LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
LUT Mechanical Engineering

Juho Venäläinen

IMPROVING PRODUCTIVITY IN VALVE BALL GRINDING WITH CERAMIC ABRASIVES

Examiners: Prof. Juha Varis
M.Sc. Jari-Antero Sivula

ABSTRACT

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Juho Venäläinen

Improving productivity in valve ball grinding with ceramic abrasives

Master's Thesis

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98 pages, 34 figures, 8 tables and 7 appendices

Examiners: Prof. Juha Varis
M.Sc. (Tech.) Jari-Antero Sivula

Keywords: Valve ball grinding, factorial experiment, sol-gel aluminium oxide, grinding fluid

This thesis aims to improve the ball grinding process by increasing material removal rate. Improvement is pursued through modern grinding tools for which optimal grinding parameters are determined and the achieved outputs are compared to each other. To familiarize the process and recognize the important components in valve ball grinding, a literature review is performed on grinding process and its components. To compare the tool alternatives, systematical experimentation is required for which Design of Experiments method is used after introducing it through literature review. Each tool is experimented equipping different factorial designs where the material removal rate and tool wear are measured. Based on the results of the experiments, the optimal parameters are determined and the respective outputs are used for comparison. In the experiments, the alternative tools were noted to be very different from the currently used tool and to require additional fluid delivery in order to perform satisfactorily. The tool performance was noticed to be more dependent on the suitability of the specification in the particular application, than on the grain type. Experiments lead to conclusions based on which the tool specifications are altered, but the final results are yet to be determined in the forthcoming experiments.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Juho Venäläinen

Venttiilipallojen hionnan tuottavuuden parantaminen keraamisella abrasiivilla

Diplomityö

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98 sivua, 34 kuvaa, 8 taulukkoa and 7 liitettä

Tarkastajat: Prof. Juha Varis
DI Jari-Antero Sivula

Hakusanat: Venttiilipallojen hionta, teollinen koe, sol-gel alumiinioksidi, hiontaneste

Tämän diplomityön tavoitteena on tehostaa venttiilipallojen hiontaprosessia kasvattamalla materiaalinpoistonopeutta. Parannuksia haetaan moderneilla hiontatyökaluilla, joille etsitään optimaaliset hiontaparametrit. Prosessin oppimiseksi ja tärkeimpien osatekijöiden tunnistamiseksi, näistä suoritetaan kirjallisuuskatsaus. Työkalujen systemaattiseen vertailuun käytetään teollista koesuunnittelua, joka esitellään osana kirjallisuuskatsausta. Työkaluille suoritetaan teolliset kokeet, joissa mitataan materiaalinpoistonopeutta ja työkalun kulumaa. Koetulosten perusteella määritellään työkalukohtaiset optimaaliset työstöparametrit ja näillä saavutettavia tuloksia vertaillaan keskenään. Kokeiden aikana vaihtoehtoisten työkalujen huomattiin olevan hyvin erilaisia nykyiseen työkaluun verrattuna ja näiden tarvitsevan lisänestettä toimiakseen kunnolla. Työkalun tehokkuuden havaittiin olevan riippuvaista enemmän työkalun muiden ominaisuuksien sopivuudesta käyttökohteeseen, kuin abrasiivin tyypistä. Kokeista tehtyjen johtopäätösen perusteella työkalujen ominaisuuksia muutetaan, mutta lopulliset tulokset ovat nähtävissä vasta tulevien kokeiden jälkeen.

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Juho Venäläinen
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LIST OF ABBREVIATIONS AND SYMBOLS

AW	Anti Wear
DMAIC	Define, Measure, Analyze, Improve, Control
DOE	Design of Experiments
EP	Extreme Pressure
FM	Friction Modifier
G-ratio	Grinding Ratio
MRR	Material Removal Rate
OFAT	One-Factor-at-a-Time
PEP	Passive Extreme Pressure
SG	Seeded-gel
WP	Workpiece

α	Clearance angle
β	Regression coefficient
γ	Rake angle
ε	Experimental error
η	Effective cutting speed angle
ρ_s	Cutting edge radius
λ	Head conductivity
c_p	Specific heat capacity
h_{cu}	Undeformed chip thickness
$h_{cu\ eff}$	Effective chip thickness
P	Grinding power
Q’	Specific removal rate

r	Heat evaporation
T_{μ}	Critical cutting depth
v	Viscosity
v_c	Cutting speed
V_c	Cylinder volume
V_{cbs}	Volume of bearing mount caps
V_{cfp}	Volume of flowport caps
V_t	Sphere total volume
x	Design factor
y	Response variable

Al_2O_3	Aluminium Oxide
CBN	Cubic Boron Nitride
SiC	Silicon Carbide
TiO_2	Titanium Dioxide
WC-Co	Tungsten Carbide Cobalt

1 INTRODUCTION

To keep up with competitive markets and to guarantee customer satisfaction, companies need to continuously develop with the market and customer demand. For companies to develop their businesses, there are different tools and approaches available. One of the most common and best known approaches is the Six Sigma, which Metso has been deploying in its different business areas for the past years.

As part of the Six Sigma development program, the goal of this thesis is to develop the ball valve's ball grinding process by finding the optimal grinding tools and parameters for the material removal rate. Almost every valve ball is ground at some point of the machining, regardless of the other machining phases. Thus improvement of the grinding process efficiency could lead to increased output and cost savings.

1.1 Introduction of the Company

Metso Corporation manufactures products and offers services for mining, aggregate, recycling, oil, gas, pulp, paper and process industries. Metso is the world leader in some of its business fields, making EUR 2.9 billion in net sales in 2015. In total, the company employs 12000 people, in 50 different countries. (Metso 2016a.)

This Thesis was written for the Metso Flow Control Inc. The Flow Control branch is manufacturing different valve solutions for petrochemical, paper and process industries. The Flow Control has a manufacturing plant at Vantaa, Finland, where the branch's headquarters is located and where this thesis was also written. The other valve manufacturing locations for the Flow Control business are Shrewsbury, MA, USA; Shanghai, China; Horgau, Germany and Chungju, South Korea.

1.2 Research Problem and Questions

The research problem of this thesis is the doubt of the performance of the currently used grinding tool in comparison to novel tools. Optimization of the grinding process for the currently used grinding tool was a success and proved there is potential for increasing the material removal rate. As a result of optimization through experimenting, the material removal rate grew several times over. Now it is estimated, that by finding an optimal tool and corresponding parameters for it, the material removal rate could be increased even further.

The main research question that the thesis is aiming to answer is: can the material removal rate be increased without impairing the surface quality, and how. Without investing in new machinery and by leaving out the human factor, the question can ultimately be split into two parts: what is the optimal grinding tool and what are the optimal corresponding grinding parameters?

1.3 Research Methods

The thesis consists of a theory part and empirical part where the introduced theories are applied. The theory covers the basic principles of grinding and the mechanics of chip formation, and it also gives an introduction to grinding tools and abrasives. The theory part also introduces Design of Experiment (DOE) practice in a depth that it is necessary for running experiments and analyzing its results. To bring out the importance of grinding for the operation of a rotary valve, a short description on the principle of operation of rotary valves is included.

The theory is based on a literature review from each subject’s respective field. The empirical research, following the principles of DOE, is based on the data collected from the test runs that are performed with a grinding machine. A regression model is composed from the collected results, based on which the optimal grinding parameters are selected and finally verified with a confirmation test as a part of the DOE process.

1.4 Limitations

As mentioned earlier in the research questions, the research is focused solely on the grinding event with the current machinery. New machine investments and human factors are eliminated from this research. The experiments are limited to five different ceramic abrasive tools from three different abrasive manufacturers. The research is limited only to grinding austenitic stainless steel in a state prior to possible chromium or other coatings.

2 GRINDING AS A PROCESS

The abrasive processes date back to the times people used to rub rocks against each other to make tools and weapons, making abrasive processes one of the earliest methods of working materials. Even the grinding of metal dates backs to the 2000 BCE, when Egyptians utilized it to sharpen tools. The basic principle of the material removal has remained the same ever since, even though everything else in the modern process has more or less changed. What we consider machining with abrasives these days, started in the 18th century. Later on 1891 abrasives took a big step forward as producing the first synthetic abrasive, silicon carbide was discovered. Finally, development has led to today's extremely hard synthetic abrasives that are crucial in modern grinding processes, on which the tools experimented in this thesis also rely on. (Malkin & Guo 2008, pp. 3–4; Klocke 2009, p. 1.)

Abrasive processes have few specific features in comparison to other conventional machining processes. Cutting edges are much smaller and there is a numerous amount them participating in the cutting process simultaneously. As a result of numerous small cutting edges and hardness of the grain, the abrasive processes have some advantages over other machining processes. The extreme hardness typical for the abrasives, makes the machining of very hard materials possible, materials such as hardened steel, carbides or ceramics. Moreover, fine surfaces as well as close dimensional and geometrical tolerances can be met. In some applications where the materials are extremely hard, machining with abrasives is the only practical option as the use of other methods is either impossible or inefficient. (Black & Kohser 2012, p. 715; Malkin et al. 2008, pp. 1–2.)

The usual abrasive processes can be split into two groups depending on the abrasive type. Grinding, that this thesis is focused on, and honing represent machining with bonded abrasives. Lapping and polishing then are examples of the usual processes done with free abrasive particles. (Marinescu et al. 2013, pp. 3–4, 7; Klocke 2009, p. 1.)

2.1 Grinding Operations

Grinding is a machining process performed with a tool where hard abrasive grains are bonded together. It is usually considered as precision machining process, where material removal rates are low, but which with high surface quality and tight tolerances can be met. However, grinding is also used as heavy duty process for example for cleaning billets at foundries, where material removal rates are high and other factors such as surface roughness are not the primary interest. The grinding method that this thesis regards, can be considered as precision process, as measures and geometry of the ball are crucial for the valve's operation. (Klocke 2009, p. 1; Malkin et al. 2008, pp. 1–2.)

Grinding operations can be grouped based on the tool shape, kinematics, workpiece and grinding head. The basic operations can be grouped on four different categories that are represented in Figure 1. (Marinescu et al. 2007, p. 6.)

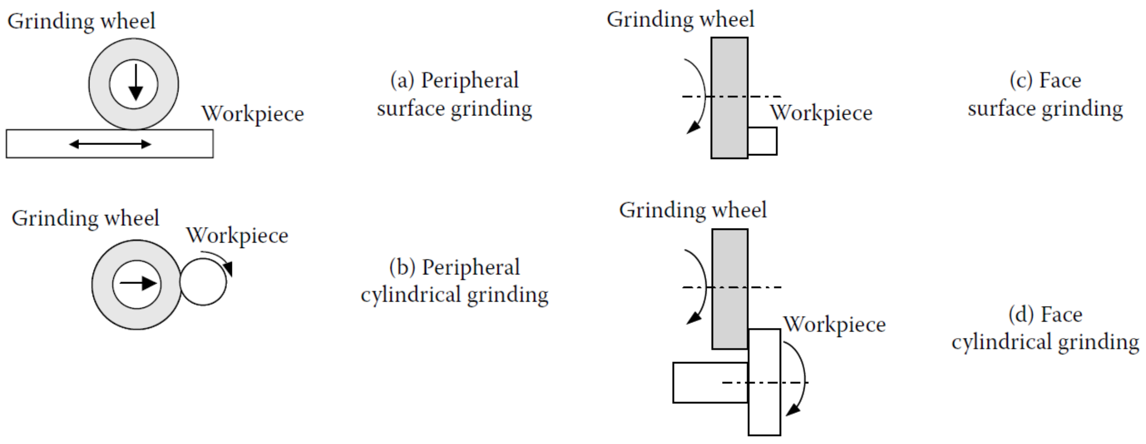


Figure 1. Four common grinding operations (modified from Marinescu et al. 2007, p. 6).

The principle of operation of ball grinding machine used at Metso is illustrated in Figure 2. It is a special application and is not directly part of any of the four groups but has similarities with several. Despite the difference in principle of operation, on a grain level the process still follows the same basic principles introduced in the second chapter.

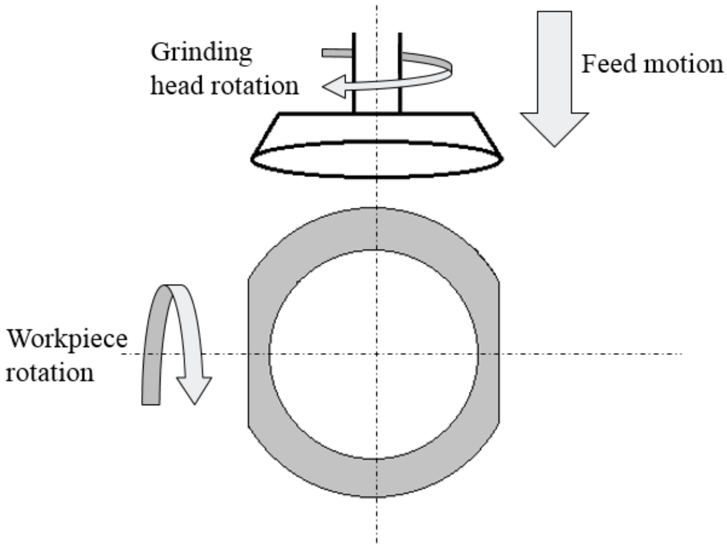


Figure 2. The principle of operation of ball grinding machine.

2.1.1 Grinding Parameters

Grinding is often considered complex and unpredictable process because of numerous of small, randomly shaped and scattered cutting edges. However, with correct equipment the process control is fairly easy and the number of parameters that need to be controlled is fairly low. (Marinescu et al. 2007, p. 9.) The following parameters cover only an extent that concerns the ball grinding application and are used in the experiments or theory. The experiments are interested mainly in material removal and tool wear, therefore other parameters such as calculations for surface roughness are not covered.

The main input parameters that the ball grinding machine users adjust, are feed rate, wheel (rotational) speed and workpiece (rotational) speed. The feed rate expresses the amount of feed motion per time unit, which is on the test machine set as mm/min. Wheel speed on the machine is set to desired RPM, which can be converted to velocity with a simple formula taking the wheel diameter into account. Like the wheel speed, the workpiece speed is set as RPM and the actual workpiece speed depends on the ball diameter. The actual wheel speed and workpiece speed are important to calculate for safety reasons. Grinding tools have maximum speed rating within which the tool is safe to use and exceeding the limit increases the risk of the wheel to shatter. (Marinescu et al. 2007, p. 11, 60.)

The output variables that the ball grinding machines gives, are not directly applicable to precise experimenting, instead they tell the information that is useful for the machine user in normal production. The machine measures the diameter of the ball which is used to calculate the volume of the ball that is required for calculating the material removal. The way the diameter is applied in calculating valve ball volume, is covered more thoroughly in chapter 7.1.3 Response variables.

To express material removal rate in grinding, the specific removal rate *Q'* is often used. The specific removal rate expresses the removal rate as material removal rate per width of tool contact. So, the unit for *Q'* is $mm^3/mm/s$. (Marinescu et al. 2007, pp. 12–13.)

To express tool wear, the ball grinding machine gives out the length of the tool. Its values are compared before and after the runs to get the change in tool length. It could be used to evaluate tool wear on its own, but long tool life itself does not mean that the tool is any good, so it is better to relate to material removal rate. Grinding ratio, or G-ratio, expresses the ratio between the volume of material removed from the workpiece and the volume removed from the tool and is often used as a main criteria evaluating the tool wear. Since it's a ratio, both sides of the equation have similar units and the output is unitless. (Marinescu et al. 2007, pp. 17–18; Rowe 2013.)

Specific grinding energy is not a factor of interest in grinding experiments, however it is used in theory and therefore its definition is given here. It measures the energy that is needed for removing a certain volume of material from the workpiece and accordingly its unit is J/mm^3. (Marinescu et al. 2007, p. 12.)

2.2 Basics of the Grinding Process

The material removal principle in grinding seems to differ from many other machining processes such as turning or milling. In these processes, the chip is removed by an insert of which size, shape and location is known. But in grinding, the material removal is a sum of countless small, randomly placed, cutting edges removing tiny particles from the workpiece. However, from a point of a single cutting edge, the material removal follows the same method as in milling or turning and the difference is in grinding's clearly negative rake angle. With countless slightly different cutting edges, the grinding tool has very complex structure which makes the forming of the single chip unpredictable. Instead of analyzing the material removal on a single grain scale, the approach is more often statistical by building up a model of an average grain, based on all the measured cutting edge profiles. An illustration of such model, representing an average abrasive grain on grinding tool, is seen on Figure 3. (Marinescu et al. 2007, p. 24; Klocke 2009, p. 3; Aurich et al. 2013, p. 81.)

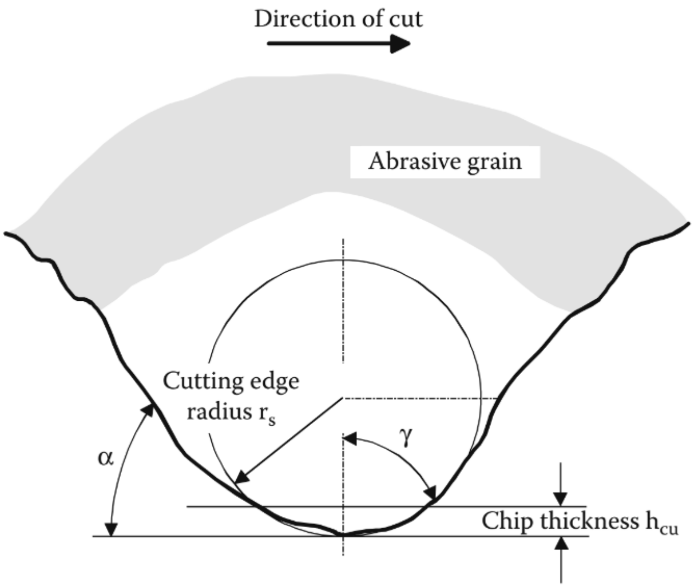


Figure 3. An illustration of an average cutting edge on grinding tool, where *α* is the clearance angle and *γ* the rake angle. The rake angle is clearly negative which is typical for abrasive cutting edges. (Marinescu et al. 2007, p. 25.)

To understand the material removal principle, it is necessary to look into the process on a grain scale. The Figure 4 represents a simplified image of a grinding tool on a workpiece surface. The dark gray abrasive grains are bonded together with light gray bond material. These abrasive grains, numbered from 1 to 5, protrude from the surface of the bond material, on random sizes, shapes and locations. The grains protruding the most and reaching the machined surface are the ones participating in the cutting process. These are called kinematic cutting edges and are marked with red circles. The yellow squares mark the static cutting edges, which are not part of the machining process yet. As a result of the tool wear, kinematic edges wear and new static edges constantly turn into new kinematic edges, becoming part of the grinding process. (Klocke 2009, p. 4.)

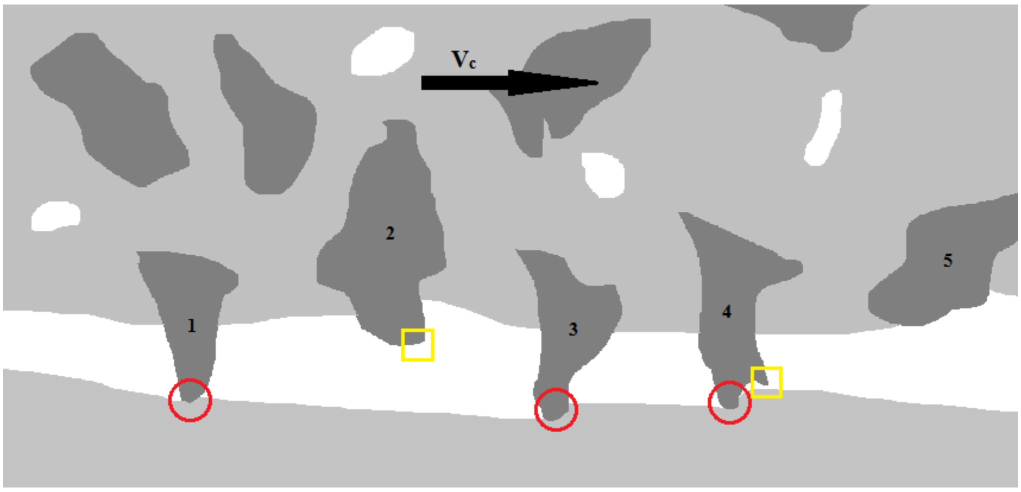


Figure 4. A simplified image of abrasive grains in bonding material (modified from Klocke 2009, p. 4).

2.2.1 Material Removal Mechanisms

The material removal mechanisms of a single grain are shown in the Figure 5. As numerous of grains protruding differently from the bond cut the workpiece simultaneously, all of the three mechanisms can occur on the workpiece surface at the same time. Whether the main mechanism is microplowing, microchipping or microbreaking, is mainly determined by the workpiece material. Ductile materials are more prone to microplowing and microchipping, where brittle-hard materials, such as ceramics are apt to microbreaking. (Marinescu et al. 2007, p. 31.)

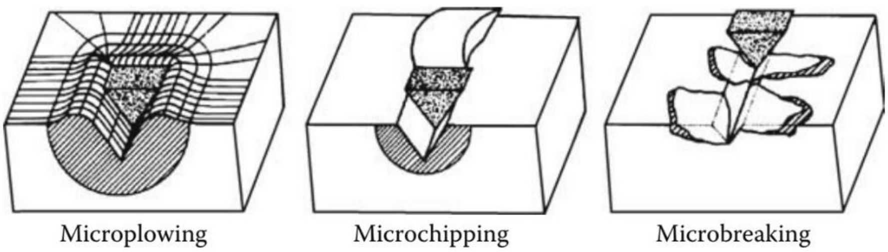


Figure 5. Illustrations of different material removal mechanisms in grinding (Marinescu et al. 2007, p. 32).

On a single grain scale, microplowing is not particularly effective material removal mechanism. The most of the energy goes to continuous plastic, or elastoplastic deformation of the material's surface. Finally, as the microplowed area gets hit enough times by various cutting edges, the part tends to break from its trace borders leading to material removal. The second mechanism, microchipping, occurs together with microplowing. The relation of these two mechanisms depends on grinding parameters as well as the suitability of the parts associating in the process, such as grinding fluid and tool. The material removal in ductile materials such as many steels, usually happens through these two mechanisms. (Marinescu et al. 2007, p. 31.)

The microbreaking is a mechanism that occurs mainly on brittle-hard materials, like ceramics. Prior to material removal, the material surface cracks and the crack spreads leading to chip removal. As seen on the Figure 5, the chips removed by microbreaking, can be very large in comparison to grinding trace. (Marinescu et al. 2007, p. 31.)

2.2.2 Chip Formation in Ductile Materials

As stated earlier, the material removal in grinding of ductile materials is mainly based on microplowing and microchipping mechanisms. Figure 6 shows a three stage model of material removal in ductile material. The effective cutting speed angle η, between the workpiece surface and the effective cutting speed v_e, that the abrasive approaches and penetrates the workpiece surface, is typically small. So, the travel path is rather flat, which leads to a certain behavior of the material, or to the three phases of the model. (Marinescu et al. 2007, pp. 32, 262-263; Klocke 2009, pp. 8–9.)

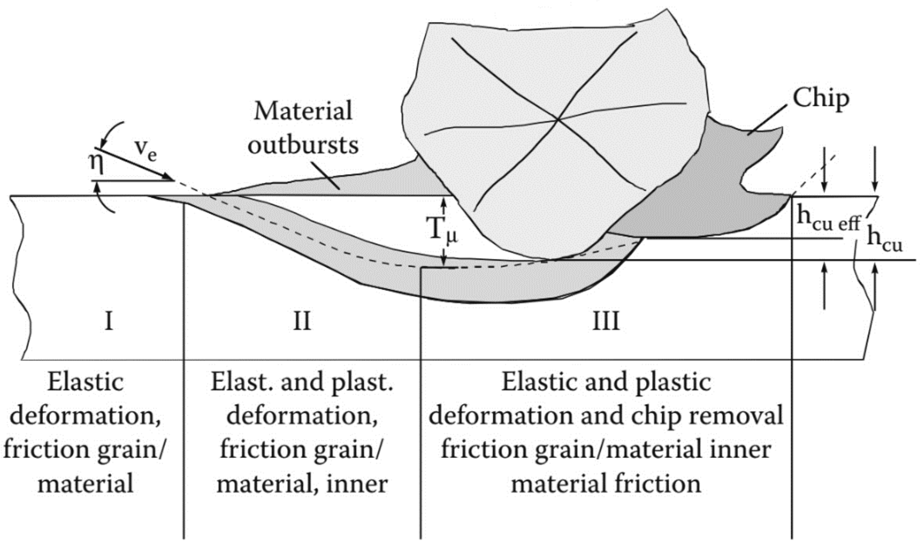


Figure 6. A basic three stage model of grinding process of ductile materials (modified from Marinescu et al. 2007, p. 32).

In the area of the first phase, the material deforms elastically which is often referred as rubbing or sliding. After the phase of elastic deformation starts the plastic deformation, sometimes called ploughing. In this phase the material flows underneath and aside of the cutting edge, forming material outbursts. Finally, in the third phase, when the undeformed chip thickness h_{cu} reaches the critical cutting depth T_{μ}, the chip formation begins. (Marinescu et al. 2007, p. 32; Klocke 2009, pp. 8–9; Rowe 2013.)

The actual volume of removed material is determined by the effective chip thickness $h_{cu\ eff}$, so by the portion of the uncut chip thickness h_{cu} that is actually removed as a chip. This relation depends on different factors in grinding process, such as the cutting edge radius ρ_s, effective cutting speed angle η, cutting speed v_c, material properties and friction. The friction between the cutting edge and the workpiece has significant effect on $h_{cu\ eff}$ and T_{μ}. Basically higher friction equals more efficient material removal, so on a grain scale, any lubrication such as cutting fluid lowers the material removal rate of a single grain. By lowering the friction, the grain cutting depth T_{μ} increases, but so does the portion of deformed sections, thus resulting in decrease in the effective chip thickness. On macroscale, the use of cutting fluids makes possible the use of higher grinding parameters and has several other benefits explained later on, so in practice they are often used nevertheless. (Marinescu et al. 2007, p. 32, 195; Klocke 2009, pp. 8–9; Rowe 2013.)

The previous three stage model for chip formation illustrates a situation where grinding is performed with wheel periphery. In the model, single grain follows a circular path of the wheel and the penetration depth into the workpiece changes with the revolving motion of the wheel. In the grinding application used at Metso, the depth of the grains penetrating the surface increases slowly and the single grain is in contact with the workpiece the majority of the time, so the contact length becomes much longer. Despite the different grinding method, similar three stages can still be recognized where the grains go through the three stages with increasing feed rate. The kinematic cutting edges not participating in the cutting, slowly turn into to active cutting edges with feed rate. At first they are barely touching the surface and they are in the first phase of the model. With feed motion they move on first to the second phase and then third, before fracturing and starting the cycle over.

2.3 Formation of Cutting Edges

A key factor in efficient grinding is the formation of new cutting edges on the grinding tool surface. Friability is a factor that describes the fracturing tendency of a grain under strain. Practically, the tendency of the grain to break and form new cutting edges. The higher the friability, more apt the grain is to fracture. For the optimal process efficiency and quality, the friability of the grain plays an important role. Too tough of a grain, does not break in time, but dulls instead. The dull grains rubbing the workpiece surface can cause thermal damage through the elevated surface temperature caused by increased friction. A grain too friable remains sharp, but then wears unnecessarily quickly, shortening tool life and thus increasing the tooling costs. (Marinescu et al. 2013, p. 247.)

Ultimately, the formation of new cutting edges depends on both the properties of the grain and the bond. When the cutting edges on the grain get too dull, grain should break creating new cutting edge and finally when the grain is worn out the bond should release the grain, making room for new grains to surface. (Marinescu et al. 2007, pp. 111–112; Badger 2012, p. 1118.)

On top of the tool properties, formation of new cutting edges also depends on other factors, of which the grinding parameters are a major one. Wrong tool does not work well with any parameters and the optimal tool with unsuitable grinding parameters unlikely works any better.

The Figure 7 illustrates the three different wear regimes of the tool that depend on so-called “aggressiveness”. Badger (2012, p. 1118) defines the aggressiveness in a following manner: “The aggressiveness is simply the factors in the calculation for chip thickness that are under immediate control of the machine operator with the cutting-point density and chip width ratio removed.” So, the grinding parameters affecting the aggressiveness are the feed rate, depth of cut, wheel speed and equivalent wheel diameter and they should be selected in a way that the aggressiveness is optimal resulting in optimal wear of the wheel. (Badger 2012, p. 1118.)

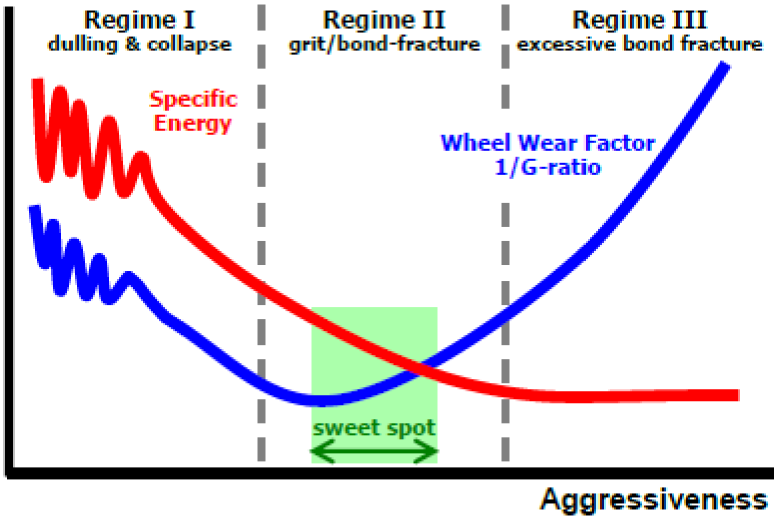


Figure 7. For an optimal grinding process, it is important to find the sweet spot between different wear mechanisms by using suitable grinding parameters (Badger 2012, p. 1118).

In the ball grinding application, not all of the parameters listed by Badger apply. The parameters controlled by the operator that define the aggressiveness are the feed rate and tool and workpiece speed.

In the area of regime I, the parameters are not aggressive enough. Not enough stress is addressed to the abrasive grains for them to fracture and self-sharpen, resulting in dulling. Dulling of the grains leads to inefficient cutting process as the portion of rubbing increases, leading to increased heat generation. The dulling of the grains eventually leads to large chunks of wheel to break off as the force towards the area of dull grains exceeds the retaining strength of the surrounding bond. (Badger 2012, p. 1118.)

In the area of regime II, the stresses addressed towards the grain are in proportion so there is no excessive dulling nor excessive bond wear due to large forces on grains. In the regime II both the specific energy and wheel wear are moderate and the tool wear occurs optimally, meaning that the grains and bond fracture when meant to. (Badger 2012, p. 1118.)

The area of regime III represents grinding with overly aggressive parameters, where the specific energy is low but the stresses addressed towards the tool surface are high. The grains on the tool remain sharp because of the excessive fracturing constantly bringing about new cutting edges. However, such overly aggressive parameters lead to catastrophic wheel wear. (Badger 2012, p. 1118.)

2.3.1 Tool Fracture Mechanics

As stated earlier, the formation of new cutting edges as the old dull, is the premise to material removal. The tool wear and generation of new cutting edges occurs through four different means, shown on Figure 8. The mechanism of tool wear and thus the generation of a new cutting edge, depends on several factors such as the grinding parameters and the type of the abrasive. (Rowe 2013.)

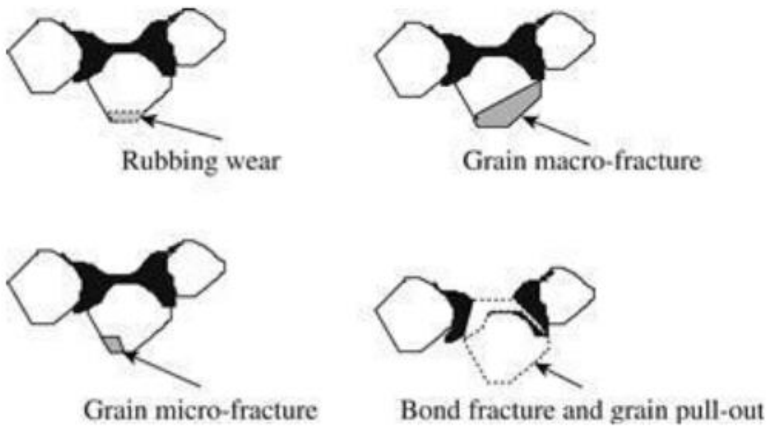


Figure 8. The different wear types of abrasive grains (Rowe 2013).

When the stresses addressed towards the grain are not high enough, fracturing does not occur. In this case the wear type is rubbing, also known as attritious wear, that leads to dulling of the grains. Despite the volume of the tool wear through attritious wear being almost negligible, it is perhaps the most important factor determining the overall wheel wear. The wear flats caused by the attritious wear determine the grinding forces to a high extent, which the probability of the bond fracture and then the overall wheel wear depends on. So, eventually rubbing results in parts of the tool surface breaking off, as explained earlier in the part regarding aggressiveness. (Malkin et al. 2008, p. 296; Rowe 2013.)

Micro-fracturing is a preferred type of grain fracture, where only a small volume of grain is lost. This results in longer tool life and grain maintaining its sharp cutting edges, keeping the grinding forces low. In macro-fracturing, the fracture usually happens along the fracture plains. This results into a loss of larger volume of the grain than in event of micro-fracture. The relation between the two fracture types is mainly dependent on the crystalline structure of the grain. (Rowe 2013; Klocke 2009, p. 29.)

In bond fracture the whole grain, or bigger chunk of bond with several grains, breaks off from the tool. The bond fracture is a wear mechanism that the overall wheel wear ultimately depends on, as the wheel can only wear as fast as the bond fractures. The event of bond fracture is highly dependent on the grinding forces addressed to the grain and the retention strength of the bond. The optimal bond fracture occurs when the grain is worn out and dull, releasing the grain and making room for new grains. The grinding forces that are too high cause unwanted and premature bond fracturing. An example of an effect of such event is seen in Figure 7, regime III, where bigger chunks of bonding material might break off causing excessive tool wear. (Rowe 2013; Badger 2012, p. 1118; Malkin et al. 2008, p. 294.)

In grinding processes with high conformity, such as the ball grinding application, the grinding pressure spreads over to large area. This means lower forces addressed towards single grain, reducing the fracturing and increasing the risk of the grain dulling and glazing. (Rowe 2013.)

2.4 The Effect of Parameters on Material Removal Rate

Every grinding tool specification has its own set of parameters it works optimally with, as well as limits when it comes to material removal rate. These practical limits for increasing the material removal rate can be process and quality related due to for example surface roughness, heat generation and chatter. Depending on the application, the limit for heat generation is different. In precision grinding the limit is often low due to accuracy problems that the heat expansion causes. In addition to quality related factors, the limit for material removal rate can be set by the machine, for instance just by lacking required power. (Rowe 2013.)

The parameters listed earlier, regarding the aggressiveness and tool fracturing, were the feed rate, tool speed and workpiece speed. As expected, the same parameters determine also the material removal rate. To increase the material removal rate, these parameters need to be changed in relation to each other. Ultimately, the material removal depends on the feed rate, as it sets the maximum theoretical value for the material removal. The portion that of the theoretical maximum value is achieved, depends on other factors. (Rowe 2013.)

Increasing feed rate while keeping two other variables constant, results in increased grinding forces and roughness, and reduces specific energy. With reduced specific energy the grinding becomes more energy efficient but a feed rate too high results in high wheel wear, reducing the G-ratio. (Rowe 2013.)

Tool speed has somewhat opposite effects from feed rate. Increasing tool speed, while other factors remain constant, reduces grinding forces and roughness and increases specific energy and tool life (Rowe 2013). Increasing the tool speed has its limit which comes from the speed the tool is rated for. For example, the grinding segments compared in the experiments are rated for 32 m/s.

The workpiece speed has usually smaller effect on material removal rate than the two other variables. However, the workpiece speed affects the probability of thermal damage, as with low workpiece speed the tool and thus the energy is focused on a single area for longer time. So in some applications, increasing workpiece speed can possibly allow the other parameters to be increased and this way increase the removal rate. (Rowe 2013.)

Despite increasing the nominator in the formula for G-ratio, G-ratio will decrease by increasing the material removal rate. The decrease in G-ratio is linear until reaching the maximum removal rate of the tool. Increasing the removal rate over the limit of the tool causes the G-ratio to drop exponentially. (Marinescu et al. 2007, p. 20.)

2.5 Grinding Errors

Defects caused by grinding are often very problematic. In many cases, grinding is one of the last machining phases, meaning that the value added to the workpiece prior to grinding is significant. If the product needs to be scrapped after grinding, it can be very expensive. In this chapter few of the known errors and their causes are introduced.

2.5.1 Excessive Heat Generation

High temperatures are known to cause several problems in grinding. The problems can occur either directly from the heat in a form of thermal damage or indirectly from the effects of heat. In ball grinding, clearly increased workpiece temperature leads to poor accuracy due to heat expansion.

The problems caused by the high grinding temperature include discoloration, tensile residual stress, surface hardening, sub-surface softening. The type of thermal damage and its severity depends on the temperature the surface is exposed to. Further issue with some of the damage types is that they are invisible to bare eye and thus difficult to recognize. (Rowe 2013.)

Low temperature grinding is to be preferred, not only because of its lower tendency to cause issues but also due to its positive effect on ground surface. Grinding with low temperature generates compressive residual stresses on the ground surface, which has positive effect on the fatigue life of the workpiece. (Rowe 2013.)

Most of the means for lowering the temperatures and avoiding thermal issues culminate on lowering the heat generation caused by friction and rubbing. This can be achieved by dressing the tool to get fresh and sharp cutting surface or by changing the tool specification altogether. Softer tool with more open structure has better self-sharpening abilities, keeping the cutting surface sharp. (Rowe 2013.)

Other mean for reducing the workpiece temperature is to improve the fluid delivery or change the grinding fluid (Rowe 2013). Grinding fluid has a significant effect in reducing the grinding temperatures as it works in two ways. It both lubricates the surfaces, reducing friction and also conveys the heat away. (Marinescu et al. 2013, p. 148.)

The last option for reducing the heat generation is to adjust the parameters so that the material removal rate is reduced. Other methods are usually priority as lowering the material removal rate is directly lowering the output. (Rowe 2013.)

