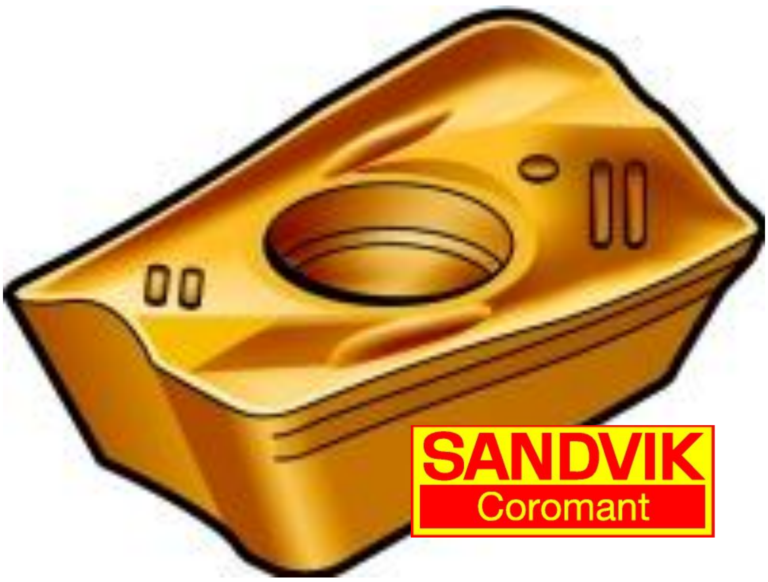
CHALMERS



Analyze of insert geometries, wear types and insert life in milling

Master of Science Thesis within the Applied Mechanics program

EMELIE BJURKA

Department of Applied Mechanics
Division of material and computational mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2011
Report No. 2011:09

MASTER’S THESIS 2011:09

Analyze of insert geometries, wear types and insert life in milling

Master’s Thesis in the Applied Mechanics program

EMELIE BJURKA

SUPERVISORS
Per Wiklund, Sandvik Coromant AB
Ragnar Larsson, Chalmers University of Technology

EXAMINER
Ragnar Larsson, Chalmers University of Technology

Department of Applied Mechanics
Division of Material and Computational Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Analyze of insert geometries, wear types and insert life in milling
Master’s Thesis in the Applied Mechanics program
EMELIE BJURKA

Master´s Thesis 2011:09
Department of Applied Mechanics
Division of Materials and computational mechanics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Insert for the R390 tool from Sandvik Coromant and the Sandvik Coromat AB logotype.

Chalmers Reproservice
Göteborg, Sweden 2011

Analyse of geometries, wear types and insert life in milling
Master's Thesis in the Applied Mechanics program
EMELIE BJURKA
Department of Applied Mechanics
Division of Materials and computational mechanics
Chalmers University of Technology

ABSTRACT

This work investigates the influence of different cutting data and geometries on the different wear types of an insert in milling. A Knowledge Development Project (KDP) called Pallas was started in 2009 with the main issue to better understand the different relationships between insert geometries and tool life during milling in steel and stainless steel.

The life of an insert is the far most important customer value since it to a large extent influences the economy of the milling operation. An interest in increasing the life of an insert is therefore a high priority when designing new inserts.
In order to investigate the dependency of different geometries of an insert a test tool and a number of different insert geometries was developed during the first sub project of Pallas. (Projekt PM [Document ID: **TM CTPM45514**])

The work presented in this report represents the first tests of those different insert geometries and prototypes. The inserts are tested according to already known test methods, developed and used at Sandvik Coromant, but evaluated with a multivariate data analysis tool called Modde. (L. Eriksson, E. Johansson etAl. , 2008))The drawbacks and benefits with this computer program are investigated as well as the different insert geometries and the behavior of the different wear types and their affection on the insert life.

The results points towards the importance of collecting accurate data when measuring, as well as giving recommendations for further testing, where it should be possible to optimize the geometry of the tool to reach as long life as possible. The parameters to further investigate concerning the geometry is the clearance angle and the chamfer width. It was also seen that the usage of center points when testing was necessary to get good results in Modde, and that repeated tests decreases the uncertainties in the test results due to undefined parameters, such as material impurities.

The measurement methods and the criterions when a test is to be interrupted used today are too unreliable to use when trying to build knowledge about what happens with the insert before it is fully worn out, but not when it is wanted to see how long the insert life is. The test results showed that the optimized chamfer width for the Pallas insert is in the range of [redacted] to [redacted].

Contents

Preface

In this master thesis inserts for milling tools have been investigated. Focus has been on the geometry of the inserts, and the analysis of the tests done was executed in the multivariate data analysis program Modde, a program developed by the Swedish company Umetrics.

The Master thesis for which the work is represented in this report was done at the Swedish company Sandvik Coromant AB, which is a part of the Sandvik AB concern. The Master thesis was performed for the division of material mechanics at Chalmers University of Technology from October 2010 to March 2011

First of all I would like to thank my supervisor Per Wiklund at Sandvik Coromant for his contribution with help and knowledge during the project. I would also like to express my gratitude towards my examiner Ragnar Larsson at Chalmers for his supportive work. Further, I would like to thank all people involved at Sandvik Coromant, and specially Marie Malm for her support, Tord Engström for his valuable explanations and help and also Daniel Jönsson for his extra time in the workshop.

Sandviken, March 2011

Emelie Bjurka

1 Introduction

This first chapter will give a brief introduction to the project which this Master Thesis is a subpart of. The reason to why the work was done the way it was is also described, as well as the aim of the Master Thesis. Finally, an outline of the report is presented to give a better understanding of how it is built up.

The Swedish company Sandvik Coromant AB, at which the work presented in this report has been performed, is a part of the Sandvik Tooling concern, which in turn is a part of Sandvik AB. Sandvik Coromant is one of the biggest supplier to the metal working industry, with big areas in milling, turning and drilling. It is a multinational company, represented in about 130 countries.

At the research and development department for milling in Sandviken, Sweden, a Knowledge Developing Project (KDP) with the working name Pallas (Projekt PM [Document ID: **TM CTPM45514**]) has been going on since autumn 2009 and it will end in June 2011. The main issue with the project was to better understand the different relationships between insert geometries and insert life during the cutting process in steel and stainless steel.

The project was founded to develop test methods and insert and tool prototypes to be able to do further knowledge developing projects concerning tool life for different insert geometries in the future. After this was done, a second part of the project was carried out to develop different insert geometries as well as evaluate the test methods and the prototype but also to give input to an upcoming product project. This second part was divided into two Master Thesis projects, where the work presented in this report is the first part.

Sandvik use the FEM program AdvantEdge (Third Wave Systems, 2011). In this program as with many others it is not possible to accurately calculate insert wear. Even if it was possible to calculate the wear it would not be practical because of the excessive amount of computing time that such calculations would require. Many of today's programs are optimized to calculate turning operations but lack information to calculate milling operations.

Factors such as grade, cutting material, insert geometry and type of operation matters a lot when testing insert life. Insert material compositions are often unique from company to company. It can also not be assumed that the insert geometries are defined in the same way in different contexts. Because of the differentiation that occurs when describing geometry for inserts in other models and calculations it is not possible to use those data to build models for the Pallas project in FEM. (Per Wiklund, AB Sandvik Coromant, 2010)

To be able to build a good model to get good results from calculations it is important to not only start with a good model but also that this model is built from good statistics. For this case, with milling inserts and different types of wear and the interaction between those a sufficient model does not exist today. This is why a good calculation model cannot be built at the time.

1.1 Aim of thesis

In order to evaluate the test methods and the developed insert prototypes, a number of tests were done. This report aims to investigate and explain the drawbacks and advantages with the tests done, as well as give input to tests aiming to optimize the geometry of an insert for a specific application. It also aims to describe methods for further development of inserts as well as give input to further projects.

The multivariate data analysis program Modde (L. Eriksson, E. Johansson etAl. , 2008) is also to be evaluated for the specific tests done and the specific purpose of analyzing the influence of different insert geometries on the tool life of the milling insert. Further the aim is to give a valuable input for optimization tests of the insert geometry.

The work described in this report is tested on specific applications in milling, using the approach angle κ_r = 90°, further described later on, and the results for other applications are not covered by this report.

1.2 Outline of the report

The report first provides the reader with useful theory to give better understanding of the work done, where after the function of the measurement equipment used is described. The advantages and drawbacks of those are also described. The next three chapters describe the test planning, the tests done throughout the Master thesis project, as well as the results of those. The final two chapters contains a discussion of the results is presented where after the most important results are posted.

2 Theory

This Chapter will describe the theory needed to understand the results of this project. First of all the milling tool is described, before looking more closely at the inserts of the tool. Finally, the analysis tool that was used during the tests is explained, to give a basic understanding of how the tests were analyzed.

2.1 The milling tool

In this section a brief description of the milling tool will be presented, together with the most important definitions used in milling. Those definitions can of course be combined to better understand the milling operation, with production speed as an example.

2.1.1 Cutting definitions

When a tool is moved forward (or the table is moving) it is done with a specific speed, that is called the feed of the operation, V_f (mm/min). The feed does of course affect the maximum thickness of the chip, h_{ex} (figure 2). The speed of the tool is defined as revolutions per minute. The illustration of tool speed and cutting feed can be seen in figure 1.

The **cutting speed** is defined as $V_c = \frac{\pi \times D \times n}{1000}$ (m/min) where D_c is the diameter of the tool (mm) seen in figure 2, and n is the tool speed in rpm. (Sandvik Coromant, 1994)

Feed per tooth is another important value in milling. It determines how much each insert edge machines under satisfactory conditions and is defined as $f_z = \frac{v_f}{n \times z}$ where z is the number of inserts machining on a periphery diameter of the tool at the same time. (Sandvik Coromant, 1994)

The definition of a_e is the **cutting width in the radial direction** of the tool, and the maximum a_e is set as the diameter of the tool (figure 2). Machining on a_e half of the diameter of the tool should be avoided. (Sandvik Coromant, 1994) The a_p is the **cutting depth in the axial direction** of the cutter. It is also defined as the distance the tool is set below the unmachined surface (figure 3).

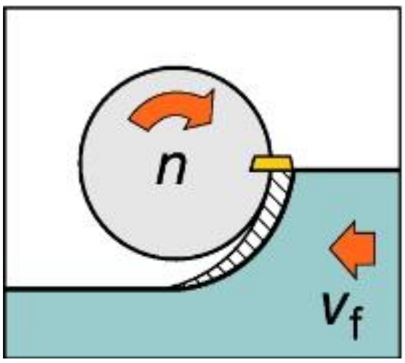


Figure 1: *Tool speed n and feed V_f*

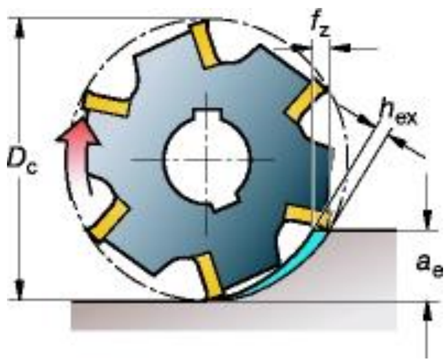


Figure 2: *Feed per tooth f_z, Tool diameter D_c, radial cutting width a_e and maximum chip thickness h_{ex}.*

The **approach angle**, κ_r, on the cutting edge is described as the angle between the workpiece and the main edge and can be seen in figure 3. The approach angle in milling is normally between 10 and 90 degrees, and many of Sandviks' tools has a name that tells the approach angle. For example the tool R390, where 90 indicates the approach angle. An approach angle close to 90° gives a thicker chip while a lower angle gives a thinner chip but a larger use of the cutting edge in the axial direction. In this project, the study has been set to only consider κ_r=90 as explained in the introduction chapter. (Sandvik Coromant, 1994)

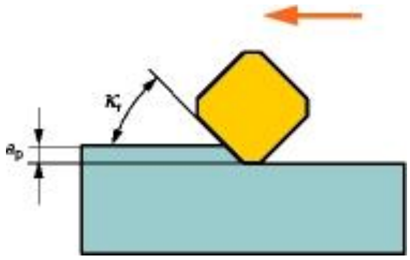


Figure 3: *Approach Angle, κ_r and cutting depth in the axial direction, a_p.*
(Red arrow shows tool feed direction)

Another important feature in milling is the rotation direction of the tool compared to the feed direction. It gives here two possibilities, up milling and down milling. **Up milling** is also called conventional milling and here the direction of feed is opposite to that of the cutter rotation in the cutting area. The procedure can be seen in figure 4, and it also shows here that the chip thickness h starts at zero and grows to maximum h_{ex} at the exit of the cut. (Sandvik Coromant, 1994)

The second direction is defined as **down milling** or climb milling, and is defined by the fact that the work piece feed is in the same direction as the cutter rotation in the cutting area. The phenomena can be seen in figure 5 and it can also be seen that the chip thickness starts at its maximum h_{ex} at the entrance of the cut, to later decrease. This is most often the most preferable way of milling since the cutter in up milling is forced into the material piece, holding the cutting edge in the cut. If the machine is not strong enough, up milling is preferable. (Sandvik Coromant, 1994)

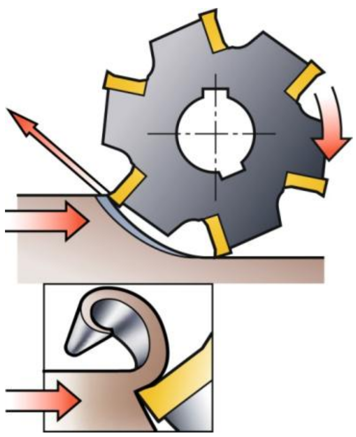


Figure 4: *Up milling / conventional milling.*

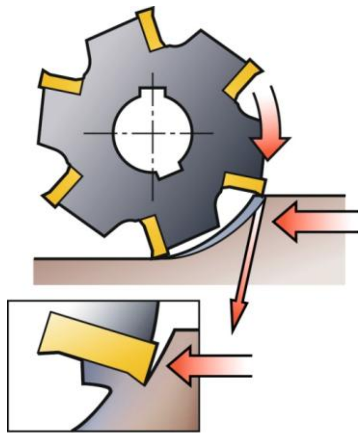


Figure 5: *Down milling / Climb milling*

2.1.2 The R390 tool

A R390 tool is one of the most used tools from Sandvik, and this tool was used in the Reference tests, and as well as some reference points in familiarization and screening tests. Since R390 is a product family, there are of course many different dimensions of the R390 tool, such as number of inserts, diameter and insert size. In this project a tool with diameter (D_c) 20mm was used. The R390 tool used has got two insert positions and can be seen in figure 6. Only one insert seat was used during the tests due to the fact that the Pallas tool is a concept with one insert position. The standard insert for R390 has got 2 edges.

