth rate is shown. Detaching chip is clearly thicker compared to lower feed per tooth rates. It also appears that in comparison, the chip shortens with higher feed values. Curling of the chip seems lowest with the highest feed which could indicate that stress along the rake face would continue higher up on the tool compared to lower feed rates. Maximum stress on the simulation for 0,01 feed per tooth was 1701 MPa. The maximum values occurred relatively soon during the analysis and steadily declined along the analysis. Variation on the maximum stress was low but some variation occurred on the end of the analysis. Average stress was relatively constant throughout the simulation but similar drop than on the 0,005mm feed per tooth analysis was found in the middle of the analysis. On this analysis, the stress seemed to distribute most around the work piece. Concentration of stress on shear plane was lowest compared to lower feed per tooth values. Above and below the shear plane the stress seemed to distribute similarly on 0,01 and 0,0075 feed per tooth rates.

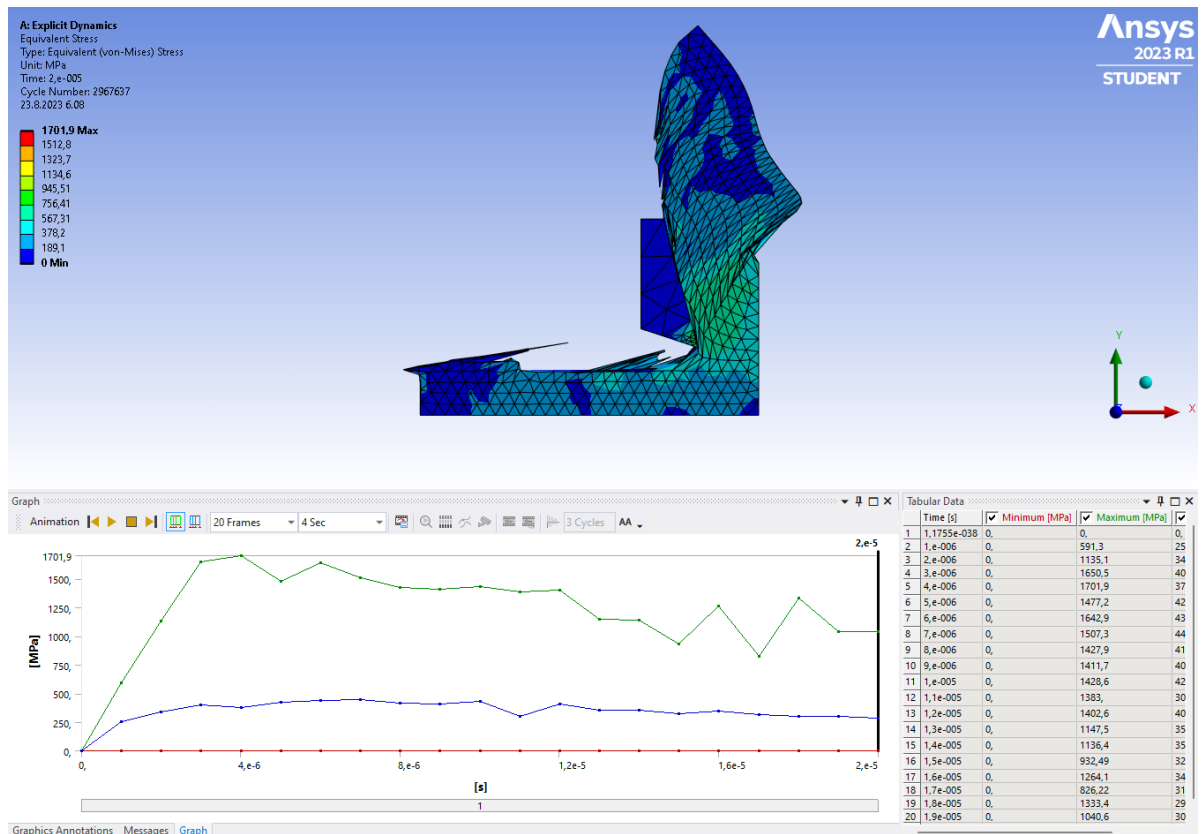


Figure 25. von Mises equivalent stress 0,01mm feed per tooth

Figures 15, 16 and 17 showed the stress of work piece and tool. Figures 18, 19 and 20 show results of the same analysis but only on the tool body. In figure 18, the tool tip of analysis with 0,005mm feed per tooth rate is shown. Maximum stress values are almost the same as in the result that included the work piece as high stress occurs between the tool and the work piece. Average stress values are a bit different but similar to those with the work piece included. Highest value of the average stress is in the beginning where the tool contacts the work piece and after that the stress decreases and is relatively steady for the rest of the simulation. On the visualization there is a higher concentration of stress a little bit above the bottom of the tip which is somewhat distributed through the tip to relief face. There can be seen a significant hotspot for stress with red colour.