2.5.2 Tool Loading

Tool loading, or clogging, can severely impair the output of grinding. In particular, it is a problem in high conformity applications with long contact length, because of their higher tendency for tool loading. The long contact length results in long chips, that get trapped between the tool and the workpiece surface, filling the pores of the tool. (Rowe 2013.)

A clogged tool impairs the grinding performance by different means. Tool loading reduces the available pore space, meaning less space for fluid and thus weakened fluid delivery to contact area. Friction increases due to weakened lubrication, leading to increased temperature and grinding forces. Ultimately, clogging leads to poor surface quality and lowered tool life. (Klocke 2009, p. 152; Rowe 2013.)

The cure for tool loading can often be found in grinding fluid. To prevent clogging of the tool, a sufficient coolant delivery using a coolant with good lubrication abilities is essential. In applications where clogging is a problem, additional coolant nozzles rinsing the tool surface can provide help targeted specifically to this problem. Other means for preventing clogging can be changing the wheel specification or adjusting the grinding parameters for example by increasing the tool speed. (Klocke 2009, p. 153; Rowe 2013.)

3 GRINDING OF VALVE BALLS

The end customer’s constant demand for more efficient processes require more from the used valve system as well. This includes tightening requirements for valve sealing properties, where the quality of valve parts plays a major role. Due to certain advantages of grinding, it is often the only machining operation able to reach the set requirements. Valve balls are not an exception.

3.1 Basic Operation of Ball Valve

A ball valve is one of the valve types that bases its operation on rotation. In a ball valve, of which an example is seen in Figure 9, the valve ball rotates in valve body, controlling the flow through the valve. In the figure, the ball flowport is aligned with piping, letting the flow through thus the valve is open. By rotating the ball by 90°, the valve is shut.

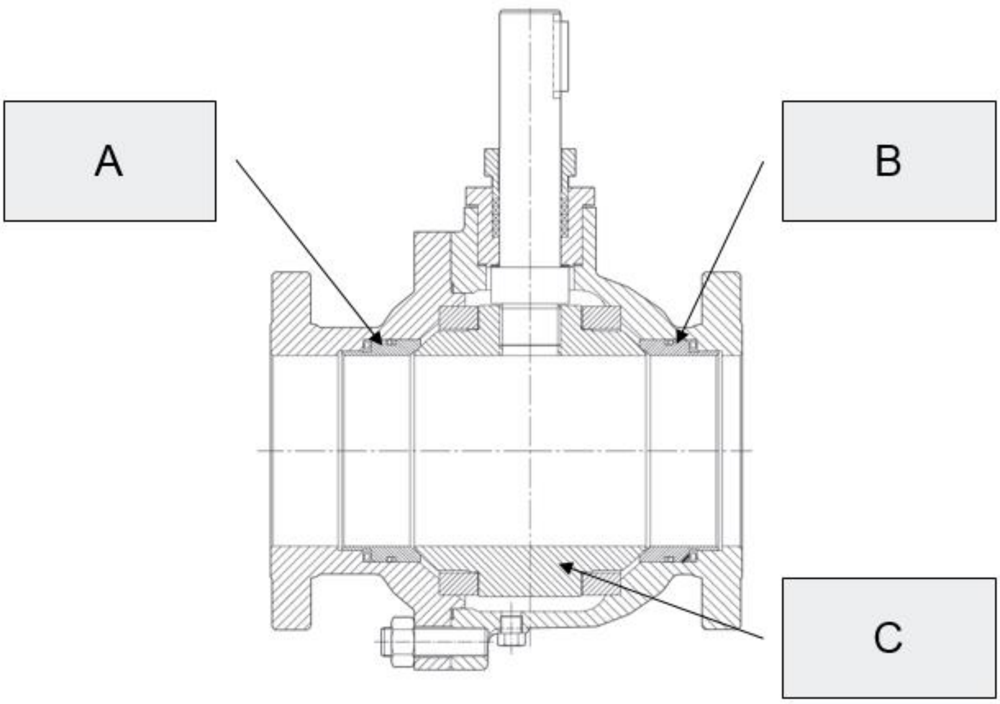


Figure 9. An example of basic metal seated valve (Metso 2016b).

The three main parts of a ball valve are seats, body and a ball, on which this thesis is focused on. In the Figure 9, the ball seats are marked with A and B, the valve ball with C, and together they are mounted in the valve body, forming the main pressure retaining parts of the valve.

The first rotary valves were equipped with soft rubber seats that based their sealing ability on local elastic and plastic deformation of the seat. Ball valves with metal seats came first on the market in the 1960's and have been gaining share of the market from soft seated valves. The metal seated valves have several benefits over the soft seated, which is why they the only option in some applications. For example, the operating temperature of metal seated valve is much wider, all the way from -200 to 800 °C and they are also fire safe. Ball valves are often used as backup valves that shutdown the process in case of emergency, a case where fire safety is a crucial feature. (Kivipelto, 1990, p. 81; Wright & Bregman, 1990, pp. 95–97.)

3.2 Requirements for Valve Balls

Unlike the soft seats, the metal seats do not base their sealing property on material deformation to the same extent. The sealing ability of metal seated ball valve depends largely on how well the seat and ball surfaces match each other. The sealing principle and an ideal contact is illustrated in Figure 10.

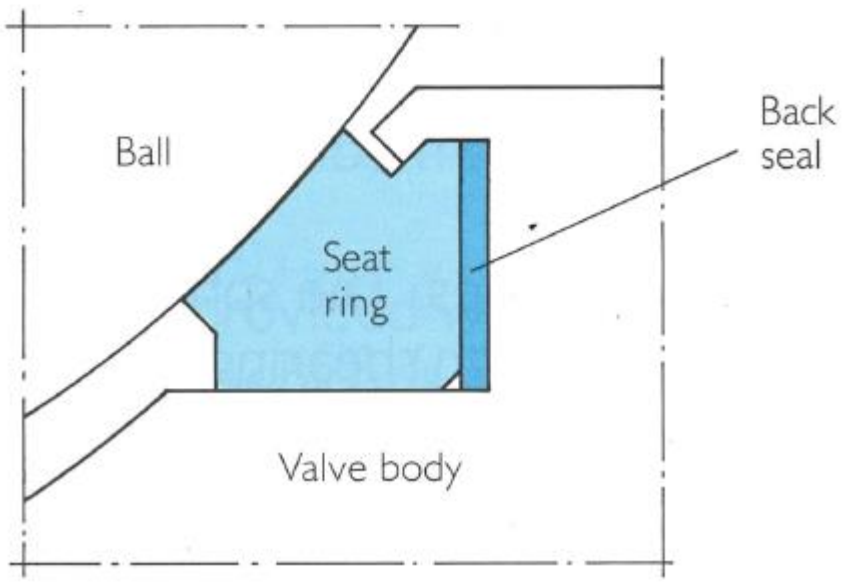


Figure 10. The ball surface and its matching seat surface forming a sealing pair (Kivipelto, 1990, p. 88).

To ensure smooth operation and tight sealing of the valve, the seats can be lapped together with the ball to form a well matching pair. Lapping, however, is a slow process and thus is avoided. The need for lapping ultimately depends on the success of grinding, or how well the parts meet their dimensional and geometrical tolerances. In many cases, the dimensional tolerances could be achieved with even faster processes than grinding. However, many of these processes cannot match grinding in the two factors that are important to sealing ability of the valve: the surface roughness and circularity.

The surface roughness depends on both the used grinding tool and the parameters used with it (Malkin et al. 2008, p. 258). The usual Ra value requirement for surface roughness for spherical surfaces of valve balls is 0.4 µm. In addition to meeting the required surface roughness and tolerances, a certain visual appearance of the ball surface is traditionally preferred. The machine users aim to have grinding marks crossing like on the ball surface in Figure 11. Cross marking has generally been visual evaluation criterion for sphere circularity. Although, the lack of cross scratches does not mean that the ball does not meet the set requirements. Vice versa, a clear cross scratching does not mean that the ball meets the requirements.

Figure 11. An example of desired cross marking on the ball surface after roughing.

3.3 Ground Materials and Grindability

Generally, all the valve balls are ground at least once at some point of their machining. Depending on the application and the customer's desire, different base materials and coatings are available, and thus are ground. The number of different ground materials is limited to rather few, but their material properties differ with large margin, changing their grindability.

The base materials are usually different grades of steel which are, based on the application, either coated or not. The ground materials can vary for example from hard WC-Co (Tungsten Carbide Cobalt) coating, that is ground with superabrasives, to basic austenitic steel. One of the most common base materials, and the material of the workpieces used in the experiments, is ASTM grade A351 CF8M austenitic steel which is a cast equivalent of wrought grade AISI 316.

Despite the fact that an exact definition of the term grindability does not exist, the term is still commonly used. It describes how difficult the material is to grind with certain tools in a certain environment. Practically, it measures the required grinding energy; the lower energy requirement equals easier grinding and thus better grindability. The required grinding energy can be calculated by diving the grinding power P with the specific removal rate Q', so it is the same as specific cutting energy in machining in general. The main factors affecting the energy are the workpiece hardness and wheel sharpness. (Rowe 2013.)

In general, the harder material equals higher grinding forces, thus lower grindability. Even though softer materials are technically easier to grind, they bring about their own problems. The soft ductile materials tend to generate long chips that lead to increased risk of clogging the tool surface. (Marinescu et al. 2013, pp. 523–524.)

Austenitic stainless steels, such like in the experiments, are considered ductile and therefore follow the typical behavior for ductile materials. They are a prime example of material that is prone to generate long chips. In addition, stainless steels have tendency to work-harden, resulting in high grinding forces and tool wear. (Klocke 2009, p. 92, Marinescu et al. 2007, p. 263.)

4 GRINDING TOOLS

The basis of all abrasive processes is understanding and controlling the relations between the abrasive grains, bonding material and the workpiece. The most important of these is between the abrasive and workpiece as it is the premise of material removal. The abrasives have to retain their hardness above the workpiece hardness throughout the whole grinding event, regardless of the temperature raise in the process. Otherwise the result is opposite from wanted and the material is removed mainly from the tool. However, the tool cannot be selected by simply making sure it is harder than the ground material. Excessive hardness will lead to other problems such as thermal damage. Thus, understanding all the parts of the process and how they are related is crucial in selection of the right grinding tool. (Marinescu at al. 2013, pp. 5–6.)

Grinding tools come in numerous different shapes and material combinations for different grinding applications. Often the grinding tools are wheel shaped but different shapes such as cups exist. Taking different shapes, abrasives and bond materials into account, the grinding tool companies might offer tens of thousands of slightly different products to fit every need. (Malkin et al. 2008, pp. 11–12.)

For ball grinding at Metso, few different tool specifications are used for different materials. The shape of the tool depends on the type of abrasive and workpiece size. The superabrasive tools are small, about 10 mm in diameter, bits attached to grinding head. Tools with conventional abrasives are cup shaped for small ball sizes. For larger valve balls, the tool consists of segments in a grinding head, essentially forming a cup with gaps between the segments. This tool related chapter focuses on the type of tools that are compared in the experiments, aluminium oxide in vitreous bond.

4.1 Tool Specification

Grinding tool consists of abrasive grains that are fixed together with bonding matrix. In addition to these two main components, different fillers and grinding aid substances can be added to the tool. The variation in grinding tools does not stop just at the ingredients, but for example, the grain size and porosity vary depending on the application and have a significant effect on the grinding process. To perceive often invisible differences in grinding tools and to be able to compare them, standardized marking systems for grinding tools have been developed. Conventional and superabrasives have both their own marking systems, of which different standardization organizations have their own slightly different versions. An example of standardized marking system for conventional grinding tools is the American National Standard Institute's ANSI B74.13, which is shown on the Figure 12**.** Other marking systems, like German DIN-standard 69 100 are quite similar to it. (Malkin et al. 2008, p. 12; Klocke 2009, pp. 45–46.)

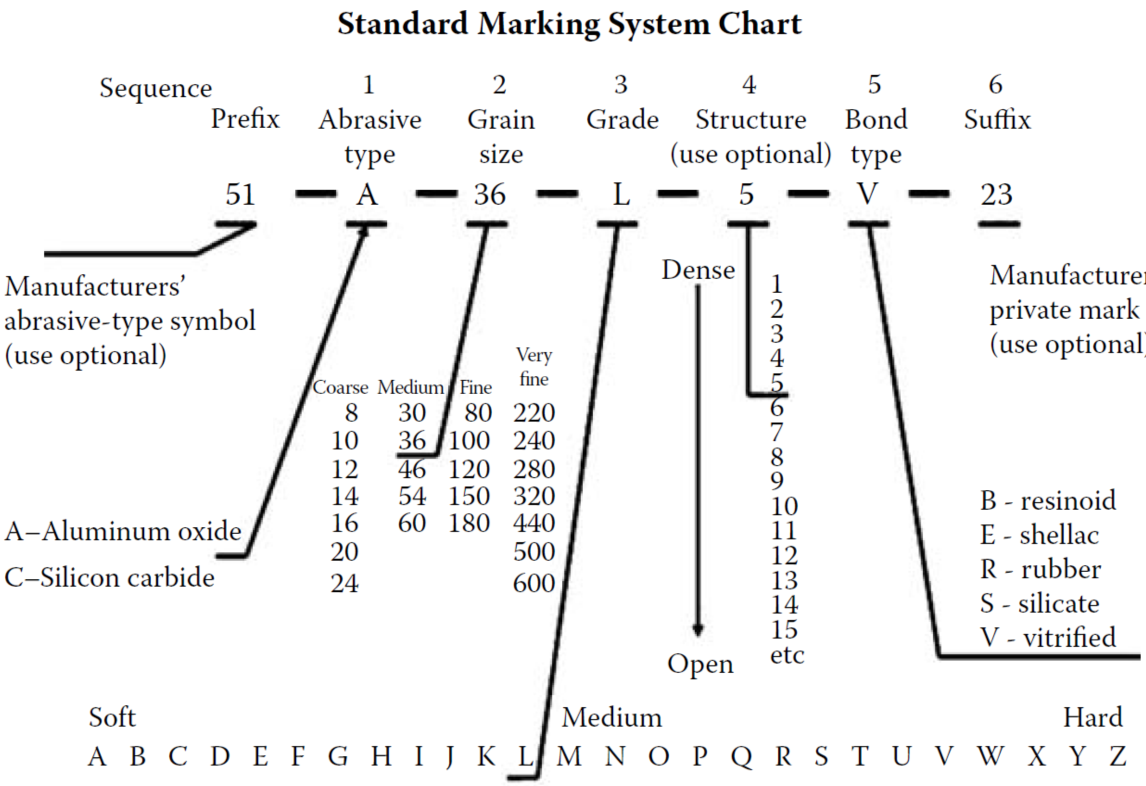


Figure 12. An example specification of a certain aluminium oxide tool according to ANSI standard (Marinescu et al. 2007, p. 109).

The tool specification, consisting of series of numbers and letters, tells the main components of the tool, as well as features of the wheel. Explanations behind each letter and number in marking system for conventional abrasives are given below.

The prefix is reserved for use of the manufacturer. The use of it is optional, but several manufacturers use it to differentiate their abrasive variants. The first actual character expresses the type of the abrasive material, which is traditionally either A for aluminium oxide or C for silicon carbide. (Malkin et al. 2008, p. 12; Klocke 2008, p. 46.) However, manufacturers seem to digress from the standard and use other letters or letter-number combinations to represents their specific kind of grain, for example the initials of the trade name.

The number after the abrasive type determines the grain size of the abrasive, which is measured a bit differently, depending on the standard. In the commonly used ANSI-standard, the grain size is reported as the mesh size of the sieve the grains were sorted with, thus the nominal grain size actually has a range of different grain sizes. Some manufacturers use an additional number after the grain size specification, to express whether the tool has various grain sizes. The number 1 usually entails that the tool consists only the indicated grain size, where the other numbers represent certain mixtures of different grain sizes. (Malkin et al. 2008, pp. 12–15; Klocke 2008, p. 47, Rowe 2013.)

Third actual character, a letter ranging from A to Z, expresses the grade of the tool, from soft to hard in respective order. The tool grade is a general determination of the strength of the tool, in other words the resistance of grits breaking from bond. This is directly related to tool wear as the softer tools tend to wear quicker. The tool grade can be defined in different ways, but a common one is based on porosity. The harder grade has more bond material and is less porous. The hardest grade of Z having about 2% porosity, Y having 4% porosity and so on. However, the scale is not universal and there is diversity between the manufacturers. (Malkin et al. 2008, pp. 15–16; Klocke 2008, p. 47; Rowe 2013.)

The fourth character indicates the volume of abrasive in the tool. The tool structure varies between dense and open, where higher number means less abrasive, resulting in more open packing density of grains. The scale for structure is not universal between the manufacturers, so the structure numbers and what they represent vary. On a commonly used scale from 0 to 25, a low end number for structure such as 4 or lower can be considered very dense. In terms of volume it equals almost 60% abrasive, resulting in tight packing. Generally, lower packing density gives grinding fluid a better access to the surface and results in more efficient swarf removal. (Malkin et al. 2008, p. 16; Rowe 2013.)

The last character before the suffix indicates the used bond material. These days, the most common bond materials are either vitrified (V) or resinoid (B) and the other types are used quite rarely. After the letter for bond material, manufacturers may use an optional suffix to further differentiate the product. (Malkin et al. 2008, p. 16.)

4.2 Abrasives

Abrasives used in grinding tools can be either natural or man-made, synthetic materials. Regardless of the origin of the abrasive, their use is based on their hardness, which is why grinding was earlier done with hard materials found from nature, such as natural corundum, garnet or diamond. These days, corundum and diamond are still widely used but are mainly synthetic. (Malkin et al. 2008, pp. 19–20.)

The abrasive materials are split into two groups: conventional and superabrasives. Corundum, or aluminium oxide (Al_2O_3) and silicon carbide (SiC) are considered as conventional abrasives, where cubic boron nitride (CBN) and diamond are called superabrasives, because of their superior hardness. (Klocke 2008, p. 19; Rowe 2013.) The experimented tools equip different types of aluminium oxide grains, on which differences this chapter is focused on.

4.2.1 Aluminium Oxide

Aluminium oxide goes by with many names, including corundum, alumina and aloxide. It is a widely used abrasive for grinding of different ferrous metals. Aluminium oxides can be grouped further to fused and sintered based on a matter how they are made. Prior to 1904 and the invention of the Higgins furnace, natural corundum was used in the form of minerals emery and corundum. These days, only the emery is still in used in coated papers. After the invention of Higgins electric arc furnace, production of various fused alumina started, which are still used widely in precision grinding processes. However, more recently founded ceramic aluminium oxides have taken a significant share of the market. (Jackson & Hitchiner. 2013, p. 20.)

Differences of Two Grain Types

Nowadays, this more novel grain comes in different variations and goes by with several general and trade names such as: ceramic, sintered, sol-gel, seeded-gel (SG) and Cubitron.

Yet, when the ceramic grain was first introduced in 1981 by company 3M coming out with their Cubitron grain, it wasn't used in grinding wheels at all. The potential of ceramic grains in grinding was discovered later, after Norton had launched their similar ceramic SG grain in 1986. It took time before the industry learned how to apply this new kind of grain. It was tougher than the conventional corundum and without altering the grinding parameters for the new kind of tool, it usually led to dulling of the wheel. To avoid excessive grinding forces resulting from the toughness and ensure required hardness, at first the sol-gel grains were mixed with the conventional grains as little as 5% of the total grain volume. These days the common mixtures of SG are 10%, 30% and 50%. (Marinescu et al. 2007, p. 80; Badger 2012, p. 1115, Rowe 2013.)

Being the same material as the conventional alumina, many of the material properties of sol-gel grain are about the same, but the different production method results in some advantages. The properties such as shape and size of the grain vary less, making sol-gel grains more homogenous. (Nadolny 2014, p. 85.) When correctly used, sol-gel grains can provide higher material removal rate with lower grinding forces and thus lowered temperature, but often the biggest benefit is its longer tool life. Because of these features, sol-gel alumina can be considered as an option to much more expensive superabrasive CBN in certain applications. (Webster & Tricard 2004, p. 598.)

The benefit of ceramic grains, over the conventional fused alumina grains, comes from their different fracturing mechanism explained earlier in the chapter 2.3.1 Tool fracture mechanisms. The both grains types have the same basic behavior, requiring enough force for the grain to fracture and self-sharpen. The biggest difference between the two is in the volume the grain loses when a fracture occurs. The ceramic grains have tendency to micro-fracture where the conventional aluminium oxide macro-fractures along the fracture plains, leading to bigger volume lost and often duller grain. (Badger 2012, p. 1116, 1122.)

As stated earlier, the fused grains are apt to macro-fracture where the sol-gel grains micro-fracture. The different fracture behavior is explained by looking at their structure more closely. A fused alumina grain is usually a single crystallite, that consists of crystallographic planes like in the illustration in Figure 13. Forces addressed to the grain in the grinding event cause cracks to advance parallel to these planes, resulting in a significant loss of volume and in the grain. This form of cracking also leads to duller cutting edges than micro-cracking of ceramic abrasives. (Nadolny 2014, p. 85.)

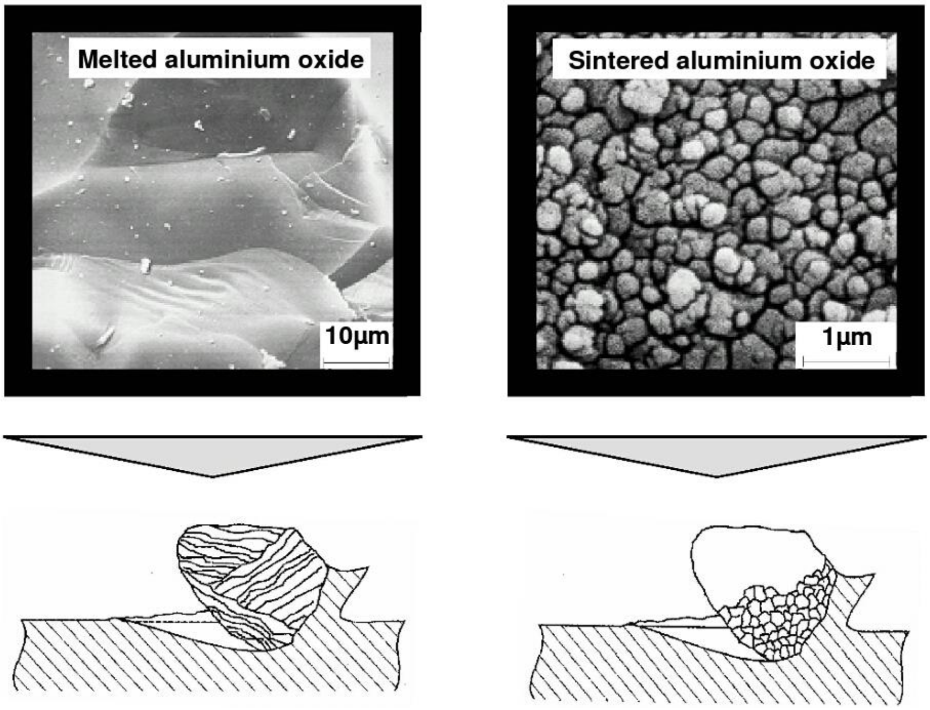


Figure 13. A representation of the microstructural differences in fused and ceramic aluminium oxide grains (Klocke 2009, p. 30).

Despite the size of a single grain being about the same whether it is fused or sol-gel grain, there is a major size difference in the microstructural scale. Instead of plane structure, a ceramic grain has a submicrocrystalline structure that consists of microparticles with usual size between 0.1 and 1μm. This difference in their microstructure can be seen in the Figure 13. Because of the microparticles the ceramic grain has ability of effective self-sharpening without significant loss of the grain’s volume. Because of this, tools with sol-gel grains have more and sharper cutting edges in comparison to fused alumina, with longer tool life. (Nadolny 2014, p. 85.)

4.3 Bond Material

Bond in grinding tool can be considered to be everything else but the abrasive grain. The bond plays an important role in the grinding process as it ties the individual grains to the tool and determines the self-sharpening abilities and wear of the tool to a high extent. (Klocke 2008, pp. 37–38; Marinescu et al. 2013, p. 275.) The properties of the bond are not dependent just on the bonding agent, but the tool grade and structure. In general, the more porous bonds provide less retaining strength. (Marinescu et al. 2007, p. 109.)

The most important task of the bond is to retain the grain until it gets dull and then release it to make room for new grains. In addition to this main task, bonding agent has other important functions as well, such as transferring the forces from the machine spindle to workpiece and dissipating the heat generated by the grinding process. (Marinescu et al. 2013, p. 275.)

Generally, there are six different bonding agent types used in grinding tools with conventional abrasives: resin, shellac, oxychloride, rubber, silicate and vitrified. The most common ones are resin and vitrified bonds, vitrified representing about a half of the market. All the grinding tools compared in the experiments, are also vitrified, therefore the bonding material chapter is focused only on vitrified bonds. (Malkin et al. 2008, p. 27.)

4.3.1 Vitreous Bonds

The vitreous bonds have multiple advantages, which is why they are so popular. One of the main advantages is the very porous structures that the vitreous bonds make possible. They are also stabile in high temperatures, brittle, rigid and resistant to oil and water. (Marinescu et al. 2007, p. 108; Klocke 2009, p. 40.)

The usual base materials for vitreous bonds are clay, feldspar and frit. The ingredients are mixed and molded in room temperature, after which the blank is fired in a kiln, transforming it into a glasslike material. To achieve highly porous structure without sacrificing too much of the structural integrity, sometimes additional ingredients are added to the mixture. They can be hollow particles such as bubble alumina, that remain in the structure and break open in the grinding event, opening up a pore. They can as well be combustible materials, such as sawdust. The combustible material burns away in the firing process, leaving behind a pore. (Marinescu et al. 2007, p. 108, 112.)

4.3.2 Bond Material Additives

In addition to materials that are mixed in the bond for production reasons, further additives may also be added to bond matrix to modify the properties of the tool and improve its performance. The additives can be added to either the bond mixture before kilning process or after the kilning as fillers by impregnating the tool. (Klocke 2009, p. 41; Marinescu et al. 2013, p. 278.)

The necessity and use of additives and fillers depend on the requirements set by the application. They can fulfill different tasks such as improve the tool strength, increase the heat resistance or act as a lubricant. (Klocke 2009, p. 41.)

Common lubricating agents added to grinding tools are sulfur, wax or resin. They are added to a tool by impregnating it, so that the tool pores are filled with the substance. For example, in internal grinding in bearing industry, where the contact lengths are usually long, wheels are often impregnated with sulfur which is an effective extreme pressure (EP) lubricant. (Marinescu et al. 2013, p. 278.)

An exact mechanism how sulfur effects the process is not very well known. However, it is believed that sulfur chemically reacts with the ground metal, forming a lubricating sulfide film. Sulfur additions to the ground metal are known to have significant increase on the G-ratio and similar effects are witnessed with sulfur additions in the grinding tool. Despite the advantages of sulfur additives in grinding, the sulfur impregnated wheels have been losing popularity due to their downside of being a possible source for health and environmental issues. (Marinescu et al. 2007, p. 113; Malkin et al. 2008, p. 306.)

5 GRINDING FLUID

The grinding fluid is often a crucial part in many of the grinding processes, as it can have significant effect on the output. The fluid is largely responsible for lubricating and cooling in the process, which are the two of its main tasks. By reducing friction between the workpiece and the tool with a lubricative film in between, grinding forces drop. Lowering the grinding forces leads to decreased the wheel wear and lowers the amount of heat that is generated in the process. (Klocke 2009, p. 113; Marinescu et al. 2013, p. 214.)

In many instances, the grinding fluid is simply referred as coolant, which derives from the second of its main functions. The grinding fluid works as a coolant in two ways, both by cooling down the contact area and by bulk cooling the workpiece by transporting the heat away. (Klocke 2009, p. 113; Marinescu et al. 2013, p. 214.)

In addition to lubrication and cooling, grinding fluid has some secondary tasks and benefits. With correctly directed and powerful enough spray, the tool surface can be flushed, cleaning out the swarf and thus preventing clogging of the tool. Grinding fluid also works also a corrosion inhibitor for both the workpiece and the machine. (Klocke 2009, p. 113, 125.)

The primary requirements for effective grinding fluid are good lubrication, cooling and flushing properties as well as good corrosion protection. These requirements for functional properties are set by the main tasks of the fluid and are related to the performance of the grinding process. The secondary requirements for grinding fluid are related to operational behavior, or efficient and safe use of the fluids. The most important of these requirements is the safety for human health and environment. The same reason why some grinding fluids or their additives have lost popularity despite fulfilling the performance requirements. Further requirements for operational behavior are for example easy filtration and recycling, bacteria resistance, low flammability and suitability for the machine and its tools. (Marinescu et al. 2007, pp. 195–196.)

5.1 Fluid Types

On a broad level the fluids can be split based on if there is water present when the fluid is applied. Straight oils (water-immiscible) do not contain water, where soluble oils (water-miscible) and synthetic fluids (water composite fluids) are water based. Different fluid types have their own basic properties which are altered with series of additives. (Malkin et al. 2008, p. 304; Marinescu et al. 2007, p. 196.) The optimal grinding fluid for each application is different and therefore selection should be done after weighing which of the fluid's tasks are the most crucial and which fluid fulfills them the best. (Klocke 2009, p. 113.)

Customarily, straight oils provide the best lubrication out of grinding fluids. The low friction, due to good lubricative properties of oil, contributes to high G-ratios, low grinding forces and good surface finish. The lubrication performance of oil is linked to its ability to reduce attritious wear and wear-flats it causes. The Figure 14 shows an area of wear-flats on a function of material removal and it compares nothing but air, two oil-water solutions with different concentrations and straight oil. The superiority of an oil as a lubricant can be clearly seen, particularly with higher material removal rates. The total area of wear flats remains rather constant with oil, where in dry grinding or with emulsion its starts to increase quickly with material removal. Between the two emulsions, increasing the oil content decreases the area of wear-flats caused by attritious wear and lowers the grinding forces. (Malkin et al. 2008, p. 304.) Besides the superior lubrication, oils are very effective corrosion inhibitors and are resistant to bacteria even without additives, therefore oils have longer lifespan than water-based fluids (Klocke 2009, pp. 116–117).

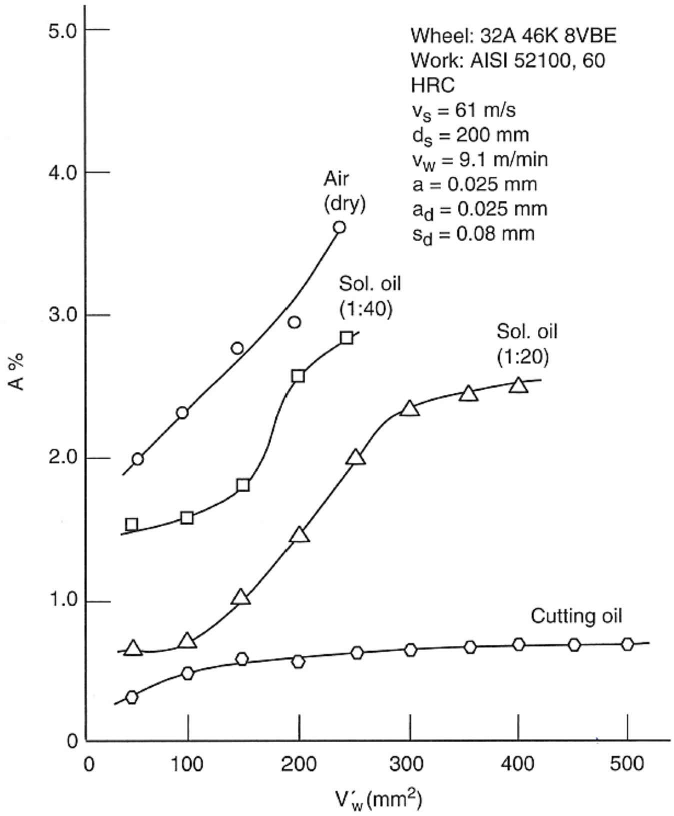


Figure 14. The area of wear flats versus material removal in certain grinding process with different grinding fluids (Malkin et al. 2008, p. 305).

The oils come with their downsides, which is why in practice the water-based fluids are used more often. The most substantial of functional downsides of oil is its poor cooling ability. From the Table 1, a comparison between the thermal properties of oil and water can be seen. The specific heat capacity of water is more than two times over the oil and the heat conductivity is more than four times higher in favor of water. The same table also shows the major difference in viscosities that explains the superior lubrication properties of oil in comparison to water. (Klocke 2009, p. 117.)

Table 1. Comparison of properties of oil and water (modified from Klocke 2008, p. 117).

		Mineral oil	Water
Specific heat capacity	c_p [J/(g*K)]	1.9	4.2
Heat conductivity	λ [W/(m*K)]	0.13	0.6
Heat of evaporation	r [J/g]	210	2260
Viscosity (40°C)	v [mm^2/s]	5…20	0.66

Due to the inferior thermal properties of oil in comparison to water, its ability to transfer the generated heat away is significantly lower. However, by using oil, there is less heat generated to begin with. Thus, the most suitable grinding fluid from lubrication and cooling perspective depends on the application. In high heat generation processes, such as creep feed grinding, where effective cooling is crucial, water-based fluids are often considered as an only option. (Marinescu et al. 2007, p. 356.)

Rest of the disadvantages of the oil are related to operational behavior and safety. The oil's tendency to form mist is problematic and causes different issues. If the machine is not fully enclosed, the machine user might be exposed to respirable oil mist, causing a possible health hazard. The oil mist is also highly flammable, posing another safety risk. A major increase in the workpiece temperate, caused for example by a sudden loss of the fluid delivery, can be enough to ignite the mist. As a preparation it is necessary to have a fire exhaust system and safety guards for the temperature. (Klocke 2009, p. 117.)

Soluble, or emulsifiable oils are concentrates that are mixed with water and emulsifier in certain ratios to create emulsions. The water content in emulsions is usually high, which is why their properties are usually more water-like. By increasing the oil content, the properties and behavior becomes more oil-like, increasing the lubrication performance while reducing the cooling abilities. The effect of increased oil content and how it affects attritious wear can be seen from the Figure 14. (Marinescu et al. 2007, p. 198.)

Much like emulsions, synthetic grinding fluids, or aqueous solutions, are water-based fluids. The main difference to emulsions is the absence of oil. To compensate this and to improve the properties, just like in other fluid types, different additives are added in the mixture. (Marinescu et al. 2007, p. 197.)

The grinding fluid used in ball grinding at Metso was earlier straight oil, but was changed to water-based emulsion in the 1990's. One of the reasons for the change was the better cooling performance that helped in reaching the geometrical tolerances. The cooling ability of the oil was insufficient to keep the valve ball cool enough during the grinding, causing the heat to distort the ball and not meet the tolerances.

5.1.1 Fluid Additives

The properties of grinding fluid are enhanced by using different additives. Additives can be split on three groups based on their function. They can serve as changing the physical properties of the fluid, such as viscosity. They can serve as changing the chemical properties of the fluid, for example corrosion inhibitors. Finally, they can work as tribologically active substances, that alter the friction conditions. Tribologically active additives include polar additives, friction modifiers (FM), anti-wear (AW) and extreme pressure (EP) additives. (Klocke 2009, p. 119–120.) The main additive types, that affect the material removal, and their modes of actions are listed in the Table 2.

Table 2. The additive types associated with cutting performance (modified from Brinksmeier et al. 2015, p. 608).

Additive type	Substances	Mode of action, function
Anti-wear additive (AW)	Acid and nonionic phosphoric acid ester, zinc dialkyldithio-phosphate	Reduces abrasive wear of rubbing surfaces by physisorption
Extreme pressure additive (EP)	Chlorineparaffine, sulphurous ester, phosphoric acid ester, polysulphide	Protection against wear by formation of adsorption or reaction layers, prevent microfusing of metallic surfaces
Friction modifier (FM)	Glycerol mono oleate, whale oil, natural fats, oils, synthetic ester	Lowers friction and wear, improve adhesion of lubricating film
Passive extreme pressure additive (PEP)	Overbased sodium or calcium sulfonate	Kind of solid lubricant, forms a film between the surfaces

Tribologically active additives is likely the group with the most significant effect on cutting performance as they improve the lubrication properties. The different additives of grinding fluid work on different operational areas. The polar additives, that are mostly fatty substances from plants and animals or synthetic esters, form a lubricating film on the workpiece surface due to their polarity. The film lubricates the process effectively until about 150 °C. (Klocke 2009, p. 120; Marinescu et al. 2007, p. 199.)

The extreme pressure additives work like the polar additives, forming a lubricating film between the workpiece and the tool. EP additives become active when the polar additives lose their effect. Common extreme pressure additives are phosphor and sulphur. Phosphor forms metal phosphates where the sulphur forms metal sulphides, which serve as solid lubricating layers. Phosphor becomes active in about 50 °C, before losing its effect in about 850 °C. Temperature range of sulphur starts from about 500 °C and ends at about 1000 °C. As mentioned in the chapter 4.3.2 Bond material additives, sulphur as an EP additive, can be added to either tool or the grinding fluid. (Klocke 2009, p. 120; Marinescu et al. 2007, pp. 199–200.)

As seen on the Figure 15, with low material removal rates the wheel wear is rather level between the different fluids. When the material removal rates start to increase, the temperature starts to increase as well and the fluid with only polar additives loses its lubrication capabilities, resulting in increased wheel wear. On the other hand, grinding fluid with sulphur addition, retains its lubricating abilities and the wheel wear stays relative flat.