Figure 6: *R390 tool.*

2.1.3 The Pallas tool

The Pallas tool was developed during the first parts of the project and has got the same cutting diameter (D_c) as the R390 tool (20 mm). It has only got one tooth since it is a tool mostly developed to investigate the geometries of the insert prototypes. As for the R390, this tool has as well got an approach angle of κ_r = 90°. The Pallas tool can be seen in figure 7 below.

Figure 7: *The Pallas tool.*

2.2 Test types

When performing the tests, different CAM programs were used when machining. The process programs were executed to generate a normal but controlled wear and they are described briefly in this section.

2.2.1 Life tests

The life tests were executed with a program with a so called rolling entrance to make it smooth. The material piece has the dimension 200x250x200mm, which implies that the above surface that was to be milled had the dimensions 200x250mm. From this, the life test program milled the piece over the 250 mm length, so that every operation had the length 250mm and the width of a_e. Thus, on one layer there were $200/a_e$ operations. The last piece of every layer is not milled with the test tool; it is taken away in another milling operation, this since this operation can give unexpected wear. A description of the CAM program can be seen in figure 8.

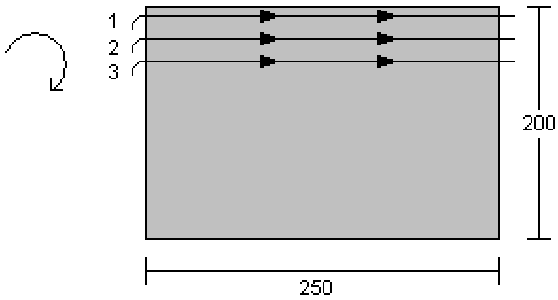


Figure 8: *Program for life tests.*

2.2.2 Toughness tests

A program called "The wedge" was used in the toughness tests. To maximize the toughness testing a program was executed so that the a_e was varying over the operation. It is possible to choose an interval for a_e during the process, for example from 20-80% of D_c. When one wedge was operated, the direction was changed so that the tool was always working in up milling. A figurative description is represented in figure 9.

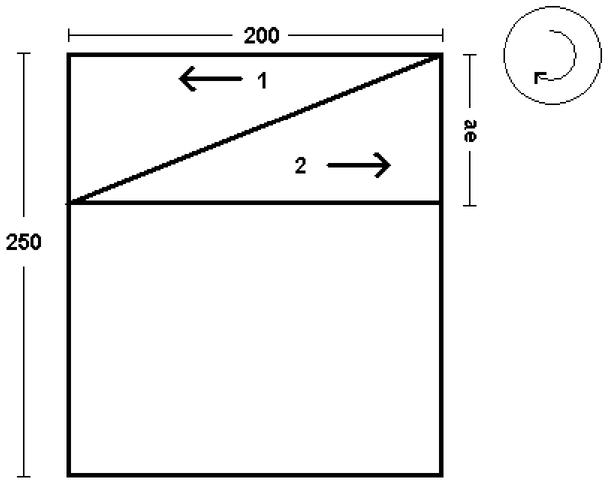


Figure 9: *Wedge program for toughness tests.*

2.3 Inserts

For industrial milling, the most common way is to use tools with exchangeable inserts. This makes the production more economic since the inserts can be changed instead of changing the whole tool. Later, the inserts has also been equipped with two or more edges on to be able to use an insert as long time as possible. In this section the most important geometries of a insert, the most common wear types, and the most common coatings of the inserts are described.

2.3.1 Insert Geometry

For each tool on the market, there are inserts, which are suited for the tool, both geometrically but also for the operation for which the tool is developed. Except from being made for the tool, the inserts have got a number of geometric parameters which can be good to be familiar with to achieve a better understanding of how the inserts look and why. Below are some of the geometrical definitions of the insert used in this project are described.

The **rake side** of the insert is the side defined as the whole upper side of the insert, or the side where the chip breaks. This surface is denoted by (A) in figure 10 . There is also a side called the **flank side**, where newly worked material passes. This side is denoted by (B) in figure 10. (Sandvik Coromant, 1994)

The **Edge Rounding** or shortly ER, is the definition of the radius of the cutting edge. In figure 8 the ER is the radius between the rake side and the flank side, a part of it marked red. An increased radius on the edge and makes it more unsharp, which increases the risk of built up edges, but it also allows better adhesion of coatings. (Sandvik Coromant, 1994)

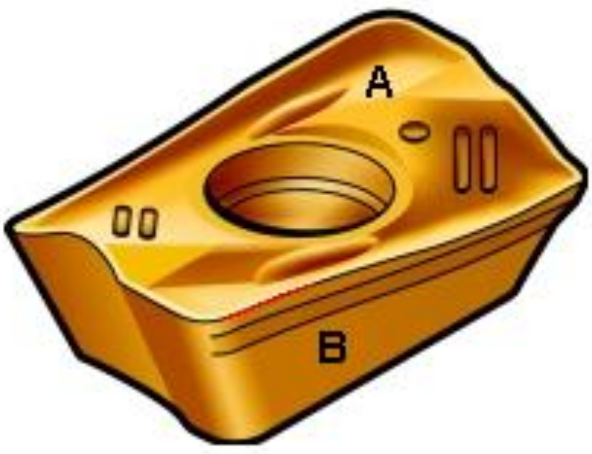


Figure 10: *(A) Rake side and (B) flank side.*

The **chamfer angle**, γ_{n1} is defined as the angle on the first chamfer of the insert. Often there is a number of chamfer angles, and then, they are numbered with the one closest to the edge as number 1. This angle can be seen in figure 11, where the major cutting edge is denoted by S. The direction of the chamfer angle is defined with the plus and minus signs in the same figure.

Looking at the rake side of the insert a small width on the edge can be seen clearly. This plane is called the chamfer, and the **chamfer width** is the defined as the maximum width of the chamfer. It can be seen in figure 11 as the width of the surface $A_{\gamma 1}$.

A **Clearance angle** is necessary so that the flank side of the insert does not come in contact with the material when machining. It can be described as the angle on the clearance side of the insert, depending also on how the insert is tilted in position. A plane parallel to the worked surface is defining the angle and it is described as α_{n1} in figure 11. The clearance angles are numbered in the same way as the chamfer angles.

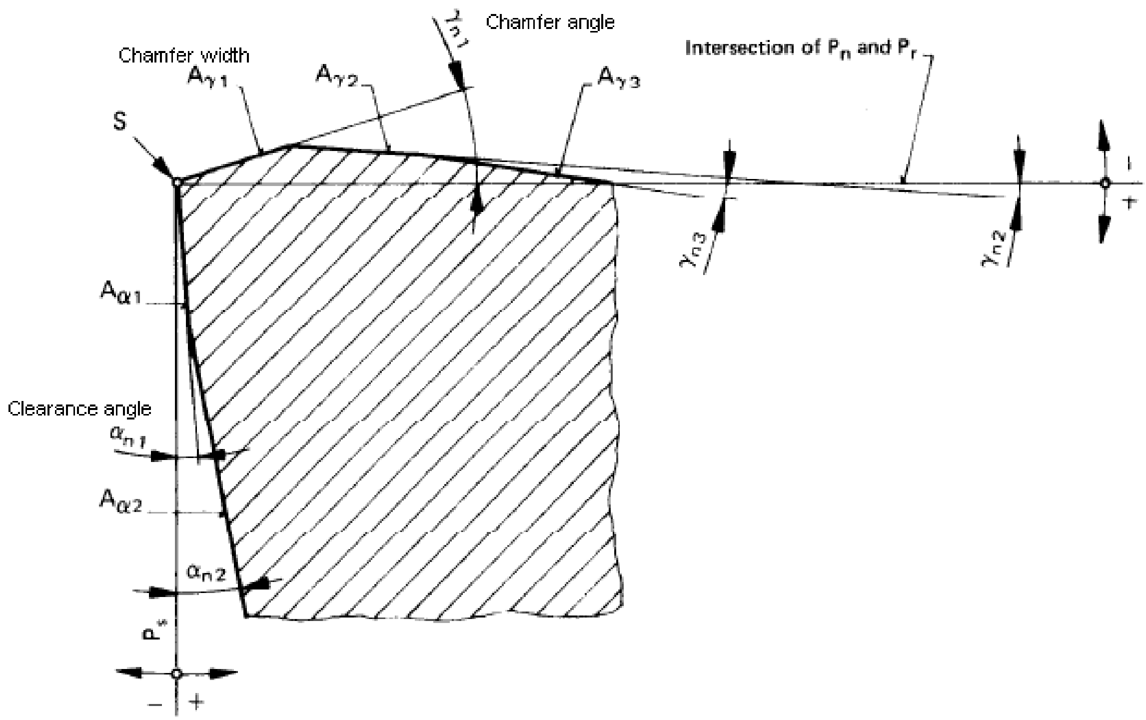


Figure 11: *Chamfer angle, chamfer width and clearance angle.*

2.3.2 Wear types

Using inserts always ends up with some kind of wear on them. Depending on how they are used different wear types occurs, and the life of the insert is varying. The most common wear types are presented in this section, as well the known reasons to why they appear. To determine whether an insert is worn out or not a failure criterion is normally set. This is on Sandvik Coromant normally set to 0.35 mm wear, no matter which wear type that makes the insert worn out or how far from breaking the insert actually is.

Flank wear is an abrasive and predictable type of wear, which is normally to prefer since it is slow and predictable. The edge is changing structure successively and therefore after a while, the quality of the machined surface is not sufficient. The more flank wear, the more cutting force is needed for the cutting process since the insert becomes more and more unsharp as the wear is developing. A typical example of flank wear can be seen in figure 12. The flank wear is measured from the unworn edge to be most exact and figure 13 is a schematic picture of how the measurement of flank wear is to be made. The VB-measure in figure 13 sets the failure criterion for flank wear, normally 0.35mm. (AB Sandvik Coromant, 2007)

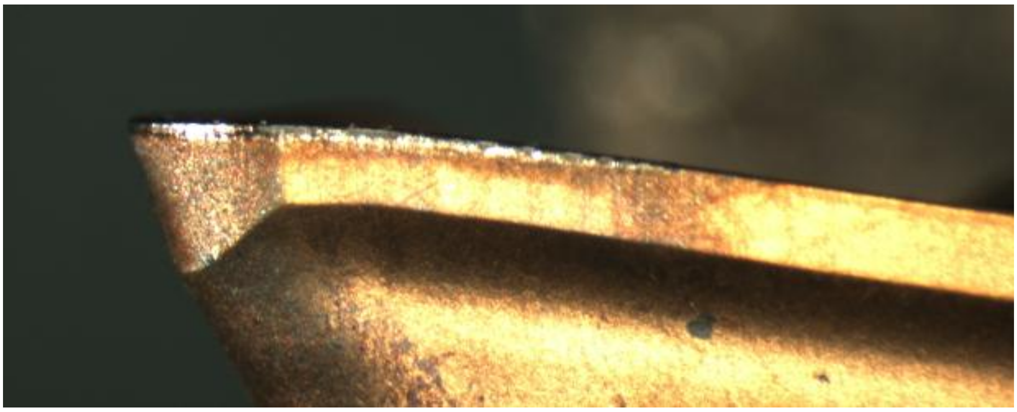


Figure 12: *Example of flank wear.*

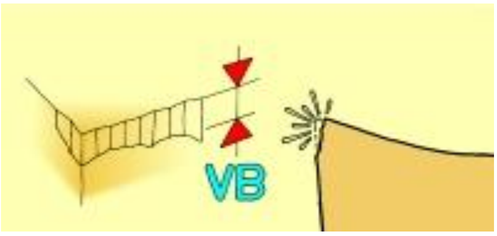


Figure 13: *Measurement of flank wear.*

Another common wear type is the **crater wear**. Figure 14 shows an example of crater wear. It is caused by the chip that is creating an abrasive wear on the chip surface of the insert. Crater wear also appears through chemical diffusion between the chip and the cutter, due to high temperatures on the surface. The cavities then appear on the part of the cutter where the highest temperatures are located, in combination with the contact with the chip of course. The feed of the machine, f_z, decides how long into the insert the crater starts. An increased feed makes the crater start further from the edge. When measuring in tests, the smallest distance to the edge is measured. When this distance is equal to zero, the test is normally cancelled. One exception is when the crater starts directly on the edge.