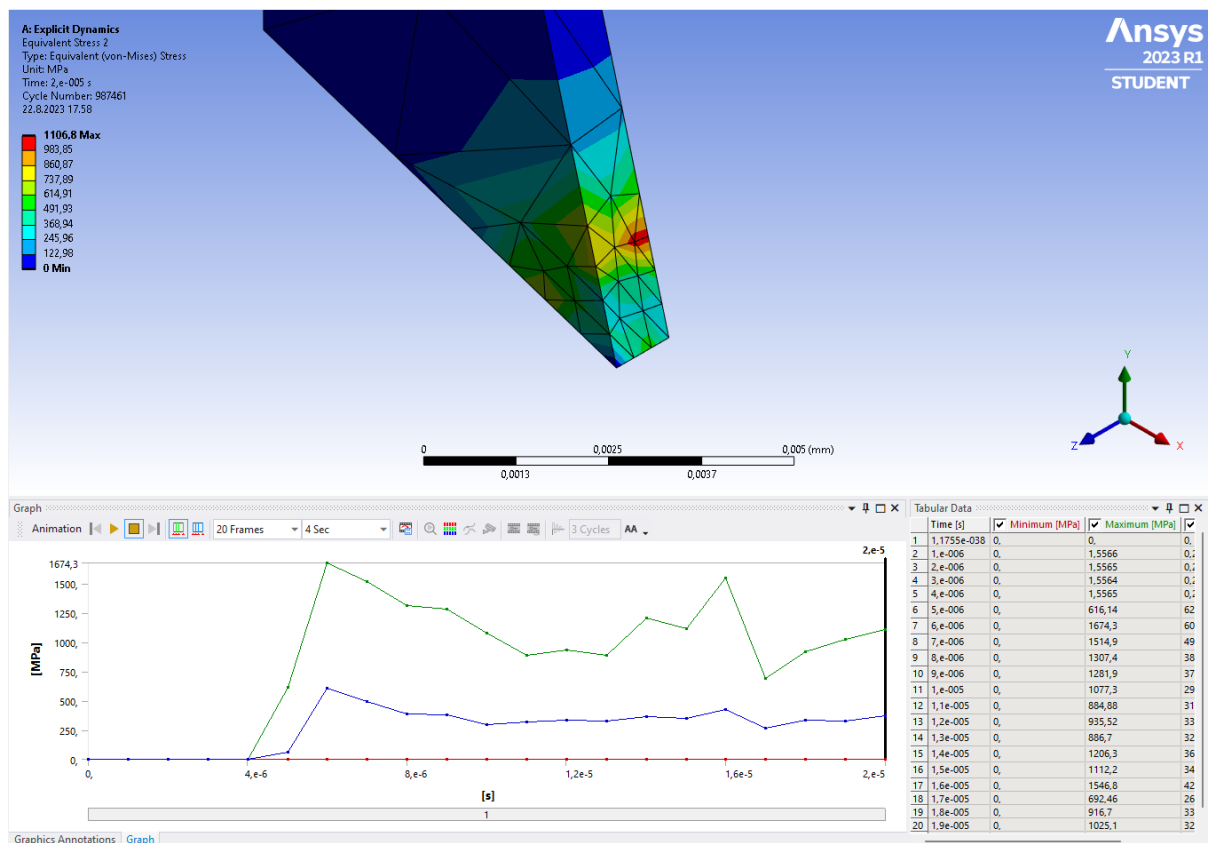


Figure 26. von Mises equivalent stress distribution 0,005mm feed per tooth

In figure 19, the stress distribution of the tool with feed per tooth value of 0,0075mm is shown. Compared to 0,005mm feed per tooth value, there is no similar concentrations for stress. The stress is relatively well distributed across the rake face surface. The distribution is also shifted more to the rake face from relief face. Highest value for stress is in the tip edge, but it is not as highly concentrated as in the 0,005mm feed rate hot spot. Average stress of the tool is relatively steady throughout the simulation. Values increase more steadily compared to 0,005mm feed rate and stay stable to the end of the simulation.

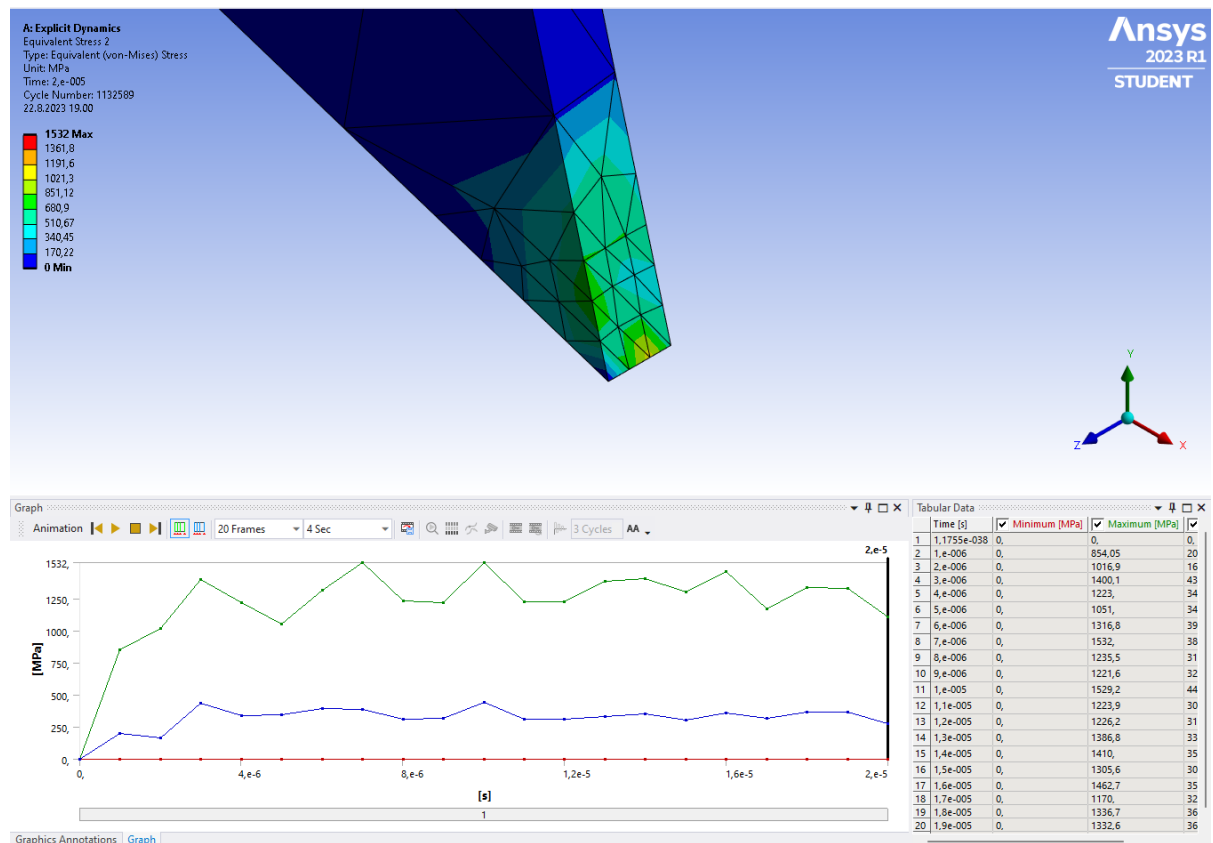


Figure 27. von Mises equivalent stress distribution on 0,0075mm feed per tooth

In figure 20, the stress distribution of the tool with 0,01mm feed is shown. In this analysis there is also no significant concentration of stress. Highest value is on the same spot than in the 0,0075mm feed but it is not as high. Stress is distributed quite evenly on the rake face. Difference between 0,0075mm feed is that the stress is distributed more through the tip to the relief face. Overall, the stress seems to be most distributed in this feed rate compared to the two previous simulations. Average stress on the graph validates this with a steady increase of stress in the beginning and stable stress throughout the analysis.