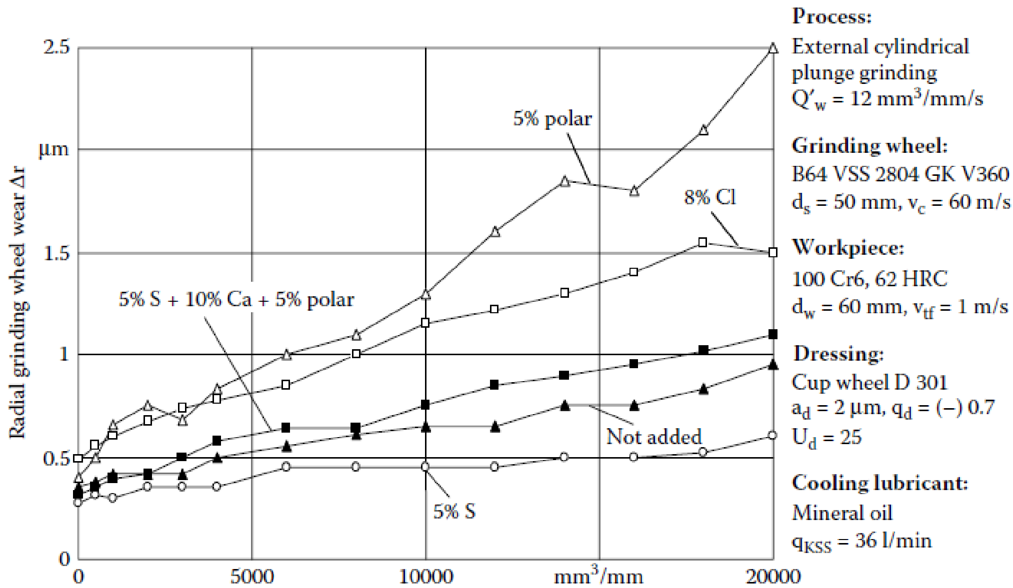


Figure 15. The effect of additives to grinding wheel wear on a function of material removal (Marinescu et al. 2007, p. 200).

5.2 Fluid Delivery

Grinding fluid can improve the output of grinding process with a magnitude. To do so, and for the fluid to fulfill its most important tasks, the fluid needs to reach the grinding zone. To ensure this, the fluid nozzles need to be selected and directed accordingly. To maximize the benefits from grinding fluid, the fluid also needs to fulfill its secondary tasks such as cleaning swarf from the tool surface and bulk cooling around the contact area. In many cases, just one nozzle or nozzle design cannot fulfill all the tasks and it is necessary to have several nozzles each for different purposes. (Marinescu et al. 2007, p. 206; Marinescu et al. 2013, pp. 214–215.)

5.2.1 Nozzle Design

A revolving tool generates an air barrier around itself, of which effect gets stronger with increasing tool speed. For the fluid to reach the contact area, the air barrier needs to be overcome. In order to do so, the fluid flow needs high enough velocity, for which a common recommendation is to match the wheel peripheral speed. Ultimately, the grinding fluid reaching the contact zone depends on the nozzle. After all, the nozzle determines the fluid flow, including the velocity, to a great extent. (Marinescu et al. 2007, p. 204, Marinescu et al. 2013, p. 228.)

The optimal design of the nozzle depends on its task. For main tasks, lubricating and cooling the contact zone, correctly directed high pressure is needed and the nozzle design should be selected correspondingly. The contact zone lubrication is not necessarily as much matter of the fluid volume as it is the fluid entering the zone. Thus, to ensure the fluid reaching the contact area, the pressure can be increased by reducing the opening of the nozzle while keeping the flowrate constant. To achieve high enough velocity with nozzles with large openings, more powerful pumps producing more heat are needed. Since it is waste of energy to accelerate higher quantities of fluid than necessary, nozzle types with limited openings are often used to deliver fluid to the contact zone. (Marinescu et al. 2013, p. 214, 230.)

For secondary tasks of the fluid, such as bulk cooling, the efficiency is not based on the pressure, but the flowrate. Even if the extra fluid from the main nozzles serves in bulk cooling, it is often more practical to have the separate nozzles for the purpose. For bulk cooling purposes, simple flood nozzles with low pressure are enough and are the most efficient solution. (Marinescu et al. 2013, p. 214, 230.)

6 DESIGN OF EXPERIMENTS AS A TOOL

Development techniques like Six Sigma use various of statistical tools on a path towards improvement, one of these tools is experimentation. The DMAIC improvement model of above mentioned Six Sigma consists of phases for Define, Measure, Analyze, Improve and Control, where it also derives its name from. Design of Experiments is a commonly used method in the analyze phase, in transition to improve. (Pyzdek 2003, p. 3.)

Experimentation is a tool that aims for better understanding and improvement of the process that it is performed on. It is widely used on all fields, but is particularly important in product design and process improvement on technical field. (Pyzdek 2003, p. 3.) In short, the usual goal of DOE is to recognize the critical process factors, measure their effect on the output and give out their optimal values for desired output (Meran et al. 2013, p. 7).

6.1 Process Model

A process, like grinding in this case, can be anything from chemical to machining processes or to something from a whole different field. As seen from the Figure 16, process is a combination of input, process factors and output. In a process, various factors working on the input, turn it into output. The input and factors can be anything from machines to materials to people. Often, the input is a material that machine and other factors turn into finished or semi-finished products. The process factors taking a part in the process can be either controllable or uncontrollable, depending on if they can be altered by the process controller or not. For example, in machining operation, the feed rate or the spindle speed can be directly controlled but the cutting fluid temperature often not. (Montgomery 2012, pp. 1–3.)

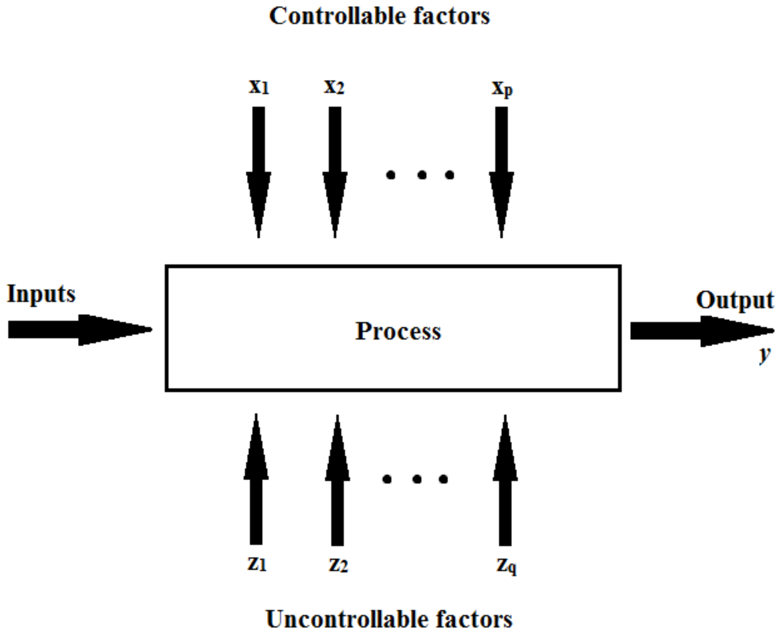


Figure 16. An example of a process model (modified from Montgomery 2012, p. 3).

6.2 Purpose of Experiments

The purpose of each experiment varies and the ultimate goal is not necessarily the obvious, maximizing the output. The purpose of an experiment might be to discover the most influential factors for the output or to determine the optimal factor levels in a way that the output is as close as possible to desired one. The reason for running an experiment might as well be to determine the factors in a way, that results to least variation in the output. (Montgomery 2012, p. 3.)

Some of the above-mentioned common reasons for running an experiment are often referred with specific names depending on the type of the experiment. An experiment aiming to identify the most significant factors and familiarize the process is often referred as screening experiment. It is usually a start point of experimenting for unknown processes and further testing follows once the process is more familiar to the experimenter. Optimization experiment commonly follows the screening experiment. Once the significant factors are known, their optimal levels for desired output are determined with optimization. (Montgomery 2012, p. 14.)

As the name suggests, confirmation experiments aim to confirm that the certain process behaves in expected manner. Confirmation experiments are commonly used in situations where some previously used part of the process is replaced with a new corresponding one or the production is moved from plant to another. It is verified that changing the factor with equivalent one or changing the site does not affect the output. (Montgomery 2012, p.14.)

Many other types of experiments do exist, such as discovery experiment used to resolve the outcome of adding something new to the process. Ultimately, the type of experiment depends on what kind of questions it is aiming to answer. (Montgomery 2012, p.14.)

6.3 Experiment Strategies

The experiment can be performed with different strategies such as best-guess approach, one factor at a time (OFAT) or different factorial designs. The most suitable design depends on the available recourses as well the experience of the experimenter. (Montgomery 2012, p. 4.)

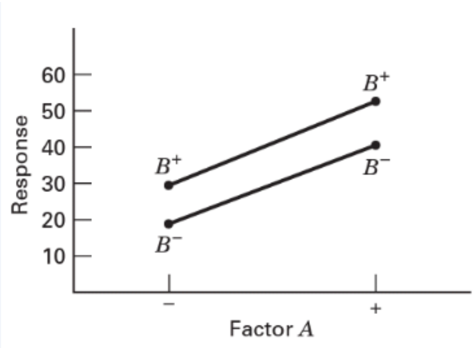
6.3.1 The Best-guess Approach

The simplest of the methods, which can also be the most time consuming, is the so called best-guess approach. In this method one or a few factors are changed at a time, based on the best guess of the experimenter observing the process. The method is often used and works fairly well, owing to the prior experience and knowledge of the experimenter. However, the method has two major weaknesses. If the initial guess is far from the desired outcome, the experimenter might have to take numerous runs without a guarantee of any sort of success. Another disadvantage of the method is its uncertainty. After the experimenter has reached the level he is happy with, there is still no guarantee that it would be the best possible level. (Montgomery 2012, p. 4.)

6.3.2 One Factor at a Time

The OFAT approach is another widely used, slightly more complex method than the best-guess approach. In beginning of OFAT, each factor is set on its baseline. Then each factor is varied while the others are kept on the baseline. After the test runs, series of graphs are composed of the test results. The graphs show the direction that changing each of the factors lead to. The optimal combination of parameters is determined by selecting the level for each parameter that lead closer to desired output. The major downside of the OFAT method is its inability to bring out possible interaction between the factors. It is possible, and quite usual, that the effect of a certain factor depends on the level of some other factor. (Montgomery 2012, pp. 4–5; Pyzdek 2003, p. 607.) Interactions between two factors are quite usual, however three and higher order interactions are rather rare in engineering sciences (Mathews 2005, pp. 213–214).

An example of interaction between two factors is shown on Figure 17. On the left side, no interaction is present as the lines B^+ and B^- run parallel. On the right side, a clear interaction of the factors can be seen. The effect of the factor B highly depends on the level of the factor A. Recognizing interactions is very important as they might have more significant effect on the response than the main effects themselves. In cases with significant interaction, the interaction can mask the real significance of the main effects. It seems that one of the factors does not have an effect, when in reality it just depends on the other factor. (Montgomery 2012, pp. 184–186.)



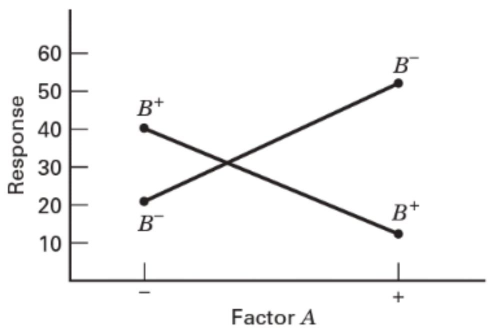


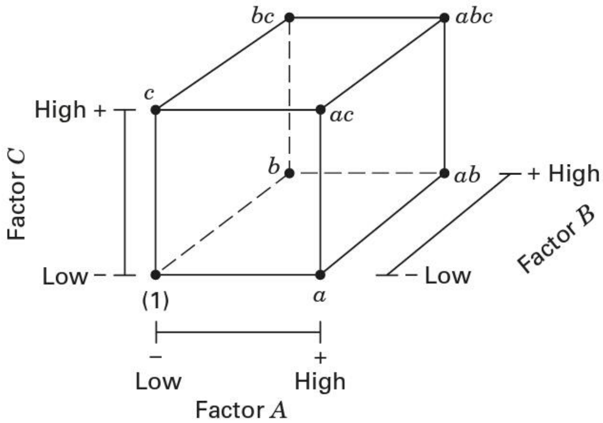
Figure 17. An example of factors that are not interacting (left) and interacting (right) (Montgomery 2012, p. 184).

6.3.3 Factorial Designs

The advantages of factorial designs are clear, thus its often the best practice for performing an experiment. As mentioned previously, factorial designs take interactions into account but they are also more efficient than OFAT method. Due to an experimental error, OFAT method is often necessary to replicate and for example in two factor two level experiment, the factorial design lowers the number of required runs from six to four. (Montgomery 2012, p. 187.)

Depending on the available resources and the number of studied variables, either a full or fractional factorial experiment can be performed. Full factorial experiment is the more extensive approach, providing more accurate information than the fractional designs. However, with number of factors increasing, the number of required test runs for full factorial design starts to increase quickly. For full factorial experiments the number of test runs follows 2^k, where the k is the number of factors. For example, an experiment with five factors would lead to 32 test runs. With limited recourses it might not be possible to run full factorial design with several factors. Particularly, when well planned one-half fractional design often provides good enough information about the main effects as well as some information about the interactions, with half a number of runs. (Montgomery 2012, pp. 5–7.)

A commonly used full factorial design that does not lead to excessively high amount of test runs, is a 2^3 factorial design, or three factors on two levels. The design leads to eight test runs which can be demonstrated with a cube, each corner representing different combination of factor levels. Such cube with its respective design matrix is illustrated in Figure 18. A minus means that the factor is on its low level and a plus expresses the high level. (Montgomery 2012, pp. 241–242.)



	Factor		
Run	*A*	*B*	*C*
1	–	–	–
2	+	–	–
3	–	+	–
4	+	+	–
5	–	–	+
6	+	–	+
7	–	+	+
8	+	+	+

Figure 18. A visual expression of the 2^3 design and design matrix it is based on (Montgomery 2012, p. 241).

6.4 Principles of Experimenting

The experimental designs are based on three basic principles of randomization, replication and blocking, which are briefly covered in this chapter (Montgomery 2012, p. 12).

6.4.1 Replication

The experiment can be performed either replicated or unreplicated. Replication means that the test runs are taken again on number of times the experiment is replicated, thus it is very time consuming. The problem with single replicate experiments, is the lack of estimate for experimental error. In single replicate experiments, where the experimental error is not well known, there is a risk of fitting the model to noise. An example of this and how to avoid it, is shown on Figure 19. On the left side of the figure, the values for variable x are set close to each other. Due to experimental error in response y, both the values for factor x resulted in same output. The effect of factor x seems to be negligible when the true factor effect shows a clear increase in response by increasing factor x. On the right side of the figure, the error in response is identical to the left side, but the estimate of the factor effects is much closer to the true factor effect. This much better fit of the estimate is a result from spacing the values for factor x far enough from each other. (Montgomery 2012, p. 256.)

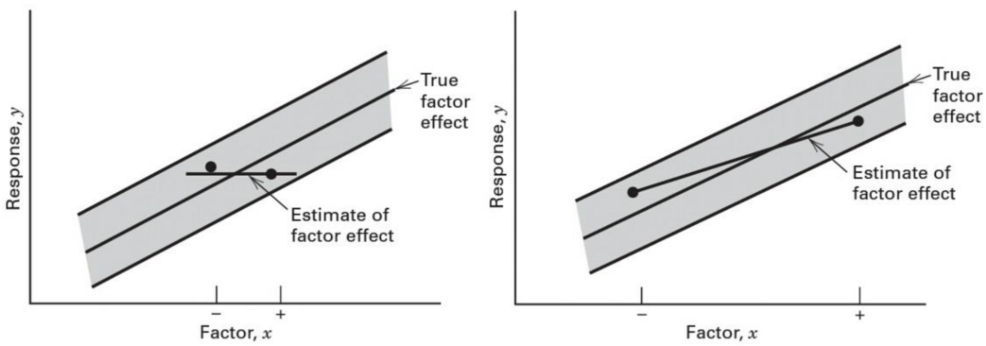


Figure 19. An example of differently set values for factor X and their effect on the estimate (Montgomery 2012, p. 256).

6.4.2 Randomization

Another important concept in experimenting is randomization. It is an important technique used against nuisance factors, or factors that can affect the results but are not an interest. Depending on the nature of the nuisance factor, there are other ways of handling them such as analysis of covariance and blocking, but they require the nuisance factor at least to be known. If the nuisance is unknown and uncontrolled, or so called noise factor, randomizing both the allocation of experiment material and the order of test runs spreads its effect between different runs and results in less biased experiment. (Pyzdek 2003, p. 611; Montgomery 2012, p. 12, 139.)

6.4.3 Blocking

Blocking is a technique that can eliminate the effects of a nuisance factor, but in order to use blocking, the nuisance factor must be both known and be controllable. In blocking, test runs are divided into blocks based on some criterion that is expected to cause variation in results. For example, if an experiment is run on several days, each day forms its own block. (Montgomery 2012, p. 12, 219.)

6.5 Planning an Experiment

Before rushing to the experiment, it is important to answer some basic question about the experiment and the process on which to base the experiment on. For example, the purpose of the experiment and what does it study and how to collect the data should be clear in mind before starting. Montgomery (2012, p. 14) has put together the following seven step guideline for planning, running and analyzing the experiment, which is illustrated in the Figure 20.

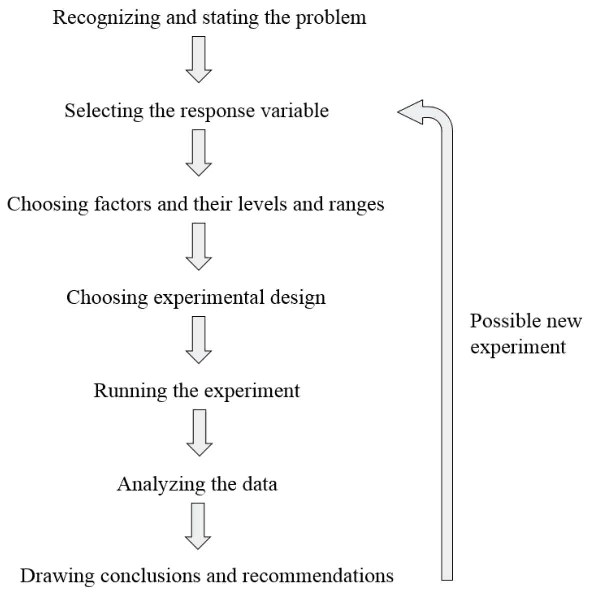


Figure 20. Steps of experimenting.

In the phase of recognizing and stating the problem, the questions that the experiment is aiming to answer, need to be determined. The objectives of the experiment are based on the questions and thus the type of the experiment, whether it is screening, confirmation or some other type. (Montgomery 2012, pp. 14–15.)

Selection of response variable, or variables, is often done together with choosing the factors. It is important that the selected response variables provide desired and usable information about the process and they are to be selected accordingly. After the response variables are selected, their measurement needs to be planned and possible issues with it given a thought. If the measurement system is known to be inaccurate, only large effects can be identified with confidence. However, if the measurement errors and inaccuracies are considered early enough in this phase, they can be at least partially compensated by replicating, for example. (Montgomery 2012, pp. 15–16.)

The factors in experiments can first be divided to potential design factors and to earlier mentioned nuisance factors. In the phase of choosing factors and their levels, the potential design factors and its subdivisions of design, held-constant and allowed-to-vary factors, are determined. The design factors are the group of factors that the experimenter has decided to study in the experiment. Despite their possible effect on the response, the held-constant factors are not an interest in the experiment and thus are held at constant level. Allowed-to-vary factors are often assumed to have small effect on the response, therefore their variation is often ignored and the randomization is expected to balance their effect. Such factors are often, for instance, materials. The nuisance factors should be dealt with the earlier explained ways, depending if the factor is controllable, uncontrollable or noise factor. (Montgomery 2012, p. 16.)

Once the design factors are selected, their levels for the experiment need to be determined. Usually the selection of the design factor levels is based on previous process knowledge that the experimenter has. If the process is not well known and the optimal region for response is unclear, particularly in screening experiments, the spacing between the levels should be wide. As the process becomes more familiar and the optimal region is better known, the spacing of the levels can be narrowed down. (Montgomery 2012, pp. 16–17.)

After the three pre-experimental planning steps, the experimental design is to be selected. Selection is very obvious if the pre-experimental phases are done properly as they determine the number of factors and levels. Moreover, the use of techniques to be equipped such as replication or blocking is determined in this phase and a tentative model for expressing the results is selected. (Montgomery 2012, pp. 18–19.)

On the fifth phase, the actual experiment takes place. During the experiment, in addition to measuring just the output, it is important to monitor the process for any deviation from the usual. Errors in following the plan or unwanted occurrences in the process without corrective measures, such as re-running the faulty test run, leads to poor validity. Sometimes it wise to perform couple trial runs before starting the experiment, particularly in cases where the process is not well known. By doing so, the chosen factors and their levels can be tested before starting the experiment and possibly wasting time on badly planned experiment. (Montgomery 2012, pp. 19–20.)

In data analyzing phase, statistical methods are equipped for interpretation of results and drawing of conclusions. Graphical methods such as diagrams and plots are a useful and easy way of expressing the results. However, expressing the results with an additional empirical model is often helpful, as it has further purposes like estimating the response with desired parameters. (Montgomery 2012, p. 20.)

Finally, based on the analyzed data, the experimenter comes up with a conclusion and gives recommendations of actions to follow. To verify the conclusions from the experiment, confirmation testing should be performed. In confirmation experiments the, the experimenter verifies that the process runs as is expected. For example, verifies that the estimates from the empirical model are accurate. (Montgomery 2012, p. 20.)

6.6 Empirical Model

After the experiment, responses with other than the experimented factor values are often an interest. The empirical model compiled in the data analysis phase, can be used for estimating the response or optimizing and controlling the process. Fitting a model on an experiment data is universally called regression model, which has different variants with own their names and features. (Montgomery 2012, p. 89, 450.)

6.6.1 Multiple Linear Regression Model

The multiple linear regression model is a regression model with two or more variables. The general form of it is (Montgomery 2012, p. 19, 450),

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \quad (1)$$

where y is the response variable, β's are the regression coefficients determined by the experiment, x's are the design factors and ε is the experimental error. The parameters as well as significance of different factors, whether they should be included in the model, can be calculated manually or as well with various computer software, such as Minitab that is used in these experiments. (Montgomery 2012, p. 457.)

7 DESIGN OF THE GRINDING EXPERIMENTS

To find the optimal tool for grinding, the tool alternatives need to be compared. In order to do the comparison reliably and accurately, systematic experimentation is needed. For fair comparison between the tool alternatives, each tool should be performing fairly close to its optimal level. To determine the optimal region for each of the tools, the parameters are determined by equipping experimental designs introduced in the previous chapter. The main interests are material removal rate and its relation to tool wear. Advantages, as well as disadvantages that surface during the experiments for each tool, are noted and used as additional means for comparison.

The Montgomery's seven step guideline for experimenting can be separated into before, during and after the experiment phases. This chapter introduces the design used in the grinding experiments, following the phases in the guideline. This chapter does not concentrate on experiments on individual level but gives an overview of the experiments. The more detailed individual reports of the experiments are found in the appendices.

7.1 Pre-planning the Experiments

The company has earlier conducted similar experiments to determine the optimal parameters for the currently used Tyrolit grinding tool. These experiments were studied and used as a help for planning the experiments for new tool alternatives.

7.1.1 Stating the Problem

The base problem in experiments for each new grinding segment was the same. Apart from their specification and visual appearance, not much was known about them. Due to such specific application, the grinding tool manufacturers were not able provide recommendations for the parameters to start with. Since the tools and their behavior was unfamiliar, the experiments were started with a broad screening approach. After getting more familiar with the tools, more accurately targeted experiments were conducted.

7.1.2 Design Factors

Based on the theory as well as the results from the earlier experiments, the main factors contributing to the output are the feed rate and tool speed. Out of the three basic factors that the machine users adjust on regular basis, the workpiece speed is expected to have only little effect on the outputs that are measured in the experiments. Nevertheless, for the first screening experiments, the workpiece speed was included in the design factors. If varying this or other some factor turns out to be insignificant in the experiment by not having an effect on the response, the extra runs caused by the factor work as a replicate.

After discovering the significance of fluid delivery for some of the tools, the factor for workpiece speed was replaced with factor for fluid delivery in some experiments. So, the feed rate and tool speed were used as design factors in all of the conducted experiments and the third factor, if needed, varied. The design factors used in each experiment are listed in the beginning of each experiment in the report sheets. The report sheets for all the tools are found from the appendices.

Held-constant Factors

Following the principles of DOE, the factors that are not design factors are to be held constant. Some of the listed factors are more likely to cause variation in response than others, if not controlled. Such factors are for example grinding time and different factors related to grinding fluid. Some of the held-constant factors, like guideway lubrication and headstock pressure, are less likely to affect the output even if they varied. The held-constant factors were following:

- Workpiece surface
- Tool surface
- Grinding fluid
- Grinding time
- Machine power output limits
- Guideway lubrication
- Headstock pressure
- Temperature

The workpiece surface was ground clear of irregularities if any were witnessed prior to starting the experiment. This procedure ensures an even start between the first and following test runs. A similar practice was done for the grinding tool surface, which can often be done together with clearing the workpiece surface. The tool surface must have total conformity with the workpiece surface when starting the experiment. If not, the contact area between the tool and workpiece changes with tool wear until the total conformity is reached.

The used grinding fluid is Henkel Bonderite 49-2 DF, a synthetic cutting fluid emulsified with water to form 3% concentration. Both the concentration and filtration were untouched during each experiment. The filters of the central system are changed and cleaned based on the normal maintenance schedule, possibly causing minor variation between different days and experiments. The fluid concentration is measured with refractometer on a weekly basis, and if it differs from the 3% level, it is regulated by either adding water or fluid concentrate. However, the method causes variation in long run which is covered in the discussion part.

Standard grinding fluid delivery is through four low pressure flood nozzles. Three of the four nozzles are seen in Figure 21 and are marked with red circles. The additional fluid nozzles that were added for most of the later experiments, are marked with yellow arrows. The nozzles remained untouched during experiments, but were adjusted or even removed between the experiments due to needs of normal production. The angle, direction and distance of the nozzles were attempted to maintain identical between the experiments, but the assessment was merely visual, so minor variation occurred unavoidably.

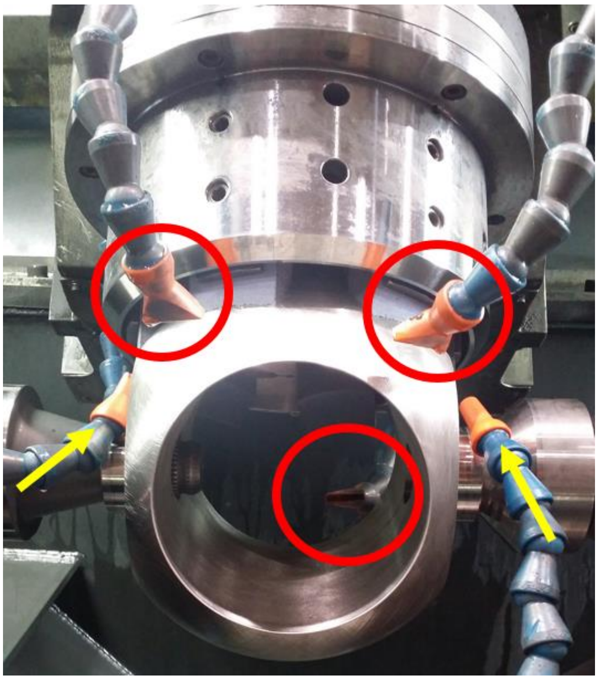


Figure 21. The standard fluid delivery setup with two additional higher pressure nozzles.

The material removal is compared in a time unit and thus could be calculated regardless of the run time of each run. But determining and sticking to certain grinding time is important for experiment’s validity and setting the run time high enough is crucial for couple reasons. If the grinding time is too short, the temperature might not reach its peak level. Reaching the maximum temperature is important as it can be a major rejecting factor. Setting the run time high enough also ensures that unwanted variation is smaller, for example resulting from uneven starts between the runs. On the other hand, setting the grinding time too high is waste of resources. The machine is out of production longer and more workpieces are needed because more material is removed.

After considering the above mentioned factors, the grinding time was set to 900 seconds, or 15 minutes. It should be enough for the process to reach its maximum temperature, as well as to balance the effects of uneven starts. The 15 minutes is measured with a manual stop watch and consists of only the roughing phase. Finishing and spark out phases are not part of the experiments and are skipped over.

The machine has limiters for spindle power outputs, which can be set how the user wants. If the power exceeds the upper limit set by the user, the machine stops the feed motion. The tool spindle continues to rotate with the set speed and once the lower limit of the power is reached, the feed motion starts again. For the experiments, the power output levels were increased from the usual level, since the power limiter was not wanted to be affecting the output. Based on previous knowledge, high power output with currently used Tyrolit segments usually leads to burn marks on the workpiece surface. Since the behavior of each grinding tool was unknown, instead of using the power limiter to prevent burn marks, the surface of the ball was visually examined after each run. The upper limit for the tool spindle power output for the experiment was set to 75% and the lower limit to 70%. The total power output of the machine was set to 90%.

The usual power limit for tool spindle for recognizing contact, two percent, lead the machine to assume that the tool had solid contact with workpiece even if it was not one. The percentage expresses how much the power output needs to increase from an idle level, when the machine is looking for a contact to workpiece. Once the limit is reached, the machine accelerates the spindle to desired speed and starts the feed motion. In the first experiments for example with Theleico, the machine assumed it had a contact and started feed motion, after which it took several minutes for power to reach the level of showing a solid contact. After few experiments with uneven contacts between the runs, the limit was decided to be set at 10%. Setting the limit high enough makes sure that the start for each run is even and the tool is actually fed into the workpiece for the whole 15 minutes.

Guideway lubrication is very unlikely to cause error to test results, but just in case a lubrication run on the machine is performed on morning of every test day. Headstock pressure is also rather insignificant factor, especially since the workpiece is fixed in place from splines. As a precaution, the headstock pressure is set to 26 bar for each test.

Even though the grinding fluid temperature is attempted to retain constant during the experiment, it is one of the factors that is difficult hold constant in practice in production environment. The fluid temperature, is cooled down to 17 °C in the central fluid system throughout all of the experiments. However, the incoming fluid temperature is somewhat higher and hard to control accurately. The exact temperature of incoming grinding fluid depends on the ambient temperature, as well as the use of the other machines connected to the central system. Small changes in grinding fluid temperature are not likely to effect the response, but since its effects are not well known, it poses as a possible nuisance factor. The machine temperature likely has no effect on the response factors and was not observed or measured in the experiments. Regardless, the machine was run before a start of each experiment, to ensure fairly similar temperature between the first and following runs.

The temperature of the workpiece during the grinding is difficult to measure or control, but being an important quality related factor, the ball temperature cannot be ignored. Since it is not possible to hold the ball temperature constant, the workpiece temperature is evaluated with human senses instead of setting a specific limit for the temperature. The main limiting and rejecting factors are burn marks on the workpiece surface and fluid vaporizing from the surface of the workpiece after run. Like the machine power output, the workpiece temperature and is not a factor that is held constant, instead both are only limiting factors and in well prepared experiments these limits should not be met. In most cases, to make sure that the parameters are within usable area, they were trialed before the start of the experiment.

Nuisance Factors

The known nuisance factors in the experiments are tool bending and variation in fluid delivery, temperature and concentration. Other nuisance factors possibly exist, but their sources or effects on the response are not known. From the known factors, tool bending has the largest effect on single experiment as the other nuisance factors do not vary as much within short periods of time and are more of a nuisance between different experiments.

Following the laws of mechanics, the longer tool means higher torque that leads to more bending. So, the bend is at its most when the tool is new and on its maximum length. As the tool wears, the lever arm shortens, resulting the segment to hold its form better. The bending of the tool results in power losses, as some of the forces intended to grinding process go to tool bending. Although the cause and effect of tool bending are known, the extent of its effect to response is not known and would require experiments of its own. To deal with tool bending in the experiments, randomization and replication balance its effects between the runs.

Before the first experiments where the fluid delivery was varied, its magnitude as a possible nuisance factor was not realized. As mentioned earlier, the fluid delivery was untouched during the experiment and thus it remained about the same within an experiment, not causing significant variation. But between the experiments, for example screening experiment and confirmation runs, the fluid delivery can cause significant variation. The extent and direction of the variation it causes is not known before the experiment.

Fluid temperature is likely not a major nuisance factor as it seemed to vary only a little in the experiments. However, its effects have not been experimented and the measuring method used in the experiment does not tell the temperature of incoming fluid reliably. The effect of fluid content and concentration is not known, but poses as possible nuisance factor over longer period of time.

7.1.3 Response Variables

As stated in the chapter 2.1.1 Grinding parameters, the measured outputs in the experiment were the change in workpiece diameter and the change in tool length. These two outputs were used to calculate more accurate and applicable responses, material removal rate and grinding ratio.

The change in workpiece diameter should not be used as a response variable, since it does not consider in the changes in ball volume. In other words, it does not take into account that grinding a millimeter off from a small sphere is not the same as grinding a millimeter off from a bigger sphere. To factor in this difference, a diameter before and after each run are used to calculate the sphere volume, however this is not accurate on its own. Since the valve ball is not a complete sphere and the ball is ground with feed motion only from one direction, the geometry of the ball changes as it is ground, causing the ball so to say, flatten. The flowport length, marked with the red arrow in Figure 22, decreases but its diameter remains the same. So, the height of the spherical cap removed from the ends of the flowport changes as well, but the diameter remains the same. And the height of the spherical cap removed from the bearing sides remains the same, but its diameter, marked with the yellow arrow, changes.

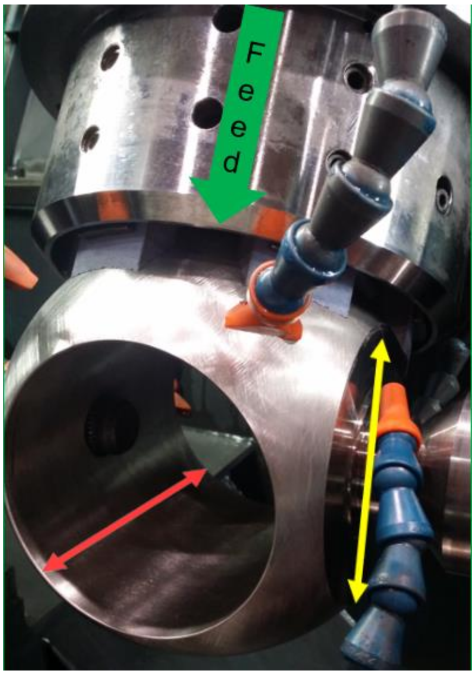


Figure 22. The dimensions that change with the ball diameter as the workpiece is ground.

To compensate the changes in ball geometry, the volume of flowport and four spherical caps are calculated before and after each run. Instead of measuring the dimensions of the ball after each run, the dimensions of a certain ball were measured before and after grinding experiments. Based on these measured dimensions, a ratio between the change in ball diameter and flowport length, as well as a ratio between the change in ball diameter and diameter of the bearing side cap, was calculated. Based on the ratio and diameter of the ball after each run, the volumes of these zones removed from a sphere are calculated and subtracted from the volume of a complete sphere.

Since the tools in the experiments share the same dimensions, instead of using specific material removal rate, *Q'*, that factors in the tool contact width, a simpler formula without the contact width is used. Thus the response variable for the material removal rate is following,

$$MRR = \frac{(V_t - V_c - 2V_{cfp} - 2V_{cbs})}{t} \quad (2)$$

where V_t is the total volume of complete sphere, V_c is the volume of the cylinder that the flowport forms, V_{cfp} is the volume of the cap removed from each end of the flowport, V_{cbs} is the volume of the cap removed from each side with bearing mounts and t is a unit of time.

The used dimensions were in millimeters and the used time unit was a minute, making the unit of equation mm^3/min.

As stated above, the experimented tools share the same dimensions. Since the dimensions are the same, the tool wear of each run could be simply expressed by comparing the tool lengths before and after the run. But, using G-ratio to evaluate the tool wear is much better option since it relates the wear to material removal. The volume lost from single segment was calculated by multiplying the area of front face of the segment with difference in tool length before and after the run. To get the total volume needed to calculate G-ratio, the volume lost from a single segment was multiplied with number of segments in the grinding head, so by six in the experiments. Finally, the total volume lost is divided by grinding time, 15 minutes, to get the same unit as in MRR.

In addition to two response variables, data was gathered about few factors that are not constant during the experiments, fluid temperature and machine power output. The factors were not a particular interest and further analyzed, but were monitored because they could give away something about the process. Measuring of the fluid temperature took place about half way in each test run and was measured from a collector tank with handheld infrared thermometer. The value for power output of the tool spindle was written down about every two minutes throughout each test run.

7.1.4 Choosing the Designs

Experimentation of each tool alternative was started with full factorial design. Since the factors were determined in the pre-experimental planning, the design came to be 2^3-form, resulting in eight runs in each experiment. Most of the following experiments were conducted with full factorial designs, with either the 2^3 or 2^2 -form. Design matrixes for each of the experiments are found in the report sheets in the appendices I through VI.

For confirmation runs, few combinations in- and outside of the experimented range were hand selected to test the fit of the model. The test matrixes for confirmation runs as well as evaluations of the models are found from the same report sheets as the above mentioned screening runs.

7.2 Running the Experiments

In total, 14 successful screening and optimization experiments were run between the currently used Tyrolit and five competing tools. Few more were started but were aborted due to unexpected occurrences such as excessive heat generation or the segments breaking. An overview of the used designs is seen in a fishbone diagram in Figure 23. The design factors in parentheses are factors that were used as a third design factor in experiments, in addition to feed rate and tool speed. Some of the factors are listed under more than one category because on some level they present several categories. The screening and optimization experiments were followed with five confirmation experiments for four different segments. Confirmation runs were conducted with similar design, where feed rates and tool speeds were the varied factors.