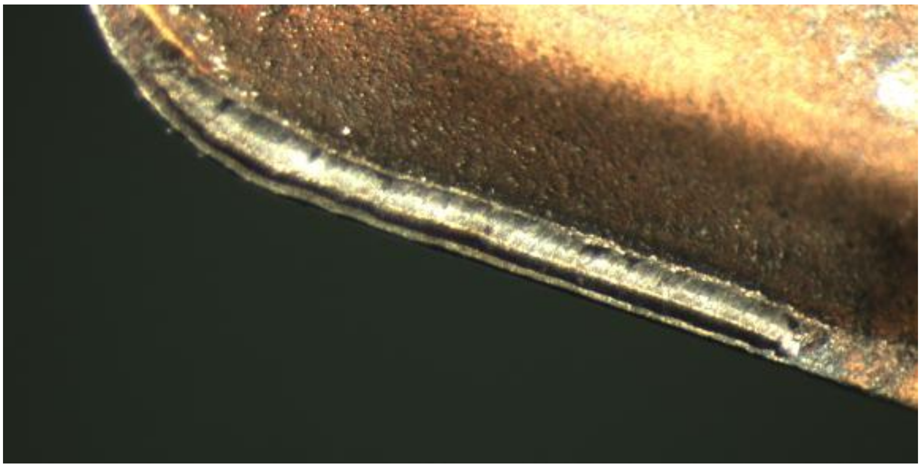


Figure 14: *Crater wear on the rake side.*

The **notch wear** always occurs at the maximum cutting depth a_p on the insert. It normally occurs on inserts used in harder materials that are subject to deformation hardening on the surface, and this surface then tears the insert up. This phenomenon can be shown in figure 15. (AB Sandvik Coromant, 2007)

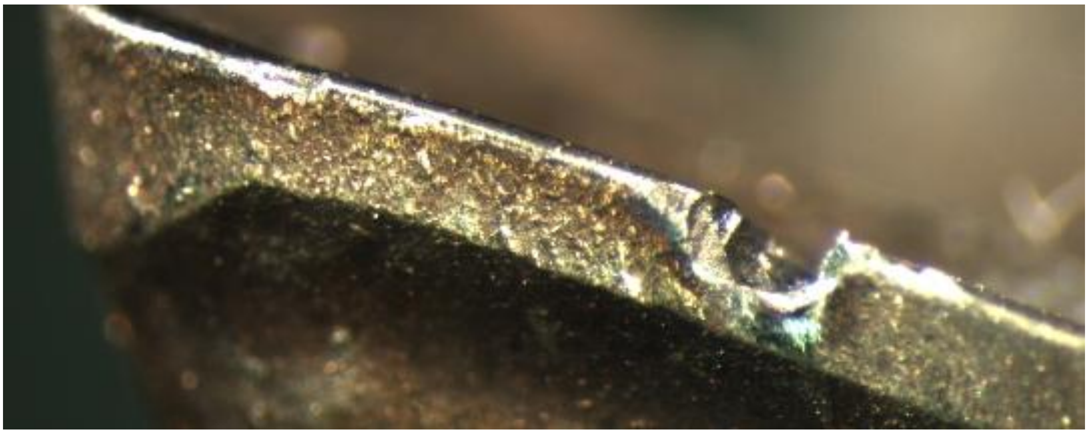


Figure 15: *Notch wear.*

The wear type **chipping** that can be seen in figure 16 is a small edge fracture that occurs often due to the fact that the crater wear has reached the edge or due to the existance of comb cracks. The size of the chipping is totally randomized, due to for example the material composition. This fact makes it hard to determine whether an insert is worn out or not, in the sense of chipping wear. The normal break criterion is set when the chipping is greater than 0.35. (AB Sandvik Coromant, 2007)

Figure 16: *Chipping.*

Comb cracks are first formed on the cutting edge, on a height that equals half of the axial depth of cut, a_p, because the yielding due to temperature is as greatest here. (Tord Engström, AB Sandvik Coromant, 2010) After the first crack has occurred, new cracks will tend to form on the half of the height from the first comb crack to the edge, and also, similar on the other side. After the comb crack has occurred it starts to erode the coating of the insert. It can therefore not be said in general when a crack turns into a cavity. It is also hard to conclude whether it is the erosion or the crack that makes the insert break. Comb cracks often leads to the formation of built-up edges. The temperature variations have a big influence on the development of the comb cracks. This is why it is not good to use coolant in milling, where comb cracks are to be avoided. (AB Sandvik Coromant, 2007) Examples of comb cracks can be seen in figure 17 and 18 below.

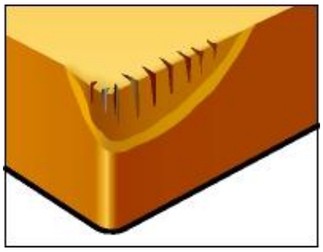


Figure 17: *Comb cracks underneath the insert coating.*

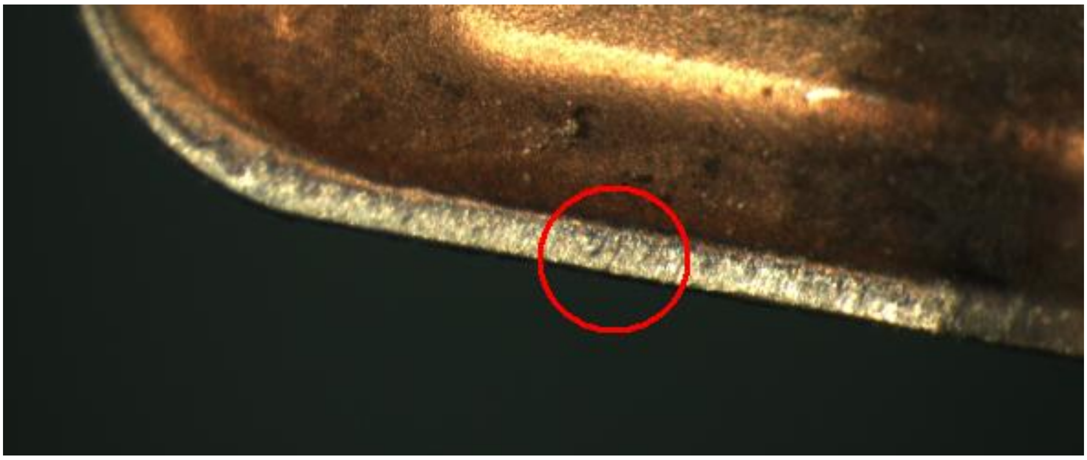


Figure 18: *Example of comb cracks.*

2.3.3 Insert coating

To make the insert last longer it is normally coated with a layer of harder and for the dedicated application better material. In this section two of the most common coating processes will be described, PVD- and CVD -coating. Some of the most common properties of the coatings are also treated.

PVD – Physical Vapour Deposition

A coating process used for inserts that is done at relatively low temperatures (around 500°C). The method is often used when you need a sharp edge, and a common material that is often used is a TiAlN-material. The PVD-coating can be recognized since it can often be seen that the insert is non-coated where it was held during the coating process. PVD-coated inserts are often more sensitive to notch wear than CVD-coated ones. A schematic picture of the PVD coating can be seen in figure 19 below. (AB Sandvik Coromant, 2007)

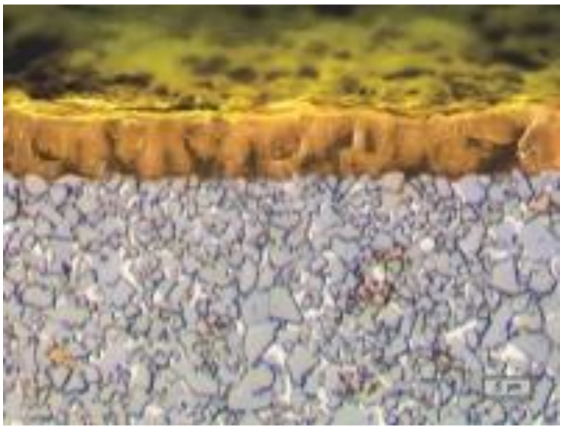


Figure 19: *The PVD coating.*

The PVD coating has generally a tougher edge line, due to the compressive stresses that occurs in the coating, (AB Sandvik Coromant, 2007) see figure 20. For a smaller edge rounding however, the coating can flake spontaneously because of stresses. All the inserts used in the testing in this Master Thesis was PVD coated either with the Sandvik Coromant coating GC1010 or the coating GC1030. **GC1010** is a coating that is optimized for working in hardened steels. It also has a good notch wear resistance, but can be bad in resisting crater wear in some applications. **GC1030** is a well known all-round coating that has good properties even in titanium. This is also the first choice coating for milling in steel.

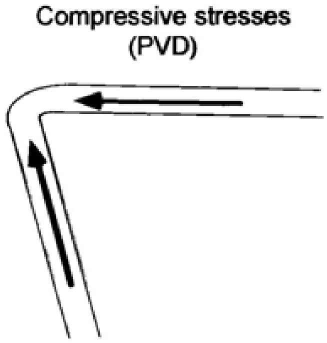


Figure 20: *Stresses in the PVD coating.*

CVD – Chemical Vapor Deposition

This coating is a coating process that is done at a medium temperature (850°C), and has a uniform thickness throughout the coating. Different layers with different characteristics are applied and the structure can be seen in figure 21. The CVD Coating is more adhesive than the PVD Coating, and is also more heat resistant (mostly because of the Al_2O_3 layer). (AB Sandvik Coromant, 2007)

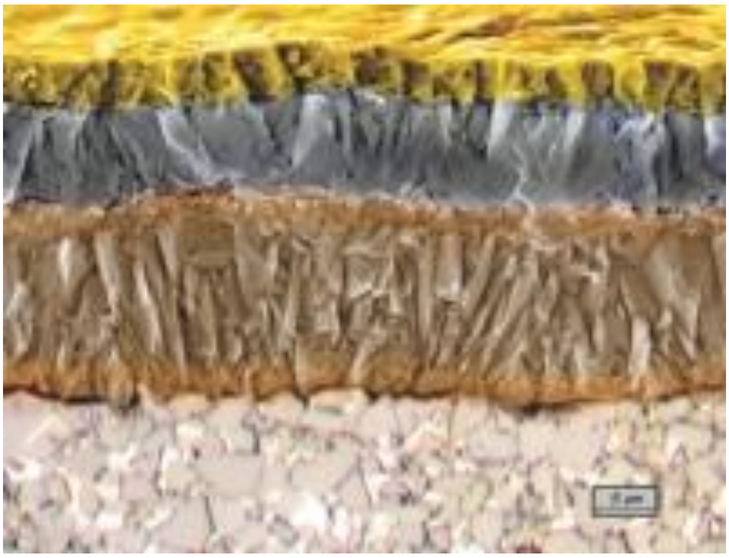


Figure 21: *The CVD coating.*

The thickness of CVD is larger than for PVD, which forces the edge rounding to be larger, but it is also good in a wear point of view. The resulting tensile residual stresses in the coating due to temperature changes make the coating quite brittle. This phenomenon is shown in figure 22.

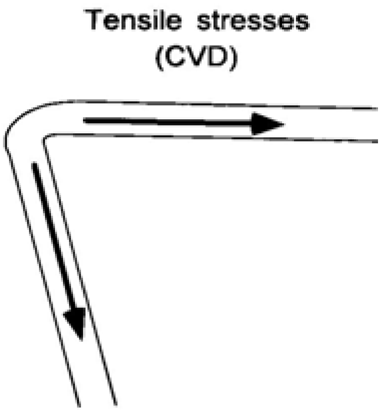


Figure 22: *Stresses in a CVD coating.*

2.4 Analysis Tool Modde

The computer software Modde (L. Eriksson, E. Johansson etAl. , 2008) is a software from the Swedish company Umetrics, that is used to analyze the results of an experimental test. Depending on which test that is to be done, there is a number of parameters, (in Modde called factors), that is varied over a number of experiments. All the different input factors can be varied, and it is also possible to choose an amount of them when performing a test. If the latter is chosen, the most common way to decrease the number of experiments is to use fractional factorial theory. When using Modde the problem to be solved can be divided into sub problems, or rather, subtasks. Those subtasks or, experimental stages, are described below and are guilty for all types of tests.

2.4.1 Problem formulation – The experimental objective

When using the computer program Modde for designing experiments, the problem to be considered is often divided into smaller sub-tasks. The understanding of how the problem is divided is described in this sub-section. The way the problem solution is carried out is described below, and the most important things with each part as well. During this Master Thesis the **familiarization** (1) and **screening** (2) parts as well as part of **finding the optimal region** (3) has been considered.

1. **Familiarization**

   The first thing to do when there is an entirely new type of application or equipment is a familiarization test. This is done to find out what is experimentally possible, and also to roughly look at the process to see how good it is. The familiarization tests are normally carried out as a so called simple factorial design which means that corner points and center points are found and then are chosen. For example; one high, one low and one intermediate value for each factor in the test. (L. Eriksson, E. Johansson etAl. , 2008)
   An important part of the familiarization tests is to do some of the tests in replicates, which means that some of the tests are repeated. This is done to be able to see if the same results are reached for the different tests or if the tests spread too much to even carry on with the next step. It is also done to get important results to carry on with further testing. Replicates are also an important issue to see whether the measurement equipment works or not. (L. Eriksson, E. Johansson etAl. , 2008)

2. **Screening**

   After the familiarization tests are done, they are of course analyzed with Modde to see whether it is warranted to carry on testing or not. Usually this is accomplished by looking at some in beforehand chosen criterions. If it is decided to carry on, the next step is the screening tests. In those tests it is tried to identify the most important factors of the test, i.e. those who causes the biggest changes in the outcome when they are varied. It is also wanted to identify the significant parameters, or the so called strong factors. A goal is the 80/20 principle, which implies that 80% of the effects on the outcomes should be caused by 20% of the factors. When choosing design for the screening, the fractional factorial design is primarily chosen. (L. Eriksson, E. Johansson etAl. , 2008)

3. Finding the optimal region

After the screening test, this test is analyzed, and then the optimal test region for the given test is sought. It is wanted to find whether the desired optimal point (the point with the best test results) exists in the experimental region or not. If it does not, the screening needs to be planned again so that an optimal region can be found. If it does, then the optimization is the next step, where the steepest descent/ascent is followed to find minimum/maximum. (L. Eriksson, E. Johansson etAl. , 2008)

4. Optimization

When the optimum test point is reached, most of the important factors in the test are known. The Optimization tests are carried out so that a few factors are explored in comparatively many runs to find the maximum or minimum point of a parametric surface. It is then important to know how the factors are interacting, and if a linear, quadratic or cubic model is needed to best describe the model. The optimization is achieved by designs from the composite family described in Modde, and the Response surface modeling that gives a prediction of results and factor setting that is optimal. The optimization is easy with 2-3 responses present but more inaccurate with more responses. (L. Eriksson, E. Johansson etAl. , 2008)

5. Robustness testing

The robustness testing is normally done before a release of a new product to ensure the quality of the same. It is also done to identify factors that *might* have influence on the outcome, but not are among the optimized factors. For robustness testing, usually a fractional factorial or a so called Plackett-Burman design is used. The Master Thesis project does not include a robustness test, and hence, more about those designs are to read in L. Eriksson, E. Johansson etAl. , 2008.