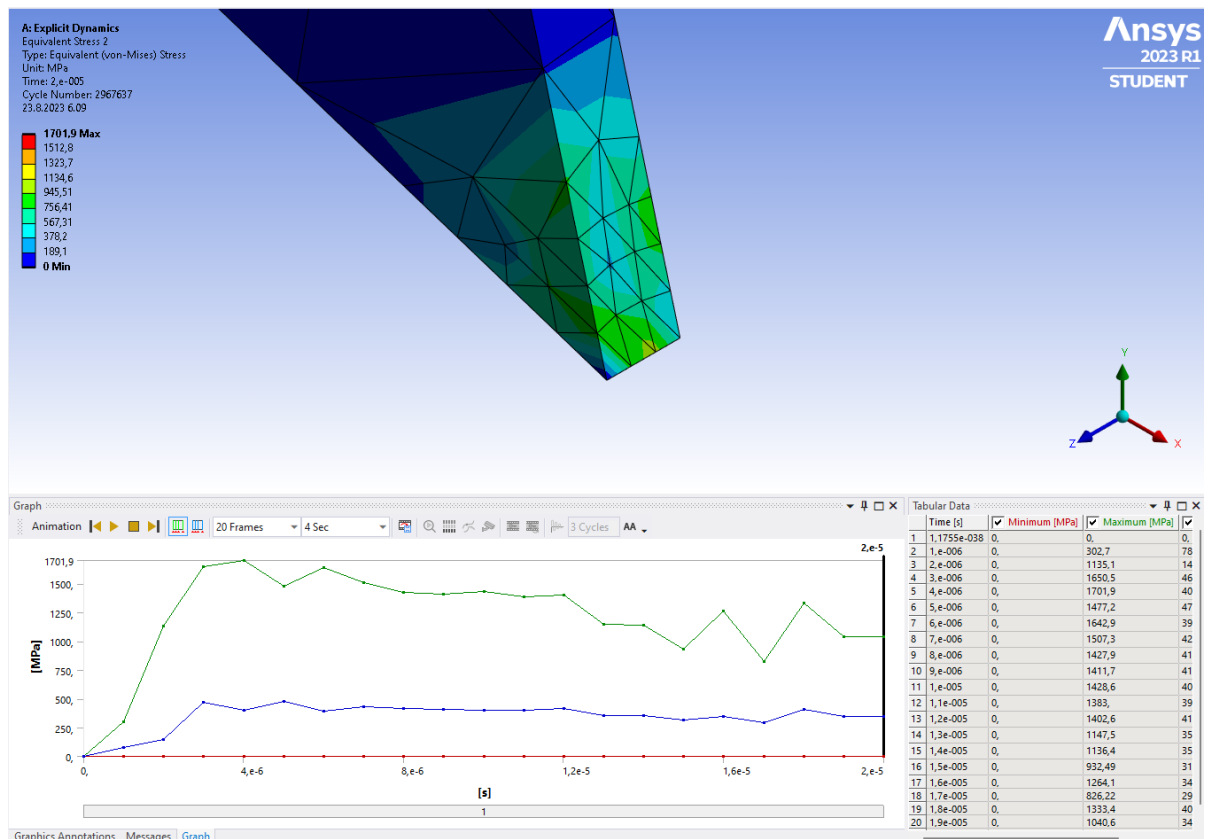


Figure 28. von Mises equivalent stress distribution on 0,01mm feed per tooth

Maximum stress values were different with all three feed per tooth values. 0,0075mm resulted in smallest value from which it can be said that increase in feed per tooth value does not result in higher stress in all cases. Regarding maximum stress on the tip, all simulations showed different behaviour with stress variation.

#### 4.4.2 von Mises equivalent elastic strain analysis

Similar to the stress analysis, strain analysis was conducted from the same simulation. Visualization is made from the side and scale for strain is on the left side with a unit of mm/mm. Below a graph shows maximum strain of the simulation with a green line and an average strain with a blue line. On the side is a table for maximum strain on a given time.

Material behaviour is same in this visualization than with the stress analysis, so only strain values are explained here.

In figure 21, a strain analysis for feed per tooth rate of 0,005mm is shown. Maximum strain value is  $4,658 \times 10^{-3}$  mm/mm at around third of the simulation time from the beginning. At the same time the stress value was highest on the simulation. Apart from this, the values for maximum strain are stable throughout the simulation. Average strain is quite consistent but has a slight drop during the middle of the simulation. Similar effect was seen on the stress analysis. The shear plane is clearly seen but some effect in front of the tip causes strain values to be noticeable. This can be caused by meshing resolution. High strain values distribute higher up in the chip compared to other feed rates. Strain values on the work piece are shown relatively low on the material but are significantly lower.