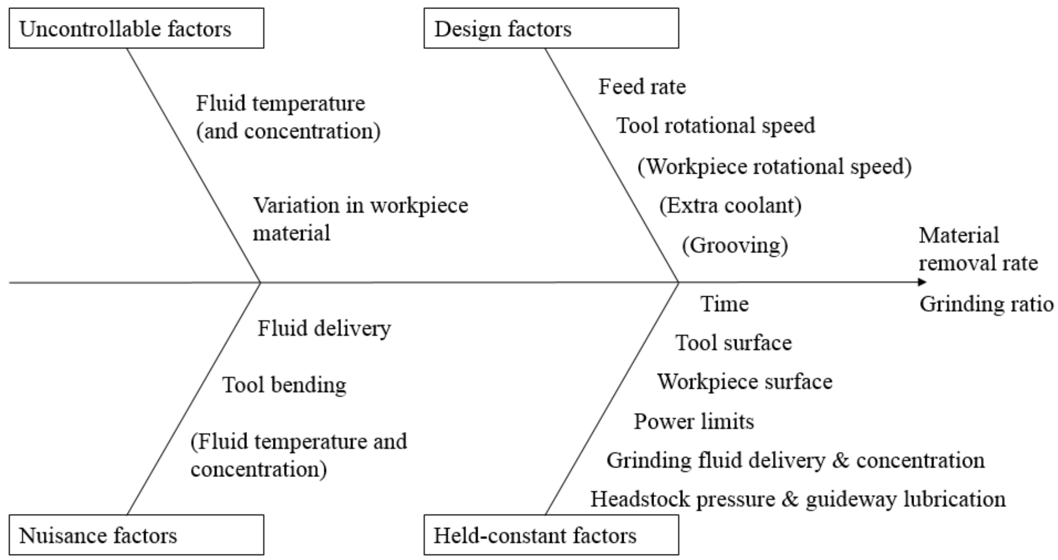


Figure 23. A fishbone diagram of the screening and optimization experiments.

The experiments in this thesis were performed over few month time span, following the steps shown in the Figure 24. The first experiment took place on 22nd of November 2016 and the last experiment, that was included in this thesis, was run on 24th of January 2017. Further experimenting following the same principles is to follow, but is limited out of this thesis. The reports for the now conducted experiments including the results, observations and conclusions are found from the appendices I through VI.

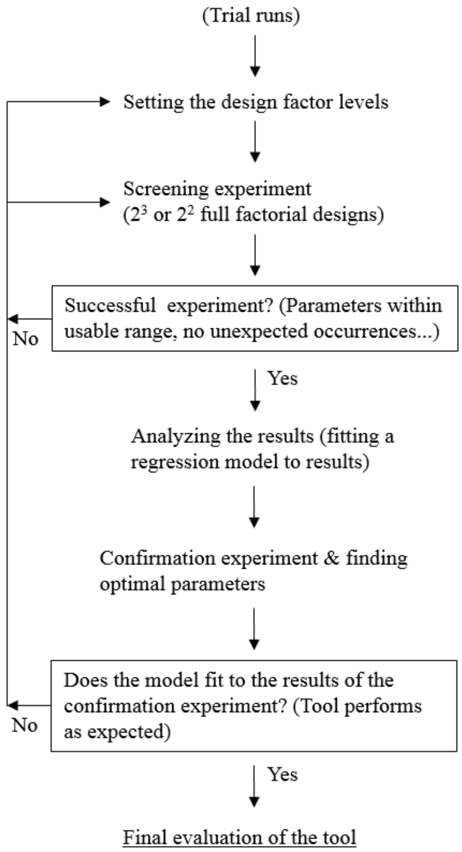


Figure 24. Progress of the grinding experiments.

7.2.1 Test Machine

The platform for testing is a Plantool BGM 600 ball grinding machine with spindle power of 22 kW. The machine is used for grinding spherical surfaces of different shutter elements used in valves, up to around 24 inch, or 600 mm in diameter. (Danobat 2017a.) Such shutter elements may be spherical segments, valve balls with a stem or stemless valve balls. Metso uses the machine to grind above mentioned shutter elements mainly from flowport sizes of 4 to 12 inches, or respective ball diameters of 165 to 470 mm.

The machine is one of the more modern grinding machines in the factory, so it is a good platform for experimentation. The parameters are easily changeable for testing purposes and the machine gives out more information about the grinding process than the older machines. For example, the spindle power outputs and their changes are displayed on the control panel, which can give out certain tool behavior such as excessive tool fracturing. The machine also measures the ball diameter with a built-in measurement probe and gives out the tool length, based on which the material removal rate and tool wear is calculated.

The workpiece is mounted to workpiece spindle from bearing mounts and is locked in place from splines. The ball rotates around the same center as it does in operation of valve and its speed can be adjusted between 1 and 500 RPM. (Puska 2013.)

As seen in the Figure 25, the grinding head consists of grinding segments on the grinding head periphery, essentially forming a cup wheel with gaps. The number of segments in the grinding head depends on the workpiece size; larger workpiece means more segments. The grinding head for the ball size of six inches, consists of six segments. The grinding head with segments is fed towards the center axis of the workpiece with adjustable speed of 0.001 to 2 mm/minute. The rotation speed of the tool spindle can be adjusted between 3 and 4500 RPM. (Puska 2013.)

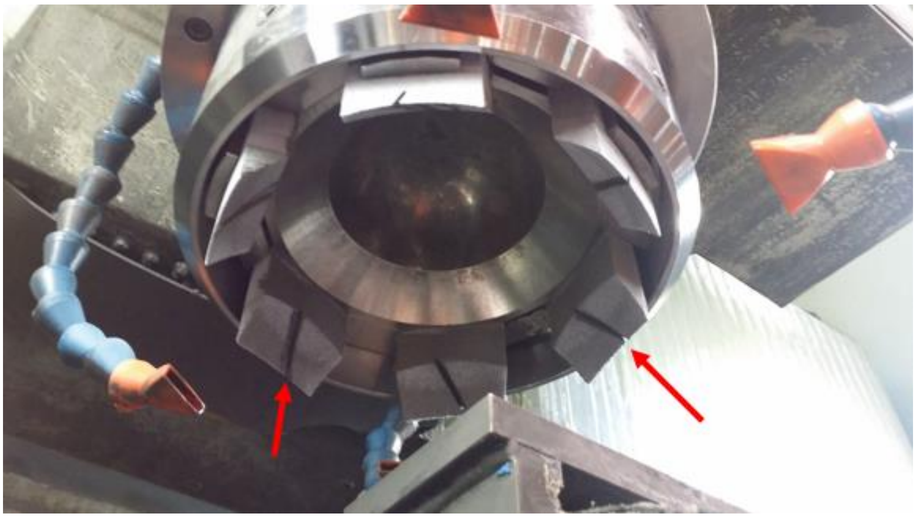


Figure 25. The grinding head type used in the experiments. In the particular experiment, the effect of grooving the segments was experimented. Two of the grooves are marked with the red arrows.

7.2.2 Test Workpiece

The inputs in the experiments, the workpieces, were valve balls made of AISI 316 grade steel. The experiments were decided to be conducted with valve balls with flowport size of six inches, since they represent about the midpoint of the most commonly ground valve ball range. Use of six inch balls keeps the experimentation costs reasonable when compared to larger ball sizes. The tool costs are lower since the larger grinding heads require more segments. The material costs also remain lower, since on start of an experiment the ball is on its final dimensions, about 247.4 mm in diameter, and after experiments the diameter far from accepted tolerance range and the ball needs to be scrapped.

7.2.3 Tool Alternatives

The five tool alternatives listed in Table 3 were recommended by their manufacturers or distributors based on the ground material and the currently used Tyrolit segment, which is the reference level in the experiments. Similar optimization experiments were conducted for Tyrolit already in 2015, so its performance level is pretty well known. But to get an up-to-date reference level for the other tools, experiments were run for Tyrolit as well.

Table 3. The compared grinding segments and their specifications (Senf 2017; Mansikka-Aho 2017; Norton 2017).

Wheel manufacturer:	**Abrasive type:**	**Grain size:**	**Grade (Soft-Hard):**	**Structure (Dense-Open):**	**Bond type:**
Tyrolit	**89A** (fused alumina)	**120**	**F**	**8**	**V** (Vitrified)
Theleico	**23A** (ceramic grain)*	**120-0**	**F**	**12**	**VM** (Vitrified)
Diprotex	**3CG** (ceramic grain)**	**120**	**G/H**	**10**	**V32** (Vitrified)
Norton F	**3NQX** (ceramic grain)***	**120**	**F**	**24**	**VS3X** (Vitrified)
Norton H	**3NQX** (ceramic grain)***	**120**	**H**	**24**	**VS3X** (Vitrified)
Norton J	**3NQX** (ceramic grain)***	**120**	**J**	**24**	**VS3X** (Vitrified)

* 3M Cubitron, ** Imerys/Treibacher, *** Norton NQ Quantum

The Tyrolit segments were selected before the ceramic abrasives had made a breakthrough in the abrasives market, so the Tyrolit segments have only conventional alumina grains in them. All the five competitors that were challenging Tyrolit have a mixture of ceramic and conventional grains. Looking at the tool specifications, all the tools are somewhat similar. But the tool specifications vary between the manufacturers and comparing the tools just based on their specification is not a reliable method. Prior to experiments, based on the specification as well as visual appearance of the tools, the main differences seemed to be in grain type and structure of the tool. The Tyrolit segment was also known to be impregnated with sulphur, but its effects were not clear before the experiments and are discussed in the chapter 8.1.1 Tyrolit.

As stated above, all of the five alternatives have ceramic grains mixed with conventional fused alumina grains. The exact proportions of grain types in Theleico and Diprotex segments are not known and Norton tools are known to have 30% ceramic grain (Norton 2017). In addition to possible differences in grain type content, the properties of ceramic grains from different manufacturers are known to have minor differences. The 3M Cubitron, that is used in Theleico's segment, is stated to be less tough and in certain applications easier to apply than Saint-Gobain's SG grain. (Badger 2011, p 6.) On the other hand, SG's higher hardness of 21GPa versus Cubitron's 19GPa can provide a longer tool life in right application (Marinescu et al. 2007, p. 81).

More recently Saint-Gobain has introduced the Quantum grain, which is slightly modified version of the SG family. Quantum grain has similar submicron crystallite size and hardness as the SG but the micro-fracturing properties are different. (Jackson et al. 2013, pp. 36–37.) The experimented segments from Norton equip the Quantum grain. The ceramic abrasive that is used in the Diprotex's segment is manufactured by Imerys but the grain's properties in comparison to two other grains are not known.

7.3 Data Analysis

Data analysis was performed using Minitab 16 software and DOE and regression analysis tools it includes. Each screening and optimization experiment was analyzed to discover the significant variables and more importantly, their effect on the response. Generally speaking, there were no surprises in significant variables, and the feed rate with tool speed determines the outputs to a high extent, just like the theory entails.

The main objective in data analysis was to build models for outputs of different tools. In most cases the model consisted of feed rate, tool speed and possibly their interaction. In few of the experiments, some of the variables did not show up as statistically significant or the results were inconsistent with the other experiments. In these cases, few competing models were built and their fit was tested in the confirmation experiments. After all the goal of the experiments was to find out the practical limit for material removal rate of each tool, not to build mathematically perfect models.

8 DISCUSSION

This chapter first covers the final results of each of the tool alternatives and discusses about the tool specific observations and findings. Later on, in the chapter 8.2 Observations and Findings on the General process, results are discussed on more general level, focusing on other than tool related factors found in the experiments.

8.1 Key Results and Tool Evaluations

Evaluation of each tool is mainly based on the maximum outputs it reached in the experiments. Other than numerical evaluation of the two responses, material removal rate and grinding ratio, if the tool was noted to have any advantages or disadvantages in the experiment, they are discussed.

The final values for outputs are listed in Table 4. The listed values for material removal rates are not necessarily the maximum values that were achieved in the experiments nor the absolute maximum that the tool can reach, but the maximum values that were reached in the experiments while considering quality factors. The following material removal rates did not lead to burn marks or the workpiece temperature raising to a level that the machine user or experimenter found problematic.

Table 4. The overall results and their respective parameters.

	Feed rate (mm/min)	**Tool speed (RPM)**	**Additional fluid delivery**	**Material removal rate (mm^3/min)**	**G-ratio (MRR/Tool wear)**
Tyrolit 89A120F8AV217T3	0.18	2000	No	5281	5.90
Theleico 23A120-0F12VM4200	0.16	3000	Yes	3464	4.74
Norton 3NQX120**F**24VS3X 3NQX120**H**24VS3X	0.2 0.15	2000 1000	Yes Yes	3397 1449	3.04 1.55
Diprotex 3CG120G/H10V32	0.16	3000	Yes	3301	3.87

Since the ceramic grain was supposed to lead to improved process, at the very least through lowered tool wear and thus increased G-ratio, question is: why did this not happen. In fact, why did the process efficiency go down by both measures. It seems that between the five alternative tools and Tyrolit, the performance of the tool was not dependent on the type of grain. Instead, the performance depended on the other factors of the specification and whether they were suitable. To determine these differences and their effects, the differences between Tyrolit and other segments need to be looked closer at.

8.1.1 Tyrolit

Despite not having the more novel ceramic grain, couple decades ago selected Tyrolit segment still achieved the highest material removal with highest G-ratio. So, the key to its success must be in other factors than the abrasive itself.

Main Differences to Other Segments

Looking at the specification, Tyrolit is not that much different from the other segments. The main difference seems to be in structure, but because of the differences between manufacturers, this cannot be stated with absolute confidence. However, the noticeably different appearance and larger mass of the Tyrolit segments support the hypothesis, and based on these it is fair to say that Tyrolit likely has tighter packing of grains. Tighter packing of grains means more kinematic cutting edges and thus is one of the explanations to Tyrolit’s higher cutting rate. This should also mean more heat generation, but with Tyrolit segments the heat generation seems to be in control.

Another difference, the Tyrolit’s sulphur treatment, is not directly noticeable from the specification. However, this difference is a major one and likely the reason behind Tyrolit’s performance. Lubrication from the sulphur impregnation helps in keeping the friction low, that keeps the temperature in the contact zone in control. The process runs well without extra coolant delivered to contact zone and the sulphur treatment seems to provide enough lubrication.

The key to Tyrolit’s performance is likely the combination of both the higher density and sulphur impregnation. Higher density means more cutting edges resulting in more heat generation, but the lubrication coming from the sulphur impregnation keeps the heat generation in control and makes the use of higher density possible. This hypothesis is to be tested later as a follow-up to these experiments, by experimenting similar segment without sulphur impregnation.

The Effects of Extra Fluid Delivery with Tyrolit Segment

When experimenting the effect of additional fluid delivery with Tyrolit segment, the response variables were expected to increase, just like in the experiments with other segments. But instead, an interesting observation was made of the extra fluid delivery lowering the responses. The reason behind this is not clear and would require further studies and experimenting. Few hypotheses are however made based on concepts found from literature.

The most likely cause is hydroplaning that is linked particularly to dense wheels. The structure of Tyrolit's segment is dense in comparison to other experimented segments, which the sulphur impregnation further incites. In hydroplaning, or hydrodynamic lift, the fluid film between the tool and the workpiece can cause the tool to hydroplane, particularly in systems where stiffness is known to be a problem (Irani, Bauer & Warkentin 2005, pp. 1700–1701). Taking into account the dense structure of the segment and their tendency to bend, this is likely at least part of the reason for weakened results with extra grinding fluid. The effect of adding the grinding fluid on Tyrolit's performance is seen in the Figure 26.

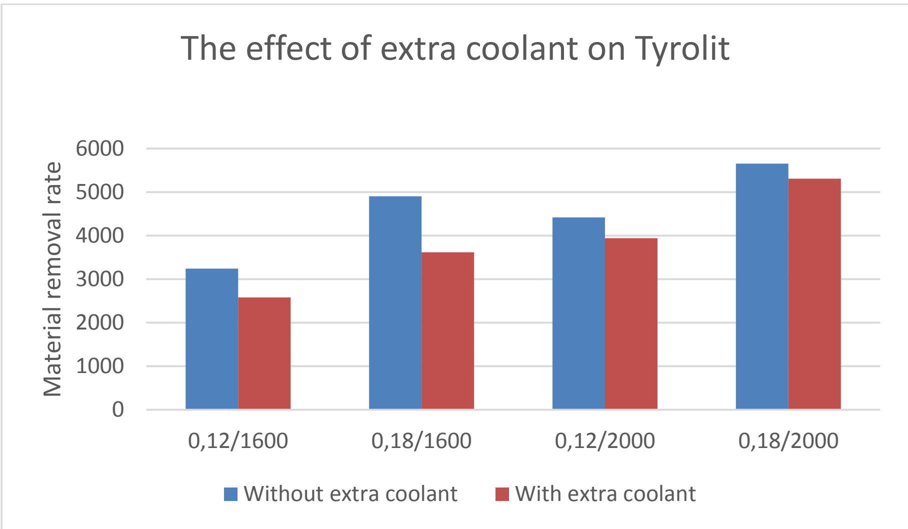


Figure 26. Material removal rates from the experiment determining the effects of extra coolant nozzles with Tyrolit segments.

In the experiment to determine the effect of extra fluid delivery, the run order was not randomized to keep the fluid delivery as constant as possible between the runs. By not randomizing the run order, the risk of biased experiment increases. As seen from the experiment report in the Appendix I, 2, the runs without extra coolant were taken first and the runs with extra coolant formed the latter half of the experiment. Since the tool bending is known to be at its maximum in the beginning of the test and decrease with tool wear, it is a nuisance factor that can distort the results and impair the validity of the experiment.

The runs without the coolant were taken first, when the effect of bending is at its most, and still resulted in higher output. It proves that the bending was not the direct cause for the decreased output with the extra fluid. Looking at the last two runs of the experiment, so the red columns on the right side of the Figure 26, it can be noticed that the outputs between runs with and without the fluid are getting closer to each other. Keeping in mind that the hydroplaning was stated to be a problem in systems where stiffness is a problem, the responses getting closer to each other could be explained with tool length and its effect on the stiffness of the system. On runs seven and eight, the tool is worn to a point that the bending hardly occurs anymore and the fluid film between the tool and workpiece does not lead to hydroplaning to a same extent as with longer tool. So, based on this theory the weakened output is a result of bending, caused by the additional fluid.

Other possible theory is related to chemical reactions on the workpiece surface. Some chemical substances are known to compete on the workpiece surface, weakening each other's effects. Whether the additives in the grinding fluid interfere with the sulphur additive on the grinding tool is not known and therefore remains as a possible factor for impairing the results. (Meyer & Wagner 2016, p. 315.)

Follow-up to Experiments with Tyrolit

To verify the hypothesis of the benefits originating from sulphur, identical segments without sulphur impregnation have been ordered. If the hypothesis is correct, grinding with similar parameters without additional coolant nozzles should not be possible because of the heat generation resulting from the lack of lubrication. To experiment the direct effect of sulphur for material removal, the segment without treatment is experimented with certain parameters that the grinding is possible and seems to work with. This is followed with an experiment with similar parameters and sulphur treated segment. If the responses are better with sulphur treated segment, the hypothesis can be verified.

In addition to experimenting the significance of sulphur, segment with ceramic abrasive and sulphur impregnation has been ordered from Tyrolit and is to be experimented. Being similar to currently used segment from rest of the specification, but equipping the more novel grain, the segment holds high potential to lead to improvement.

Based on the hypothesis of advantages of sulphur working as a solid lubricant, another solid lubricant is to be experimented as an alternative to using sulphur. Similar segment to sulphur impregnated one has been ordered from Tyrolit, but instead of sulphur impregnation, the segment is impregnated with wax. If the wax impregnated segment matches the performance of the sulphur treated, it is considered as a replacement for the sulphur impregnated segment because of the health and environmental problems related to sulphur.

Grooving the segments' contact surfaces was experimented with Theleico, for which it did not result in improvement. Since the Tyrolit segment is likely suffering from hydroplaning when the additional fluid is used, grooving could be beneficial. It could reduce the segment's tendency to hydroplane, in similar manner as in threads on car tires. If the grooves would work on alleviating the hydroplaning, the fluid could be used without drawbacks and the fluid would lower the contact zone temperature. Lower temperature would either reduce the time needed for finishing and spark out phases through better geometrical integrity after roughing or it would allow increase in material removal rate. This hypothesis of advantages of grooves on Tyrolit's segment would have to be confirmed with an experiment.

8.1.2 Theleico

Theleico turned out to be the best contender for the current Tyrolit segment. After discovering the benefits of the extra grinding fluid delivered to the contact zone, the material removal rate grew about 2.5 times over and the G-ratio increased even more. Without the additional coolant nozzles, the segment was clearly lacking lubrication and wearing out really quick.

Looking at the parameters and the responses from the experiment on 24th of January, that are listed in Table 5, it can be noted that the lower feed rate resulted in higher G-ratio and similar MRR. Despite that the runs are from the experiments where grooving was examined, the behavior should be about the same. So, if lower feed rate of 0.15 mm/min, maybe even 0.14 mm/min, would have been tested on January 3rd, the achieved final results for Theleico could have been better, but still not affecting the ranking of the segments to a direction or another.

Table 5. The best result achieved with Theleico and two different feed rates and their respective responses.

Date	Feed rate (mm/min)	Tool speed (RPM)	MRR (mm^3/min)	G-ratio (MRR/Tool wear)
3.1.2017	0.16	3000	3464	4.74
24.1.2017 (with grooves)	0.15	3000	3031	3.75
24.1.2017 (with grooves)	0.16	3000	3033	3.40

Looking at the behavior of the Theleico's segment in overall and the run with highest responses, the surface roughness was noted to be on a good level and the workpiece remained really cool throughout the experiments, which is linked to good circularity values. In cases where the workpiece is already close to its final dimensions, and there is only little to be ground, Theleico could already be a suitable option. The material removal rate is lower, so the roughing phase is longer, but the time required for finishing and spark out phases would be shorter.

Follow-up Experiments with Theleico

Few conclusions can be drawn about how the specification should be changed for improvement. The heat generation would likely increase as a result of increasing the material removal rate, but this could be only confirmed through more experimenting. Since the heat generation remained in low level, there would probably be some room for increasing MRR without compromising quality too much.

Like all the other segments, the rated maximum speed for Theleico is 32 m/s. With grinding head diameter of 190mm its means maximum rotational speed of slightly over 3200 RPM. So the segment would allow minor increase in speed, but in the experiments exceeding 3000

RPM caused vibration, so the imbalance of the grinding wheel set the limit for tool speed. Since the tool speed is practically on its maximum value and the temperature is still not a problem, the segment seems to be on a bit softer side. Slight increase in hardness would likely lead to at least improved G-ratio. But then again, the fracturing of the grains need to be in proper relation to bond fracture and whether increasing the bond hardness would result in unfavorable relation is not known. This would have to be confirmed through further experimenting.

Judging by the specification 120-0, the grain size on Theleico's segment is a mixture of different grain sizes. This lead to noticeably better surface roughness in the experiments when compared to Tyrolit segment. An easy way to improve material removal would be to increase the grain size, which would obviously lead to rougher finish. The reference level being the surface roughness achieved with Tyrolit, which is noticeable rougher, increasing the grain size would be possible.

Based on the conversations had with Theleico representative, Theleico sent another test batch to be experimented. Because of scheduling, the experiment is not analyzed as part of this thesis but the results are briefly covered in paragraphs below. The new batch included segments with two different specifications, that were both used, alternating on the grinding head. The specifications were 40A80-0F11V7210 and 24A120-0E12VM4180. So, one of the segments had conventional alumina and larger grain size and the other one was quite similar to already experimented segment, just slightly softer (Theleico 2015).

As seen from the results listed in Table 6, the new combination, setup 2, did not bring any improvement. Leaving some room for variation between the experiments, the new combination was at the most on the same level as the earlier experimented setup 1 with specification 23A120-0F12VM4200.

Table 6. Results from the latest experiments with new Theleico segments.

Specification	Feed rate (mm/min)	Tool speed (RPM)	Material removal rate (mm^3/min)	G-ratio (MRR/Tool wear)
Tyrolit 89A120F8AV217T3	0.18	2000	5281	5.9
Theleico 23A120-0F12VM4200 SETUP 1	0.16	3000	3464	4.74
24A120-0E12VM4180 + 40A80-0F11V7210 SETUP 2	0.14 0.16 0.18	3100 3100 3100	2502 3034 3143	3.32 3.51 3.19
23A120-0F12VM4200 + 40A80-0F11V7210 SETUP 3	0.16 0.18	3100 3100	4408 3776	5.47 3.9

With the combination of new specifications, the workpiece was noticed to remain as cool as in the earlier experiments with the setup 1. Since increasing the hardness was earlier hypothesized to lead to improvement and slight increase in temperature would not be a problem, the new harder segment was decided to be experimented by alternating it on the grinding head with the first specification 23A120-0F12VM4200, which is harder than the now delivered 24A120-0E12VM4180.

This setup 3 resulted in two of the highest responses for material removal rate, excluding Tyrolit's results. As expected, the temperature increased from the setup 2, but only to about similar level as with Tyrolit. Lowering the feed rate from 0.18 to 0.16 mm/min shows a trend of increasing responses towards lower feed rate. If lowering the feed rate to 0.14 mm/min is beneficial, would have to be experimented to confirm its effects. But looking at the segment surface after the run with 0.16 mm/min, the bottom half of the segment with conventional grain was quite badly glazed, and lowering the feed rate would likely lead to less fracturing and thus worse glazing and temperature increase.

The newly found results and observations were passed to Theleico and possible further changes to specifications are being discussed.

8.1.3 Diprotex

Diprotex segment was quite similar to Theleico's segment from the visual appearance as well as behavior and results. In the first experiments without additional coolant nozzles, the segment was fracturing excessively and the responses were poor. After the introduction of the additional coolant to the process, the excessive fracturing stopped and the responses increased by an order of a magnitude, but are still far from the Tyrolit's level.

As seen from the results in Table 7, much like with Theleico, slightly lowering the feed rate from 0.16 mm/min could possibly lead to minor increase in responses. Judging from the surface of the segment after the run however, lowering the feed rate would cause the surface of the segment to glaze even more and increase temperature. Even if lowering the feed rate would result in higher feed rate or increased G-ratio, it would not match the Tyrolit's performance.

Table 7. Two of the best runs with Diprotex segment.

Feed rate (mm/min)	Tool speed (RPM)	MRR (mm^3/min)	G-ratio (MRR/Tool wear)
0.16	3000	3301	3.87
0.18	3000	3160	3.04

The conclusions from the experiments are similar to ones drawn from experiments with Theleico. But with Diprotex, the route of changing the segment specification is different. Based on the results and observations made on the experiments conducted with both Diprotex and Tyrolit, as a follow-up to Diprotex experiments, new specification with sulphur impregnation is ordered. Once the new segment arrives, it is experimented in the similar way as the other segments in this thesis.

8.1.4 Norton Grades F, H & J

Of the three segments from Norton, the softest one with grade F turned out to be the most suitable. Like other segments, excluding Tyrolit, Norton segments benefitted from additional coolant nozzles. But the behavior of Norton's segments before adding the fluid nozzles was very different from Theleico or Diprotex, which hints towards very different bond hardnesses.

In the first screening experiments, Theleico and Diprotex seemed to be fracturing excessively and the power output remained on really low level. Where with Norton segments, with about similar parameters, the power output was higher and the segment did not seem to fracture on a same extent. Instead, the segment started to glaze and temperatures increased to level that caused burn marks on the workpiece surface. The grains started to dull, increasing the grinding forces, but the bond still retained the grains leading to above mentioned issues. The issues were worse with the harder grades H and J, and the grinding with the initial parameters was not even possible because the machine kept hitting the power limiter constantly.

With additional grinding fluid, the heating problems with grade F were partially resolved, but still remain to be a problem with higher material removal rates. In the test runs with higher material removal rates, the workpiece temperature started to increase to a point that the fluid was vaporizing from the workpiece surface after the run. Such high temperatures cause the heat to distort the ball geometry and results in poor dimensional quality.

Looking at the results and parameters in Table 8, it can be seen that if the heat generation was not an issue, the material removal rate could be increased over the level of Theleico or Diprotex. Norton grade F would benefit from the improved fluid delivery and cooling capabilities more than Theleico or Diprotex. For their MRR the limiting factor is the segment itself, not an outside factor like for Tyrolit and Norton.

Table 8. Results of Norton's segments.

Specification:	**Feed rate (mm/min)**	**Tool speed (RPM)**	**Material removal rate (mm^3/min)**	**G-ratio (MRR/Tool wear)**	**Temperature**
3NQX120F24VS3X	0.2	2000	3397	3.04	On the limit
	0.18	2200	3651	4.11	Too high
	0.22	1800	2951	2.25	Acceptable
3NQX120H24VS3X	0.14	1400	1874	4.14	Too high
	0.15	1000	1449	1.55	Acceptable

The Table 8 also shows results for grade H, but because of the thermal issues, even with additional coolant, the best results have to be rejected. An example of glazed tool surface and burn marks that severe glazing causes is seen in Figure 27. Such tool glazing occurred throughout the experiment and as expected, with lower feed rate and higher tool speed it was worst. The burn marks seen on right side of the figure, was more extensive when the ball was rotating slower, however occurred with higher workpiece speed as well.

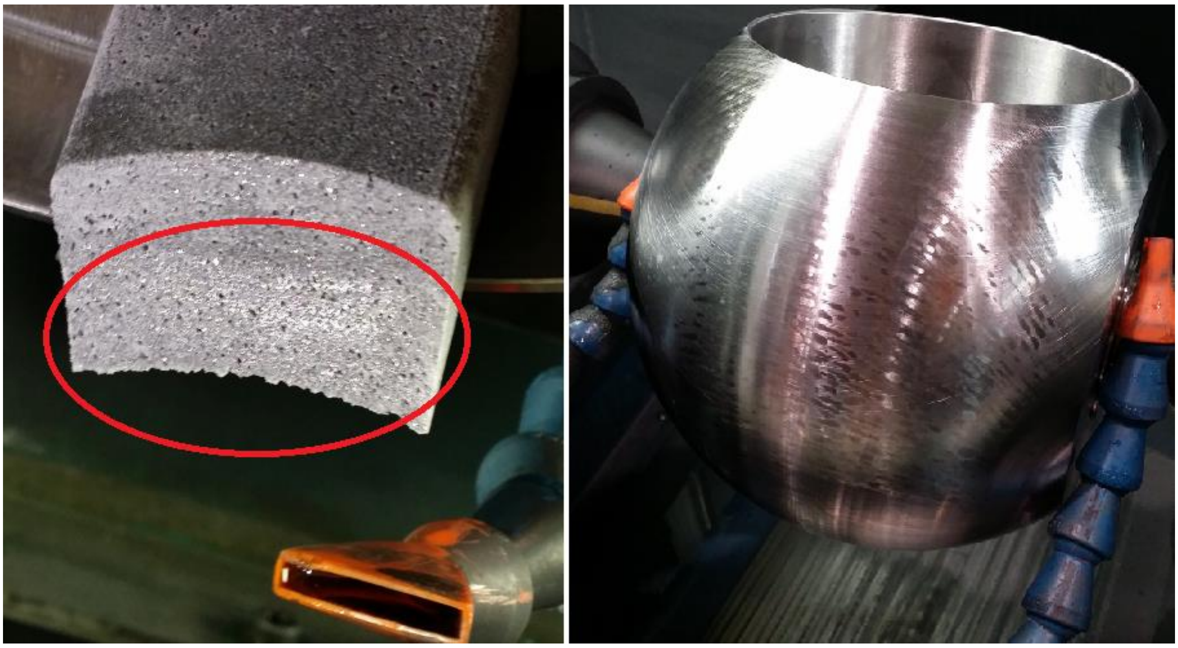


Figure 27. Glazed tool surface and its effect on workpiece surface from screening experiment with Norton grade H.

Since both the grade F and in particular the grade H had thermal issues, the hardest of the Norton segments was not experimented further from the initial screening experiment and was simply declared to be too hard.

Follow-up to Experiments with Norton

Further experiments with Norton segments have not been planned so far, but by analyzing the test results, conclusions about the direction of changes can be drawn. The grade F showing the most potential, points to direction of softer grades. Even the grade F tends to glaze when increasing the material removal rate and thus experiment softer grade, such as E, would be an interest. If segments with lubricative additives like sulphur are available, its effect together with increasing grain content would be a possible route to improvement. Further, the grain size could be changed to larger as the surface roughness seemed to be on better level than with Tyrolit.

8.2 Observations and Findings on the General Process

Even if the five segments failed to bring improvement to material removal or tool wear, the experiments conducted with them provide a good reference point and indicated the direction of change. After the completion of this thesis, follow-up experiments with altered tool specifications continue. In addition to tool specific observations made in this thesis, several other interesting observations about the process were made. Some of the observed phenomena are discussed in this chapter and the recommended actions are covered in chapters 8.3 Development possibilities and 8.4 Further research topics and experiments.

8.2.1 Observations on Fluid Delivery

On the test machine, Tyrolit segments have been used for years with just four low pressure flood nozzles. The low pressure, alignment and distance of the nozzles from the contact zone likely results in very little of grinding fluid actually reaching the contact zone and the fluid works mainly as cooling the workpiece. There has been no need for additional nozzles and as discussed earlier, this is based on the hypothesis of the effects of the sulphur impregnation. Because there was no need for the additional nozzles earlier and the effects and whole reason of the sulphur impregnation of Tyrolit segment were unclear, the poor performance of the alternative segments was not linked to shortage of lubrication at first. This was recognized after couple experiments in when the additional nozzles were first added in.

All the alternatives were already experimented without additional fluid before the nozzles were added and their benefits were discovered. As a result, experiments for each tool, excluding the Norton grade J, had to be started all over with the additional nozzles as a part of the process. Adding the nozzles was beneficial for all of the alternative segments as seen from the Figure 28, more comparisons between runs with and without fluid can be found in the reports in the appendices. In the case of Theleico and Diprotex, fluid applied directly to the contact zone stopped excessive fracturing and the G-ratio increased by a magnitude. With Norton’s segments, the introduction of fluid reduced the heat generation and made the use of wider parameter scale possible.

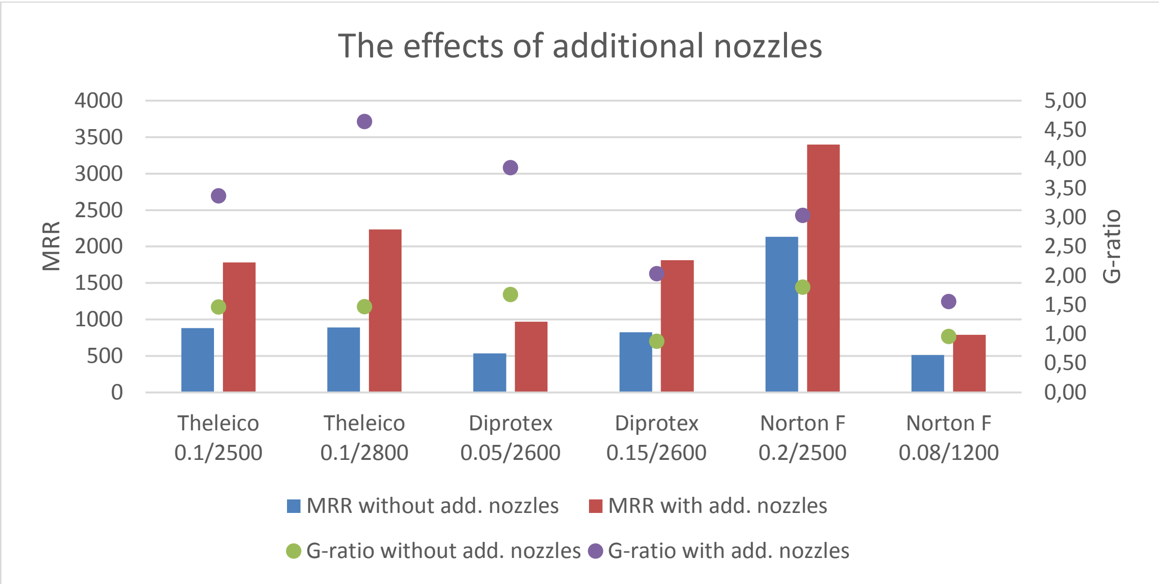


Figure 28. Some of the directly comparable responses between runs with and without additional fluid delivery. The number values below the names of the segments represent the grinding parameters, first being the feed rate and the latter the tool speed.

After the fluid delivery was discovered to have such large impact on the responses and being a difficult factor to retain constant between experiments, its high possibility of acting as a nuisance factor was realized. The Figure 29 shows the difference in responses between three identical runs, taken with Diprotex's segment, apart from the fluid delivery.

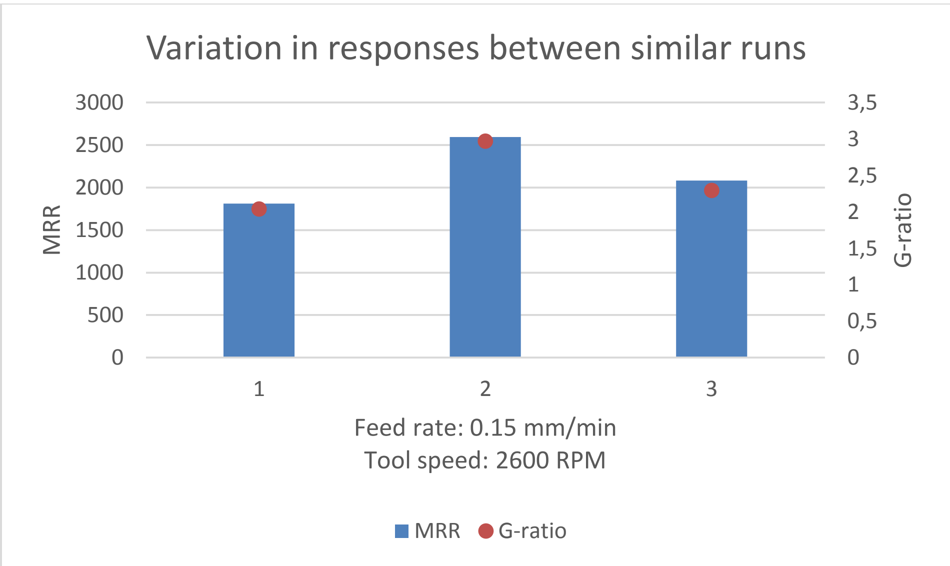


Figure 29. Variation in responses between three runs with identical grinding parameters.

The other known nuisance factor, tool bending, might explain some of the poor response of run 1 as the tool was significantly longer than on runs 2 and 3. But the difference between runs 2 and 3 cannot be explained with tool bending, since on run 2 the tool was actually longer. The run number one is taken from screening experiment conducted day earlier than runs 2 and 3 that were part of confirmation experiment. Between the two experiments, the machine was used for normal production and the fluid hoses were removed. The factors from the screening experiment were tried to be replicated for the confirmation experiment, but there was clearly difference in fluid delivery as the responses between runs 1 and 2 are so far off. For the last couple confirmation runs, including the number 3 in the Figure 29, the fluid flow and pressure were decreased and the nozzles were re-aligned and the response was much closer to run 1 from the previous day. This can be also seen by looking at the model and its fit to confirmation runs on the Appendix III, 13 and 14.