6. Mechanistic modeling

When reaching this point a real model based on the test results is normally established. At this point it is also normal to rely and to be able to rely heavily on use of a correct problem formulation, experimental design and a correct data analysis. (L. Eriksson, E. Johansson etAl. , 2008)

2.4.2 Test Designs

When designing the tests, a number of design methods were considered, to see which of them that was best in the specific tests done in the Master Thesis. Normally, when handling test planning in Modde, and planning of a screening in specific, either Resolution IV design or D-optimal design is used. In this section those two designs as well as a factorial design are described more accurately.

Resolution IV Design

The resolution of a design is depending on how many factors leads to how many responses in a design. In a resolution IV design, a design with the main effects unconfounded with the two-factor interactions is achieved, but there is still some confounding between the two-factor interactions themselves. (L. Eriksson, E. Johansson etAl. , 2008)
Creating a resolution IV- design with 7 factors gives a so called 2^{7-3} design, which generates 2^4=16 runs. This is called a two-level experimental design in seven factors, reduced three steps. Using those tests in the Master Thesis, the edges with the longest and shortest lives were searched, respectively. The tests were also to be chosen so that it was easy to add more tests if necessary. The Resolution IV design is good for screening tests, since it can be completed with many more tests from a D-optimal design. (L. Eriksson, E. Johansson etAl. , 2008)

The biggest advantage of adding tests with a D-optimal test is that tests can be added where they are needed, i.e. in interesting points, or to solve confoundings, instead of just adding more tests all over the region, as would be the case if for example a so called fold-over design was used. (L. Eriksson, E. Johansson etAl. , 2008)

D-Optimal Design

The D-optimal design is short for words determinant-optimal design, and the main choices of tests are done to maximize the determinant of the X'X matrix, where the X matrix is the matrix with the different factors for the test. The tests with the largest determinant are the ones who give the largest resolution, which implies that those tests are the one chosen. (L. Eriksson, E. Johansson etAl. , 2008)

Factorial Designs

In a so called full factorial design you test all points and variants possible to test, but in a Fractional Factorial Designs in DOE (Design Of Experiments) you take some experiments away, to make the number of experiments smaller. This is not done in a unpredicted way of course. In fractional factorial design the experiments that will have the least influence on the responses are found, and then those are taken away from the order of experiments. (L. Eriksson, E. Johansson etAl. , 2008)

2.4.3 Analysis

When analyzing a test using the computer program Modde there are some things to have in mind to be able to get a good model with reliable results. This section describes the most important terms and plots and what can be done to refine the results that is achieved using Modde.

Fit method

When choosing fit method to fit the data to mathematical models or formulas, there are two opportunities. Either Partial Least Squares fit (PLS) or Multiple Linear Regression fit (MLR). The MLR is used in most simple tests. If there are several correlated responses in the data, the condition number is above 10 and if there is small amounts of missing data in the response matrix, then the PLS method is preferable. (L. Eriksson, E. Johansson etAl. , 2008)

Model Validity – Difference between good and bad results.

There are different ways to check whether the model that is achieved is good or bad, and as well if the results achieved with the model used are trustworthy or not. The easiest way is to first check the tests design. This is done by evaluating the test model in Modde, and from this check whether the design of the test is good or bad. Here the **Condition number**, which shows the ratio between the smallest and largest singular values of the matrix of extended factors used as a measure value can be seen. For a screening and a robustness testing, a good design should have a value below 3, and for an optimization the condition number should be below 8 for a satisfactory test design. (L. Eriksson, E. Johansson etAl. , 2008)

The next thing to take look at is the **Summary of fit plot**. An example of such a plot is shown in figure 23. The green stack shows the R_2 value, or the goodness of fit value. The R_2 value shows how good the raw data can be refitted with the regression data. 1 is a perfect fit and 0 indicates no fit at all. A drawback with the R_2 value is that it easily can be modified so that it comes close to 1 by for instance including more terms in the model. (L. Eriksson, E. Johansson etAl. , 2008)

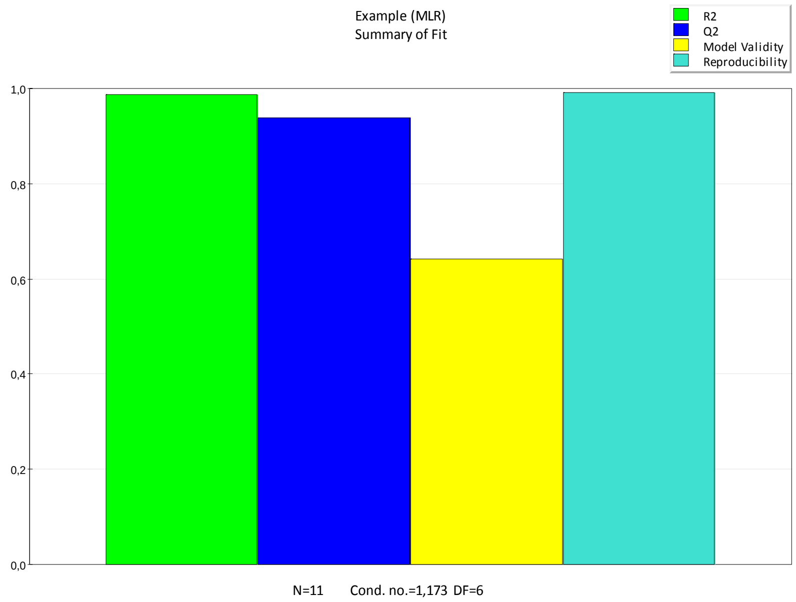


Figure 23: *Summary of fit plot*

The blue stack shows the value Q_2, or the **goodness of prediction** value. This is the best and most sensitive indicator of a good model. This value also varies between 1 and 0 (1 for perfect and 0 for no fit) and is much better than R_2 when looking at the usefulness of the model. The meaning of experiments is to be able to build mathematical models of the data collected, and this value indicates how easy it is to predict values for results for which experiments are not made. When having a very good value of Q_2 (>0.9), the Model validity might be low. This happens when there is a high sensitivity in the test or if the replicates are extremely good. (L. Eriksson, E. Johansson etAl. , 2008)

The yellow stack shows the model validity, i.e. if the right type of model was chosen when designing the test. If the model validity is to low it can be considered to redesign the tests with another type of model (for example linear, interaction or quadratic). (L. Eriksson, E. Johansson etAl. , 2008)

The last, light blue stack shows the reproducibility of the model. This is a summary of the variation of the results plotted in the **Replicate plot**, see figure 24. The replicate plot shows how much the repeated experiments vary with the repetitions plotted on the same stick. The higher numerical value in the light blue stack, the smaller replication error is seen across the entire design. (L. Eriksson, E. Johansson etAl. , 2008)

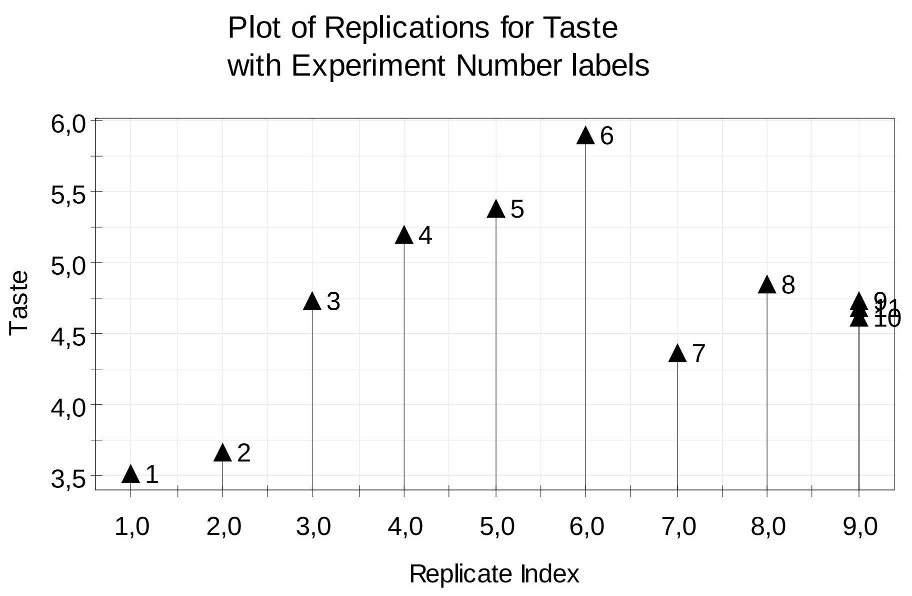


Figure 24: *Example of a Replicate plot.*

To be able to determine whether the model is good or bad in the summary of fit plot, there are some basic guidelines to follow. Those can be seen in table 1.

Table 1: *Guidelines for a good model in a summary of fit plot. (L. Eriksson, E. Johansson etAl. , 2008)*

	Value
Difference R_2-Q_2	<0.2-0.3
Q_2	>0.5
Model Validity	>0.25
Reproducibility	>0.5

Other things that might affect the results of the summary of fit plot are shown in other plots when analyzing a test. Here some smaller changes in the model can be done to improve the design. The first plot that is to be discussed is the **Histogram plot**, see figure 25. (L. Eriksson, E. Johansson etAl. , 2008)

The histogram plot shows the shape of the response distribution and with help from this, it can be seen whether a transformation of the data is needed or not. If the distribution is good, and a transformation is not needed, the histogram is normally distributed and looks bell-shaped. For example, if the histogram is skew a log transformation is normally recommended. If it is negatively skew, a negative log-transformation is recommended. To be able to look at the histogram there must be at least 11 data points in the tests. By selecting an appropriate transformation a non normal distribution might be transformed to normal distribution and hence a better model will be achieved.
(L. Eriksson, E. Johansson etAl. , 2008)

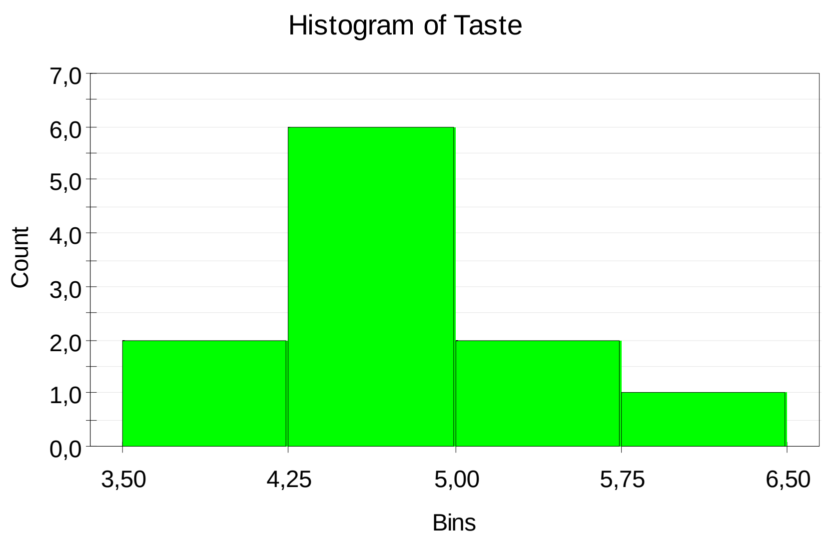


Figure 25: *Example of histogram plot.*

Another plot that is shown when analyzing the tests is the **Coefficient plot**. This plot gives a graphical view of the model terms' significance, and also their rate of significance. In figure 26 below a significant model term (A) and an insignificant model term (B) can be seen. To refine the model it is possible to take away insignificant terms, and in this way optimize Q_2. (L. Eriksson, E. Johansson etAl. , 2008)

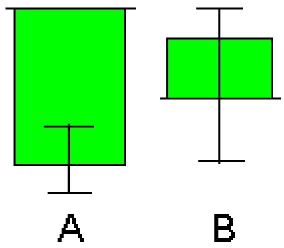


Figure 26: *(A) Significant mode term and (B) insignificant model term.*

The **Residuals N-plot** in figure 27 below shows the residuals of a response vs. the normal probability of the distribution. If all points are diagonally distributed on a straight line, the residuals are normally distributed which is the ideal result. Points that lie outside the red lines in the figure, such as experiment 1, indicate outliers that should be checked. (L. Eriksson, E. Johansson etAl. , 2008)

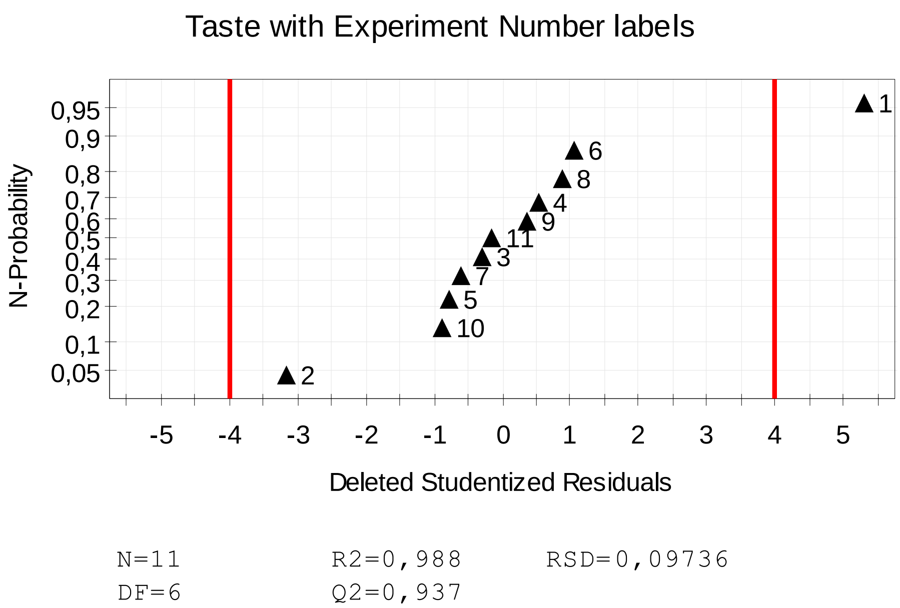


Figure 27: *The residuals N-plot.*

There are of course more methods in Modde to check whether there is a good model or not. One of them is the ANOVA plot, where the lack of fit number can be seen, and it needs to be changed if the model does not fit. If the model has no lack of fit, then $p > 0.05$. (L. Eriksson, E. Johansson etAl. , 2008)

3 Measurement Equipment

This chapter deals with the measurement equipment that has been developed during the Pallas project and was used in the tests. First a fixture that has been used to hold the tool and tool holder when measuring wear types, and then a data form in Microsoft Excel that has been used to document the measured values in the tests. The aim of this chapter is to describe the function of those two measurement equipments, and analyze them by discussing the advantages and drawbacks with them for further usage.