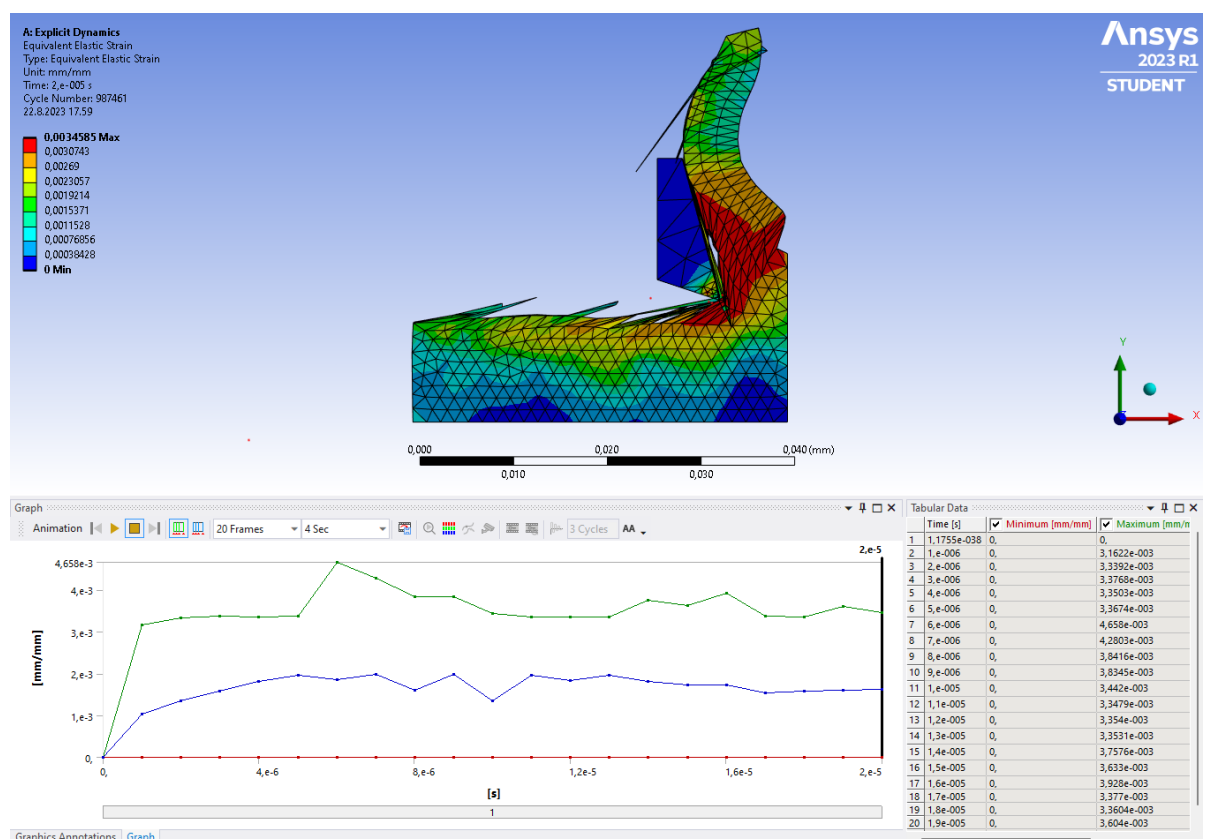


Figure 29. von Mises equivalent elastic strain on 0,005mm feed per tooth

In figure 22, the strain analysis on 0,0075mm feed per tooth value is shown. Maximum shear values behave similarly than with stress analysis resulting in a maximum strain value of  $4,708\text{e-}3$  mm/mm. Some variation on values is visible in the beginning but slight decrease in values is shown later, and stable values carried out to the end of the simulation. Average strain is the most stable compared to other feed rates. Shear plane is now clear and expected behaviour is occurring ahead of the tip. Strain values are more concentrated around the shear plane compared to 0,005mm feed rate analysis and shear values on the chip are noticeable lower. Behaviour below the cutting line is similar than with the 0,005mm feed per tooth analysis.

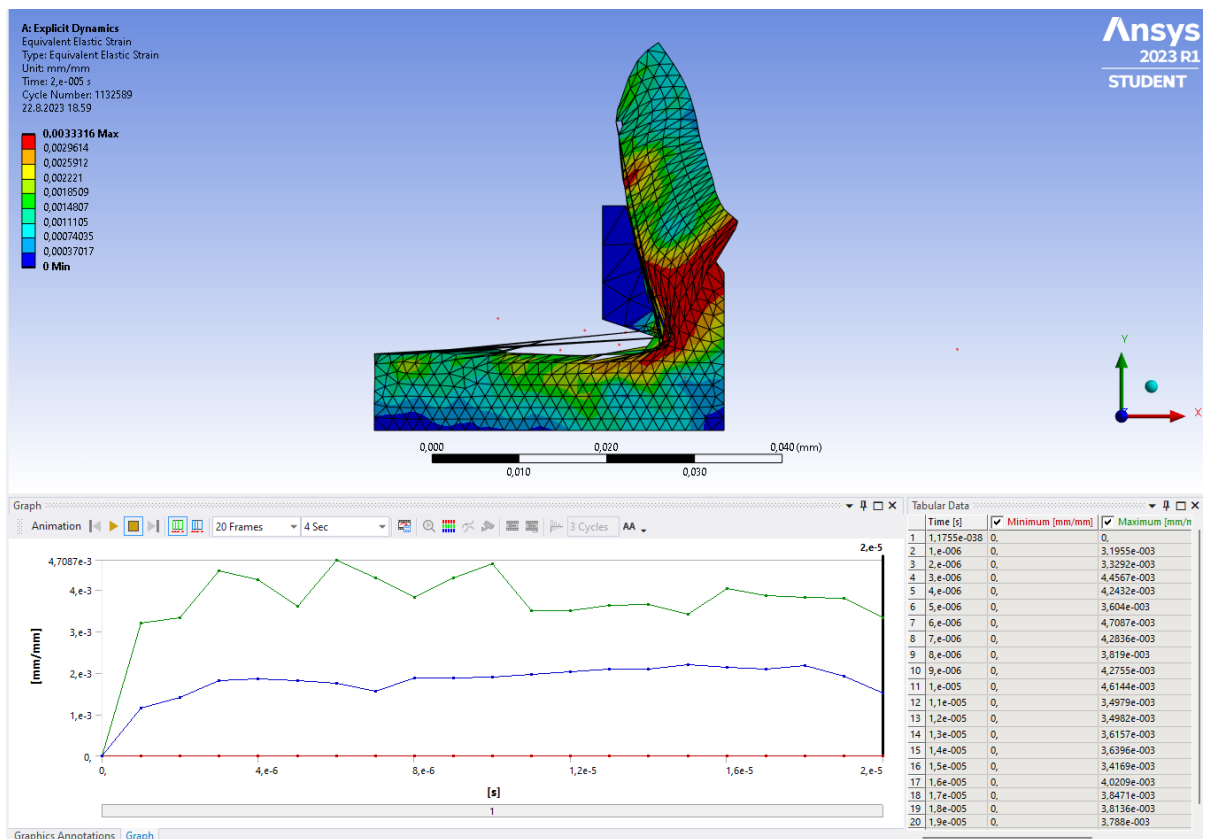


Figure 30. von Mises equivalent elastic strain on 0,0075mm feed per tooth

In figure 23, the strain analysis on 0,01mm feed per tooth value is shown. Maximum strain value is  $4,615\text{e-}3$  mm/mm and it occurs in the beginning of the simulation. Slight decrease of strain value happens during the simulation with two local increases on the end part of the simulation. Average strain builds up gradually and is quite stable throughout the simulation