Since the fluid delivery is so important, in particular with segments without after treatments, a new and improved hose and nozzle setup has been ordered. Needle nozzles that have several small openings are to be used to deliver the fluid to contact zone with high pressure. Using high enough pressure could possibly improve the flushing of the tool and help with the phenomenon that started after the additional nozzles were added. The Figure 30, shows the surface of a segment and a ball after a run with additional coolant nozzles in use.

Figure 30. By using the additional nozzles to deliver fluid to contact zone, two distinct surfaces start to generate on the segment’s surface, which the segment starts to replicate on the ball surface.

The Figure 31 could explain the cause for two distinct surfaces of the segment after the additional fluid nozzles are used. As seen, the segment reaches over the edge of the spherical surface. Momentarily, when the bottom half of the segment is free of contact, the grinding pressure coming from the feed rate is focused on much smaller area that is in touch with the workpiece. The decreased area causes the pressure to increase and fractures the top part, creating a fresh surface that is seen in the Figure 30 above.

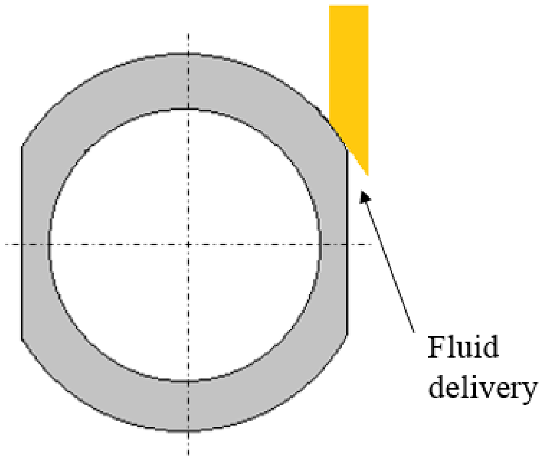


Figure 31. An illustration of a single segment over the bearing side and how the fluid is delivered to contact zone.

The phenomenon occurs with all segments but is the most noticeable with the soft Diprotex and Theleico segments. With Tyrolit it is noticeable only with certain parameters when the feed rate is low and tool speed is high. The reason this does not occur without the additional fluid, at least with Theleico and Diprotex, could be the segment fracturing constantly because of lack of lubrication. When the fluid is introduced to contact zone, the constant fracturing stops, making the bottom part of the segment last longer and turn gray from swarf while the top part of the segment, so to speak, self-dresses because of the momentary pressure increase.

As mentioned, the high pressure nozzles could possibly alleviate the distinction of the two surfaces by flushing the swarf stuck on the tool as well as by removing loose grains. In the Figure 32 is a badly clogged segment and a close up of its surface, where the gray material is swarf. The pictures were taken prior to experiments with additional coolant nozzles and even with the with limited pressure obtained from them, the tools have not clogged as bad as in the Figure 32.

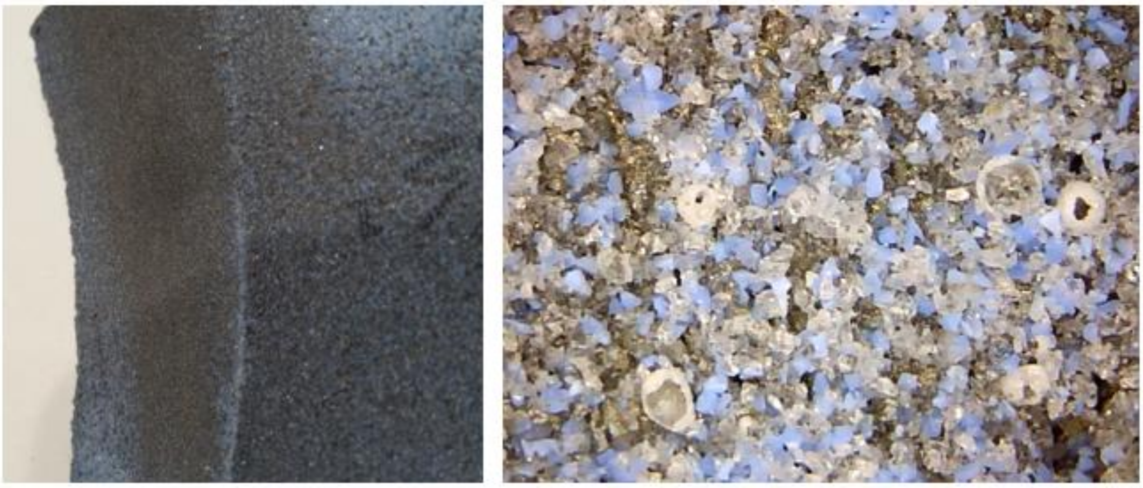


Figure 32. Severely clogged surface of Diprotex segment.

8.2.2 Fluid Content and Concentration

The grinding machine users have been expressing their doubt about the performance of the grinding fluid as it ages. To analyze the quality of the fluid, emulsion concentration is measured with refractometer on regular basis and bacteria and mold levels are monitored with laboratory tests to make sure they stay within limits. According to above mentioned tests, the fluid is as good as new, but none of the tests consider the cutting properties of the fluid.

As corrective measure to maintain the emulsion concentration, it is regulated by adding either more water or emulsion in the central system. This keeps the mixture of emulsion on the wanted 3%-level, but the exact contents of the grinding fluid are not known. To start the research of grinding fluid, samples of the fluid were taken on the end of the week from one of the grinding machines and on the beginning of the next week from the central system. The fluid currently in use in the central system has been in circulation for about a year. For reference, another sample was taken of clean, unused grinding fluid. The samples were sent to a laboratory, where the contents of the samples were analyzed. The goal of the analysis was to find out if any of the substances that are added in the fluid for purpose by the manufacturer, are filtered out in the central system. The other objective was to find out if any of the ground materials start to concentrate in the grinding fluid, possibly hinting that the filtration is not working optimally. The report of the grinding fluid samples is in the Appendix VII.

The substances that were looked for from the samples were the additives that were known to be added in the fluid based on the fluid's safety manual and substances that were known to be used in fluid as friction modifiers such as EP additives. Additionally, the concentrations of substances coming from ground coatings, base materials and what could originate from the grinding segment were analyzed. Nearly all of the analyzed substances had very high concentrations in comparison to fresh sample.

The sulphur content was a particular interest since it is known to be used as an additive in both the grinding tools and fluid. And because of the information found from the literature, such as research conducted by Nadolny et al. (2013, p. 118), where sulfur from grinding tool liquefied as a result of high temperature in the grinding contact zone. The temperature in the contact zone in ball grinding is not known, but sulfur becoming liquid in certain conditions cannot be ruled out.

The above mentioned possible liquidation of sulphur is just one way of certain substances concentrating in the grinding fluid. Looking at the report in the Appendix VII, concentrations of many other substances are elevated as well. Based on the concentrations of chlorine, boron and sulfur in the fresh sample, they are all used as additives in the fluid in different forms. But comparing their concentrations between fresh and currently used sample, the concentrations in the used sample are several times higher. This is very likely a result of regulating the emulsion concentration by adding emulsion concentrate. It has not been known whether their concentrations change in relation to emulsion's concentration and judging by the report they do not. By adding in more of the emulsion, the fluid starts to accumulate with substances that do not evaporate from the fluid.

Researches reveal extensively high concentrations of certain chemical substances, that are added in the fluid as beneficial additives, increasing the grinding forces and wear (Brinksmeier et al. 2015, p. 614). Whether the concentrations in the grinding fluid samples are high enough to be disadvantageous is not known, but the findings from the literature would back up the machine users' complaints about slowly deteriorating performance of the fluid.

The other substances, mainly metallic materials, do not have as high concentrations, but comparing to fresh sample, they likely should not be in the fluid. In particular, nickel and chromium concentrations are high and could be a sign of ineffective filtration. The difference in grinding performance that the substances cause between the fresh and used sample, could be determined with experiments. Changing the grinding fluid in the system has been discussed and experiments before and after are planned to discover the real impact of grinding fluid. Based on the results of experiments with new and used fluid, a schedule for future grinding fluid changes could be estimated.

As the concentrations of different substances likely accumulate with time as the fluid is used and the effects of the substances or their extent are not known, grinding fluid causes variation between experiments in the long run. The experiments in this thesis were conducted over the time span of couple months. Although, the fluid is not estimated to be a severe nuisance factor within this time, its effects cannot be ruled out, thus slightly harming the reliability of the experiments and the research.

8.2.3 Bending of the Segment

The grinding head design that is used with six inch balls and several other ball sizes, is robust and thus very stable and unsusceptible to chatter. The design however has some drawbacks, of which the tool bending is the most crucial for experimenting. The other drawbacks and possible improvements are discussed more closely in the chapter 8.3 Development possibilities.

The machine users were aware of the tool bending slightly when the segment is new and on its full length. But its extent was not known before the experiment with Theleico, where grooving of the segments was experimented. In such experiments, where the run order was not randomized, the bending poses as a serious nuisance factor that can distort the results of the experiment. Prior to the grooving experiment, the bending was not considered a nuisance factor.

The effect of tool bending and how it can lead to false conclusions can be seen by looking at the experiment more closely. The initial conclusion from the experiment with grooves was that grooving the segments is beneficial for material removal rate. Looking at the two leftmost blue columns in the Figure 33, the grooving seems to have increased the MRR and the same applies to two of the leftmost red columns. After six runs with three different parameter combinations, all pointing to same direction, the grooving was stated to be beneficial. To confirm this, another three test runs were taken: the rightmost blue column and the two rightmost red columns. Now with the parameter combination one and without grooving, the material removal rate was on the similar level to earlier run with grooving. The same happened with the parameter combination two. The run without grooving resulted in rather identical MRR. The last run of the experiment, the rightmost red column was taken with grooving again and it resulted in even slightly lower MRR than the earlier run without grooving.

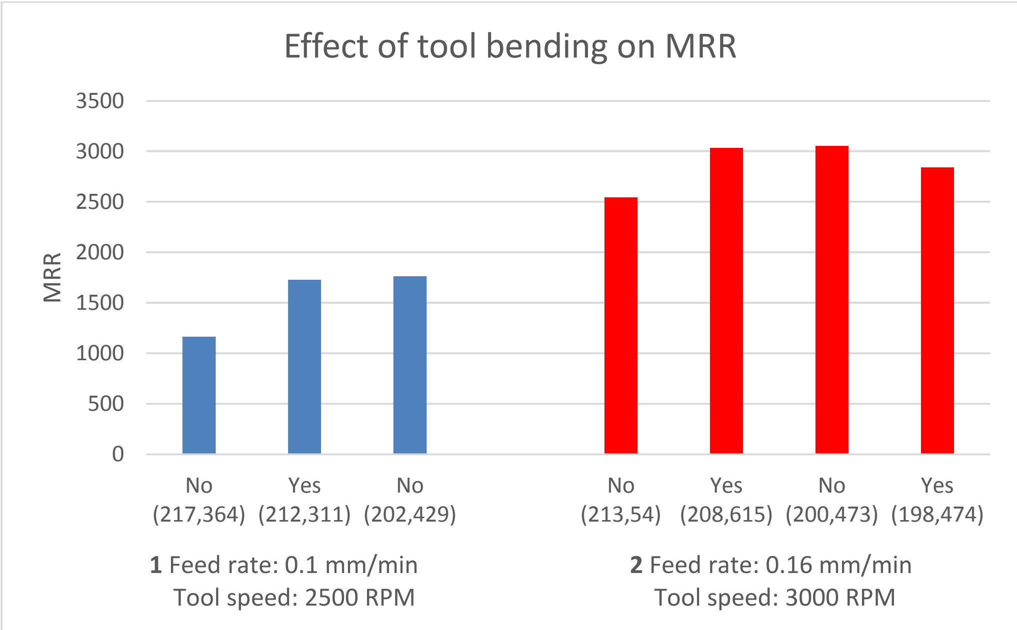


Figure 33. Material removal rates from experiment where the effect of grooving was determined. Yes or no stating whether the segment was grooved and the value below it expressing the tool length after the run.

The experimentation of grooving finally proved two things. Grooving is not advantageous for Theleico and unlikely for any of the segments that are porous enough to not to be prone to hydroplaning. The experiment also proved the effect of bending, how it depends on the tool length and how it can lead to false conclusions if not taken into consideration.

8.3 Development Possibilities

This chapter covers mainly improvements and changes for the grinding machine. Some of these proposals would be mainly to help in the future experiments and some of the proposals are based on the machine user's feedback and would be beneficial in the everyday production as well.

The most significant single improvement would be changing the design of the grinding head. There are several issues related to it, of which the tool bending was already touched on. To eliminate bending or to at least reduce it, the distance of the segment contact area from the support point would have to be reduced. When the segments are worn and they are shorter, the lever arm is shorter like on the right side of the Figure 34, leading to less bending.

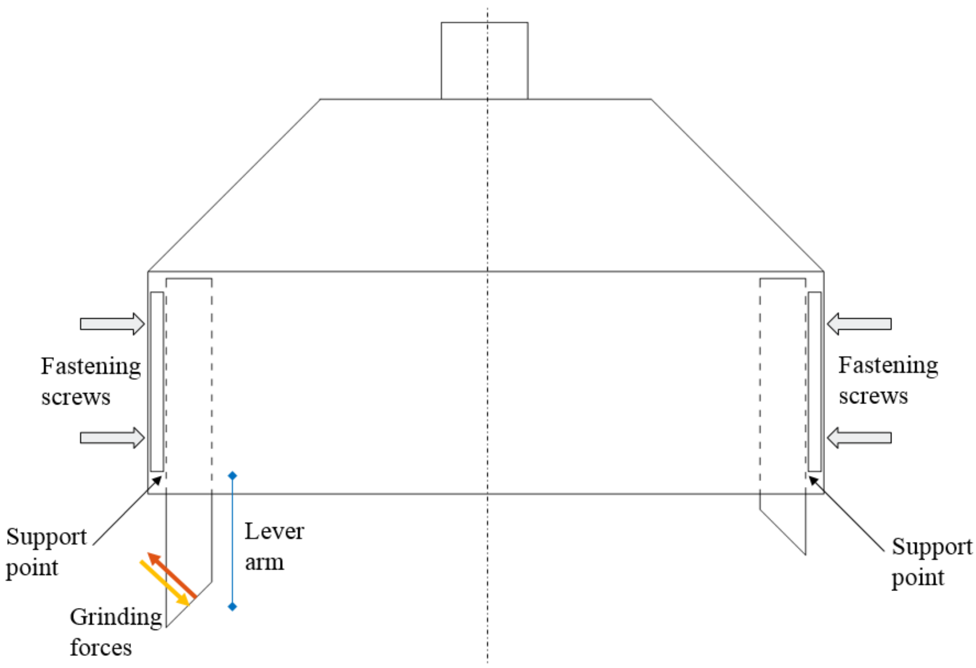


Figure 34. The current grinding head design.

Which takes us to the second issue with the grinding head design: fastening the grinding segments. The machine users say that fastening method of the segments is unnecessarily complex, requiring either two screws to be tightened at the same time or by tightening them alternately little by little. The tight fit of the segments without a possibility to disassemble the grinding head to clean the swarf causes segments to get stuck. In few of the experiments the method of fixing the segments to grinding head was also noticed to cause point loads on the segment surface, inducing splits on the segment surface and causing them to break.

The design of the grinding head has also a third major flaw. Only about half of the segment can be used, after which the segment cannot be fastened to grinding head securely. Once the top of the segment reaches about the halfway between the fastening points, the segment is changed to new. The half used segments can be still put to use in the older grinding machine with different grinding head design, but that does not make the drawback of the grinding head any less justified.

For an improved grinding head, the machine users have been proposing a design where the segments are fastened in place with a band surrounding the periphery. The design is still on idea level and requires work but could reduce the time needed for change or adjustment of the segments, while providing support for the segment in grinding, reducing the bending phenomenon. In production that is constantly moving towards smaller batch sizes, reducing the setup times is becoming more and more crucial and could be achieved with better grinding head design.

Another suggested improvement for the machine, also originating from the machine users, would be dressing possibilities for the segments. Self-sharpening seems to work rather well in production when grinding uncoated workpieces like in the experiments. Chromium coating is however problematic and sometimes the machine users are required to manually dress the surfaces by using another segment to scrape the contact area surface. Built-in dressing tool would speed up the process but the characteristic extremely long contact length of the application would likely lead to very frequent need of dressing. So, the primary interest is to find a separate grinding segment for chromium coating and eliminate the need for dressing altogether.

In the experiments so far, the power output has been monitored from the control screen of the grinding machine and collecting the data has simply been writing down the power output value every two minutes. The information about the power output is really valuable in predicting the tool behavior because the power output and its changes can tell what is happening in the contact zone, where the eye cannot see. A data logging feature on the machine would be more accurate and easier method to collect the data, without necessarily leading to huge investments.

Some of the other grinding machines at Metso have a fluid delivery inside the grinding head, through the spindle. The feature is helpful in getting the fluid to reach the contact zone evenly during the rotation of the tool, as long as the fluid is correctly directed and the velocity is high enough. Before investing in changes that would be required on the fluid delivery system and the machine, the benefits of the fluid delivery through spindle would have to be experimented, which more about in the next chapter 8.4 Further research topics and experiments.

8.4 Further Research Topics and Experiments

Various segment specifications have been and are being ordered based on the experiments conducted in this thesis. The follow-up experiments for these segments are going to continue in similar manner to determine their performance and whether they bring an improvement. In addition to these follow-up experiments already discussed in evaluation of each tool, few other experiments would be highly beneficial to determine the effects of certain factors. These additional experiments and further research topics are covered in this chapter.

The steel base material, that is ground in the experiments in this thesis, represents only some of the ground material range. Titanium dioxide (TiO_2) and hard chromium coatings are also ground with the same Tyrolit segment. In particular, grinding the chromium coating has been an issue as described earlier. The chromium coating has always been ground with a sharp edge on the segment, keeping the contact area between the workpiece and the segment small. Once the segment would wear, starting to contour the spherical shape, the tool would have to be cut to obtain a sharp edge with small contact area again. To eliminate the need for earlier mentioned manual scraping of the tool surface, that the machine users are required to do, and perhaps to make possible the use of the whole surface area of the segment, new specifications for grinding chromium coating are experimented. To start the grinding experiments with chromium coating, a modified specification of the Tyrolit segment has been ordered based on the Tyrolit’s recommendation.

For grinding titanium dioxide coating, specification with silicon carbide abrasive was in use years ago. According to machine users, the specification worked much better on TiO_2 than the Tyrolit with aluminium oxide grain. The manufacturer of the segments closed down and few substituting segments have been tried years ago with poor results. Now to start the search for a better tool for grinding titanium dioxide, a specification based on the Tyrolit's recommendation has been ordered.

On top of reducing the thermal issues, increasing the workpiece speed seemed to result in minor increase in material removal rate in most of the experiments. Since the workpiece speed seems to be limited only by the quality related factors, such as vibration and its effects, and the higher speed is otherwise beneficial, the limits for the workpiece speed would be beneficial to determine. If the thermal issues can be reduced by increasing the workpiece speed, this could possibly allow increase in material removal rate. Practical limits for the workpiece speed could be determined with experiments where the responses would be quality related, such as dimensional and geometrical integrity.

After the grinding fluid in the central system is changed, the effect of the fluid can be determined by running experiments prior and after the change. Furthermore, these experiments should be conducted regularly as the grinding fluid ages, for example every couple months. This practice would help in understanding the connection between the aging of the fluid and its performance. Even better, if the experiments are done together with collecting and analyzing samples of the grinding fluid, a possible correlation between the contents of the fluid and the cutting performance can be determined.

Another grinding fluid related factor of which effect would need to be determined through experimenting, is the emulsion concentration. Currently, the concentration is kept at 3%, so at the lower limit of the fluid manufacturer's recommendation (Henkel 2013). As shown in the Figure 14, increase in oil content shifts the properties closer to oil from water. Whether increasing the emulsion concentration would lead to improvement in this application could only be confirmed with an experiment.

The experiments proved the additional grinding nozzles to be beneficial for all the alternative segments with aluminium oxide grains. Since superabrasives, diamond and CBN, are also widely used, the effect of introducing extra fluid in a process would have to be determined through experimentation.

The way of grinding valve balls with high conformity cup or segmented wheels is not the only available method; grinding machines with other principles do exist. For example, a machine in which the tool is a traditional grinding wheel oscillating on the ball surface. The machine would be also capable of grinding for example valve seats and thus having its own advantages. The advantages and disadvantages of the currently used grinding machinery are rather well known, but how they compare to other grinding principles and machines in the market is unclear. Research on other machinery would be highly valuable for future investments which is why its listed here on the further research topics. (Danobat 2017b.)

8.5 Validity and Reliability

This thesis was able to answer the main research questions about the grinding tools and the parameters by using statistical methods where randomization and confirmation tests equipped, leading to valid results. The questions raised during the experiments and writing of the thesis are discussed based on the literature, however many hypotheses requiring further experimenting are left open, and therefore slightly hindering the overall validity of the research.

Despite the validity and reliability being on fairly good level, there are several factors that harm the reliability and in particular replicability of the experiments. Some of their effects are known better after this thesis and can be prepared for in the forthcoming experiments. The factors are:

- Tool bending causing experimental error
- Fluid delivery causing experimental error
- Evaluating the workpiece temperature with human perception

The same factors are the nuisance factors in the experiments and their impact is covered in the chapter 7.1.2 Design factors.

9 CONCLUSIONS

The goal of this still ongoing research is to find a grinding segment that would improve the grinding process. The main interest is in increasing the material removal rate while not giving up on quality. The experiments conducted for the five segments that were initially recommended by the grinding tool manufacturers, proved that the combination of the factors in tool specification ultimately determines the material removal rate. Potential benefits from single factors, from a more novel grain in this case, are not realized unless the other factors are suitable.

Despite that the five initial tool alternatives failed to bring improvement to the process, valuable knowledge and observations were gathered from the experiments. This knowledge is now used to alter the tool specification of the initially recommended tools towards more suitable. The first experiments with altered specifications show an improvement to initial level and the performance is closing the minimum target level set by the currently used segment.

The importance of lubrication that the correctly set-up fluid delivery brings, was noted in the experiments. With the alternative segments, the material removal rates grew up to four times the level that was achieved without additional fluid delivery. The introduction of fluid delivery directly to the contact zone through the additional nozzles was a crucial find for the performance of the segments that do not have lubricating additives in the tool itself and remains in use in the future experiments.

Using design of experiments approach with full factorial designs proved to be an effective method for optimization tasks. However, once the experimenter is familiar with the tool behavior, one-factor-at-a-time method can be used as effectively.

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Results and analysis: Tyrolit – 89A120F8V217T3

Tyrolit's segment has already been experimented in 2015 and the optimal parameters for it are known. To get more recent and thus fair reference for the other segments, Tyrolit was decided to be experimented as well.

EXPERIMENT 1: 15.12.2016

The optimized parameters for Tyrolit's segment were known to be:
Feed rate: 0.15 mm/min
Tool speed: 1800 RPM
Workpiece (WP) speed: 50 RPM

These parameters were used as a middle point for the parameter setting for the experiment.

The test matrix for Tyrolit was following:

StdOrd	**RunOrd**	**Feedrate**	**Tool RPM**	**WP RPM**	**Tool L 1**	**Tool L 2**	**WP D 1**	**WP D 2**	**Fluid temp.**	**MRR**	**G-ratio**
5	1	0,12	1600	80	225,476	224,093	245,966	245,24	18,8	2825	4,44
3	2	0,12	2000	20	224,093	222,894	245,24	244,225	18,9	3936	7,14
8	3	0,18	2000	80	222,894	220,948	244,225	242,857	19,1	5281	5,90
7	4	0,12	2000	80	220,94	219,682	242,857	241,857	19,4	3842	6,64
4	5	0,18	2000	20	219,682	217,791	241,857	240,402	19,1	5561	6,39
6	6	0,18	1600	80	217,791	215,715	240,402	239,222	18,9	4485	4,70
2	7	0,18	1600	20	215,715	213,621	239,222	238,037	18,6	4481	4,65
1	8	0,12	1600	20	213,621	212,263	238,037	237,186	18,4	3204	5,13

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK, slightly warm	Normal	21-35	
2	Hot, fluid vaporizing	Slightly glazed	25-44	
3	OK, slightly warm	Normal	34-46	
4	OK, slightly warm	Normal	32-41	
5	Hot, fluid vaporizing	Slightly glazed	29-44	
6	Cool	Normal	26-38	
7	OK, slightly warm	Normal	26-36	
8	Cool	Normal	24-35	

Overall observations:
No problems occurred during the experiment. In overall, the parameters seemed to be close to optimal, as the response was on rather high level on every run. Higher workpiece speed helped to keep the workpiece temperature lower.

Analysis:
Naturally, increasing the feed rate and tool speed show an increase in MRR, as seen from the Figure 1. The effect of workpiece speed is small, as expected. No interaction between the feed rate and tool speed was present, likely due to narrow parameter range. Surprisingly the feed rate and workpiece speed seem to be about as significant for G-ratio, both showing decrease towards the higher values.

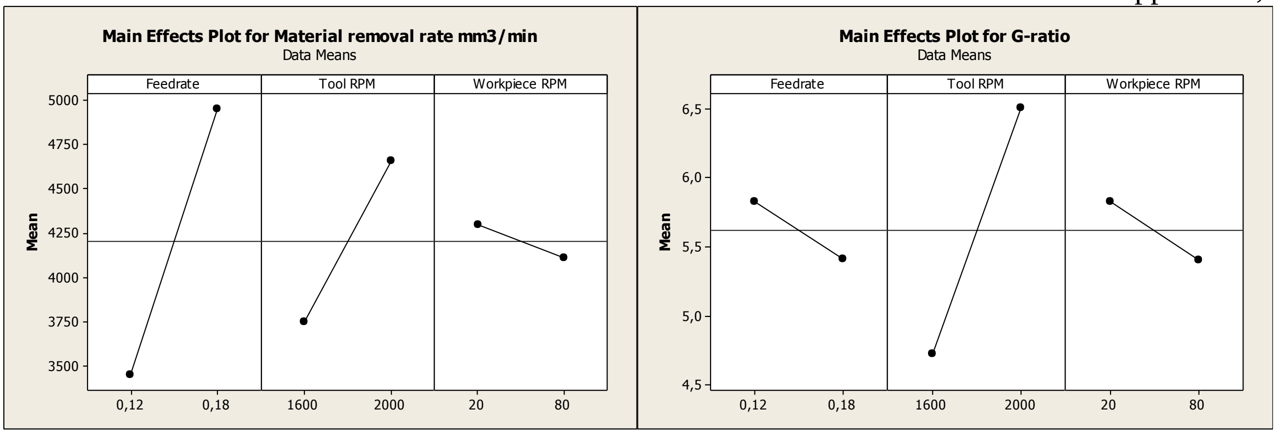

Figure 1. The effects of design factors on MRR and G-ratio

The third run resulted in highest material removal rate with acceptable temperature, however right one the limit. The temperature would not allow much higher MRR, however minor increase in feed rate could slightly improve the MRR but on the expense of G-ratio. Thus the results from the third run are used as reference for other segments.

Since the Tyrolit's performance and behavior is well known and has been modeled in the experiments conducted in 2015, the process is not modeled in this thesis, unlike the other segments.

EXPERIMENT 2: 27.12.2016 - Screening

Additional fluid nozzles lead to improved responses with alternative segments and therefore their effect was experimented with Tyrolit as well. The design matrix had identical values for feed rate and tool speed from the earlier experiment, but being rather insignificant for MRR, the workpiece speed was replaced with factor for extra coolant. The lower workpiece speed seemed to result in higher MRR in the first experiment and was then decided to be set at 20 RPM, despite of possibly leading to workpiece heating. The higher heat generation was in fact considered to be beneficial in the experiment, to bring out the effect that the extra fluid delivery has on the workpiece temperature.

StdOrd	RunOrd	Feedrate	Tool RPM	Extra cool.	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
1	1	0,12	1600	No	221,928	220,577	246,804	245,973	18,8	3243	5,22
2	2	0,18	1600	No	220,577	218,535	245,973	244,712	18,5	4902	5,22
3	3	0,12	2000	No	218,535	217,363	244,712	243,571	18,6	4415	8,19
4	4	0,18	2000	No	217,363	215,465	243,571	242,103	18,7	5651	6,47
5	5	0,12	1600	Yes	215,465	214,033	242,103	241,43	18,9	2579	3,92
6	6	0,18	1600	Yes	214,033	211,823	241,43	240,483	18,9	3617	3,56
7	7	0,12	2000	Yes	211,823	210,622	240,483	239,447	19	3941	7,13
8	8	0,18	2000	Yes	210,622	208,681	239,447	238,045	19,1	5305	5,94

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK, slightly warm	Normal	12-26	
2	OK, slightly warm	Normal	17-33	
3	Hot, fluid vaporizing	Normal	16-36	
4	Hot, fluid vaporizing	Normal	21-38	
5	Cool	Normal	25-46	
6	Cool	Normal	24-42	
7	OK, warm	Top half clearly open, bottom half normal	25-60	
8	OK, warm	Normal	33-63	

Overall observations:
The additional fluid seemed to result in lowered responses and cause the power output to go up significantly. It did keep the workpiece cooler however and the fluid seemed to be warmer in runs with the extra delivery, since more heat was conveyed in it.

Analysis:
As seen from the Figure 2, for MRR the extra coolant shows a clear downwards slope towards the extra coolant and the effect is naturally similar on the G-ratio.

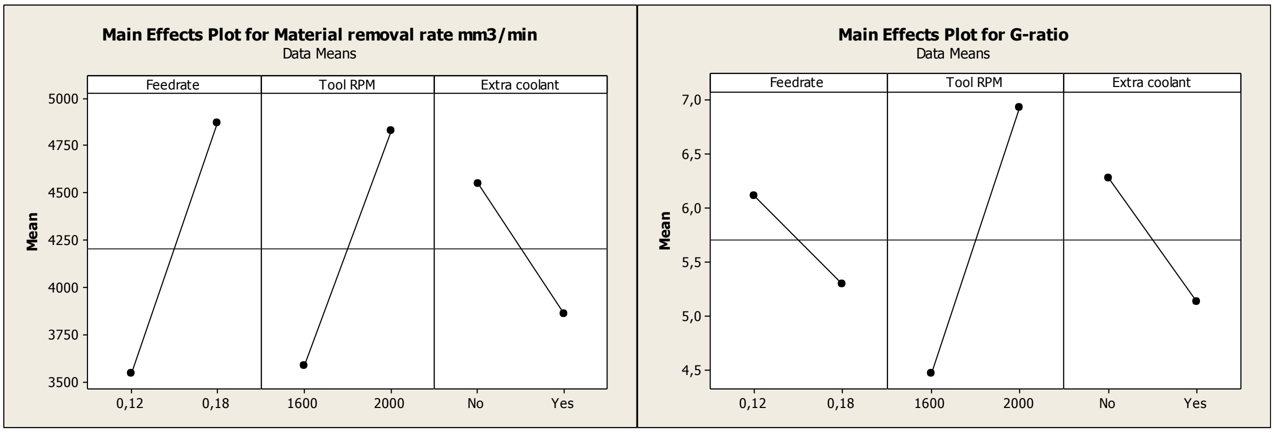

Figure 2. The effects of design factors on MRR and G-ratio.

In overall, the extra coolant impaired the responses, however the difference between runs with and without extra coolant seemed to balance out towards the end of the experiment. The experiment does not change the evaluation of the segment and it the reference level is still the run number three from the first experiment.

Results and analysis: Theleico – 23A120-0F12VM4200

EXPERIMENT 1: 30.11.2016 - Screening

The test matrix was then decided to be set based on the screening experiment conducted for Diprotex segment. With high feed rates the Diprotex segment was wearing out quickly, so the feed rate was lowered. Also, the output seemed to increase by increasing tool speed, so the experiment with Theleico was decided to be started with higher tool speed. For which different tool speeds were cautiously tested prior the start. The highest tested tool speed was 2500 RPM, with which no problems occurred.

The test matrix for the first screening of Theleico was finally following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
1	1	0,03	1200	20	214,216	213,771	244,497	244,445	18,3	201	0,98
7	2	0,03	2500	80	213,771	213,496	244,445	244,243	18,3	782	6,18
2	3	0,1	1200	20	213,496	211,987	244,243	244,197	17,9	178	0,26
3	4	0,03	2500	20	211,987	211,682	244,197	244,046	18,4	584	4,16
4	5	0,1	2500	20	211,682	210,327	244,046	243,855	18,2	738	1,18
8	6	0,1	2500	80	210,327	209,076	243,855	243,503	18,8	1359	2,36
5	7	0,03	1200	80	209,076	208,626	243,503	243,468	18,5	135	0,65
6	8	0,1	1200	80	208,626	207,101	243,468	243,416	18,6	201	0,29

Overall observations:
No problems occurred in the first screening experiment of Theleico. Like with every other segment, the higher tool speeds seemed to result in higher outputs. The performance was still far from the goal set by Tyrolit but after the first round of screening experiments, Theleico showed the most promise. The ball surface quality seemed good after every run and no heating problems occurred.

EXPERIMENT: 20.12.2016 - Confirmation

Regression models were composed of the first screening experiment and the accuracy of the models was tested in confirmation experiment, with a following test matrix:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,04	2500	80	219,45	219,015	246,914	246,749	19,1	645	3,22
x	2	0,06	2000	80	216,933	216,158	246,749	246,624	19,1	488	1,37
x	3	0,06	2500	80	214,16	213,453	246,624	246,434	19,3	742	2,28
x	4	0,08	2000	80	213,453	212,363	246,434	246,314	18,6	468	0,93
x	5	0,08	2500	80	212,363	211,364	246,314	246,093	18,6	862	1,88
x	6	0,1	2500	80	211,364	210,056	246,093	245,867	18,6	881	1,46
x	7	0,1	2800	80	207,861	206,542	244,834	244,604	18,8	892	1,47

The models follow the changes in actual tested values sufficiently as seen from the Figures 1 and 2, but the tested output is much below the estimated throughout the test matrix. The error is emphasized on the G-ratio as the lacking material removal basically transforms to tool wear. The estimates could be corrected by adjusting the constant in the model, by doing so the MRR predictions reach a 90 percent prediction interval. However, by correcting the constant in the G-ratio model, the predictions are still far off. This kind of constant error hints towards variation in conditions between the screening and confirmation experiment. After realization of the major influence that the fluid has, the difference was likely in delivery of the coolant. Even though the both tests are conducted with just flood nozzles, their alignment was probably different, leading to different amount of fluid reaching the contact area.

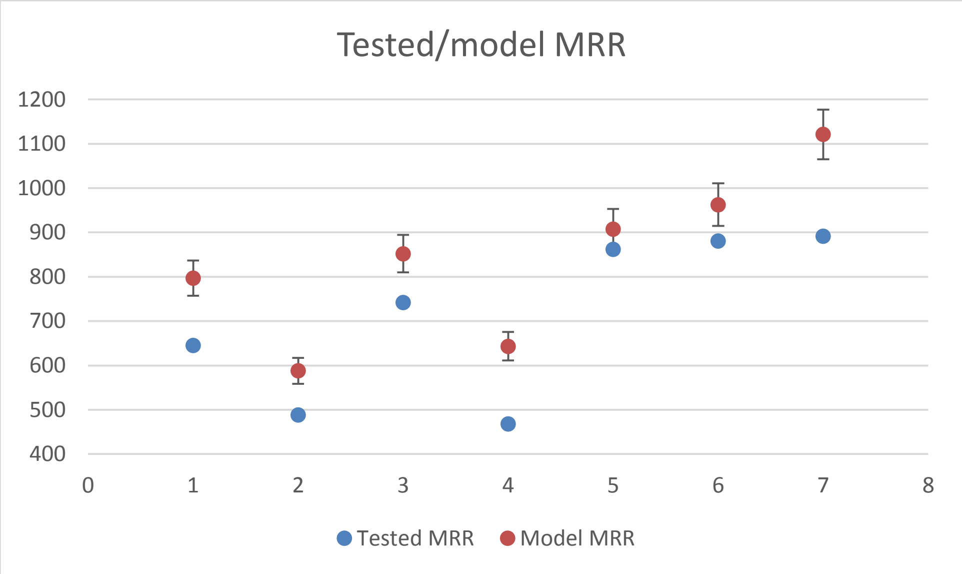

Figure 1. The fit of the MRR model to confirmation runs, with 10% error bars.

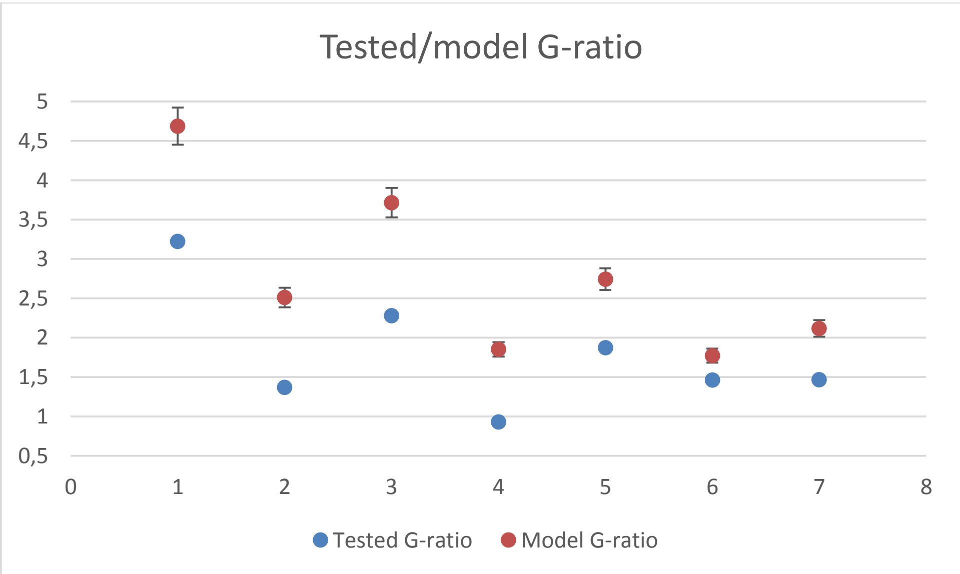

Figure 2. The fit of the G-ratio model to confirmation runs, with 10% error bars.