3.1 Fixture

During earlier measurements of the insert wear, a fixture that only holds the tool in the same position has been used. To increase the accuracy of measurements when performing prototype testing, a new fixture was developed for Pallas as a part of the project. The main issue for this fixture was that it should be able to measure in the exact same way for each time of measure so that an increased accuracy could be reached.

3.1.1 Function

The fixture that was built for the project is shown in figure 28 below, where it can be seen that the fixture can rotate in all different directions (X-, Y-, Z-rotations in the figure). The tool and holder is placed in the red part of the fixture, and from here wear types are measureable through microscope. The fixture can also be tuned in so that tool can be rotated around the edge of the insert, which implies that focus can be held on the edge during the measurement without changing the settings in the microscope, so that for example the scale can be held constant.

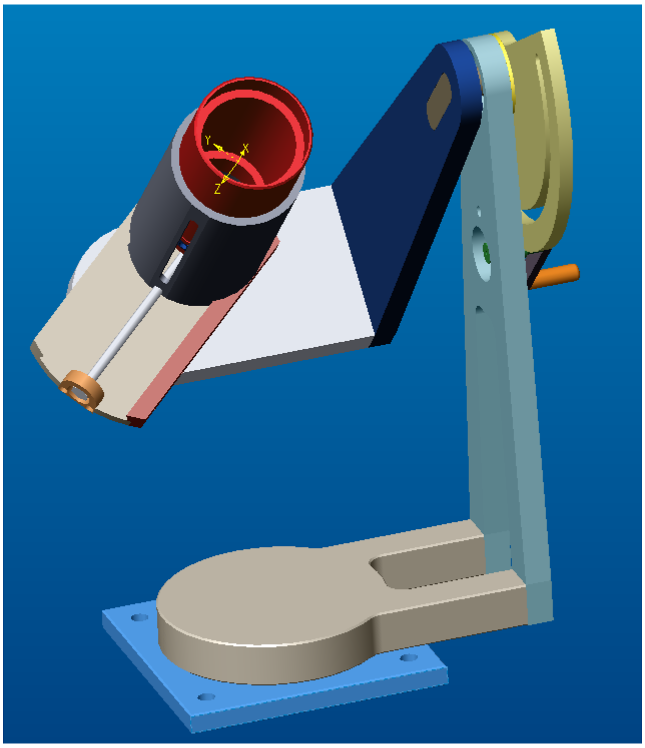


Figure 28: *Fixture for tool.*

3.1.2 Analysis

The feature with the fixture able to rotate in all directions was one of the issues that worked really well, but there are some potential for improvement with the steering of the rotations. An important thing when measuring is that the tool can be placed in the exact same position for each measuring which is not really possible today without too long turning times. Some marks on the fixture would be good as reference points. A proposal is to have dashes with numbers laser marked on the fixture. This will also make it easier to follow the edge of the insert without changing the settings of the microscope, which was a difficult tuning to make.

To get accurate values when measuring, some experience is needed. But once this is achieved, the fixture fills its purposes. The drawback is that when it comes to small values of for example flank wear, the whole measurement method is quite inaccurate. The best would of course have been if all measurement could be done in a fast way on a computer screen where the insert is fitted in every measurement. (There are methods today, but they are too time consuming when testing prototypes)

Another drawback with the measurement during those tests was that the button where to reset the measurement in many occasions happened to be below the “arm” of the fixture, so that a pen was needed to reset the measurement tool each time a measurement was to be done.

3.2 Data form

To efficiently be able to analyze data from tests a number of different data collecting forms have been developed at Sandvik Coromant during the years. For the project Pallas a new data form was developed where the measured data was to be collected.

3.2.1 Function

The first thing to do when starting a new test was to open an empty data form. From here a new test was initiated, after the correct direction of the data base and the data base name in K3 and the correct direction of the data base in K5 was filled in, see figure 29.

Figure 29: *Start page of data form.*

In this new data form both pictures and measured values was stored, and when the test was ready, all the data was sent to a database where it was stored so that different tests could be compared easily. The schematic look of the data form in excel is shown in figure 30.

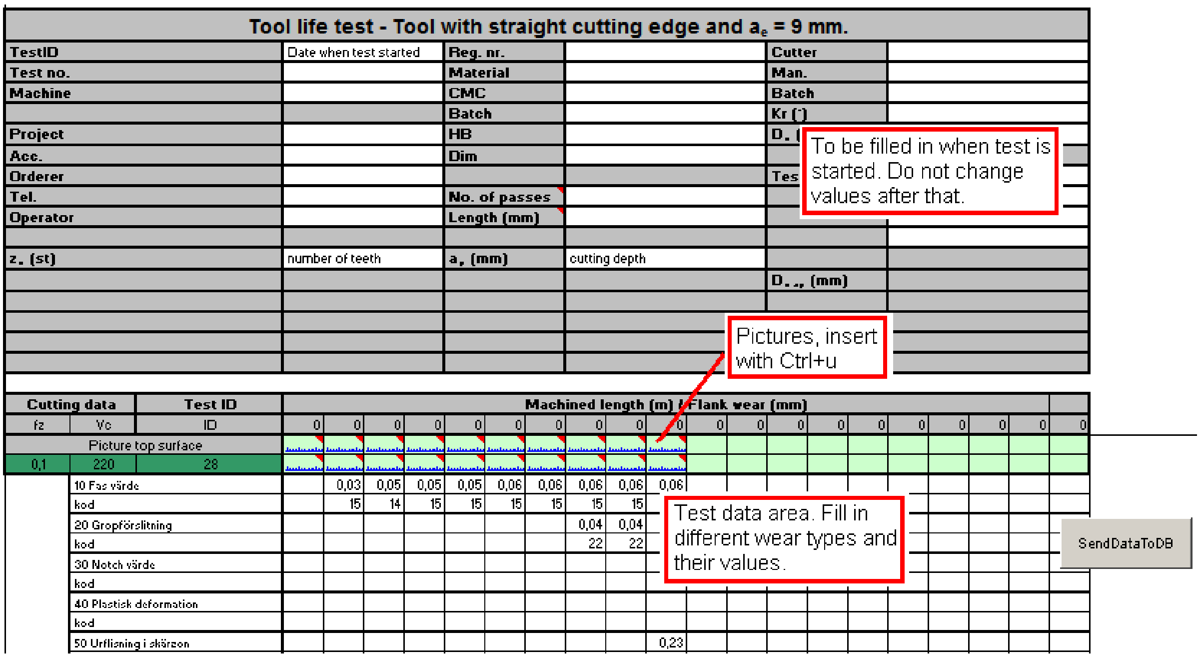


Figure 30: *Data form.*

When the data was sent to the database via the button seen to the left in figure 30, it was to be analyzed. This was first done in excel, where the data was found for each point of measure by making one test for each measure point where after the program picked the correct data out. This interface can be seen in figure 31 below, where the test is chosen by date, and the columns of f_z, V_c, InsertID and Length is filled in as they were noted in the data form.

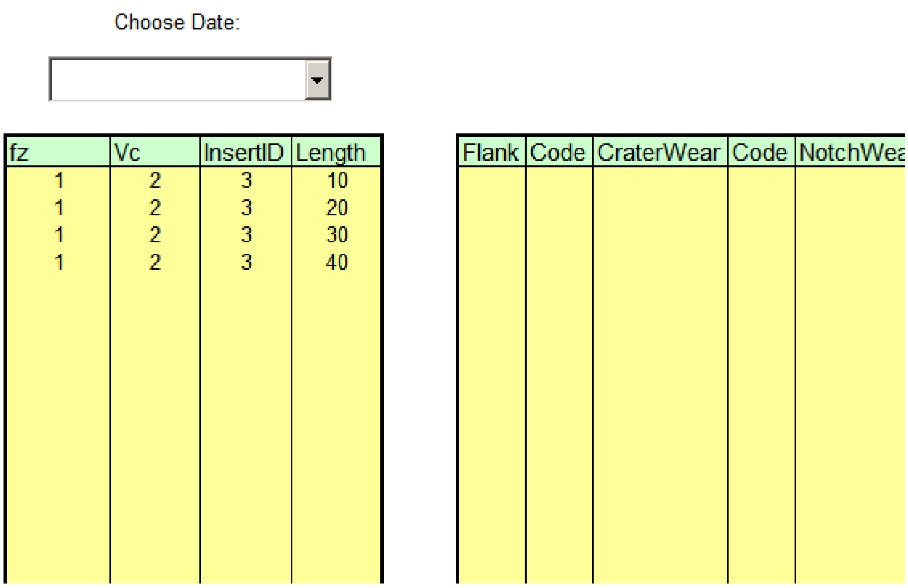


Figure 31: *Data handling.*

3.2.2 Analysis

The data form worked as planned after some instructions. It would have been easier to use the data form if the user interface was more limited; that less of the program was able to change by the user. For example that it was able to move the database file to another location during the tests. Best would have been if the data base was located on a place unable to reach for the user, and that the program always referred to this, so that the values in excel data sheet "Pallas – Inmatningsformulär" column K, row 3 and 5 did not need to be changed.

It would also have been good if it was easier to do changes in the data form, for example that a picture that is pasted into the form with a hyperlink, and then moved from its original position or if the wrong decimal separator was used. If the "send to DB" button is pressed, the first data is sent to the data base, before the warning that the link to the picture does not exist or the wrong sign is used occurs. This makes it impossible to correct the error and then send the data to the database again. It would have been better if the program first checked that it does not encounter any problems, and after this send the data to the database.

Further, the data sheet in the program is quite difficult to use. First of all, the data fields presented in figure 31 above are too short for most of the analyses done; it would have been great if they were as long as the number of data points. It is of course good to be able to investigate the tests wanted to investigate, but still it would have been preferable if there was a button that investigated all data points, so that they does not need to be filled in manually.

4 Reference tool tests

The first tests were the reference tests, where the main point was to see if the experiments were realistic. The first thing too look at in those tests was to see whether there was dispersions in the tests, and in those cases it was, if the dispersion was too large to be able to make conclusions from them or if it was in an acceptable range.
It was also wanted to see if the experiments gave any direct answers or if the uncertainties were bigger than the dispersions of the outcomes on the responses.

The first tests were done with a R390 tool from Sandvik, used for milling, which is one of the most commonly used tools on the market. This tool is also the one that most looked like the Pallas tool developed. Since the R390 tool looked much like the Pallas tool a test of it could say whether the tests that were to be done with the Pallas tool, (the familiarization and screening tests,) was reasonable at all.

One of the goals for the reference tests was to find reasonable values for cutting speed and tooth feed, that was to be used in the other tests. Therefore, very high and very low values where set on the speed and feed, to cover a large testing area. It was also set in this way to as clear as possible show the dispersion in the tool properties, and also with the fact in hand that extrapolating data in Modde is not always good, while interpolating is preferable.

The reference tool testing was also done to evaluate the measurement techniques, and as well to see if it was able to specify the dispersion due to material and material batches.

4.1 Test planning

The planning for the reference tests was mostly done with help from Modde, where different factors to vary were defined and after this a test was outlined.

It was first to be decided whether the milled length should be set as a factor or as a response. When concluding that different inserts should have different life it was decided that the length was to be a factor, since it is not measureable at the same data points in each test, depending on life.

An important factor that was discussed was how to vary the tests so that the material variations played as little role as possible. It was then decided that the tests should be run in the given test order, measured at each measuring point until the insert broke, to after this carry on with the next test. If there were replicates in the design, they should be done on different depths throughout the material piece.

For the reference tests three different tests were carried out. Two of them were done in steel (SS2541) and one of them in stainless steel (SS2343). After deciding which tests that was to be done the execution manner was to be decided for each test respectively.

4.1.1 Test 1

The first test to be carried out was a so called life test for steel. This test was done to give a first hint about how the testing worked. The test values for cutting speed and feed was chosen with respect to Sandvik's recommendations for the tool and the inserts that was used in this test. It was wanted though, that the tool was to be run in some extreme points, and this is why the feed 0.06 and 0.12 and cutting speeds 200 and 350 was chosen. See [AB Sandvik Coromant (2010)] for recommendations in specific materials.

To further see possible variations the a_e was also varied between 25% and 75% of the tool diameter (in this case 20mm.) For those three factors Modde gave the tests presented in table 2, which was to be done on each point of measure for the milled distance as outlined above.

Table 2: *Experiments for life test for steel, for each measure in distance, test 1*

Exp No	Exp Name	Run Order	Incl/Excl	f_z [mm]	V_c [m/min]	a_e [%]/D_c [mm]
9	N9	1	Incl	0,11	300	50
4	N4	2	Incl	0,16	350	25
10	N10	3	Incl	0,11	300	50
3	N3	4	Incl	0,06	350	25
5	N5	5	Incl	0,06	200	75
2	N2	6	Incl	0,16	200	25
8	N8	7	Incl	0,16	350	75
7	N7	8	Incl	0,06	350	75
1	N1	9	Incl	0,06	200	25
6	N6	10	Incl	0,16	200	75
11	N11	11	Incl	0,09	300	50

4.1.2 Test 2

The second test that was to be done was a toughness test in stainless steel. It was evaluated in the same manner as test 1, but it was decided that the data was to be chosen so that either a fast bulk breakage or a longer life will occur.