with the exception during the middle of the simulation where a slight drop is shown similarly than in the 0,005mm feed per tooth analysis. Shear plane is clearly visible, but shear values are much more distributed compared to the two other simulations. Strain values are noticeable generally in every part of the material in either the chip or work piece bottom.

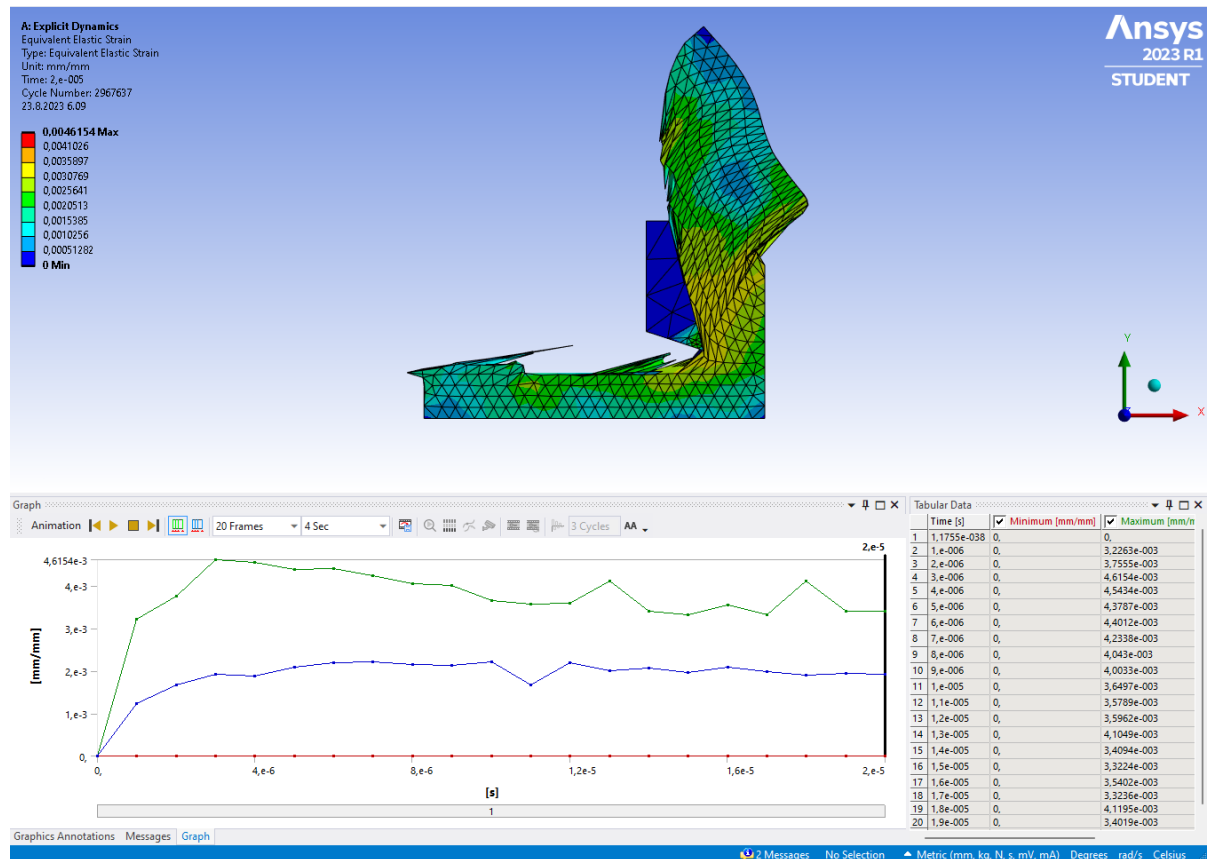


Figure 31. von Mises equivalent elastic strain on 0,01mm feed per tooth

#### 4.4.3 Wear analysis

Tool wear analysis was done by using the highest stress values found in the stress analysis for all three different feed per tooth values. Values simulated were 1674 MPa for feed per tooth value of 0,005mm, 1532 MPa for feed per tooth value of 0,0075mm, and 1701 MPa for feed per tooth value of 0,01mm A simulation was performed with similar model than the stress and strain analysis, but model body was made smaller to reduce nodes. Tool was

moved above the work piece and in the simulation, the tool was moved to the surface of the work piece to result a desired stress between the work piece and the tool. In figure 24, a visualization of the simulation is shown halfway of the simulation's duration. It can be observed that the pressure concentrates on the tip of the tool as desired.