EXPERIMENT 3: 20.12.2016 – Screening

After the confirmation runs for the regression models, the introduction of extra coolant nozzles was experimented for the first time and the results were promising. Since the outputs were greatly enhanced, the evaluation of the segment was decided to be based on a setup with extra coolant nozzles. Thus a screening experiment was conducted with a setup with additional fluid nozzles.

The test matrix for the screening experiment was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,1	2500	80	210,056	208,907	245,867	245,409	18,6	1782	3,37
x	2	0,1	2800	80	208,907	207,861	245,409	244,834	18,9	2233	4,64
x	3	0,15	2500	80	204,464	202,611	243,328	242,733	19,1	2292	2,69
x	4	0,15	2800	80	202,611	200,848	242,733	241,962	18,9	2962	3,65

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Cool	Normal/slightly glazed	32-38	
2	Cool	Normal/slightly glazed	34-43	
3	Cool	Normal/slightly glazed	31-41	Distinct surfaces of the segment start to replicate to the ball surface
4	Cool	Normal/glazed	39-49	

Overall observations:
The additional coolant nozzles resulted in a new unseen phenomenon on the segment surface where the surface had two clearly distinct sections to it. The bottom half looked normal like before adding the nozzles. The top part then was clear, the color was bright and there was visibly less swarf clogging the surface.

Analysis:
Based on the earlier experiments, the workpiece speed was already left out from the test matrix by setting it to 80 RPM. Therefore, the design factors were feed rate, tool speed. Neither of the terms or their interaction come up as statistically significant, as seen from the Figure 3. Based on the previous tests however, all of the three terms will be included in the regression models and the suitability and fit of the models are verified through confirmation experiment.

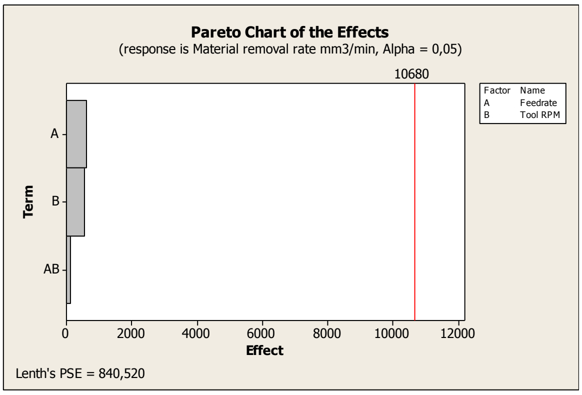

Figure 3. Statistical significance of the terms with α=0.05

The material removal rate improves by increasing the feed rate and the tool speed, as seen from the Figure 4. Looking at the interaction plot, also very minor interaction can be seen. The small effect of interaction can likely be explained with the narrow scale of the tool speed. For the interaction to be more influential, the difference in tool speed, or the feed rate, would have to be large enough to cause the tool behavior to change.

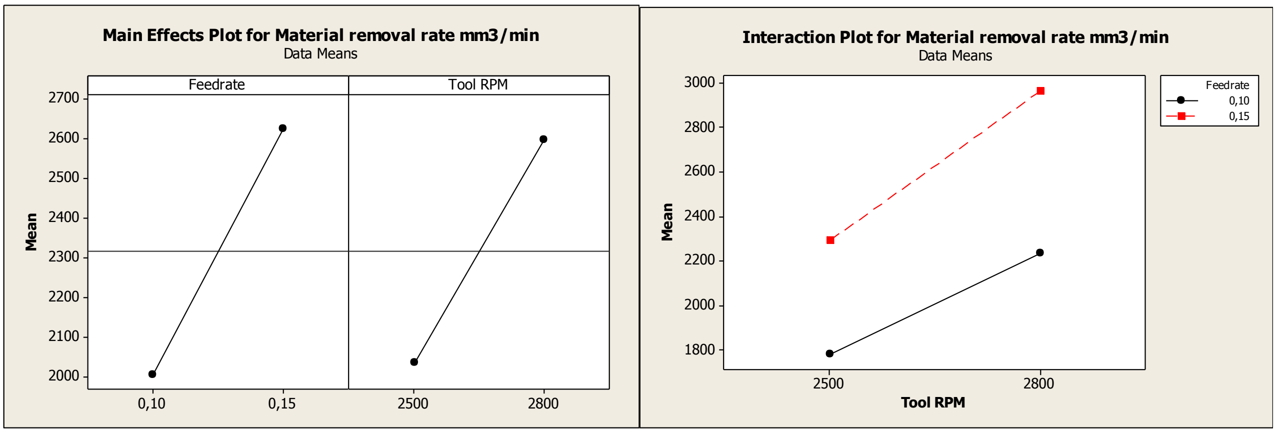

Figure 4. The effects of design factors on MRR.

The significance of terms for the G-ratio is similar to MRR. The initial model will include the main factors and their interaction and the fit of the model is verified with confirmation experiment.

As seen from the Figure 5, the slopes for effects follow the trend from the previous experiments. The higher tool speed increases the G-ratio and the increase in feed rate goes more towards the tool wear. The interaction for G-ratio is minor but noticeable.

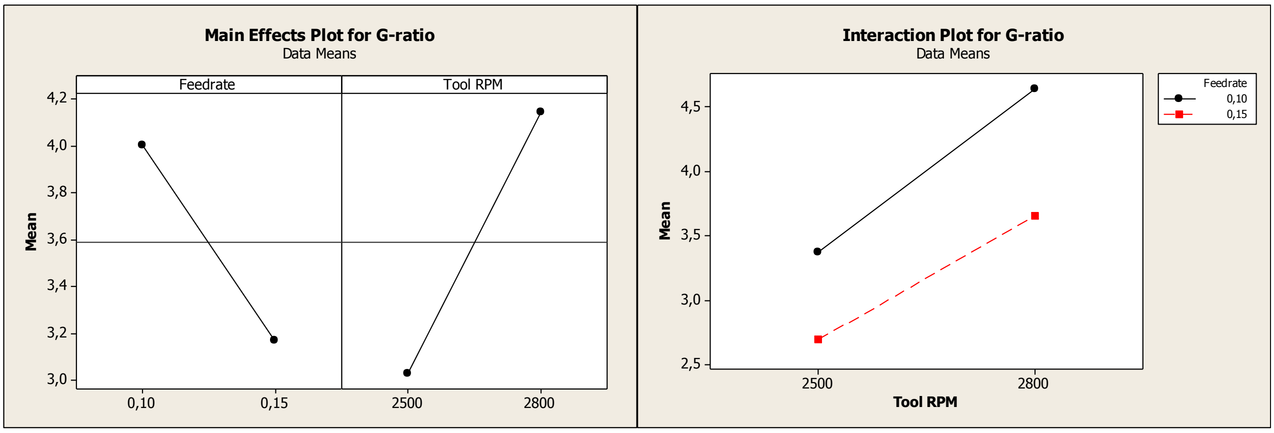

Figure 5. The effects of design factors on G-ratio.

Conclusions:

The high and low values for the variables were quite close to each other on the screening run, but all the values are relatively close to the area where the segment seems to work. Based on the observations made during and after the screening experiment, none of the value combinations caused unwanted event such as excessive fracturing or thermal damage. The parameters that are set close together increase the risk of fitting the regression model to noise but the responses are far enough from each other to rule this out. Also, the parameters set close to optimal area should provide an accurate model, as the tool behavior has not drastically changed during the screening experiment.

The primary models for the both outputs are based on feed rate, tool speed and their interaction. Models without interaction are also composed and compared to primary models with the interaction term.

The coefficients for the primary model for MRR with the interaction term in place:

```
Estimated Coefficients for Material removal rate mm3/min using data in uncoded
     units

Term                    Coef
Constant             653,685
Feedrate            -26288,2
Tool RPM           0,0437612
Feedrate*Tool RPM    14,5925
```

The coefficients for the primary model for G-ratio with the interaction term in place:

```
Estimated Coefficients for G-ratio using data in uncoded units

Term                     Coef
Constant             -10,9379
Feedrate              37,3363
Tool RPM           0,00627072
Feedrate*Tool RPM  -0,0204009
```

EXPERIMENT 4: 3.1.2017 – Confirmation

For the confirmation test, parameter combinations within the screened area as well as outside of it were selected. Based on the screening experiment, the optimal parameters were likely to be found over 2800 RPM tool speed as long as the temperature does not become a problem. For estimates outside the screened area, the model was extrapolated. The test matrix for the confirmation experiment was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,08	2200	80	226,633	225,819	243,561	243,232	18,8	1269	3,39
x	2	0,12	2500	80	225,819	224,584	243,232	242,671	18,5	2160	3,80
x	3	0,16	2200	80	224,584	222,665	242,671	242,199	18,9	1814	2,05
x	4	0,08	3000	80	222,665	222,1	242,199	241,648	18,8	2113	8,13
x	5	0,16	3000	80	222,1	220,511	241,648	240,742	18,6	3464	4,74
x	6	0,15	2800	80	220,511	218,972	240,742	239,944	18,8	3040	4,29

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Cool	Normal (distinct colors)	27-39	
2	Cool	Normal/slightly glazed	38-45	
3	Cool	Normal/slightly glazed	25-42	
4	Cool	Normal/slightly glazed	42-51	Distinct surfaces replicate to workpiece
5	Cool	Normal/glazed	45-61	Distinct surfaces replicate to workpiece
6	Cool	Normal/glazed	45-56	Minor streakiness due to distinct surfaces

Overall observations:

On test runs with high tool speeds, the power output reached rather high levels. Despite the high power output, the workpiece surface remained cool throughout the tests. The material removal rate achieved on the fifth run was the highest the alternative segment has reached so far. The distinct surface of the segment started to replicate to the ball surface on some of the test runs, but not to a problematic extent.

Conclusions:

The model for material removal rate with terms for feed rate, tool speed and their interaction was confirmed to be accurate, as seen from the Figure 6. The parameters for runs 1, 3, 4 and 5 were outside the screened area to which the regression model was fit. Despite that the model was extrapolated for these runs, the accuracy is still on good level. From 10% error bars on the tested values it can be seen that almost all the estimates for MRR reach more than 90 % prediction interval.

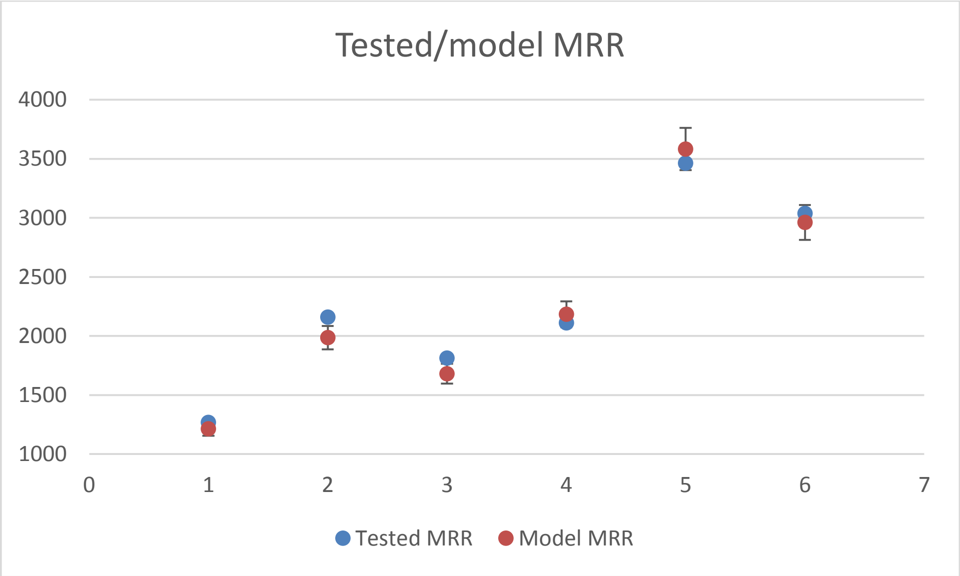

Figure 6. The fit of the MRR model to confirmation runs, with 10% error bars.

The model for G-ratio is not as accurate as the model for MRR. Both the models with and without the interaction term for the feed rate and tool speed were compared. The model without the interaction fit the tested output better and is presented in the Figure 7. By adjusting the constant in the model, all the estimates except the number four can be fit within the 90 % prediction interval. The right value for the constant seems to depend on the day and how well the conditions are replicated from the experiment the model is based on.

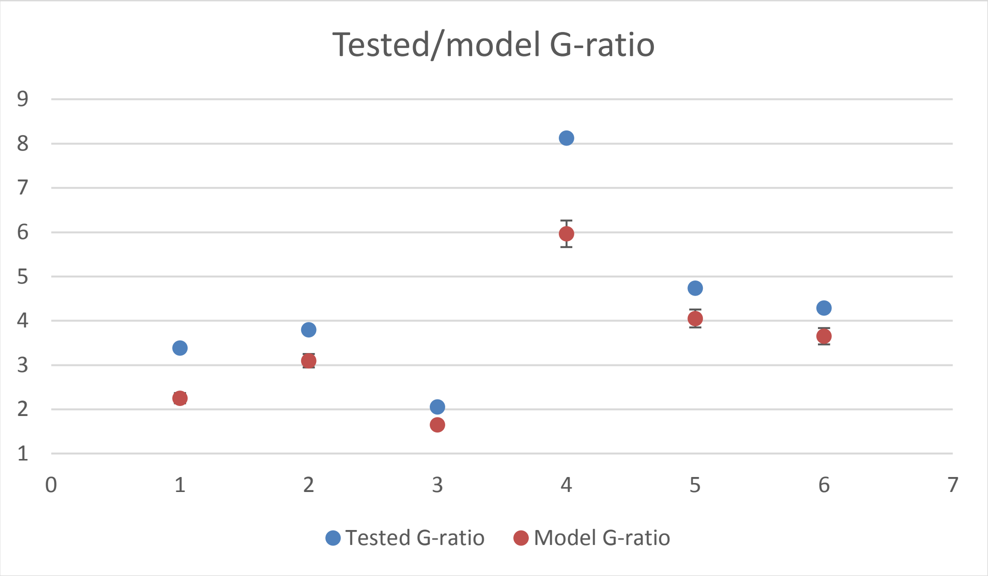

Figure 7. The fit of the G-ratio model to confirmation runs, with 10% error bar.

The error on the fourth run and its direction is not surprising. Both the parameters are out from the screening range and the estimate is based on extrapolation. The regression model is fit to certain behavior of the segment from which these values cause the behavior to differ from. The feed rate is lower than screened, decreasing the fracturing. The increased tool speed also promotes the same kind of behavior. Together they make the tool behave much harder than the model, which resulted in higher G-ratio than the model predicted.

EXPERIMENT 5: 24.1.2017 – Screening

After the realization of the importance of the coolant, more interest was attracted towards its delivery and how it could be improved further. As one method to improve the access of the coolant to grinding zone, grooving the segments was experimented. At first, the test matrix consisted of three runs with and without grooves on the segments. To make the testing easier and save time, the order of the runs was not randomized and the runs without grooving took place first. After the sixth run, three more runs were added as a confirmation. Selected parameters for the experiment were following:

StdOrd	RunOrd	Feedrate	Tool RPM	Groov.	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,1	2500	N	218,669	217,364	246,95	246,652	18,7	1165	1,94
x	2	0,15	3000	N	217,364	215,512	246,652	246,083	18,4	2220	2,61
x	3	0,16	3000	N	215,512	213,54	246,083	245,43	18,6	2542	2,80
x	4	0,1	2500	Y	213,54	212,311	245,43	244,985	18,9	1729	3,06
x	5	0,15	3000	Y	212,311	210,553	244,985	244,203	19	3031	3,75
x	6	0,16	3000	Y	210,553	208,615	244,203	243,418	18,6	3033	3,40
x	7	0,1	2500	N	203,683	202,429	243,325	242,867	18,6	1763	3,06
x	8	0,16	3000	N	202,429	200,473	242,867	242,072	18,7	3053	3,39
x	9	0,16	3000	Y	200,473	198,474	242,072	241,33	18,9	2840	3,09

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Cool	Normal (distinct colors)	18-28	
2	Cool	Normal/slightly glazed	28-38 / 21-30	Power varied in cycles
3	Cool	Normal/slightly glazed	34-43 / 27-36	Power varied in cycles
4	Cool	Normal (distinct colors)	24-30	Groove filled with swarf
5	Slightly warm	Normal (distinct colors)	34-43	Groove filled with swarf
6	Slightly warm	Normal (distinct colors)	34-42	Groove filled with swarf
7	Cool	Normal (distinct colors)	24-29 / 30-45	Power varied in cycles
8	Slightly warm	Normal (distinct colors)	32-40 / 48-55	Power varied in cycles
9	Slightly warm	Normal (distinct colors)	24-31 / 41-51	Power varied in cycles, groove filled with swarf

Overall observations:
After the third run, it seemed that the performance is not on the same level as in the previous test conducted three weeks earlier. The very same parameters with the same kind of setup gave about one third of a lower material removal rate.

The fourth, and the first run with grooves, gave much higher output than its comparison run without grooves. The same trend went on with runs five and six. So, after six runs it seemed that the grooves do improve the grinding performance. Since the run order was not randomized, uncontrollable variables that change as the experiment progresses could distort the results to one way or another.

To confirm the hypothesis of the benefits of the grooving, few more runs were conducted how the experiment was started, without grooves. Interestingly, the seventh run without grooves, gave much better results than similar run number one. In fact, it resulted in the same, or even slightly higher, material removal rate than the fourth run with grooves in place. This points out towards rejecting the hypothesis of the grooving being beneficial. To confirm this, the runs number three and six were replicated. Again, the same parameters on the run eight gave now higher output than on run number three and the output matches the one from the run with grooves. For final confirmation, the segments were grooved again for the ninth run. It was taken right after the eighth run and it actually resulted in lower output.

So, despite the fact that grooving seemed potential at first, it ended up not having much of an effect, or even impairing the performance. However, the variation between the results of earlier and later runs raise question about its source. The largest variation was between the similar runs one and seven, the latter resulting in about 50% higher output. Since the parameters were not changed, the only variables that changed notably between these two runs, were the workpiece diameter and tool length. The change in ball diameter cannot cause such a drastic difference, especially since the change in dimensions is corrected mathematically. The source of variation had to be related to tool length.

Event that was known to occur on some extent, is bending of the segment. The amount that each segment bends and how that affects the final output is not very well known. But based on experience with Tyrolit segment, it was assumed to be less significant than seen on these test results.

Analysis: Diprotex - 3CG120G/H10V32

The experiments were started with Diprotex segment. The first tests took place on 22nd of November 2016.

Diprotex segment was noted to be very porous and open in comparison to currently used Tyrolit segment. The segment also feels much lighter.

EXPERIMENT 1: 22.11.2016 - Screening

Without better knowledge, the test parameters were set according to optimized parameters for Tyrolit segment. The optimized parameter values for this size with Tyrolit are 0.15 mm/min for the feedrate, 1800 RPM for the tool speed and 50 RPM for the workpiece speed. These were selected as midpoints for the test parameters, so the test matrix for Diprotex segment was following:

StdOrder	RunOrder	Feedrate	Tool RPM	Workpiece RPM
3	1	0,1	2200	20
8	2	0,2	2200	80
7	3	0,1	2200	80
5	4	0,1	1400	80
2	5	0,2	1400	20
4	6	0,2	2200	20
6	7	0,2	1400	80
1	8	0,1	1400	20

In the second test run with all the parameters set to high value, one of the segments broke three minutes into the test. The test had to be stopped for further examination. The cause for the breakdown of the segment was examined and was very likely the lack of support plate behind the segment. Two out of six segments on the opposite sides of the grinding head were left without such plates. The plates are not meant to come off from the grinding head and are difficult to put back. Without the support plate, the distance of the support point from the grinding area increases, which increases the torque addressed towards the segment. Without the plate, the fastening screws are also digging in the segment, possibly causing the segment to fracture. To continue testing, all the plates were put in place despite the difficulties. As in further precaution, the tool speeds were also reduced by 200 RPM.

EXPERIMENT 2: 22.11.2016 - Screening

After failure of one of the segments, the test matrix with reduced tool speeds was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MR R	G-ratio
3	1	0,1	2000	20	223,396	222,098	243,803	243,693	18,6	425	0,71
6	2	0,2	1200	80	222,098	219,136	243,693	243,637	18,5	216	0,16
4	3	0,2	2000	20	219,136	216,335	243,637	243,477	18,9	618	0,48
5	4	0,1	1200	80	216,335	214,862	243,477	243,431	18,9	178	0,26
1	5	0,1	1200	20	214,862	213,37	243,431	243,396	18,9	135	0,20
8	6	0,2	2000	80	213,37	210,521	243,396	243,244	18,8	586	0,45
2	7	0,2	1200	20	210,521	207,515	243,244	243,209	18,4	135	0,10
7	8	0,1	2000	80	207,515	206,142	243,209	243,096	18,4	436	0,69

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1		Slightly glazed		Power varied in cycles
2		Clearly open		Power remained low
3		Normal		Power varied in cycles
4		Normal		Power remained low
5		Normal		Power remained low
6		Normal		Power varied in cycles
7		Clearly open		Power remained low
8		Normal		Power varied in cycles

Overall observations:
The segment seemed to fracture excessively in all of the test runs. In every run with the tool speed of 1200 RPM, the power output remained very low, likely signing that the tool was fracturing as it was fed into the workpiece. The runs with higher tool speed of 2000 RPM, the power output varied in cycles. As the theory entails, this is clearly the right direction for the tool speed, as the constant fracturing stopped. The fact that the power output still varied, reaching virtually an idle level before building up again, is still a sign that there is still too much fracturing.

Analysis:
The Figure 1 shows the statistically significant factors for MRR. Since the parameter placement is quite wide and the tool behavior and performance changes depending on the parameter combination's fit to each other, the interaction term between feed rate and tool speed shows up as statistically significant with significance level of 0.05.

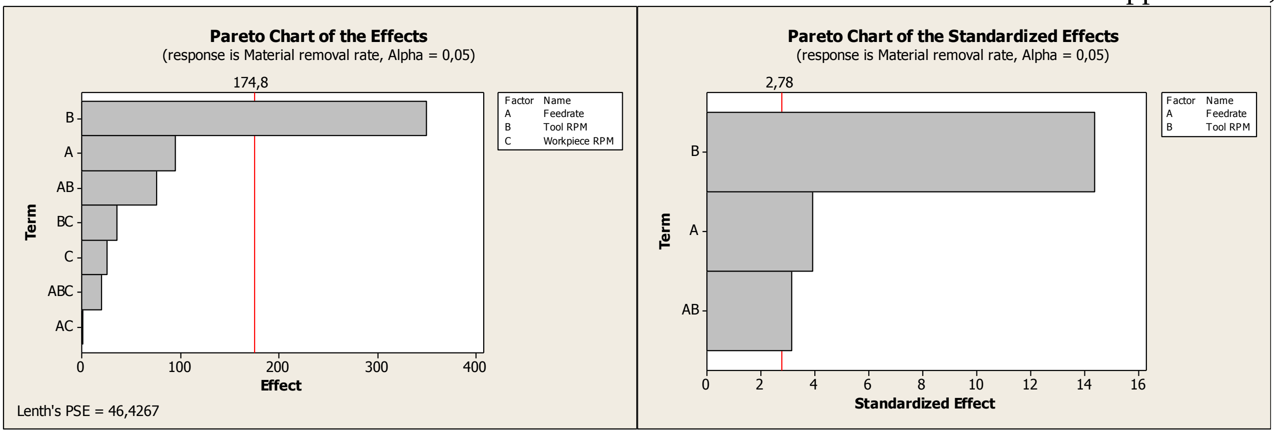

Figure 1. The statistically significant factors for MRR.

```
Estimated Effects and Coefficients for Material removal rate (coded units)

Term                Effect    Coef  SE Coef      T      P
Constant                    341,01    12,20  27,96  0,000
Feedrate             95,52   47,76    12,20   3,92  0,017
Tool RPM            350,15  175,07    12,20  14,36  0,000
Feedrate*Tool RPM    76,18   38,09    12,20   3,12  0,035

S = 34,4942      PRESS = 19037,6
R-Sq = 98,30%    R-Sq(pred) = 93,20%    R-Sq(adj) = 97,02%
```

The slope of the effect of tool speed is steep towards the high value as seen from the Figure 2. Feed rate shows an upward slope, meaning that in general, the high value resulted in higher material removal rate. But comparing the results of the runs with low tool speed, for example the runs 5 and 7 or 2 and 4, it can be seen that the higher feed rate did not lead to much better results. So, the effect of the feed rate is dependable on the tool speed, which is why the interaction term is significant. If the tool speed is too low and the feed rate is already too aggressive in relation to it, further increasing the feed rate will not lead to any better results.

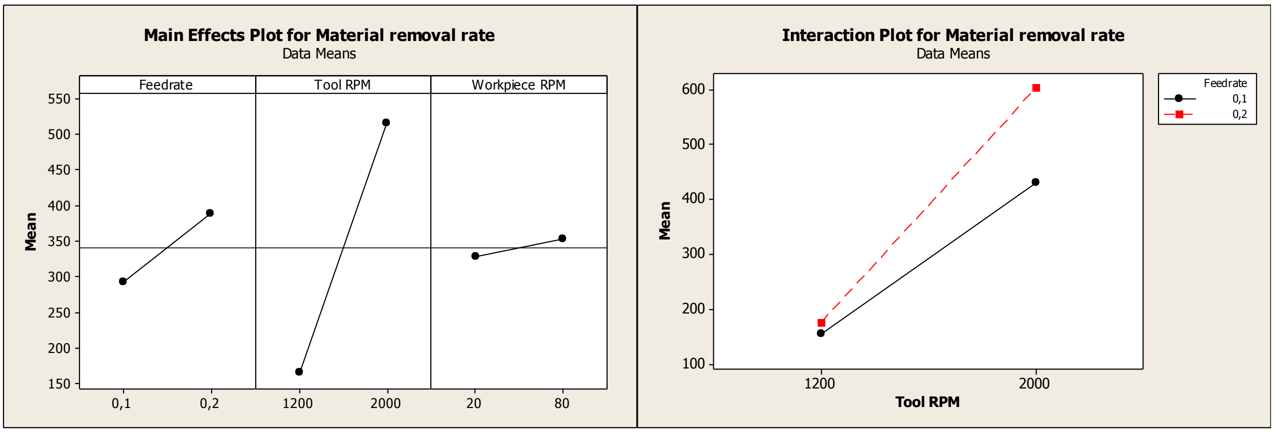

Figure 2. The effect of design factors on MRR.

Half of the G-ratio comes from the material removal rate, thus the factors for G-ratio logically follow the ones for material removal rate, as seen from the Figure 3. With the significance level of 0.05 and after eliminating the insignificant factors, the significant factors remain to be the same as for the material removal rate.

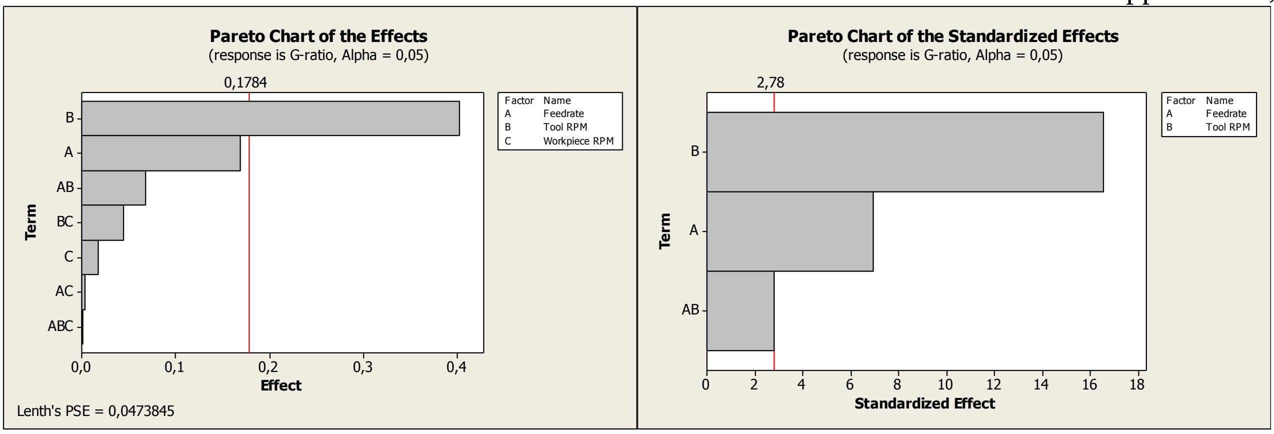

Figure 3. The statistically significant factors for G-ratio.

```
Estimated Effects and Coefficients for G-ratio (coded units)

Term                 Effect      Coef  SE Coef      T      P
Constant                      0,38037  0,01219  31,20  0,000
Feedrate           -0,16925  -0,08463  0,01219  -6,94  0,002
Tool RPM            0,40323   0,20162  0,01219  16,54  0,000
Feedrate*Tool RPM  -0,06805  -0,03403  0,01219  -2,79  0,049


S = 0,0344799   PRESS = 0,0190218
R-Sq = 98,80%   R-Sq(pred) = 95,20%   R-Sq(adj) = 97,90%
```

The tool speed has an obvious positive effect for the G-ratio as seen from the Figure 4. If the feed rate is kept the same, and there is more removed from the workpiece by increasing the tool speed, it means that there must be less removed from the tool. So, increasing the tool speed basically transforms the volume removed from the tool to volume removed from the workpiece, making it to have an “double” effect on the G-ratio. The higher feed rate showed somewhat positive effect for material removal rate but same cannot be said for the G-ratio. As mentioned earlier, looking at the run pairs 5 & 7 and 2 & 4, the increase in feed rate went straight to the tool wear. Naturally, the G-ratio is then influenced by the interaction of the feed rate and the tool speed.

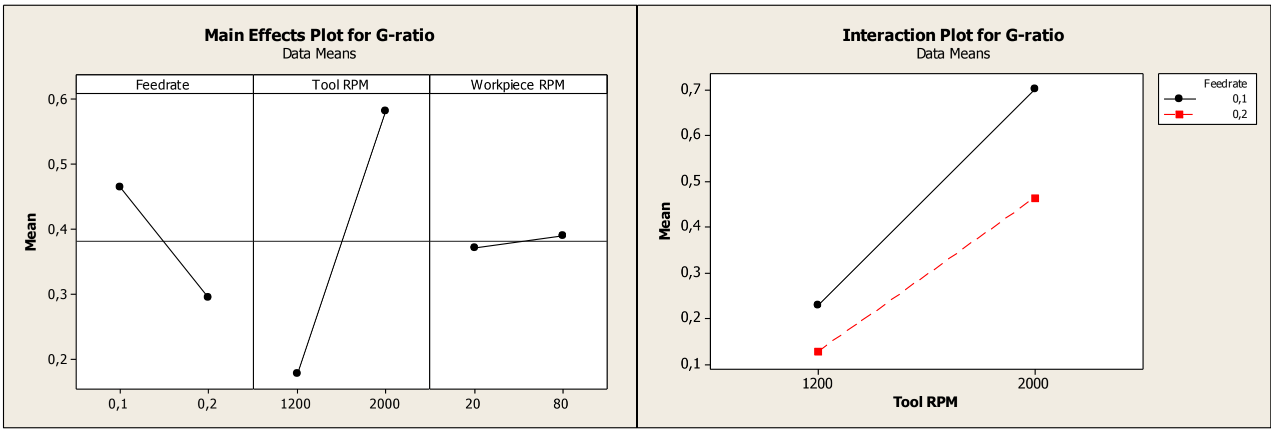

Figure 4. The effect of design factors on G-ratio.

Conclusions from the first screening experiment

The parameters were clearly unsuitable for the segment and new experiment is needed for fitting a regression model. Based on the observations at machine and the results of the analysis, it is clear that the feed rate was overly aggressive in relation to other parameters.

The tool would very likely benefit from increasing the tool speed further than 2000 RPM as the high tool speed value resulted in clearly better output. By increasing the tool speed, the material removal rate should go up, as the tool wear would go down. The effect for workpiece speed is rather small for both outputs, higher resulting in slightly better results.

To adjust the process closer to the optimal parameters for the next experiment, higher tool speed combined with lower feed rate should be experimented.

EXPERIMENT 3: 1.12.2016 - Screening

The results from the first screening experiment with Diprotex segment were disappointing, but pointed out the direction the parameters should be changed to. The first experiment showed that the parameters that are close to optimal for Tyrolit segment, are far from optimal for Diprotex.

Before the third experiment for Diprotex, visually quite similar segment from Theleico was also experimented. For the third experiment, the test matrix was set similarly to the experiment conducted with Theleico.

The feedrate was reduced significantly. The new high value was now the old low value, because even with the low value in the previous test, the segment was fracturing excessively. To spread out the parameters enough, the new low value for feed rate was set to 0,03 mm/min. The new high value for tool speed was set to 2500 and the low value was kept the same.

The test matrix for the third screening experiment was following:

StdOrd	**RunOrd**	**Feedrate**	**Tool RPM**	**WP RPM**	**Tool L 1**	**Tool L 2**	**WP D 1**	**WP D 2**	**Fluid temp.**	**MRR**	**G-ratio**
1	1	0,03	1200	20	223,688	223,239	243,305	243,272	17,6	127	0,62
6	2	0,1	1200	80	223,239	221,743	243,272	243,234	18,3	147	0,21
5	3	0,03	1200	80	221,743	221,288	243,234	243,214	18,3	77	0,37
7	4	0,03	2500	80	221,288	221,026	243,214	243,107	18,2	412	3,42
4	5	0,1	2500	20	221,026	219,735	243,107	242,896	18,8	813	1,37
2	6	0,1	1200	20	219,735	218,229	242,896	242,858	18,4	146	0,21
8	7	0,1	2500	80	218,229	216,965	242,858	242,592	18,9	1023	1,76
3	8	0,03	2500	20	216,965	216,668	242,592	242,495	18,1	373	2,73

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK	Slightly glazed	8-16	
2	OK	Normal	9-16	
3	OK	Slightly glazed	8-16	
4	Warm	Slightly glazed	20-30*	See Figure 5
5	OK	Slightly glazed	10-36**	Power varied in cycles
6	OK	Normal	7-13	
7	OK	Slightly glazed	25-32	
8	Warm	Glazed and clogged	13-33***	See Figure 5

*Took four minutes to reach the 10%-level, ** Took two minutes to reach the 10%-level, *** Took over five minutes to reach the 10% level.

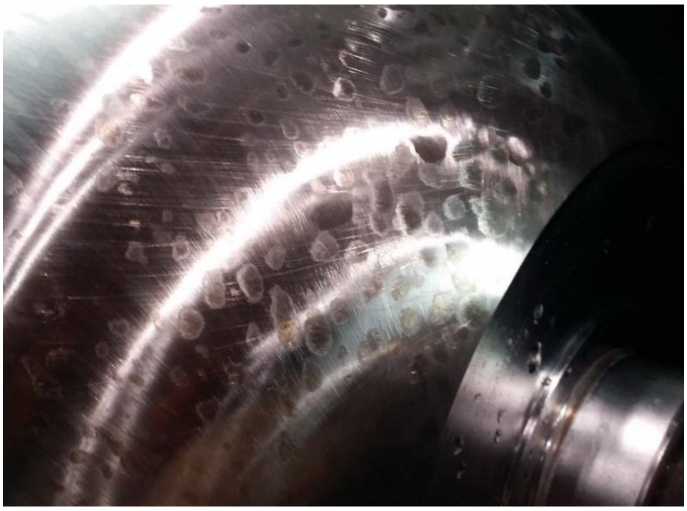

Figure 5. The ball surface after the test run number 8. Burns marks could be found all over the ball surface, mostly focused on the edges of the bearing sides.

Overall observations:
In some of the test runs, the 10% power output level was achieved only after several minutes in the test. In test run lasting 15 minutes, it can heavily distort the results. For reliable evaluation of the segment, re-run of the experiment is needed and the experiment design needs to be changed for all experiment so that the test run starts are even.

The low value for the feed rate seemed to be too low. It resulted in the very opposite behavior of excessive fracturing, glazing of the tool surface. Glazing of the tool was already witnessed with low tool speed, but in particular, with the high tool speed resulting in burn marks. The low feed rate with low tool speed combination seemed to result in glazing by not fracturing enough. And as could be expected from the previous experiment, the high feed rate with low tool speed resulted in excessive fracturing.

As expected, the high feed rate with high tool speed combination seemed to be the most promising. The hypothesis of the improved results through added tool speed proved to be right. With the tool speed of 2500 RPM, the tool surfaces started to show some glaze. With such high tool speeds, it could be beneficial to slightly increase the feed rate as well.

Analysis:
The significant factors for material removal rate, seen in the Figure 6, are the same as in previous test, feed rate, tool speed and their interaction. The effects have changed slightly, likely due to adjusted parameters and thus changed behavior of the segment. The tool RPM is still the parameter with the most effect, but the segment not fracturing to the same extent as in previous test, balances the differences.

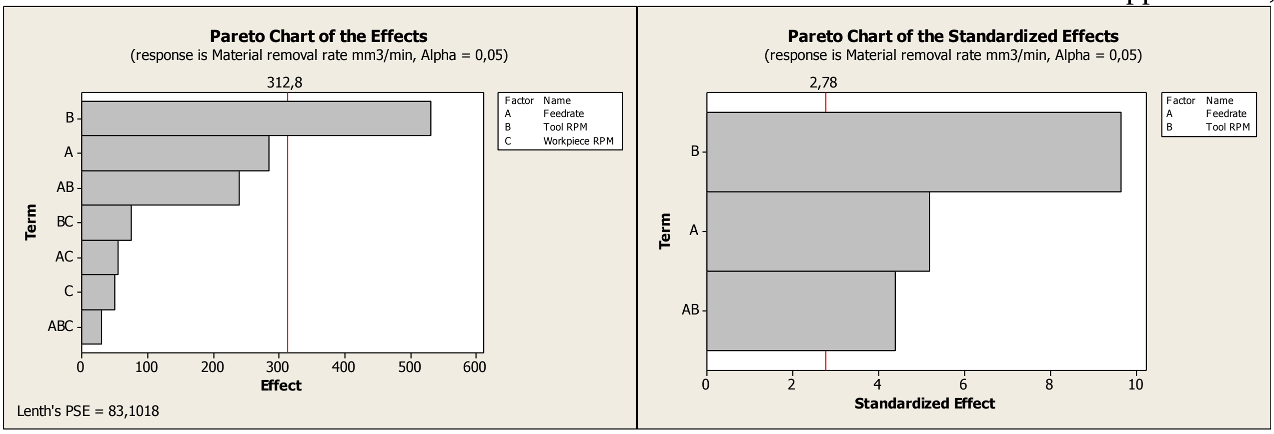

Figure 6. The statistically significant factors for MRR.