The data was therefore chosen a bit rougher than for the steel test. Those tests can be seen in table 3. As for the first test all of those tests were also done for different milled distances or points of measure. The tests were evaluated this way since the different tests would go different distances before the insert was broken.

Table 3: *Stainless steel experiments test 2. All tests carried out for different lengths.*

Exp No	Exp Name	Run Order	Incl/Excl	Feed [mm]	Speed [m/min]
13	N13	1	Incl	0,11	200
6	N6	2	Incl	0,11	200
8	N8	3	Incl	0,16	150
10	N10	4	Incl	0,16	250
2	N2	5	Incl	0,16	150
12	N12	6	Incl	0,11	200
7	N7	7	Incl	0,06	150
5	N5	8	Incl	0,11	200
3	N3	9	Incl	0,06	250
1	N1	10	Incl	0,06	150
4	N4	11	Incl	0,16	250
11	N11	12	Incl	0,11	200

4.1.3 Test 3

Test three was again done in steel but this time a toughness test as for the stainless steel. The main reason why this test was done was to see the differences between this test and the first tests, and also to predict which material that was to be the best choice for the familiarization and screening tests later on.

The test is also run in 3 center points. This was done to better see the diffusion of the test, which can appear due to differences in material and maybe also in batches. The aim of running the same test a couple of times were to give a good measurement of the natural diffusion of the test.

The test planning for the Reference test was carried out in Modde and gave the results that can be seen in table 4.

Table 4: *Run order for reference test three SS2541.*

Exp No	Exp Name	Run Order	Incl/Excl	Feed [mm]	Speed [m/min]
1	N1	3	Incl	0,06	350
2	N2	4	Incl	0,06	200
3	N3	6	Incl	0,16	350
4	N4	7	Incl	0,16	200
5	N5	2	Incl	0,20	350
6	N6	1	Incl	0,20	200
7	N7	5	Incl	0,16	150

4.2 Testing / Analysis

The first test that was done was a center point, and it was tested for how long the insert was working, so that a proper measure domain could be set. For the first steel test it was set between 1 and 20 meter and for the stainless steel it was set between 0.4 and 8m.

The testing then started according to the test plans proposed above. Measurements were done at every second measuring point. For the steel tests at 1m, 3m, 5m, 7m and so on, and for the stainless tests at 0.4m, 1.2m, 2m, 2.8m and so on.

When analyzing the test data, the different measured data was normalized so that it could be compared. The values for crater wear were normalized with equation 1 below, and the values for chamfer wear with equation 2. The W_{max} was set to the break criterion 0,35 for chamfer wear, and the maximum value of the distance to the edge for crater wear.

$$W_{crater} = \left(1 - \frac{W_v}{W_{\max}}\right) \cdot 100 \qquad (1)$$

$$W_{chamfer} = \left(\frac{W_v}{W_{\max}}\right) \cdot 100 \qquad (2)$$

4.2.1 Test 1

After the tests were done and some of them were replicated, the first investigation that was done for the first test was that of the life of the insert. The life is then measured in meter to the first break criterion of 0.35mm is satisfied. The analysis was then done in Modde, and since there were some outliers they were removed to give a better model fit.

The summary of fit plot after optimizing the model for life in test 1 can be seen in figure 32. Here, the condition number, in this case 1,798, which is good for a screening design can be seen.

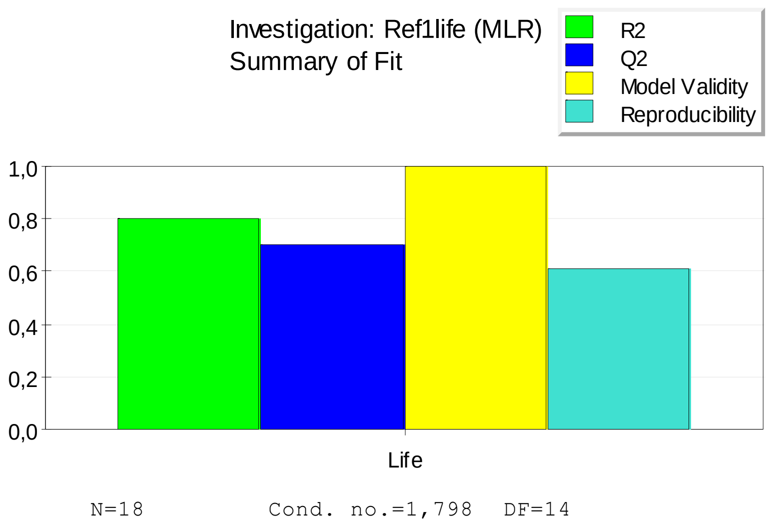


Figure 32: *Summary of fit, test 1.*

It can be seen in figure 33 that the remaining significant factors for test 1 are the a_e and the V_c parameters, hence the feed has no or less influence on the test result. The Q_2 value can as well be seen in this figure, and is estimated to 0,706, which indicates a good model.

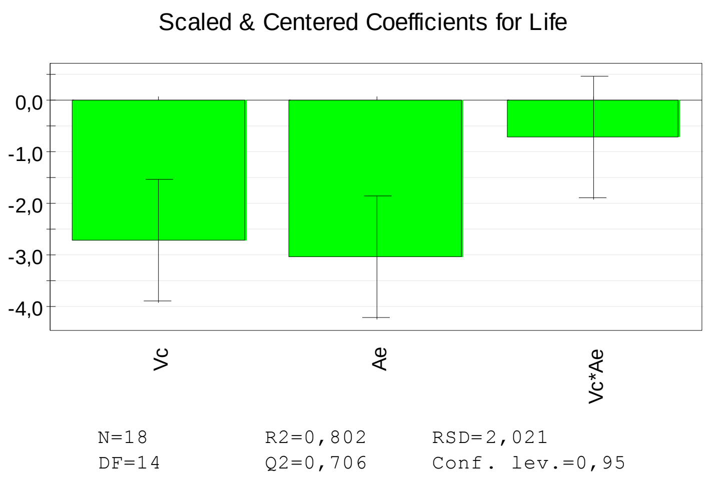


Figure 33: *Significant coefficients for test 1.*

The life investigation of test 1 is shown in figure 34 below, and it shows that a low a_e and a low V_c is good for a long life.

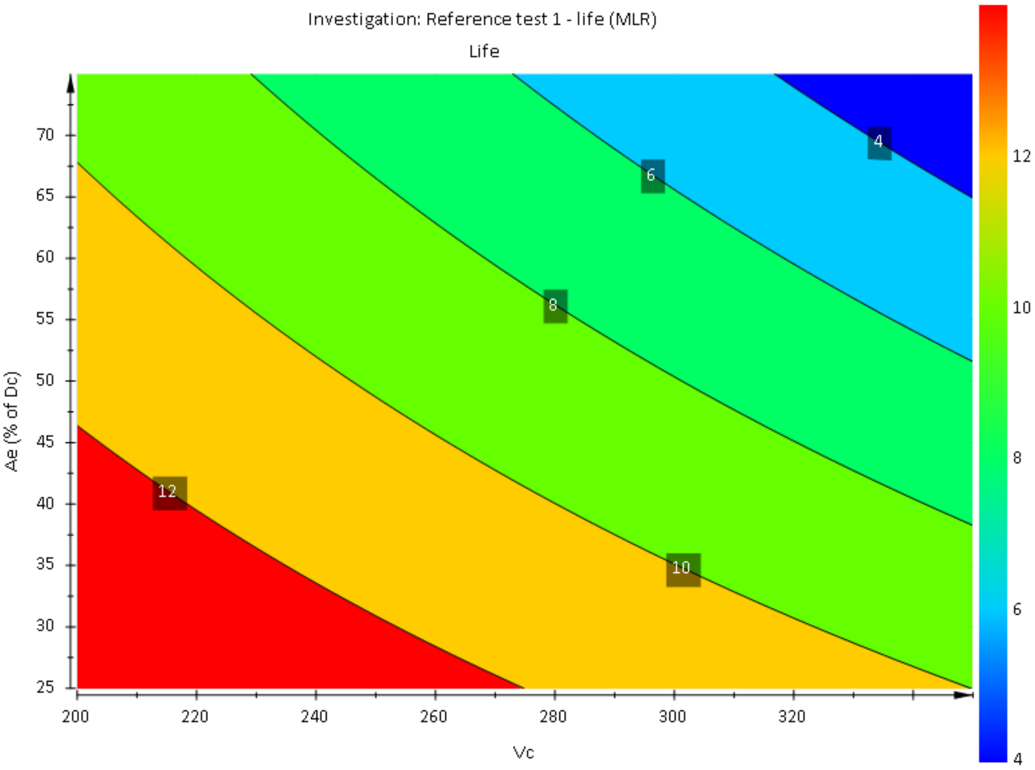


Figure 34: *Investigation of life of test 1.*

A number of other investigations were tried on the data that was from the first test but there were some problems. The measurements were done on different points, which implied a big data dispersion. Also, the data points were too few according to the many parameters that were varied. This made it impossible to find any models that had a good fit so that the results could be reliable.

It was not able to achieve any good results for the crater wear in the reference tests. This mostly because there was too little data measured. Though; there were tendencies in the tests that the a_e had an influence on the crater wear, but this has to be further investigated.

4.2.2 Test 2

For test 2 an investigation was made for the data measured for flank wear and crater wear for the second test. Both the crater data and the flank data was normalized so that they were given in percent of the break criterion. Implementing data gave condition number for flank wear and crater wear, and they were 3.38 and 2.94 respectively. This indicates models that are good for screening for the crater wear and almost good for the flank wear.

The summary of fit plots for the test are presented in figure 35 below, where it can be seen as posted before that both models are good, and it can also be seen that the model for crater data to the right is marginally better than the one for flank data to the left.

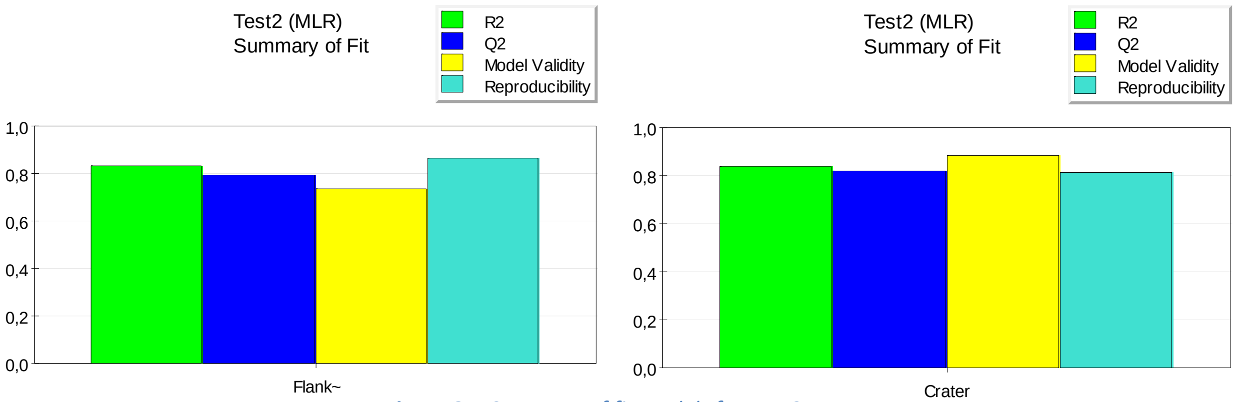


Figure 35: *Summary of fit models for test 2.*

In the further investigations prediction plots were used, and this shows how trustworthy the results are. In prediction plots the normal confidence interval is for 95%, but in Modde it can also be changed to 99% to see this as well.

One thing that is important using prediction plots is to not trust the middle line too much but also to think that it can vary arbitrary between the confidence lines. This is why it is not possible to say much about the flank wear varying with speed. As can be seen in figure 36 the flank wear (percent of break criterion on y-axis) can almost be independent of speed (in m/min on the x-axis), even if the tendency is that an increased speed gives increased flank wear. The reason to why the results look as they do is of course the dispersion in the flank wear results probably due to the inaccurate measurement methods.

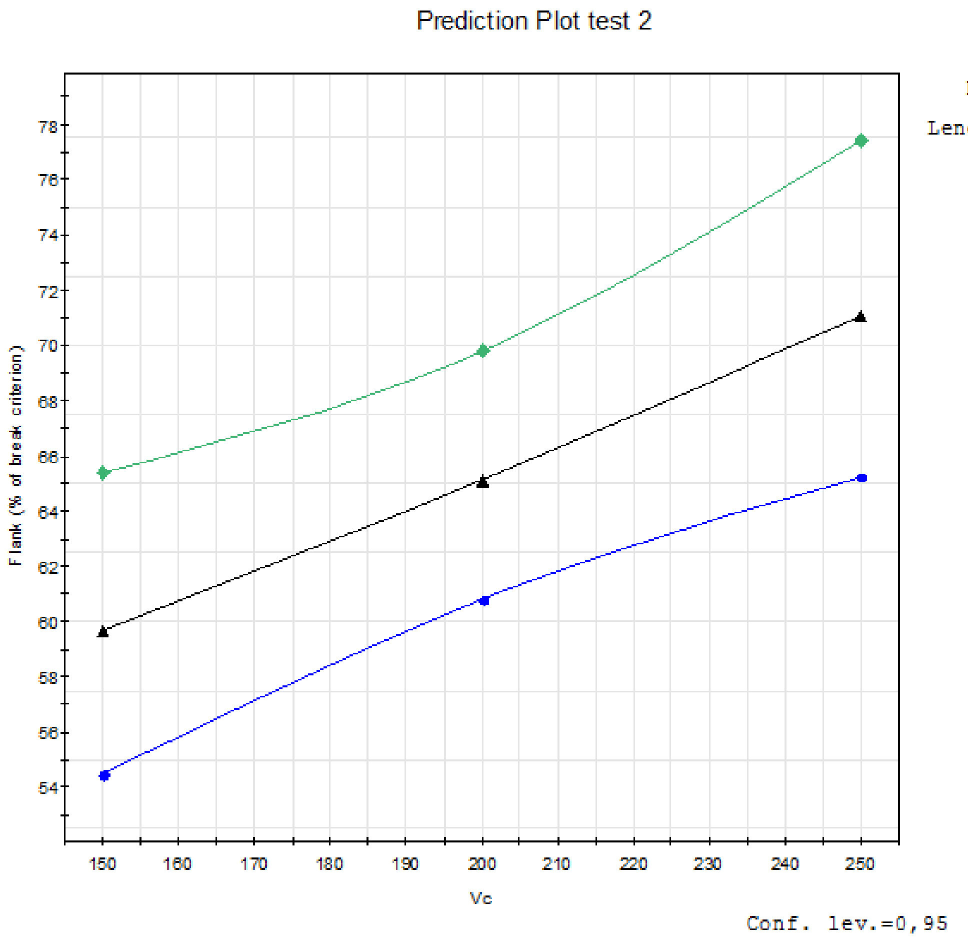


Figure 36: *Flank wear [%] versus speed [m/min].*

The next thing that was investigated was the flank wear due to the passed length. As investigations from other tests conclude, the flank wear has an exponential growth, which also can be seen in figure 37. In this plot the speed and feed are set at a center value. This means that the parameter that is viewed in the plot is varied while the others are held at the center point of its values. Changing any of those to higher or lower values gave the same result tendencies. The reason to the dispersion for higher length which can be seen in the figure is the fact that inserts break, and data for flank wear is not possible to get.