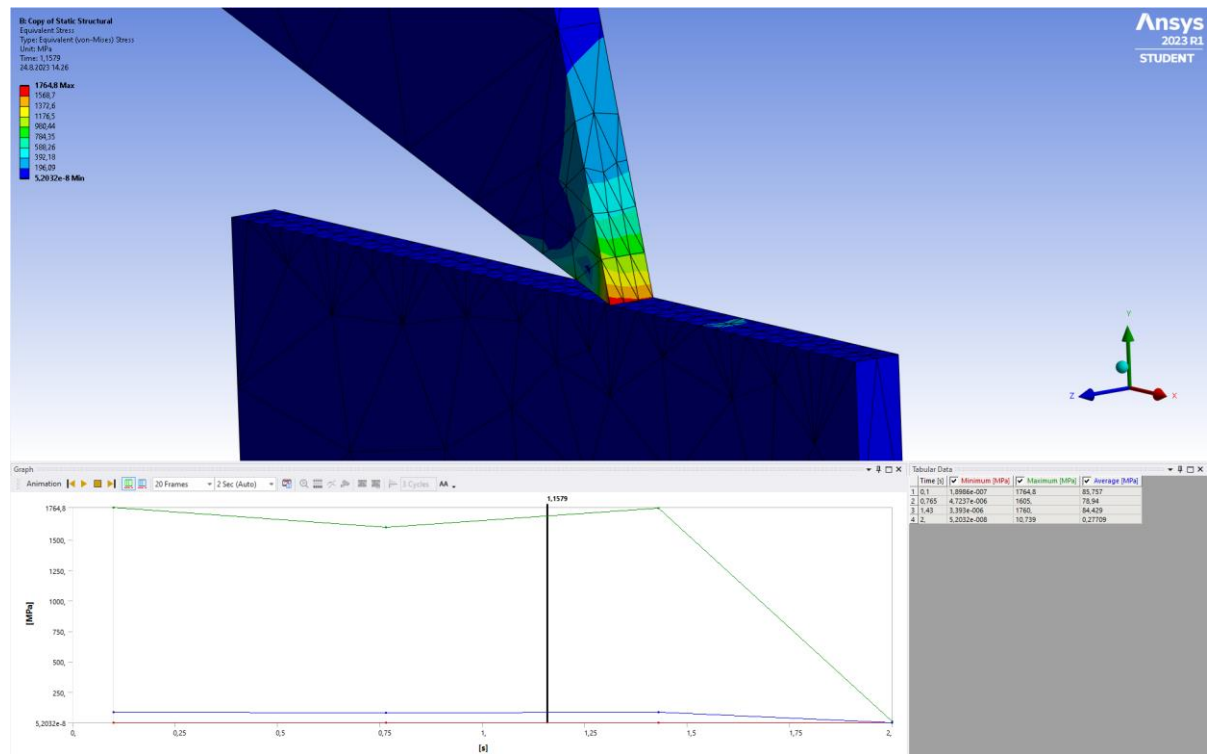


Figure 32. Wear simulation

Wear volume was obtained with an Archard extension to Ansys. For inputs, a wear coefficient of 1 was used. Material hardness value was  $5e5$ , pressure exponent 0,8 and velocity exponent 1,3. Results for the wear analysis can be seen in table 4. Wear values were obtained from Ansys for the dimensions of the simulation bodies. On the bottom row of table 4 are values which are scaled to real size of the sawing process. The scaled values also consider the length on the cutting process.

For the scaled values, simulations values were multiplied from 0,001mm thickness to 1,6mm thickness. Length of the cut was scaled for a scenario of cutting 30 hours of 300mm diameter bar. With feed per tooth value of 0,005mm and 508 teeth saw blade, a single tooth cuts the work piece 104 times during one cut of a bar resulting in a distance of 5426 meters over the

course of 30 hours. Feed per tooth value of 0,0075mm cuts the work piece 69 times and results in a distance of 5421 meters. 0,01mm feed per tooth value cuts the work piece 52 times and results in 5414 meters of cutting. The number of passes for singular tooth is lower with higher feed per tooth values but results for cutting distance over 30 hours are close to each other as the number of cuts is higher.

In this simulation, the wear volumes resulted to be very low. Some differences between feed per tooth values can be observed but the volumes are so low over the period of time that it seems unlikely that these results show significant difference in cutting performance or decreased saw blade life. From these results wear volume decreases with higher feed per tooth values. It is expected that temperature is a significant factor in cutting process as simulation without considering temperature did not result in significant wear.

Table 4. Wear volume between feed per tooth values in simulation.

Feed per tooth (mm)	0,005	0,0075	0,01
Stress (MPa)	1674	1532	1701
Wear (mm <sup>3</sup> )	1,87816E-28	1,87831E-28	1,87819E-28
Wear scaled (mm <sup>3</sup> )	1,08336E-16	1,08234E-16	1,08088E-16

#### 4.5 Archard calculation

The results of the Ansys simulation on Archard wear did not perform as expected. Therefore, wear was decided to be calculated using the Archard equation as the values to solve the equation were known. For wear coefficient a value of 2,99e-6 was used based on Yang's (2004) experiment made on tungsten carbide tool. Hardness value was taken from Konyashin's (2014) experiment on cemented carbide tools where hardness values varied between 2800 and 3600 MPa with different mixtures of alloys. Value 3000 MPa was used as exact material for the tool is not known. Stress values were taken from finite element analysis in this research for three different feed per tooth values. Average stress was used as it was more realistic than maximum stress of the analysis. Table 5 shows the results of the calculations. Feed per tooth values 0,005 and 0,01 resulted in increased wear and feed per

tooth value 0,0075 had the lowest amount of wear. On table 5 in the last row shows the increase of wear compared to 0,0075mm feed per tooth value. Higher average stress to the saw blade tooth results in higher wear volumes by 18% in 0,005mm feed per tooth value and 21% in 0,01mm feed per tooth value. In figure 25, a graph of the values found in table 5 are shown with a trendline to visualize the change in wear volume with different feed per tooth values. Spots indicate results and orange line is a linear trendline.

Table 5. Wear volume between feed per tooth values.