Estimated Effects and Coefficients for Material removal rate mm3/min (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		389,8	27,52	14,17	0,000
Feedrate	284,8	142,4	27,52	5,17	0,007
Tool RPM	531,1	265,5	27,52	9,65	0,001
Feedrate*Tool RPM	240,6	120,3	27,52	4,37	0,012

S = 77,8374 PRESS = 96938,6
R-Sq = 97,20% R-Sq(pred) = 88,81% R-Sq(adj) = 95,10%

For the material removal rate, the main effects plot shows the same direction as before. Increasing the feed rate is beneficial as well as increasing the tool speed, which can already be assumed based on theory and previous experiments. The fact that the slope, on the Figure 7, is really steep, points out that increasing the tool speed even further could be beneficial, but with low feed rate, the temperature limit has been reached because the tool glazes and the feed rate should be obviously increased.

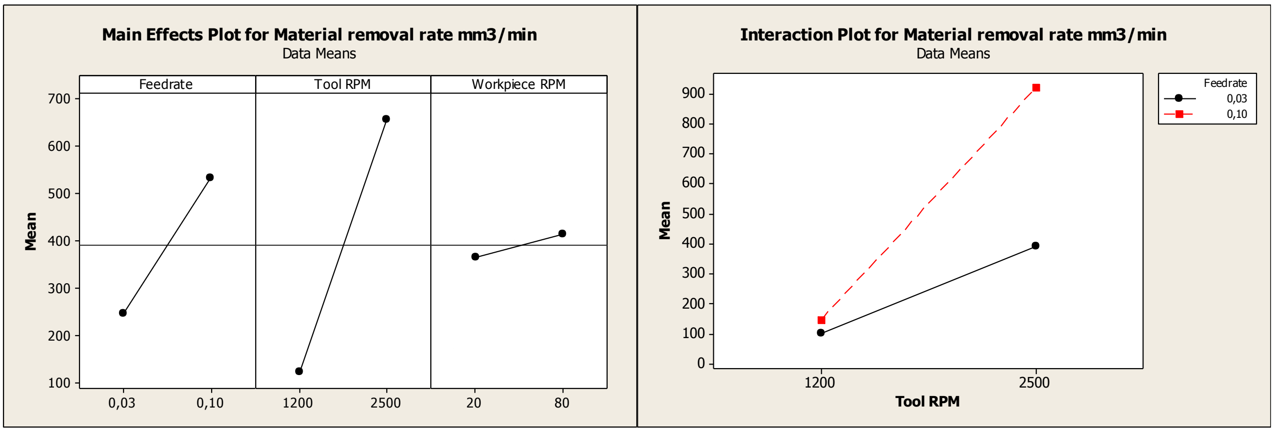

Figure 7. The effect of design factors on MRR.

The interaction term between the feed rate and tool speed seems to have major effect. The severe interaction can likely be explained with very different behavior between high and low tool speeds combined with high feed rate. With the low feed rate, the difference between high and low tool speed is more moderate since in either case the segment does not fracture, causing the surface to glaze and likely dulling of the grains. Where with high feed rate, the low tool speed output starts about from the same level as it does low feed rate, even though the behavior is the opposite, excessive fracturing. But with increasing the tool speed, the behavior changes from excessive fracturing to actual cutting, while showing only minor glazing on the tool surface.

The significant factors, seen in the Figure 8, for the G-ratio are the same as they are for material removal rate and the same they were in previous experiment.

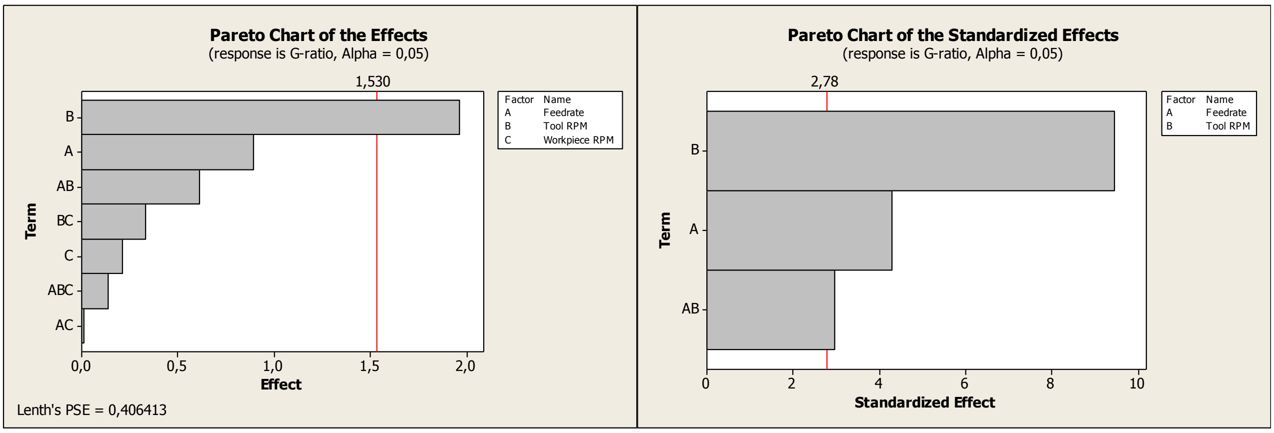

Figure 8. The statistically significant factors for G-ratio.

The low feed rate resulted in better G-ratio, but only due to low tool wear through the tool not fracturing. Just by looking at the plot for G-ratio in the Figure 9, the optimal combination would seem to be high tool speed with low feed rate but that is why also the evaluation is not based on only single output. In addition, the combination resulted in thermal issues.

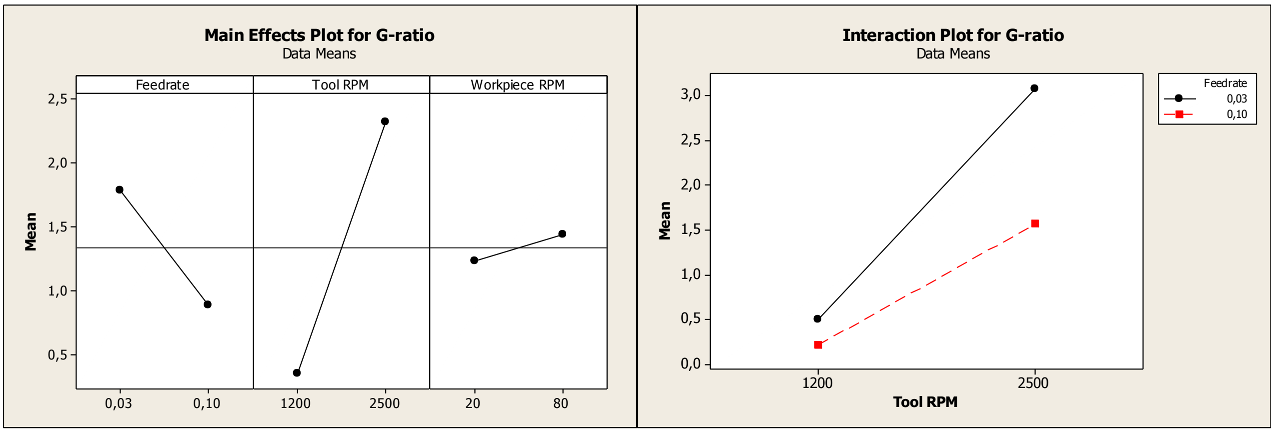

Figure 9. The effect of design factors on G-ratio**.**

Conclusions from the second screening experiment

A model based on the third screening experiment, with uneven test run starts and large variation in tool behavior, is not likely very accurate. Instead, it is necessary to perform 4th screening experiment with slightly adjusted parameters, which to base the model on.

For the next experiment, the low value for feed rate should be increased to get the tool to fracture. The high value for feed rate could be increased slightly. The scale for tool speed should also be shifted up. The low value in the previous tests has been unnecessarily low and the segment seems to perform better with high speeds.

When removing the segments from the grinding head, it was noticed that one of the segments had broken from the middle and had to be scrapped.

EXPERIMENT 4: 10.1.2017 - Screening

Before conducting another screening experiment for the Diprotex segment, a modified cooling setup was experimented first with Theleico and then with Norton grade F. It provided a major increase in the performance in both cases and made the use of higher parameters possible. So, the similar setup was tested with Diprotex segment as well.

The run order of the tests was not randomized, instead, the runs with extra coolant were first, followed by the runs without coolant. The valves used on the fluid delivery for extra hoses are simple shut off type and thus maintaining the fluid volume and velocity constant is difficult if the handle needs to be adjusted to anything between either fully open or closed. Since the current hose setup prevents keeping the valve fully open, the runs with the extra coolant took place first so the handle could remain untouched before closing it for the final four runs.

To keep the number of requires test runs reasonable, instead of adding another factor, one was replaced. In any of the previous experiments, the workpiece speed has not raised to be a significant factor and was thus replaced by the factor for extra coolant. Since the high workpiece speed in previous experiments has proven to result in higher output, the workpiece speed was set to 80 RPM.

The test matrix for the screening experiment with extra coolant nozzles was following:

StdOrd	**RunOrd**	**Feedrate**	**Tool RPM**	**Extra cool**	**Tool L 1**	**Tool L 2**	**WP D 1**	**WP D 2**	**Fluid temp.**	**MRR**	**G-ratio**
1	1	0,05	1800	Yes	225,894	225,204	246,73	246,614	18,9	453	0,95
2	2	0,15	1800	Yes	225,204	223,033	246,614	246,429	19	722	0,33
3	3	0,05	2600	Yes	223,033	222,485	246,429	246,18	18,9	971	1,68
4	4	0,15	2600	Yes	222,485	220,552	246,18	245,715	19,3	1812	0,88
5	5	0,05	1800	No	220,552	219,822	245,715	245,633	18,6	319	1,43
6	6	0,15	1800	No	219,822	217,656	245,633	245,549	18,3	327	0,72
7	7	0,05	2600	No	215,746	215,052	245,549	245,411	18,3	537	3,85
8	8	0,15	2600	No	215,052	213,014	245,411	245,199	18,4	824	2,04

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK	Normal/glazed	12-25	Distinct surfaces replicate to ball
2	OK	Normal/slightly glazed	13-25	
3	OK	Normal/badly glazed	24-35	Distinct surfaces replicate to ball
4	OK	Normal/slightly glazed	34-41	Distinct surfaces replicate to ball
5	OK	Normal	8-15	
6	OK	Normal	8-13	
7	OK	Normal	14-18	
8	OK	Normal	15-19	

Overall observations:
The additional coolant nozzles seemed to have positive effect on the performance of the Diprotex segment as well. The introduction of the additional nozzles does bring the similar effect as it does with the Theleico’s segment. The surface of the segment is clearly open and bright blue from the top part, but the bottom part is darker and in some occasions glazed. The disparity of the tool surface then starts to show on the ball surface in a form of alternating streaks.

The segment surfaces seemed less glazed with high feed rate runs as they were fracturing more. This also resulted in less visible streaks on the ball surface. The power output seemed to be lower on the runs without the extra coolant.

Analysis:
The three main effects come up as having the most effect on the output, as seen from the Figure 10. After removing the factors with lesser significance and keeping just the main effects, only the tool speed comes up as statistically significant with significance level of 0.05. However, looking at the results extra coolant is obviously significant and the feed rate has to be included in the model whether it comes up statistically significant or not.

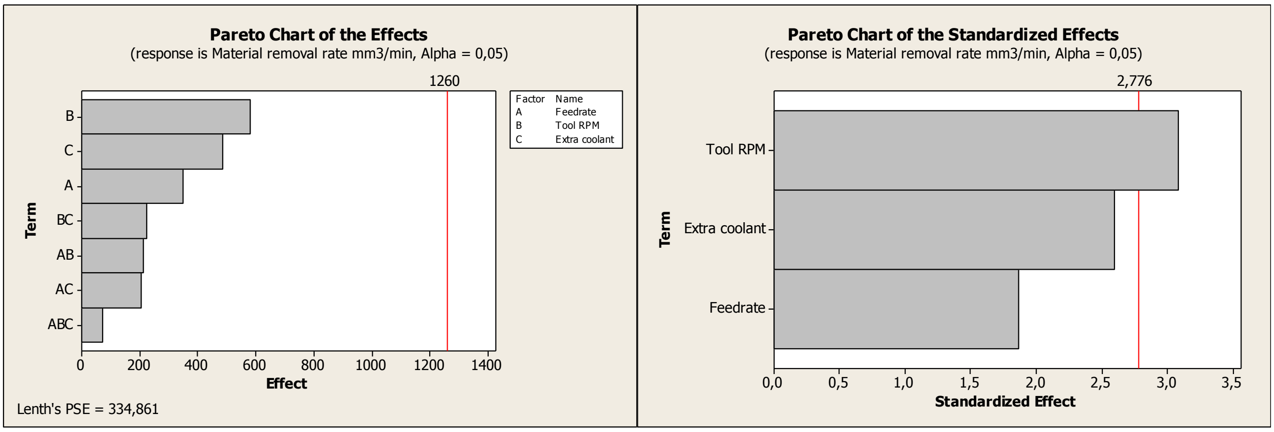

Figure 10. The statistically significant factors for MRR.

Despite the extra coolant not coming up statistically significant, it was proven to have a major performance boost in this experiment, as seen from the effect plot in the Figure 11. For that reason, any further testing as well as the model will be conducted with the extra coolant nozzles.

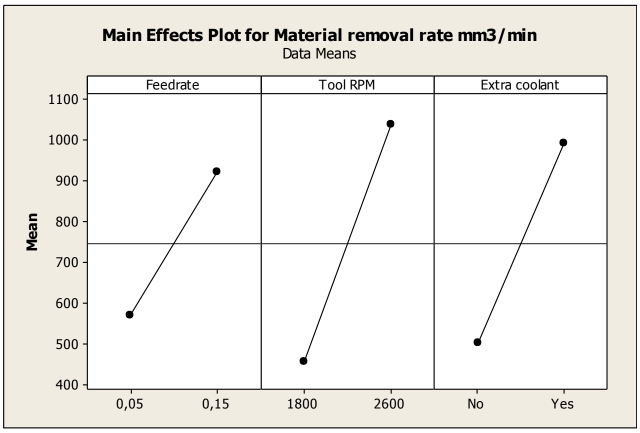

Figure 11. The effect of design factors on MRR.

The first four runs are analyzed separately, forming its own two factor, two level full factorial design. The regression model for the segment performance will be based on that half of the experiment.

After taking out the coolant variable from the process, leaving the feed rate and the tool speed are the only variables. Their significance from statistical point of view drops like the Figure 12. Less surprisingly, introducing the extra coolant to the process, does not change the direction how different variables influence the output. Increasing feed rate and tool speed improve the material removal rate and are somewhat dependent on each other like in experiments before. Although, the interaction of the feed rate and the tool speed is far from being statistically significant, clear interaction can be seen on the interaction plot in the Figure 13.

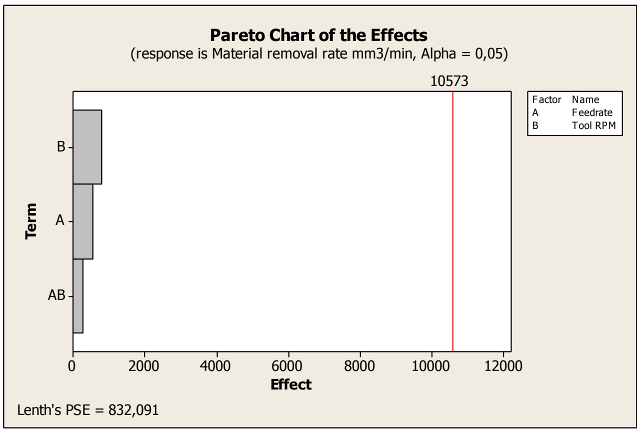

Figure 12. The statistically significant factors for MRR.

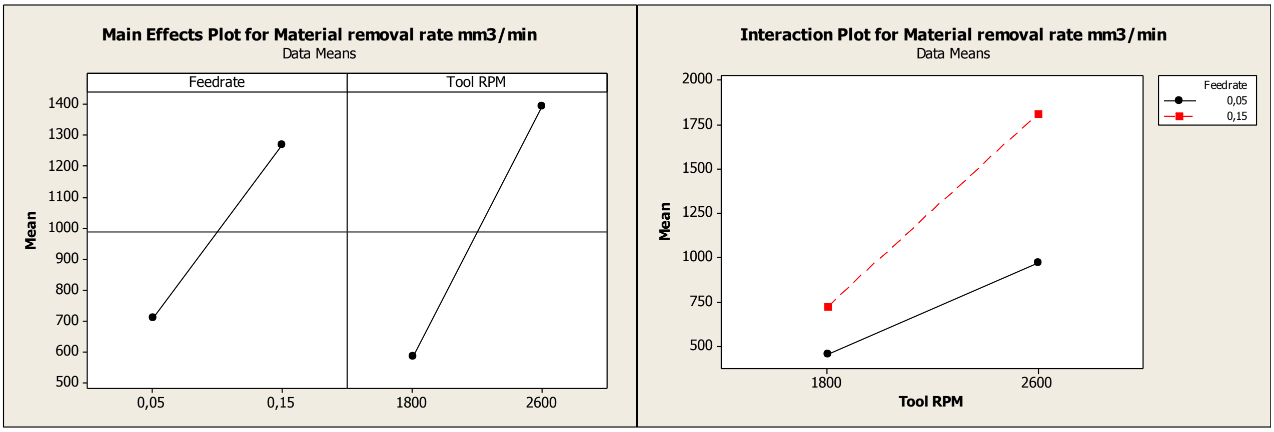

Figure 13. The effect of design factors on MRR.

Like for the material removal rate, any of the terms for G-ratio do not appear to be statistically significant with significance level of 0.05, as seen from the Figure 14. To make even the closest to significant factor, the tool speed, statistically significant, the significance level needs to be increased to over 0.50.

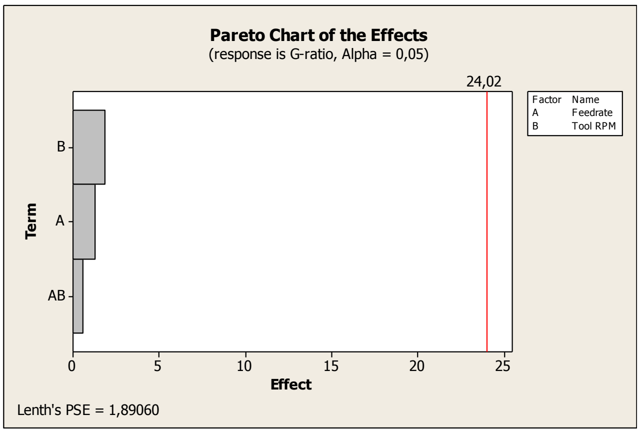

Figure 14. The statistically significant factors for G-ratio.

The main effects and the interaction term for G-ratio, in the Figure 15, follow the same logical trend as before. The increase in feed rate lowers the G-ratio as more of the increase goes to tool wear than to material removal rate. The tool speed has the same influence by increasing the material removal rate and decreasing the tool wear.

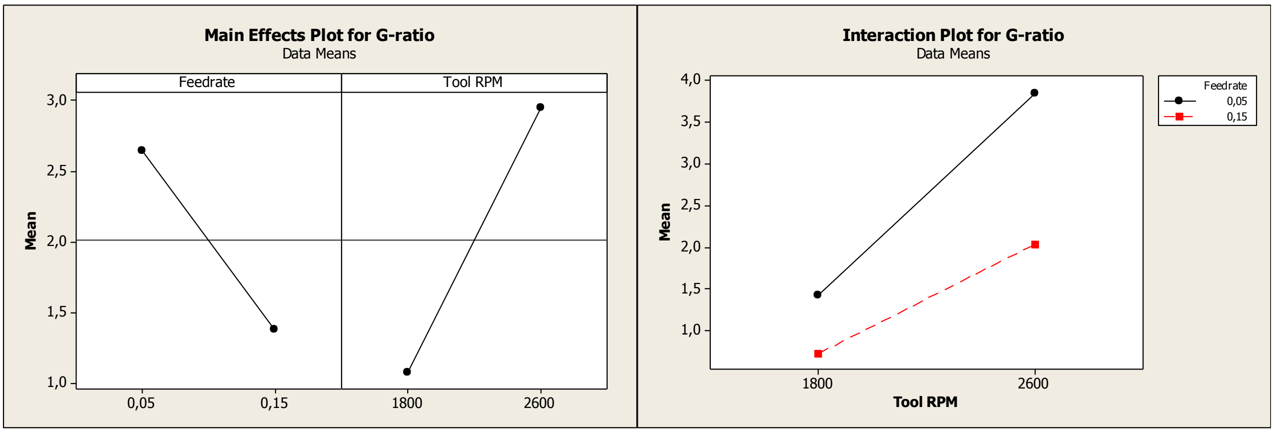

Figure 15. The effect of design factors on G-ratio.

Conclusions from the third screening experiment:
The introduction of extra coolant to the process improved the tool performance with a large margin. Like with other segment alternatives, the further tests will be conducted with the additional coolant nozzles in place.

From statistical point of view, the terms for both material removal rate and G-ratio would have to be rejected from the regression model as statistically insignificant. Nevertheless, the model will be compiled from these terms and its accuracy will be confirmed with confirmation test. If the model turns out to be too inaccurate, another screening experiment, perhaps replicated, might be in order.

Like in the previous experiment with Diprotex segments, when removing them from the grinding head, one of the segments was noticed to be broken.

EXPERIMENT 5: 11.1.2017 – Confirmation

For the confirmation experiment of the model, different parameter combinations were selected mixing higher and lower feed rate and tool speed parameters. To find the optimal parameters for the performance of the segment, the model was also interpolated outside the parameter range of the screening experiment.

StdOrd	RunOrd	Feedrate	Tool RPM	Extra cool	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,06	2000	Yes	214,745	213,987	244,335	244,092	19	940	2,70
x	2	0,12	2000	Yes	213,987	212,37	244,092	243,773	19	1233	1,66
x	3	0,1	2300	Yes	212,37	211,123	243,773	243,311	19,2	1783	3,11
x	4	0,14	2000	Yes	211,123	209,206	243,311	242,963	18,8	1341	1,52
x	5	0,15	2600	Yes	209,206	207,309	242,963	242,289	18,6	2592	2,97
x	6	0,16	3000	Yes	207,309	205,457	242,289	241,428	18,6	3301	3,87
x	7	0,18	3000	Yes	205,457	203,201	241,428	240,601	19,1	3160	3,04
x	8	0,15	2600	Yes*	203,201	201,226	240,601	240,054	19,3	2084	2,29
x	9	0,1	2300	Yes*	201,226	199,914	240,054	239,707	19,1	1319	2,19
x	10	0,06	2000	Yes*	199,914	199,126	239,707	239,477	18,9	873	2,41

*Nozzle alignment was re-adjusted

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK	Normal/glazed	16-38	Distinct surfaces replicate to ball
2	OK	Normal/slightly glazed	22-40	Distinct surfaces replicate to ball
3	OK	Normal/slightly glazed	24-40	Distinct surfaces replicate to ball
4	OK	Normal/slightly glazed	36-47	Distinct surfaces replicate to ball
5	OK	Normal/slightly glazed	44-55	Distinct surfaces replicate to ball
6	Slightly warm	Normal/glazed	53-65	Distinct surfaces replicate to ball
7	Slightly warm	Normal/glazed	49-64	Distinct surfaces replicate to ball
8	OK	Normal/glazed	36-48	Distinct surfaces replicate to ball
9	OK	Normal/glazed	28-40	Distinct surfaces replicate to ball
10	OK	Normal/glazed	22-42	Distinct surfaces replicate to ball

Overall observations:
The segment performance seems to be highly dependent on the fluid delivery. Two runs with same machine parameters in this confirmation test, as well as one the runs from the earlier screening test resulted in very different material removal rate. The material removal rate changed from 1812 to 2592 mm^3/min between the screening experiment and the run number five. After the nozzles were re-aligned the MRR dropped closer to screening experiment level, 2084 mm^3/min that was achieved on run number eight.

Comparing the runs six and seven, it is noted that the lower feed rate resulted in higher MRR. The higher feed rate of run seven takes the segment over its limit and the MRR starts to decrease. The run number six will be used to compare the segment to others.

Evaluating the model:
The regression model for material removal rate, with feed rate, tool speed and their interaction as terms, is:

```
Estimated Coefficients for Material removal rate mm3/min using data in uncoded units

Term                    Coef
Constant                -205,006
Feedrate                -10158,4
Tool RPM                0,290901
Feedrate*Tool RPM       7,13895
```

The Figure 16 shows that the model with interaction term follows the changes in actual material removal rate rather well, but the model is way below the real value. Some of such constant error can be corrected by increasing the constant term or adding an error term. The main cause for error is probably the difference in fluid delivery in screening and confirmation experiments. For the runs 8 to 10, the fluid delivery was adjusted by redirecting the nozzles. Redirecting the nozzles caused the output to go down but took the tested values closer to model, which can be seen by comparing, for example, runs four and nine. The difference in fluid delivery could also explain the increasing error towards the higher tool speeds in runs 4, 5 and 6. Based on the interaction of the extra coolant term with the tool speed term, that is seen in the Figure 17, the influence of the fluid delivery is emphasized on higher speeds.

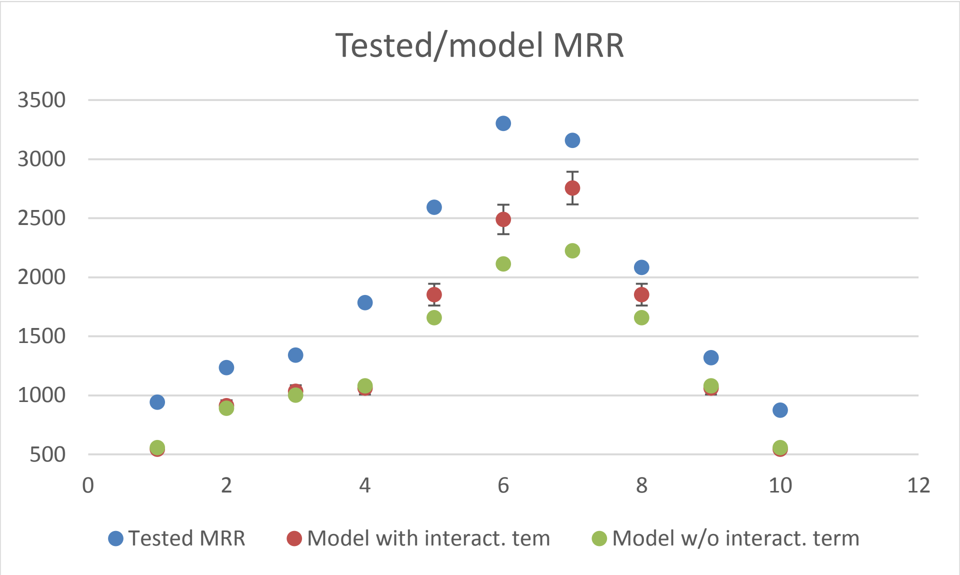

Figure 16. The fit of the MRR models to confirmation runs.

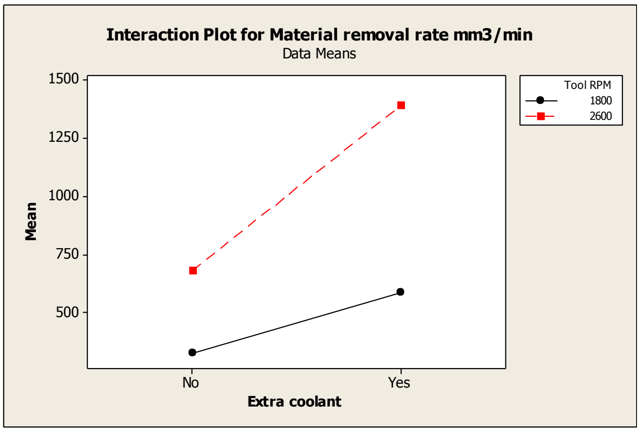

Figure 17. The interaction between fluid delivery and tool speed.

The model for G-ratio is separate from the model for MRR, but both are based on the same test runs, thus showing similar kind of error. As seen in the Figure 18, the model for G-ratio follows the changes of the actual G-ratio. But the higher than expected MRR on the test runs increases the numerator while lowering the denominator, which has a major effect of lowering the G-ratio and causing constant error on the model. The model without interaction seems to give a better estimate than the one with the interaction.

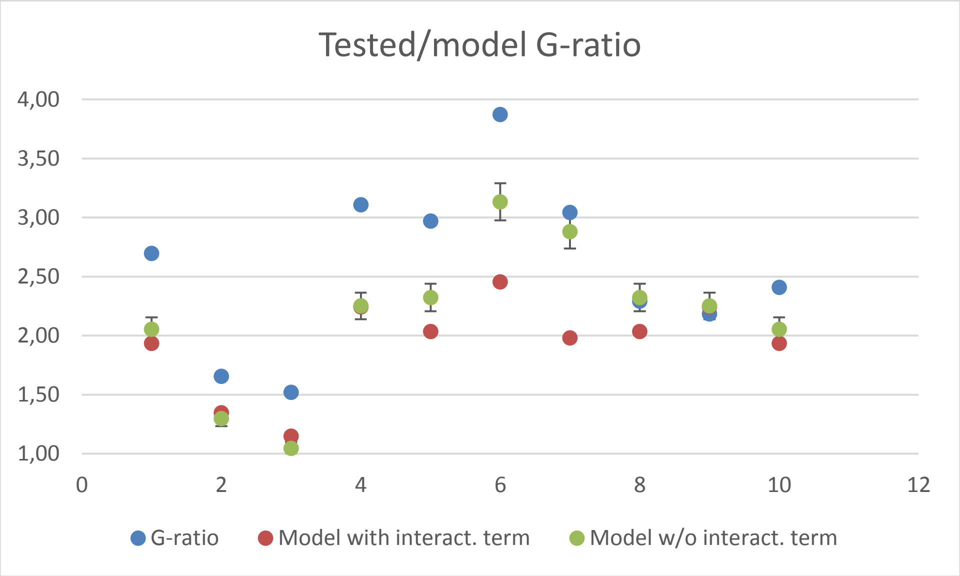

Figure 18. The fit of the G-ratio models to confirmation runs.

The regression models for the segment proved to be pointing out in the right direction, but the output estimates were on a much lower level than tested. This is caused by variation in conditions and terms that are hard to standardize, mainly the fluid delivery. Different test runs between various fluid delivery setups have proved that the placing of the nozzle and the fluid flow characteristics have major influence on the output.

Analysis: Norton – 3NQX120F24VS3X

The third experiment was conducted on the softest of the Norton segments, grade F. The first screening for the segment took place on 28th of November, 2016.

Visually the grade F does not differ from two other Norton segments. By holding the segments, difference in weight can be noticed however, the grade F being the lightest.

EXPERIMENT 1: 28.11.2016 - Screening

The Norton with the hardest grade was already experimented earlier and it was noticed not to work with the same parameters as Tyrolit. Since the Norton grade F is softer than the grade J, the Tyrolit parameters would more likely work with it. Thus, the parameters for Tyrolit were used as a rough starting point for the screening. With some adjustments, the test matrix was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
3	2	0,05	2000	20	234,7	234,255	245,943	245,779	18,4	639	3,12
7	4	0,05	2000	80	234,255	233,849	245,779	245,555	18,6	872	4,67
8	1	0,2	2000	80	233,849	231,328	245,555	245,009	19,1	2122	1,83
5	3	0,05	1200	80	231,328	230,671	245,009	244,917	18,4	357	1,18
1	6	0,05	1200	20	230,671	230,003	244,917	244,819	18,6	380	1,24
2	8	0,2	1200	20	230,003	227,122	244,819	244,62	18,5	772	0,58
6	7	0,2	1200	80	227,122	224,227	244,62	244,441	17,9	694	0,52
4	5	0,2	2000	20	224,227	221,663	244,441	243,89	18,4	2132	1,81

The point of sound contact was uneven in the first screening experiment, as in some runs it took several minutes for the power output to climb over 10%-level. Due to this, the experiment was decided to be run again. Based on the observations, the workpiece started to warm up a little on the first and last test run, but no catastrophic fracturing nor severe glazing of the tool occurred and the experiment was repeated with same parameters.

EXPERIMENT 2: 13.12.2016 - Screening

The screening run was repeated with the same test matrix, but to ensure even starts between the runs, the power limit for contact was changed from 2% to 10%, like with every other experiment from that point on. However, after the first run, the workpiece was hot and the fluid was vaporizing from the surface. The fluid was vaporizing also after the second run. The workpiece warmed up a little in the first experiment on 28th of November, but significantly less than in the rerun.

If the factor setting causes the workpiece to warm up too, the parameters are outside the practical operational range. Screening outside the area that could be used in production is waste of resources. Since the parameters seemed to generate too much heat, they were lowered after two runs and the second experiment was started over. After adjusting the parameters, the test matrix was:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
3	1	0,08	1200	20	218,116	216,961	242,795	242,672	18,7	473	0,89
7	2	0,08	1200	80	216,961	215,801	242,672	242,539	18,4	511	0,96
8	3	0,16	1200	80	215,801	213,47	242,539	242,368	18,1	657	0,61
5	4	0,08	600	80	213,47	212,258	242,368	242,317	17,8	196	0,35
1	5	0,08	600	20	212,258	211,014	242,317	242,281	17,8	138	0,24
2	6	0,16	600	20	211,014	208,574	242,281	242,234	17,8	180	0,16
6	7	0,16	600	80	208,574	206,151	242,234	242,173	17,9	234	0,21
4	8	0,16	1200	20	206,151	203,783	242,173	241,996	18,4	679	0,62

In particular, the tool speed was dropped to clearly lower level, which also resulted to inferior responses on the second screening. The best results from the second experiment were less than one third of the best results of the first experiment. Although, the workpiece temperature remained low throughout the second experiment and would have allowed use of slightly higher tool speed.

After seeing the impact that the fluid delivery had on the other segments, the reason behind the poor performance, or the excessive heating, was very likely in fluid delivery. Both experiments were taken with the similar nozzle setup with four low pressure flood nozzles, but in the first experiment, the nozzles must have been aligned in a way that at least some fluid reached the contact area. And in the second experiment there was likely little or no fluid at all lubricating the contact zone.

EXPERIMENT 3: 20.12.2016 - Screening

Earlier a modified coolant setup was tested with Theleico, with promising results. The other segments were then decided to be screened with the modified coolant setup as well. Before experimenting the Norton grade F with extra coolant, few parameter combinations were tried to ensure they are within practical operational range. After the trial runs, final test matrix for screening experiment with extra coolant was:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
3	1	0,08	1800	20	229,736	228,869	246,326	245,94	18,9	1505	3,77
7	2	0,08	1800	80	228,869	228,012	245,94	245,545	19,3	1538	3,90
8	3	0,2	1800	80	228,012	225,55	245,545	244,84	19,3	2739	2,42
5	4	0,08	1200	80	225,55	224,447	244,84	244,636	19	791	1,56
1	5	0,08	1200	20	224,447	223,338	244,636	244,453	19,1	709	1,39
2	6	0,2	1200	20	223,338	220,491	244,453	244,173	18,8	1084	0,83
6	7	0,2	1200	80	220,491	217,652	244,173	243,879	18,6	1137	0,87
4	8	0,2	1800	20	217,652	215,122	243,879	243,163	18,9	2764	2,37

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Slightly warm	Normal/glazed	29-51	
2	Slightly warm	Normal/glazed	32-54	
3	Slightly warm	Normal/slightly glazed	36-60	
4	Cool	Normal/glazed	25-38	
5	Cool	Normal/glazed	25-37	
6	Cool	Normal/slightly glazed	23-36	
7	Cool	Normal/slightly glazed	49-64	
8	Warm	Normal/glazed	37-62	

Overall observations:
The Norton grade F benefitted from the extra coolant nozzles. Based on the human perception, the temperatures remained lower, but unquestionable sign was the increase in material removal rate. The first screening experiment shares two runs with similar parameter with the now conducted screening. The MRR in test runs 6 and 7 increased from the screening experiment without extra coolant by about 40% in the run 6 and over 60% in the run 7.

The extra coolant generating two different surfaces on the segment continues with Norton grade F. However, despite the segment having clearly distinctive surfaces, on this screening experiment it did not seem to be replicating to the ball surface.

Analysis:
As seen in the Figure 1, the feed rate, tool speed and their interaction show up as statistically significant for the MRR with significance level of 0.05.

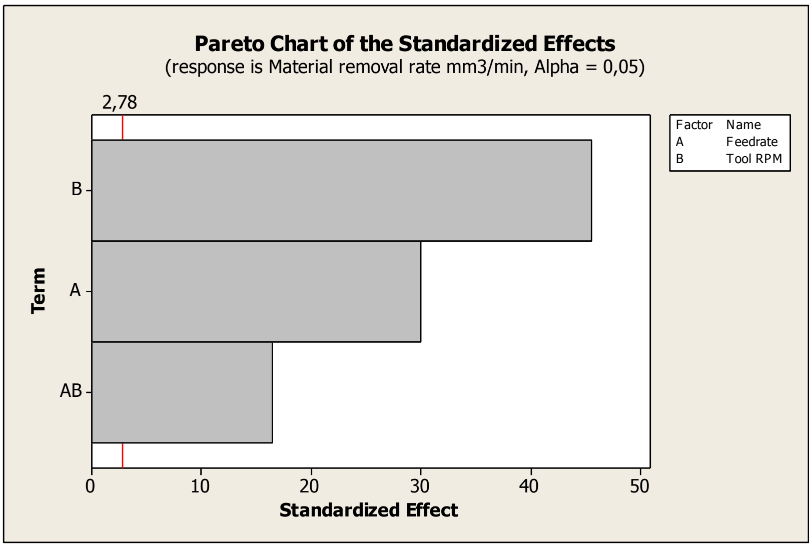

Figure 1. The statistically significant factors for MRR.

```
Estimated Effects and Coefficients for Material removal rate mm3/min (coded
     units)

Term                 Effect    Coef  SE Coef       T      P
Constant                     1533,4    13,23  115,89  0,000
Feedrate              795,1   397,6    13,23   30,05  0,000
Tool RPM             1206,0   603,0    13,23   45,57  0,000
Feedrate*Tool RPM     434,7   217,4    13,23   16,43  0,000


S = 37,4224      PRESS = 22407,0
R-Sq = 99,88%    R-Sq(pred) = 99,51%   R-Sq(adj) = 99,78%
```

The difference between the low and high value of feed rate being so wide, the effect of feed rate is the expected one and having a rather significant effect, as seen in the Figure 2. The slope for effect of workpiece speed is rather flat, not having much of an effect with Norton grade F either. The slopes on the interaction plot show the parameters being clearly dependent on each other.