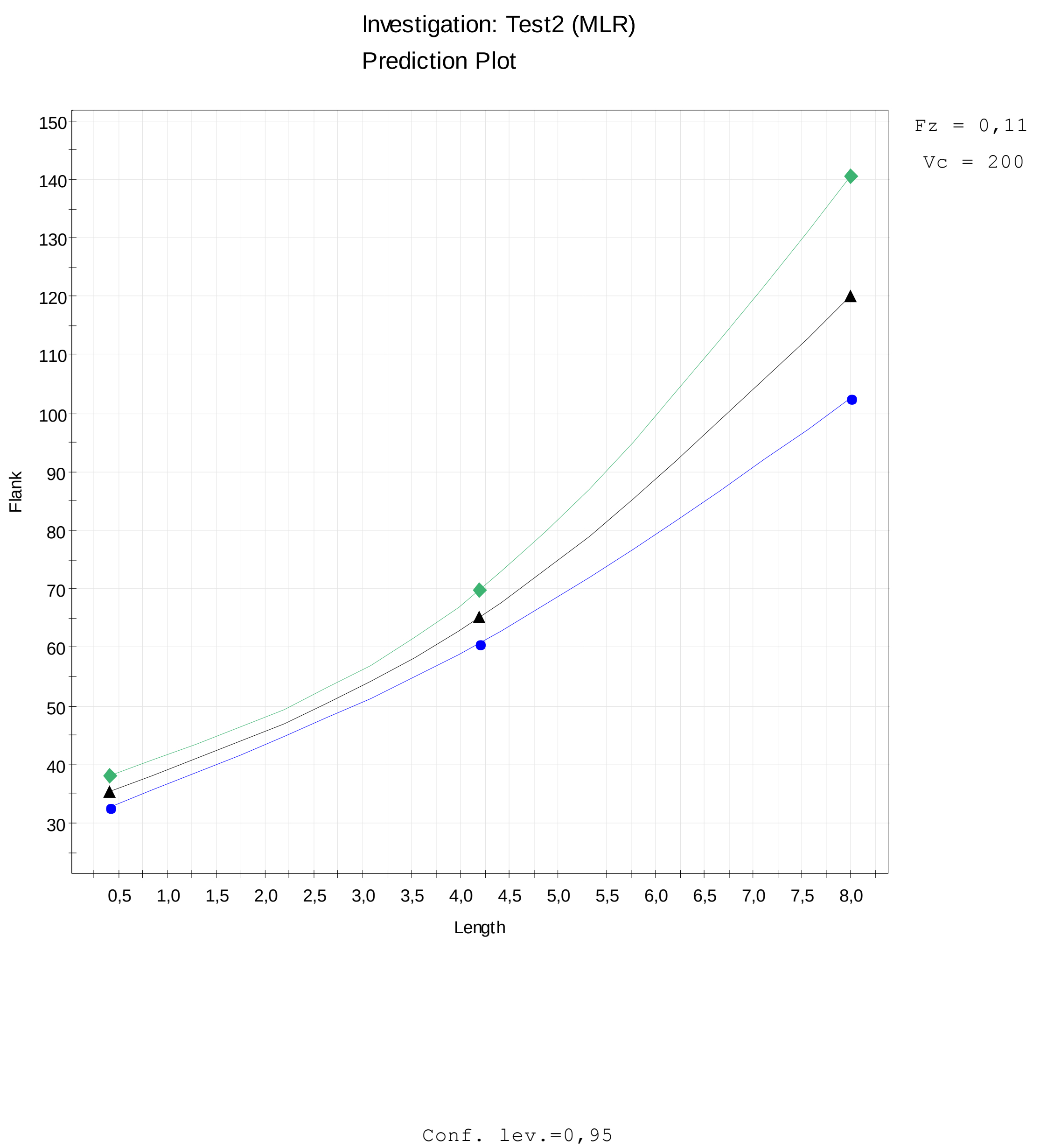


Figure 37: *Flank wear [%] due to machined length [m].*

The data investigation continued with looking at the crater data. As for the flank data, the speed and the feed were set at center values when looking at the crater growth for worked length. The result for this investigation can be seen in figure 38, where it is shown that the crater grows quite linear for passed length.

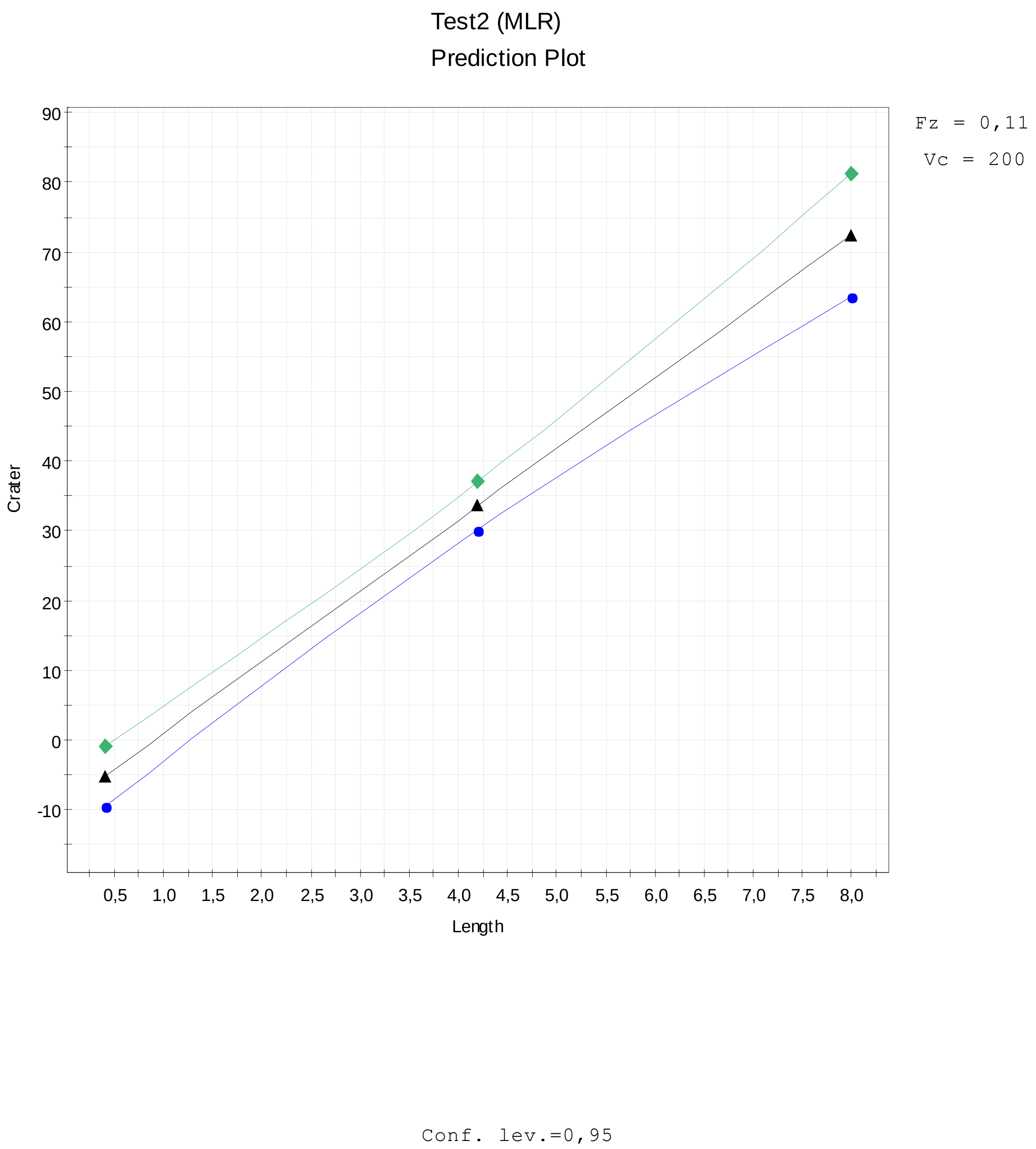


Figure 38: *Crater wear [%] due to passed length [m].*

4.2.3 Test 3

For the third test, which was a toughness test in steel, it should be said that the tool worked too well, and that the toughness for the insert and the tool was sufficient. Though, the measured data was investigated, and as for the second test the data was normalized to be represented in percent of the break criterion. Since the data was set tighter this test resulted more in a optimization test than in a screening test, as can be seen when looking at the condition number that became 6.30. Looking at the model for the flank wear in the summary of fit plot in figure 39 it can be seen that it is not as good as for the other tests, which most probably depends on the amount of data, which in this test is less than for the other tests.

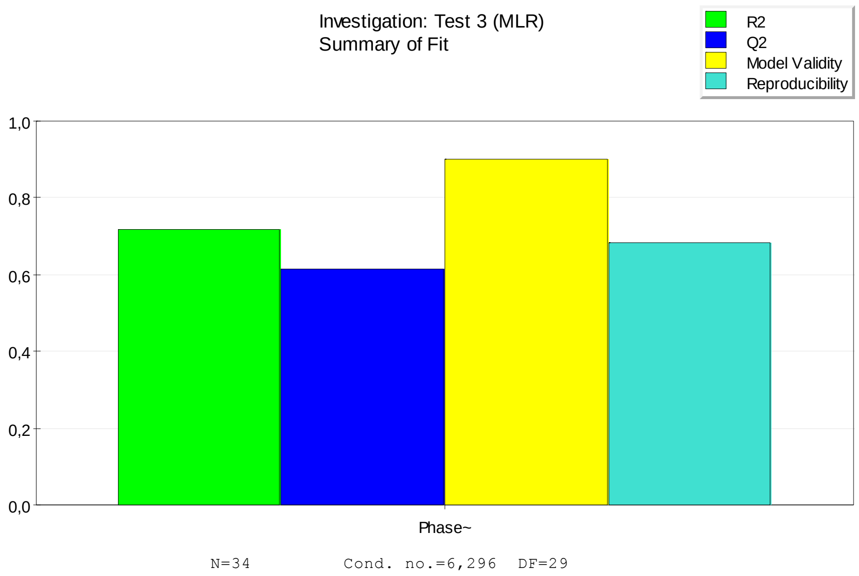


Figure 39: *Summary of fit for test 3.*

Looking at the coefficient plot in figure 40 it can be seen that the Q_2 value is 0,615, which is above 0,5 and thus indicates a good model even if the feed coefficient is not significant, this fact can also be seen in later plots. This plot also indicates that a higher speed as well as a longer passed length will increase the flank wear. It is also interesting to see that the interaction factor speed multiplied by length has some influence. It is an issue for further investigations to solve this interaction.

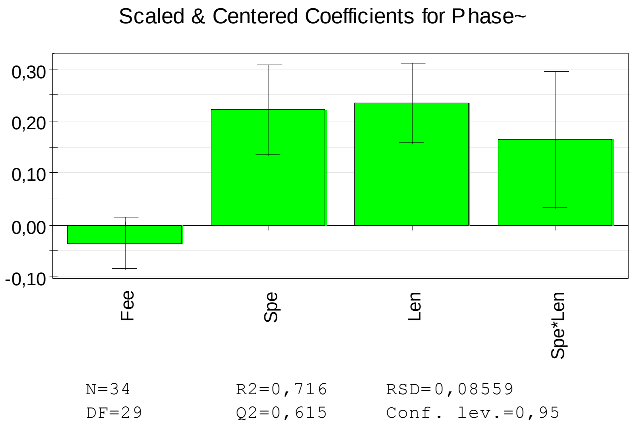


Figure 40: *Coefficient plot for test 3.*

As posted before, the flank wear due to feed is a quite unsecure investigation, but it does show the same tendencies as earlier, namely that a higher feed decreases the flank wear, which is an interesting issue to investigate further in the future. As in earlier prediction plots, the factors that are not investigated is set in the center point. For lower speed and length the same tendencies can be seen even if the flank wear is lower. For higher values of speed and length an unreasonable result can be seen since the data is extrapolated due to the fact that no data for those points exists. The investigation result can be seen in figure 41, where the unsecure result can be seen as well.