Feed per tooth (mm)	0,005	0,0075	0,01
Stress (Mpa)	382	325	392
Wear (mm <sup>3</sup> )	2,066	1,758	2,120
Difference (%)	18 %	0 %	21 %

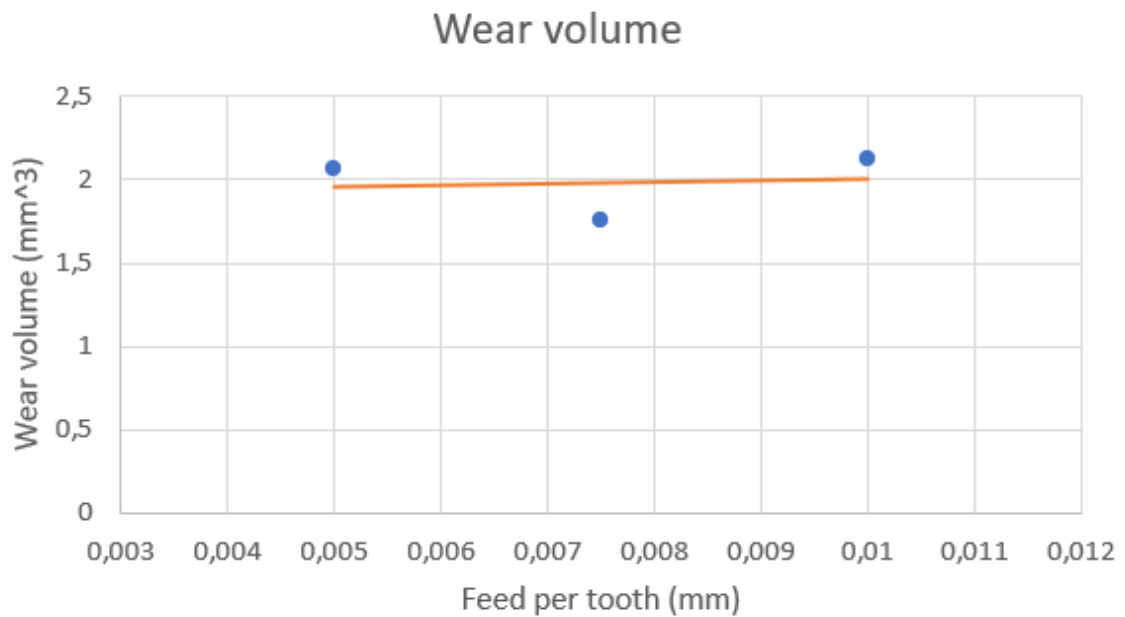


Figure 33. Wear volume graph

## 4.6 Solutions

Suggested actions based on results are updating the parameter lists and orientating saw operators on the findings of this research. Findings suggest that increased feed per tooth rates on sawing parameters might not be the only reason for saw blade wear, but also decreased feed per tooth rates. Therefore, it is important that correct parameters are used and that mix ups between different saw blades parameter lists do not occur.

### 4.6.1 Updated parameter list

During the operator interviews was noted that some hesitation on which parameter list contained the correct parameters for the saw blade in use was present. Findings showed that especially with the coarse saw blade with lowest number of teeth, the feed rate in relation to cutting speed was significantly higher compared to the other two saw blades that were studied. Using wrong values would result in significant change in feed per tooth values which were found to increase the possibility of higher saw blade wear.

Present parameter lists contained data in an interval of 100mm of diameter. Work pieces were found to have more variation in diameters for example 460mm. This resulted in operators having to either pick the parameters close to an even 100mm, in the case of 460mm, a 500mm parameters. Other option was to try to calculate or guess optimal parameters between 400mm and 500mm parameters.

To avoid confusion and guess work, an updated table for parameters was created. The interval between diameters was changed to 20mm to provide more precise parameters for specific material diameters. All materials provided in the original parameter list were kept in the new list and most common materials 18CrNiMo7-6 and S355 steel are highlighted with green and blue colours to make it easier to find values further the diameter range. The three different saw blades main difference is the teeth per inch value. This value is written in a large font to decrease the possibility of picking the value from a wrong parameter list. Due to confidentiality issues, the updated parameter list is not published in this thesis.

#### 4.6.2 Training of operators

Findings of this research are suggested to be shown to operators. The operators have had training for the use of saw blades but based on the interview, it seemed that effects of parameter change might not be known. Some conjectures from the operators sounded like slower values for cutting speed and feed rate would guide the process to safer properties in terms of wear. Understanding on faster speeds in cutting and feed were known to cause problems by the operators which is likely to be true. Showing the results are expected to make operators aware of the issues with low feed per tooth values and increase respect the relation between cutting speed and feed rate.

Suggested way to present the findings of this research is to summarize the key results and show the visualizations of the finite element analysis. Also, the graphs for feed per tooth values are expected to be interesting for the operators as it is unlikely that this information is available for the operators or that they have calculated them by themselves. Orientation should lead to discussion on the effects of parameter relations between cutting speed and feed rate and help operators understand the importance of correct parameters.

## 5 Discussion

In this chapter, a discussion on the research results is carried out. Expectation was that feed per tooth values in the process would increase significantly as operators decrease the cutting speed more in relation to feed rate and saw blade wear would increase. Although this was a valid concern and signs of this happening occurred, the amount and effects of decreased feed per tooth values were not expected. The methods of this research showed noticeable results in lower feed per tooth values than high feed per tooth values. This could be the reason why the results of this research are more informative in the low feed per tooth range and the effects of high feed per tooth values might be hidden.

Different stress values between sawing parameters were found which suggests that this research is on a right course. Amount of data for used parameters was low but it showed that in some cases, the feed per tooth rates can fluctuate significantly. Low amount of data causes the assumption of systematic issues in parameter selection to be questionable. Still, one in three values for S355 steel and two in eleven values for 18CrNiMo7-6 were noticeable out of manufacturer's guidelines. More measurements would verify this assumption.

It was found on the research, that feed per tooth values decrease significantly with larger dimensions of work pieces. This was not clearly noticeable before from parameters lists. Reason for this could be that different reasons for saw blade wear occurs with larger dimensions. One reason for this could be that the amount of material extracted from the work piece during one pass of a saw blade tooth is higher. If the material builds up in the cavity between the saw teeth and has no way of going anywhere, the pressure on the tip of the saw blade could decrease as the swarf obstructs the saw blade from moving down. Other reason could be thermal conditions which could be expected to change as cutting distance in the middle of the work piece increases. Previous studies showed that increased feed rate generated more heat. This could be compensated by the manufacturer in their parameter guidelines by decreasing the feed per tooth rate when cutting distance increases.

From the three saw blades formerly been in use, the middle range saw blade was found to be in constant use. As the buildup of swarf could be a restricting factor for higher cutting and feed speeds, the saw blade selection could be reviewed. Looking at the parameter guidelines, it would seem that coarse saw blade would provide the highest efficiency.