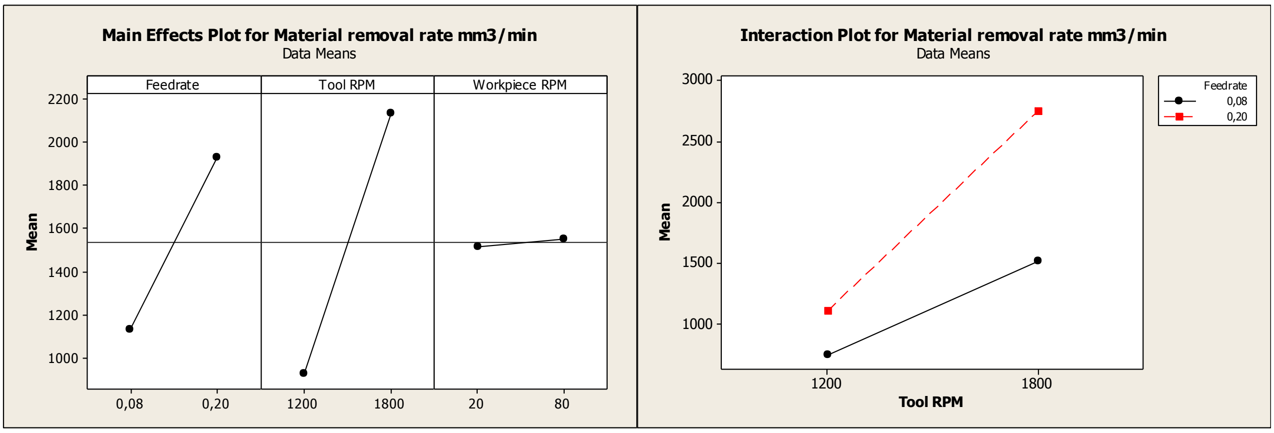

Figure 2. The effect of design factors on MRR.

With significance level of 0.05, the workpiece speed becomes close to being statistically significant for G-ratio. Regardless, the workpiece speed is left out from the initial regression model for the G-ratio.

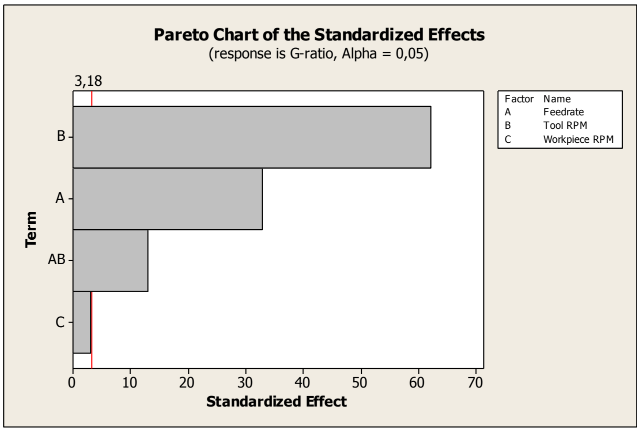

Figure 3. The statistically significant factors for G-ratio.

```
Estimated Effects and Coefficients for G-ratio (coded units)

Term                 Effect     Coef  SE Coef       T      P
Constant                      2,1395  0,02755   77,67  0,000
Feedrate            -1,0331  -0,5166  0,02755  -18,75  0,000
Tool RPM             1,9549   0,9775  0,02755   35,48  0,000
Feedrate*Tool RPM   -0,4076  -0,2038  0,02755   -7,40  0,002


S = 0,0779133    PRESS = 0,0971278
R-Sq = 99,76%    R-Sq(pred) = 99,04%    R-Sq(adj) = 99,58%
```

The effects plot in the Figure 4 looks similar to every other screening experiment conducted so far. Increasing the feed rate has more effect on tool wear as it does on the material removal rate, thus having negative slope towards the higher feed rate. The increase in tool speed results in higher material removal rate on expense of the tool wear, leading to higher G-ratio.

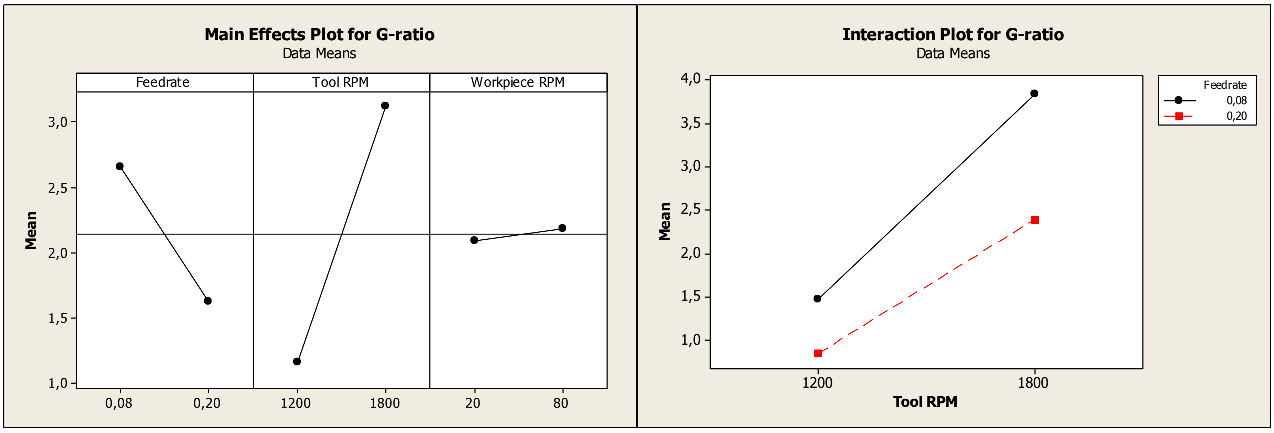

Figure 4. The effect of design factors on G-ratio.

The extra coolant has positive effect on material removal rate both directly and indirectly. On comparative test runs, the extra coolant has resulted in higher MRR while lowering the tool wear. Indirect benefit from the extra coolant is the possibility to use higher parameters.

The workpiece speed was statistically insignificant for both the measured outputs. In all the experiments conducted so far, including this one, its effect has been a minor positive slope towards the higher value of 80 RPM. For the confirmation experiment, the workpiece speed is set to 80 RPM.

The regression model for material removal rate consists of terms for feed rate, tool speed and their interaction. The material removal rate can be estimated with a model with following coefficients:

```
Estimated Coefficients for Material removal rate mm3/min using data in uncoded
     units

Term                    Coef
Constant             126,671
Feedrate            -11487,4
Tool RPM            0,319363
Feedrate*Tool RPM    12,0756
```

The regression model for G-ratio consists the same terms as the MRR model. The coefficients are following:

```
Estimated Coefficients for G-ratio using data in uncoded units

Term                      Coef
Constant             -3,92039
Feedrate              8,37507
Tool RPM           0,00484345
Feedrate*Tool RPM  -0,0113230
```

EXPERIMENT 4: 12.1.2017 – Confirmation

The test parameters for confirmation experiment were selected to represent different combinations, concentrating on the high end of the scale. The test matrix for confirmation experiment was:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,1	1200	80	226,522	225,116	246,831	246,668	18,9	637	0,98
x	2	0,1	1600	80	225,116	223,893	246,668	246,289	19	1480	2,63
x	3	0,14	1600	80	223,893	222,08	246,289	245,832	19	1781	2,14
x	4	0,18	1800	80	222,08	219,8	245,832	245,174	19	2559	2,44
x	5	0,2	2000	80	219,8	217,365	245,174	244,305	19	3370	3,01
x	6*	0,2	2000	80	217,365	214,932	244,305	243,426	19	3397	3,04
x	7*	0,18	2200	80	214,932	212,999	243,426	242,478	19,2	3651	4,11
x	8*	0,22	1800	80	212,191	209,346	242,269	241,498	19,4	2951	2,25

*Fluid pressure and volume increased by opening the valve more

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Cool	Normal/glazed	22-34	
2	Cool	Normal/glazed	27-48	
3	Cool	Normal/glazed	33-52	
4	Slightly warm	Normal/glazed	40-62	
5	Hot, fluid vaporizing	Normal/badly glazed	50-68	Distinct surface replicates to ball
6	Warm	Normal/glazed	53-73	
7	Hot, fluid vaporizing	Normal/badly glazed	57-75	Hit the power limiter several times
8	Slightly warm	Normal/glazed	45-71	

Overall observations:
Redirecting the nozzles between the runs 5 and 6, seemed to lead to better cooling performance. It did not have a direct influence on the MRR, but by keeping the workpiece cooler, it allowed the use of higher parameters without causing the workpiece to warm up excessively. On the run 7, the machine hit the power output limit several times. Since the feed was not constant for the whole 15 minutes, it might have a minor effect on the output.

The run number six on the confirmation experiment resulted in the best MRR with acceptable temperature and is used to compare the segment to other segments.

Evaluation of the model:
As the Figures 5 and 6 show, the models fit the tested values well, especially the model for MRR. A relatively small error can be seen on G-ratio's model but most of the runs in the confirmation experiment fit in the 90% prediction interval illustrated with the error bars.

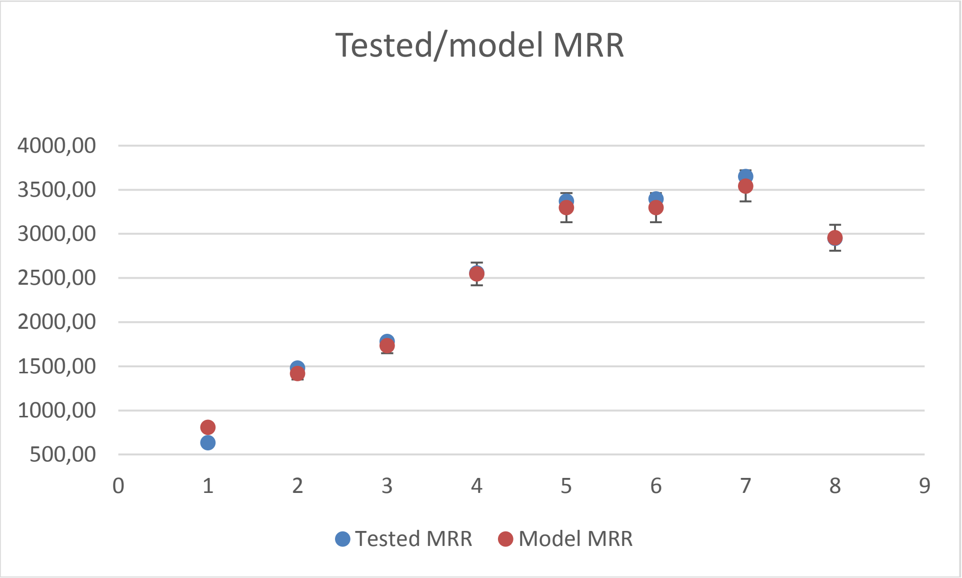

Figure 5. The fit of the MRR models to confirmation runs.

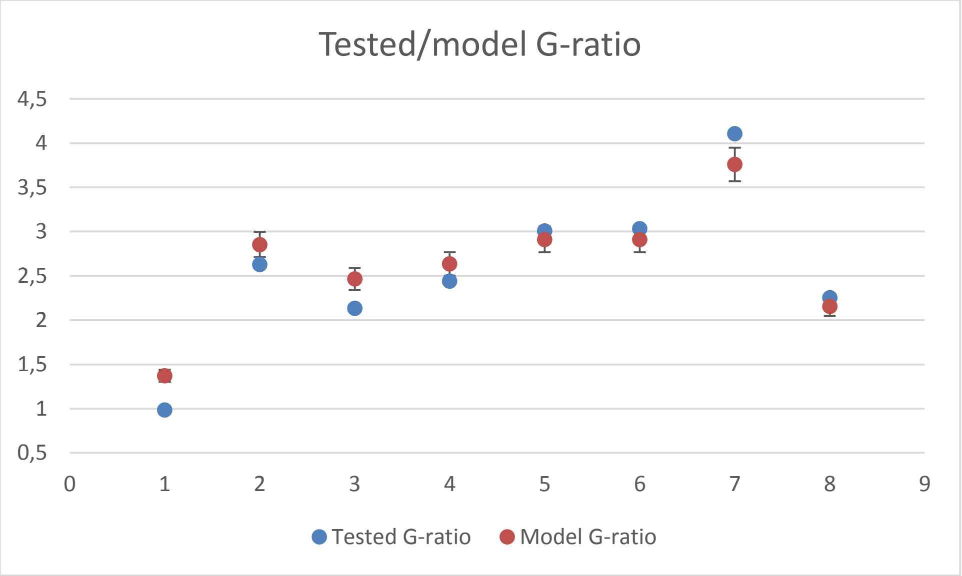

Figure 6. The fit of the MRR models to confirmation runs

Analysis: Norton – 3NQX120H24VS3X

Norton grade H was the last of the Norton segments to be screened. Visually it was similar to the two other Norton segments and its grade was between the two. So, its hardness and behavior was expected to be somewhere between them.

EXPERIMENT 1: 29.11.2016 - Screening

Before setting the final test matrix, different parameter combinations were tried together to make sure excessive heating does not occur during the screening experiment. The final test matrix for screening after the trial runs was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
1	1	0,05	400	20	233,472	232,692	244,722	244,647	18,4	291	0,81
7	2	0,05	1000	80	232,692	232,018	244,647	244,571	18,8	295	0,95
2	3	0,15	400	20	232,018	229,765	244,571	244,471	18,3	387	0,37
3	4	0,05	1000	20	229,765	229,105	244,471	244,376	18,6	368	1,21
4	5	0,15	1000	20	229,105	227,055	244,376	244,071	18,7	1180	1,25
8	6	0,15	1000	80	227,055	224,962	244,071	243,831	19	928	0,96
5	7	0,05	400	80	224,962	224,192	243,831	243,752	18,6	305	0,86
6	8	0,15	400	80	224,192	221,906	243,752	243,686	18,5	255	0,24

To prevent excessive heating of the workpiece, the high value for tool speed had to be kept on rather low level. To keep the scale between the values wide enough, the low value for tool speed was set to really low level. Such a low tool speed led primarily in tool wear and the results were very poor. In some of the test runs with high tool speed the workpiece started to warm up a little, but not to a problematic extent. Thus the tool speed could be increased a little, both the low and high values. Based on the first experiment, the Norton grade H seems quite hard and heat generation is problematic.

EXPERIMENT 2: 13.1.2017 – Screening

Before the second experiment for Norton grade H, modifying the coolant setup by adding additional nozzles was experimented with other segments. Based on the positive influence it had on the output of the other alternative segments, the Norton grade H was also experimented with modified nozzle setup. The parameters were adjusted from the screening without the extra coolant and the test matrix was following:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
3	1	0,07	1450	20	220,694	219,928	246,556	246,131	19,5	1658	4,71
2	2	0,15	750	20	219,928	217,714	246,131	245,944	19,3	729	0,72
5	3	0,07	750	80	217,714	216,716	245,944	245,816	18,6	499	1,09
6	4	0,15	750	80	216,716	214,531	245,816	245,647	18,6	658	0,65
7	5	0,07	1450	80	214,531	213,894	245,647	245,251	19,5	1540	5,26
8	6	0,15	1450	80	213,894	213,318	245,251	244,799	19,6	1755	2,28
1	7	0,07	750	20	213,178	212,167	244,753	244,642	18,8	430	0,93
4	8	0,15	1450	20	212,167	210,822	244,642	244,013	19,4	2436	3,94

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	Hot, fluid vaporizing	Glazed/badly glazed	27-58	Burn marks
2	OK	Normal/slightly glazed	18-38	
3	OK	Normal/glazed	16-31	
4	OK	Normal	22-38	
5	Hot, fluid vaporizing	Normal/badly glazed	41-75	Some burn marks, hit the power limiter
6	Warm	Normal/badly glazed	44-75	Hit the power limiter
7	OK	Normal/slightly glazed	20-35	
8	Hot, fluid vaporizing	Normal/badly glazed	45-71	Burn marks

On a start of the sixth run, when the machine was looking for contact with the workpiece, for some reason the tool took contact with the workpiece too early, causing the machine to stop. After this the starting point where the machine starts to look for contact had to be set again. The reset point was not the same as initially, so the value for tool length was reset. The value for tool length after the fifth run had to be estimated. The feed motion per minute times 15 minutes, minus the change in ball diameter, gives fairly good estimate of the tool wear. Comparing the value given by the machine to the calculated one, the difference is usually around 5%.

The Norton grade H benefits from the additional coolant nozzles but excessive heating is still a major issue. Regardless, a regression model is composed and confirmed in confirmation experiment.

Analysis:
In analyzing the screening experiment results, as seen in the Figure 1, only tool speed comes up statistically significant with significance level of 0.05. After removing the effects with lesser significance, feed rate comes close to being significant. Common sense tells that the regression model for material removal rate cannot be based only on tool speed. Based on earlier experiments, the tool speed, feed rate and possibly their interaction gives the most accurate model. The fit of different models will be tested with confirmation experiment.

```
Estimated Effects and Coefficients for Material removal rate mm3/min (coded
     units)

Term      Effect    Coef  SE Coef      T      P
Constant          1213,1    83,54  14,52  0,000
Feedrate   362,5   181,2    83,54   2,17  0,082
Tool RPM  1268,3   634,1    83,54   7,59  0,001


S = 236,278     PRESS = 714587
R-Sq = 92,57%   R-Sq(pred) = 80,99%   R-Sq(adj) = 89,60%
```

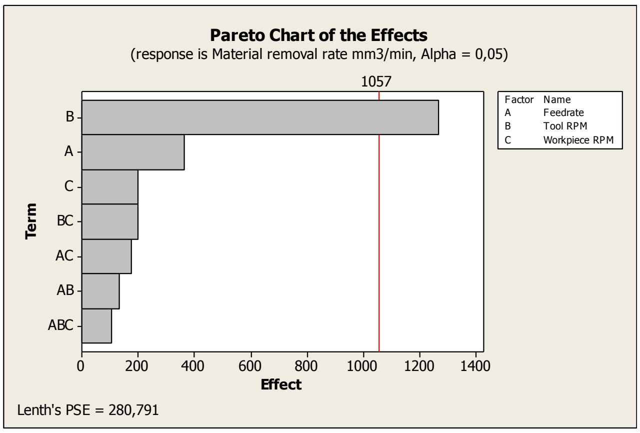

Figure 1. The statistically significant factors for MRR.

Even though the feed rate does not come up as statistically significant, comparing the output between similar runs with only changing the feed rate shows a positive change in MRR towards the higher value of feed rate, which is also seen in the Figure 2. All of the interactions terms show a little effect which can be seen for example looking at the output of the runs where only the feed rate is changed. The effect of the feed rate varies a lot between the different runs.

The workpiece speed shows much clearer effect than in other experiments. The effect also seems to be opposite as the lower value resulted in higher MRR. The workpiece speed also shows some interaction with other terms. The terms are not close to being statistically significant, but a model based on an experiment where all the terms show effect to a certain extent and are dependent on each other, might be inaccurate.

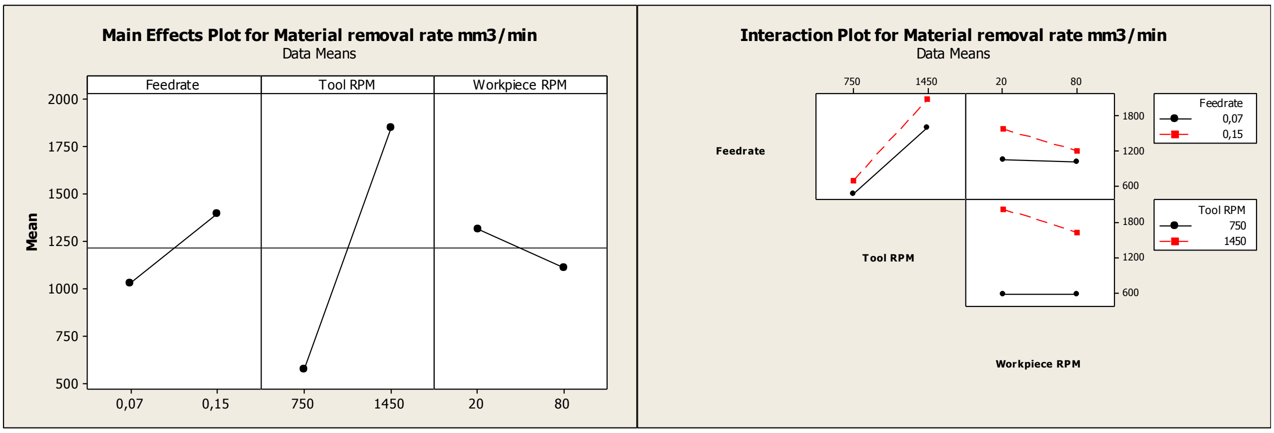

Figure 2. The effect of design factors on MRR.

The factor significance is quite evenly balanced for G-ratio as well, only the tool speed showing up as clearly distinct. However, the effects for G-ratio seem to be following the other experiments more closely. The tool speed, feed rate and their interaction are the three most significant terms. With significance level of 0.05, only the tool speed comes up as statistically significant. The model will be initially based on the three, but competitive model without the interaction term will be also tested through the confirmation experiment.

```
Estimated Effects and Coefficients for G-ratio (coded units)

Term                 Effect      Coef  SE Coef       T      P
Constant                       2,4449   0,2193   11,15  0,000
Feedrate            -1,0970   -0,5485   0,2193   -2,50  0,067
Tool RPM             3,1989    1,5995   0,2193    7,29  0,002
Feedrate*Tool RPM   -0,7763   -0,3882   0,2193   -1,77  0,151


S = 0,620317    PRESS = 6,15668
R-Sq = 93,99%   R-Sq(pred) = 75,97%   R-Sq(adj) = 89,49%
```

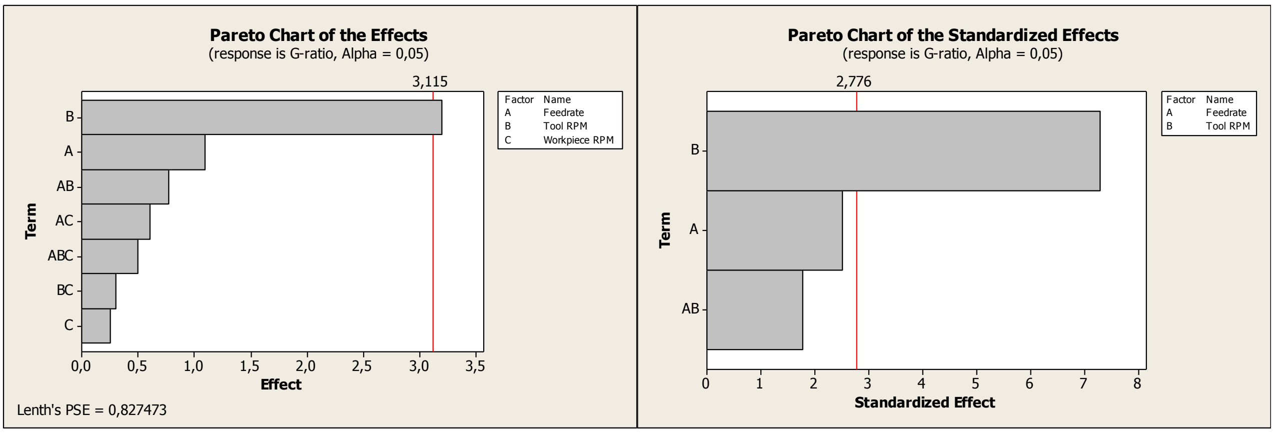

Figure 3. The statistically significant factors for MRR.

The effects for G-ratio are as usual and shown in the Figure 4. The feed rate increases the tool wear, resulting in weaker G-ratio. The tool speed reduces the wear and increases the MRR, improving the G-ratio. In the interaction plot of feed rate and tool speed below, the slopes for two feed rates are not parallel, thus showing some interaction.

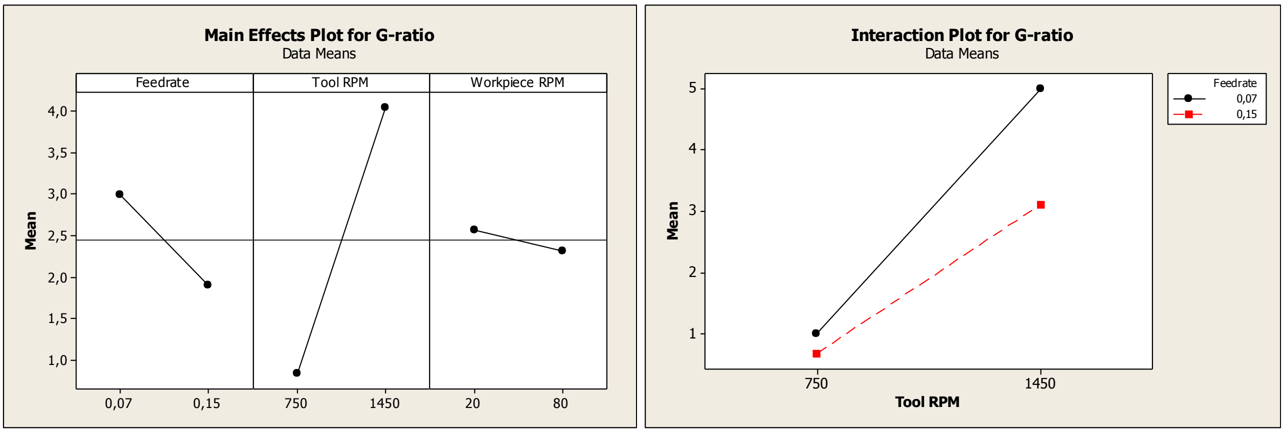

Figure 4. The effect of design factors on G-ratio.

The initial regression model for material removal rate consists of terms for feed rate and tool speed. Output estimates are also calculated with models consisting other terms. If some other model proves to be more accurate, it will be used instead. The primary model consists of following coefficients:

```
Estimated Coefficients for Material removal rate mm3/min using data in uncoded
     units

Term          Coef
Constant  -1278,27
Feedrate   4530,65
Tool RPM   1,81179
```

The initial model for G-ratio is composed of terms for feed rate, tool speed and their interaction. The other models and their fit to results from confirmation runs are compared and if some other models proves to be better fit, it can be used instead. The primary model for G-ratio consist of following factors:

```
Estimated Coefficients for G-ratio using data in uncoded units

Term                     Coef
Constant             -4,42845
Feedrate              16,7860
Tool RPM           0,00761977
Feedrate*Tool RPM  -0,0277259
```

EXPERIMENT 3: 18.1.2017 - Confirmation

For confirmation experiment, parameters were selected within the range of screening values as well as outside the range. The workpiece speed not being part of the either of primary models, it was decided to be set constant. Based on the effects plot, the more desirable output was reached with lower value. Since the segment is prone to thermal issues, the workpiece speed was set to high value.

The test matrix for the confirmation experiment consisted of following test runs:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
x	1	0,08	800	80	208,344	207,195	243,671	243,552	19	459	0,87
x	2	0,14	1400	80	207,195	206,212	243,552	243,066	19,3	1874	4,14
x	3	0,12	1000	80	206,212	204,616	243,066	242,71	19,1	1371	1,87
x	4	0,1	1200	80	204,616	203,389	242,71	242,269	19,3	1695	3,00
x	5	0,14	800	80	203,389	201,441	242,269	241,996	19,1	1048	1,17
x	6	0,15	1000	80	201,441	199,407	241,996	241,618	19,1	1449	1,55

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK	Normal/glazed	23-38	Distinct surface replicates to ball
2	Hot, fluid vaporizing	Normal/badly glazed	46-75	Hit the power limiter
3	Warm	Normal/glazed	33-53	
4	Warm	Normal/glazed	43-70	
5	Cool	Normal/slightly glazed	24-42	
6	OK	Normal/slightly glazed	32-59	

Overall observations:
With lower tool speeds the workpiece remains cool and the segment does not glaze as bad. With higher tool speeds, the G-ratio starts to increase with MRR but the temperature starts to raise as well. The second run led to best output measured by numbers, but also to worst quality.

Since the run number six lead to highest MRR among the acceptable runs, the material removal rate of 1449 mm^3/min from it, will be used to compare the segment to the others.

Evaluation of the models:

The estimates given by the model and their fit to tested values are shown in the Figure 5. The estimates for first two runs are rather accurate but for the remaining four, the estimates are on average 280 units lower than the tested values. With several factors showing some level of significance, the model could be expected to have some inaccuracy.

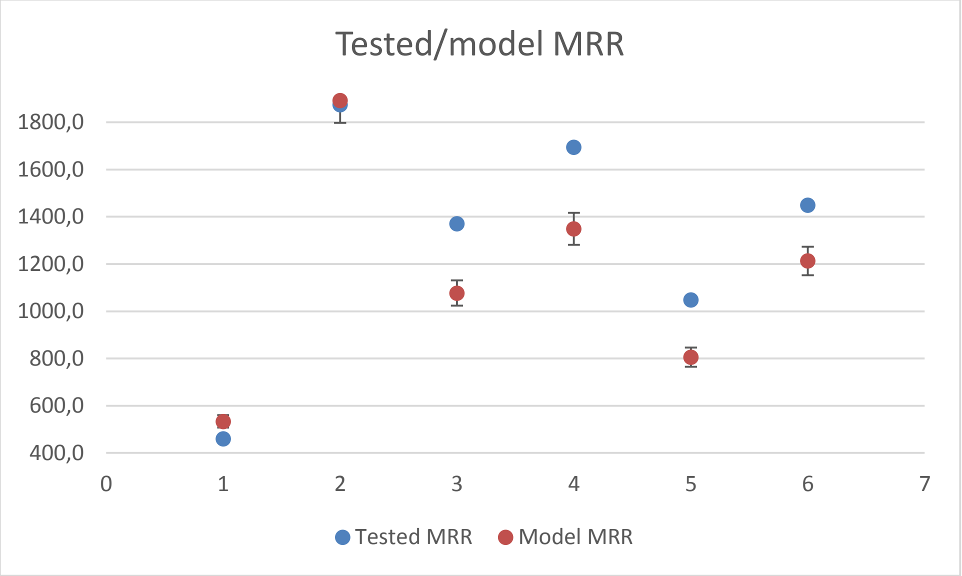

Figure 5. The fit of the MRR models to confirmation runs

The model for G-ratio, shown in the Figure 6, is the total opposite of the model for MRR. For G-ratio, the biggest error appears to be on two of the first runs and the rest of the estimates seem to be following the tested values nicely.

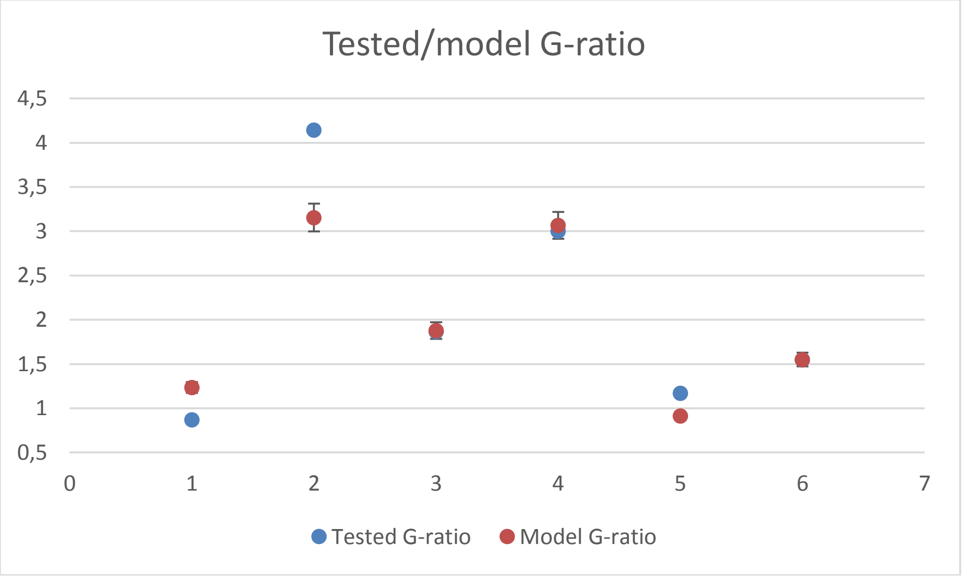

Figure 6. The fit of the MRR models to confirmation runs

Analysis: Norton – 3NQX120J24VS3X

The second experimented alternative was the hardest of the Norton segments and very likely the hardest of all the tested alternatives. The testing of the Norton grade J was started on 24nd of November, 2016.

EXPERIMENT 1: 24.11.2016 - Screening

Like with the Diprotex segment, not much was known about the segments that Norton had provided for the test. The testing had to be started somewhere and the parameters would have to be corrected based on the results and observations. Visually, the Norton segments are closer to Tyrolit than the other alternatives. So with once again, without better knowledge, the testing was started with parameters that work with Tyrolit segment. The experiment was conducted before discovering the benefits of the additional coolant nozzles. The test matrix for screening the Norton J segment was following:

StdOrder	RunOrder	Feed rate	Tool RPM	Workpiece RPM
2	1	0.2	1200	20
5	2	0.1	1200	80
4	3	0.2	2000	20
8	4	0.2	2000	80
7	5	0.1	2000	80
1	6	0.1	1200	20
3	7	0.1	2000	20
6	8	0.2	1200	80

The first run was stopped at two minutes due to the machine reaching the set limit for power output. The surface of the ball had severe burn marks and the fluid on the workpiece surface was vaporizing. It was clear after just two minutes that the bond on Norton J is much harder than Tyrolit or Diprotex and the parameters would have to be adjusted.

Before starting the experiment over, the effect of dropping the feed rate to half was tested. With feed rate of 0.10 mm/min, combined with tool speed of 1200 RPM and workpiece speed of 20 RPM, the power output limit was no longer reached. After few quick test runs, the test matrix parameters for the first screening experiment were set to:

StdOrd	RunOrd	Feedrate	Tool RPM	WP RPM	Tool L 1	Tool L 2	WP D 1	WP D 2	Fluid temp.	MRR	G-ratio
2	1	0,1	400	20	239,224	237,813	245,866	245,776	18,1	350	0,54
5	2	0,03	400	80	237,813	237,399	245,776	245,728	17,7	187	0,98
4	3	0,1	1200	20	237,399	236,456	245,728	245,411	19,1	1233	2,84
8	4	0,1	1200	80	236,456	235,602	245,411	245,09	19,3	1247	3,18
7	5*	0,03	1200	80	235,602	235,552	245,09	245,015	18,7	291	12,66
1	6**	0,03	400	20	235,552	235,171	245,015	244,979	18,8	140	0,80
3	7**	0,03	1200	20	235,171	234,977	244,979	244,903	18,4	295	3,31
6	8	0,1	400	80	234,977	233,592	244,903	244,826	18,4	299	0,47

*A solid contact after 11 minutes, **Contact after several minutes into the test run

Observations:				
Run:	Ball temperature:	Segment surface:	Power (%):	Additional details:
1	OK	Normal		
2	OK	Normal		
3	Hot, fluid vaporizing	Glazed		
4	Hot, fluid vaporizing	Glazed		Hit the power limiter once
5	-	Normal		
6	OK	Normal		
7	Hot	Glazed		Burn marks
8	OK	Normal		

Overall observations:
The results from some of the test runs are not valid, since a sound contact was not reached instantly. The experiment has to be rejected. Despite the results being distorted the segment can be stated to be too hard. The bond not fracturing is causing thermal issues.

The grade H already being too hard, the grade J is not experimented further.

Concentrations of certain substances in grinding fluid

Analysis	Method	Fresh sample	Sample 1	Sample 2	Unit	Uncertainty (%)
Chlorine, Cl		11 000	100 000	78 000	µg/l	10
Boron, B, total	EN ISO 11885:2009	62 000	460 000	460 000	µg/l	20
Boron, B, soluble	EN ISO 11885:2009	57 000	370 000	370 000	µg/l	20
Sulfur, S, total	EN ISO 11885:2009	8 800	72 000	70 000	µg/l	20
Sulfur, S, soluble	EN ISO 11885:2009	8 400	57 000	56 000	µg/l	20
Phosphorus, P, total	EN ISO 11885:2009	< 50	440	440	µg/l	20
Phosphorus, P, soluble	EN ISO 11885:2009	< 50	270	260	µg/l	20
Cobolt, Co, total	EN ISO 11885:2009	< 15	220	130	µg/l	20
Cobolt, Co, soluble (0.45 µm)	EN ISO 11885:2009	< 15	47	39	µg/l	20
Chromium, Cr, total	EN ISO 11885:2009	< 20	240	1200	µg/l	20
Chromium, Cr, soluble (0.45 µm)	EN ISO 11885:2009	< 20	110	110	µg/l	20
Manganese, Mn, total	EN ISO 11885:2009	< 3	30	71	µg/l	20
Manganese, Mn, total (0.45 µm)	EN ISO 11885:2009	< 3	14	22	µg/l	20
Molybdenum, Mo, total	EN ISO 11885:2009	< 15	270	390	µg/l	20
Molybdenum, Mo, soluble (0.45 µm)	EN ISO 11885:2009	< 15	180	180	µg/l	20
Nickel, Ni, total	EN ISO 11885:2009	< 30	390	3700	µg/l	20
Nickel, Ni, soluble (0.45 µm)	EN ISO 11885:2009	< 30	< 30	< 30	µg/l	20
Titanium, total	EN ISO 11885:2009	< 10	100	110	µg/l	20
Titanium, soluble	EN ISO 11885:2009	< 10	73	72	µg/l	20
Hydrocarbons, C10-C40	EN ISO 9377-2:2001 mod					
C10-C21		58	690	49	µg/l	40
C21-C40		860	3500	2400	µg/l	40
Hydrocarbons, C10-C40, total		920	4200	2400	µg/l	40