However, the operators and the supervisor felt that it is not a good option, as the surface quality of the cut is much rougher which is understandable as feed per tooth values are high and surface ridges are probably more visible. The saw blade containing the highest number of teeth per inch has higher feed rates and would therefore be more productive compared to the mid-range saw blade that was used. This could be because there is more teeth to carry the swarf out from the cutting process. Feed per tooth rates in this blade was similar to the mid-range saw blade so this could indicate that the amount of swarf in the cutting process is the limiting factor for higher feed rates.

## 5.1 Interviews

Operator interviews highlighted that pipe as a work piece caused issues in the cutting process. Reason for this was not known for the operators. Two reasons could contribute in this issue. One is that on the inside of the pipe, swarf accumulates. When the cutting process approaches the top of the bottom side material on the pipe, the swarf could be picked up by the saw blade. This could cause a similar effect with the swarf build up between saw blade teeth than discussed before. Pipes cut on this saw usually have a large thickness on the wall so the cutting distance on the second wall of the pipe can be significant. If the cavities between the teeth are filled with swarf before the cut, it could cause uneven distribution of cutting pressure on the saw blade tip between pipe walls. Other reason for increased wear on pipes could be number of entries to the material by the saw blade teeth. In a solid bar, the saw blade tooth collides with the material once per pass. With pipes this happens twice.

Breaking in of the new saw blade was answered to be done by reducing the cutting speed to 50% and feed rate to 25%. This instruction was provided by the saw blade manufacturer's representative. In light of this research, it would seem that this would increase the pressure on the blade tooth tip and could be problematic. However, the purpose of the breaking in period is to make the blade a bit duller so that the teeth do not break. Too sharp blade could cause peaks in cutting forces and rip the teeth or even break the saw band. Well done break in probably effects the life cycle of the saw blade but it was not possible to demonstrate this with the methods in use for this research.

## 5.2 Finite element analysis

Saw blade tooth tip material was not known exactly in this research. Information on the tooth tip material was requested but not provided. Reason for this was the saw blade manufacturer's secrecy of their product. For the analysis, it was assumed that the material would be similar to commonly known materials used in machining. However, the exact values for stress were not the aim of the research but rather the magnitude of value changes between parameter changes.

From the results of the finite element analysis, it could be argued that higher feed per tooth rates would produce more efficiency with minimal to no effect in wear. This is probably not the case as thermal conditions are not considered. Previous research also shows that higher feed rates create higher residual forces so conclusions on higher feed per tooth rates based on this research should be evaluated carefully.

Jadhav and Ramgir (2015) studied orthogonal cutting with finite element method cutting AISI 4340 steel with different feed rates. Similar effects from the results occur with increasing the feed rate of the tool than in this research. However, the rake angle influenced the chip curling and rake angles on Jadhav and Ramgir's study were higher than in this research and with certain rake angles the chip started to curl more again when increasing the feed rate. Still the results on this research can be considered similar to a certain point and conclusion that higher feed per tooth value infinitely reduce chip curl can-not be made.

In the results of the finite element analysis, string like elements from nodes detaching from each other occurred. Reason for this is not known. Mesh size could be a relevant factor and other parameters defined in the simulation causing local elastic behaviour just before plastic deformation.

## 5.3 Next steps

Further studies could be carried out simulating the thermal effects on the sawing process. For more precise wear results, the thermal conditions could provide more informative results. Similarly, the effect of cutting fluid mixture could be worth investigating. Yang

(2004) found that wear coefficient increased when temperature of the cutting process was higher which is a significant factor in wear volume accumulation.

In addition to researching thermal conditions, the wear simulation could be improved. Archard simulation did not produce valid results in this research with the methods used. Methods for the simulation could be reviewed and improved methods could be applied for further study.

Operators reported relatively significant deviations on cutting fluid mixtures but did not report it having an effect on the saw blade wear. This might not be the case as wear can occur slowly for example in a period of one week and therefore if the root cause would be cutting fluid mixture, it might be disregarded and a conclusion that cutting parameters or material were the reason for increased wear.

## 6 Conclusions

Aim of this research was to find out, what is the current state of the operation, what is the optimal way to operate, and how important it is to have specific values in the sawing process of large diameter steel bar. Current state of the operation was discovered by interviewing the operators and monitoring their behavior through spot checks. Optimal way to operate was discovered by analyzing the saw blade manufacturer's parameter guide and comparing it to the results of finite element analysis. Importance of correct parameter use was evaluated through results of finite element analysis for different parameters.

Operators were found to be choosing the sawing parameters relatively well regarding feed per tooth values. However, the feed rate was for 18CrNiMo7-6 was 25% lower and S355 steel was 85% lower than the saw blade manufacturer suggested. Feed per tooth values were mostly close to the manufacturer's guided values but some significant deviations were found.

Optimal way to operate was found to be close to feed per tooth value on 0,0075mm. Finite element analysis showed that lowest amount of stress was subjected to the saw blade tooth with this value and increased stress was found with lower feed per tooth value of 0,005mm and higher feed per tooth value of 0,01mm. However, the manufacturer's directions showed, that feed per tooth values were on suggested parameters decreased significantly when the work piece diameter increased. Previous studies showed that increased temperature on the process causes increase on wear coefficient which would lead to higher wear volume. Also, the amount of swarf is higher for larger cutting distances per tooth and swarf accumulates between the saw blade teeth. This research studied the stress behavior on the tip of the saw blade and did not consider thermal effects of swarf accumulation. Manufacturer's parameter guide is expected to take these phenomena into account.

Wear volume was found to be 18% higher with 0,005mm feed per tooth value and 21% higher with 0,01mm feed per tooth value compared to 0,0075mm feed per tooth, which was considered closest to optimal from the simulated values. Therefore, it was found that suboptimal parameter use can decrease the saw blade life around 20% with the parameters studied in this research.

Previous studies were found to focus a variety of different machining methods such as milling or turning. These studies also had variety of different research problems that were studied such as tool geometry effects or specific known material behaviors. This research had a specific scenario that was studied with known work piece material and saw blade geometry. Values for this research results were known not to be exact before the research as information on the saw blade tip material cannot be obtained. Overall, the research questions were answered and desired results were obtained.

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