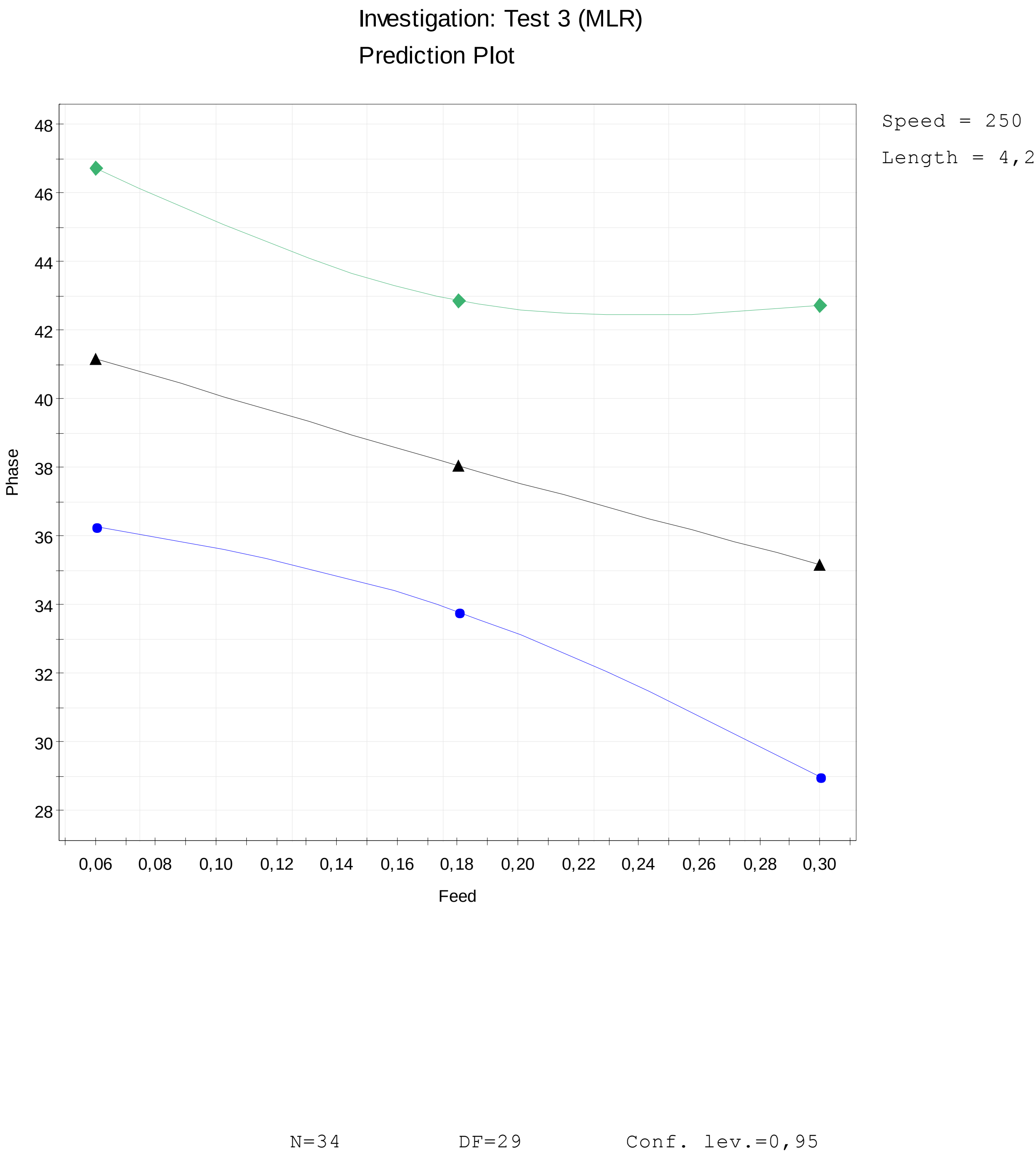


Figure 41: *Flank wear change [%] due to changed feed [mm].*

For the flank wear dependency of changed speed a result can be seen in figure 42 where it is obvious that an increased speed increases the flank wear. This was shown also in earlier tests and is also a well known result. As for earlier tests it is also concluded that the data point is too few at higher speeds, mostly because the inserts broke too early to give good data.

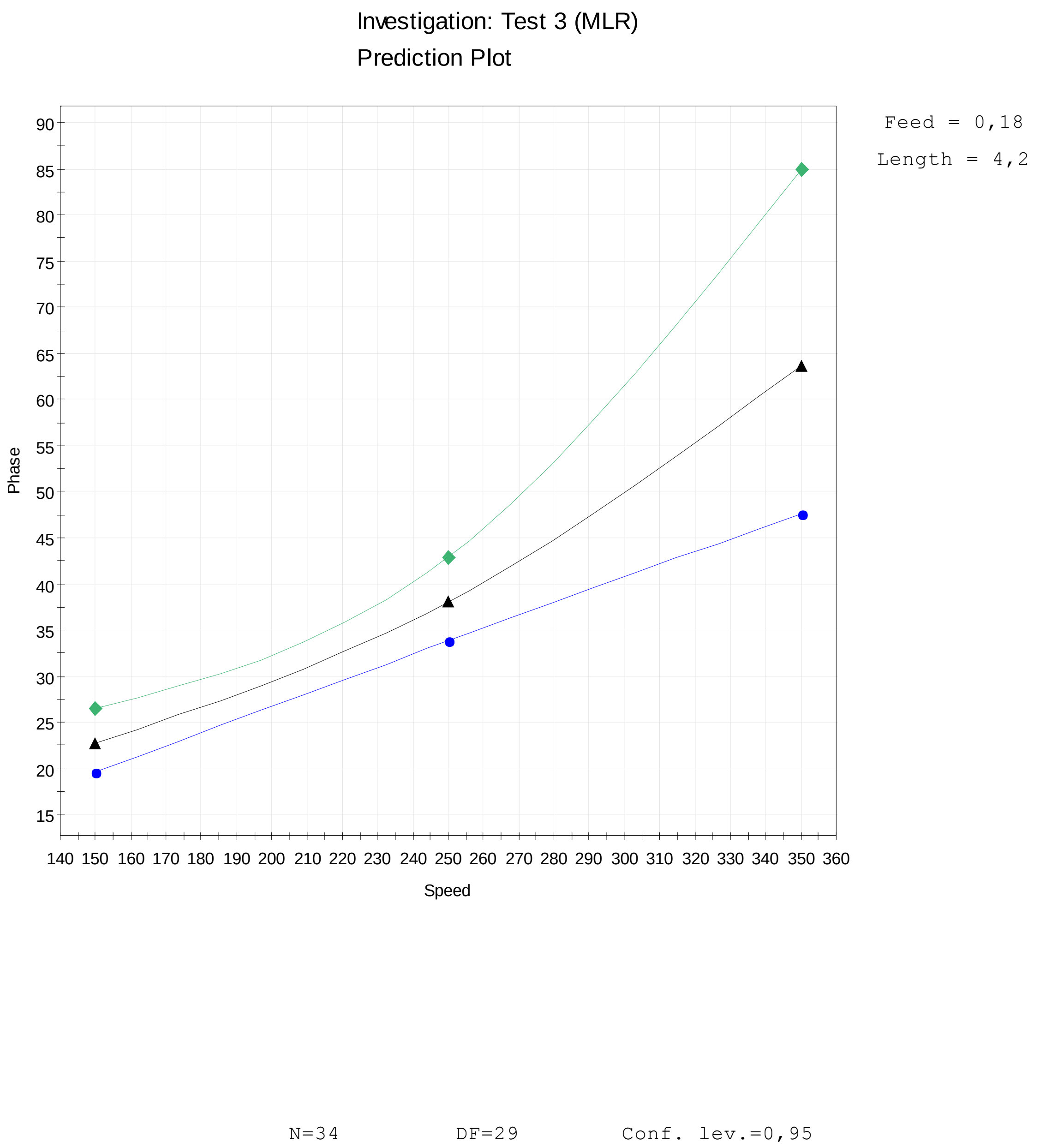


Figure 42: *Flank wear [%] as function of speed [m/min].*

The last investigation done on test 3 was the flank wear as a function of length, and as in earlier tests it can be seen in figure 43 that it looks like it is an exponential behavior, which was also well known.

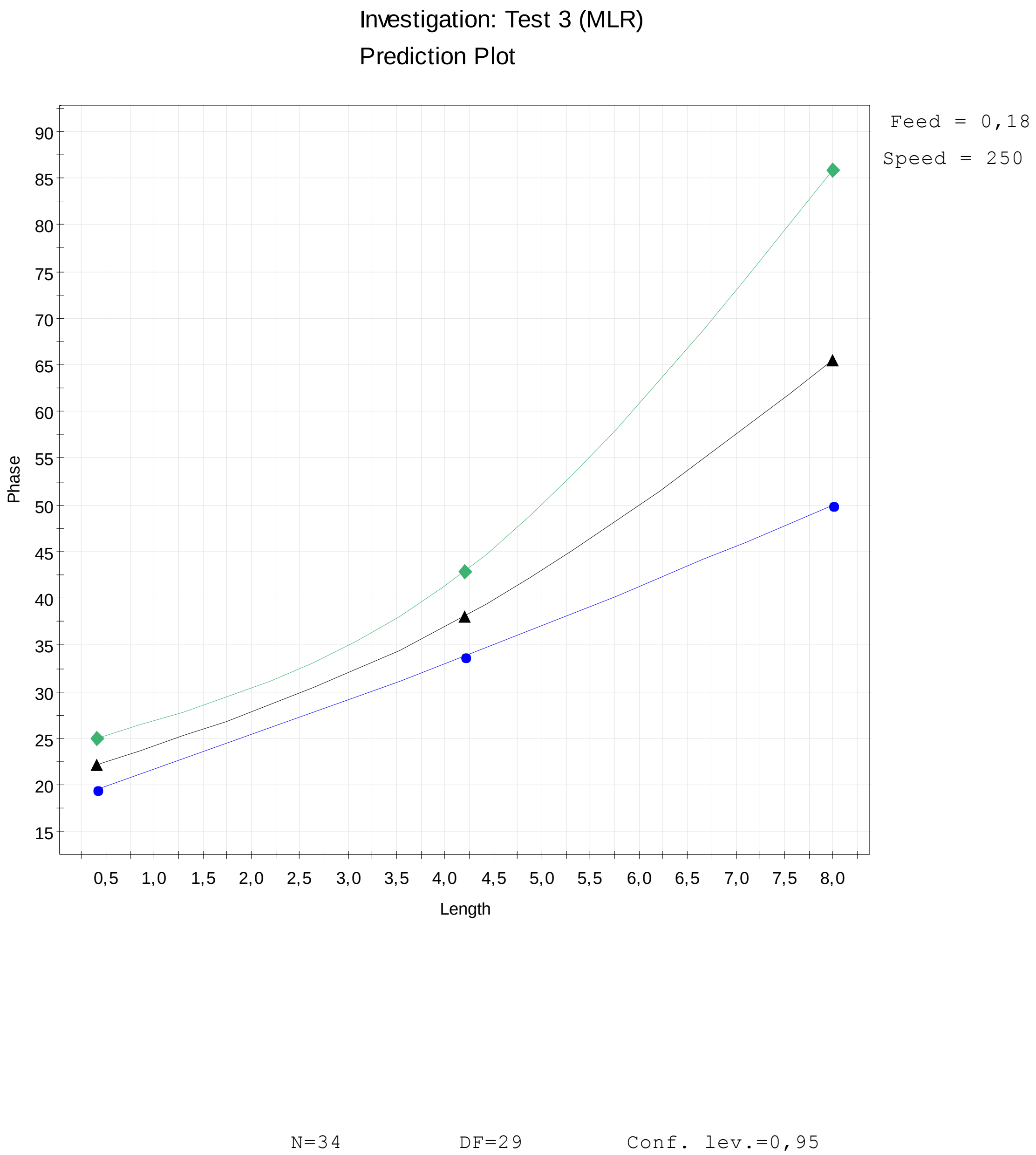


Figure 43: *Flank wear[%] as a function of length [m] for test 3.*

4.3 Conclusions

When the tests were done and the test results were analyzed, conclusions was to be made to be able to continue with the further tests. This section describes the most important results of the reference tests, as well as analyzing the test methods used.

It was concluded in the reference tests that the material dispersions were manageable, but if it was possible, that the tests should be rotating as much as possible. The best would be if one insert could go to one point of measure before it was changed and the next test was run to its point of measure, and so on.

The tests done for the reference tool seemed in many points to have too few data points to give accurate models. The dispersion in the outcomes was too large. This was solved by repeating the tests as much as possible so that the dispersion could be seen more clearly. The tests performed in the reference tests were not measured on the same lengths in all tests, which tended to give bad models in Modde. This was solved by deciding in beforehand on which lengths measurements should be made. It was also decided that repetitions was very important, and as well that the number of factors to vary should be limited.

To limit the number of factors and since the flank wear and the crater wear seemed to be the most common wear types it was decided that two data sets should be developed. The main reason was that it was wanted to gain as much knowledge as possible about the most significant wear types and the geometries, not about the cutting data.

For all of the toughness tests that was done the inserts did not break as wanted or they were intact too long to be able to be defined as toughness tests. This made the choice of tests for the familiarization interesting. The fact that the inserts did not break for the data chosen for the R390 concept was to be evaluated for the Pallas concept as well.

Due to this, it was decided that a toughness test was first to be done to see if the bulk toughness was good enough, and if it was, just consider the bulk toughness sufficient.

Another interesting issue that came up during the reference tests was the fact that an increased feed seemed to decrease the flank wear of the insert, which was as well a point of investigation in further tests.

5 Familiarization tests

The second tests that were done were the familiarization tests. In this section they will be described more closely. When having a completely unknown test-area it is always good to start with familiarization tests. The main reason to do familiarization tests is to see that the diffusion is not too big, and also that the measurement equipment works (L. Eriksson, E. Johansson etAl. , 2008)

The familiarization tests were the first tests where the Pallas tool was evaluated. The reason for familiarization tests is except the above mentioned reasons, to get a good view of the test area, but also to see whether the experiments in the screening tests are possible to fulfill or not. One further reason to do a familiarization test is also to be able to see how good the process is. A familiarization test is normally done with a simple factorial design, as some corner points and a couple of replicates in the center points.

5.1 Test Planning

The inserts to be used in the familiarization tests was designed and ordered by the earlier subproject in Pallas. This resulted in three types of inserts for the test planning, all of them coated with a PVD GC1010. The geometries of those inserts are presented in table 5. The only geometry of the insert that is varied in this case is the chamfer angle. The ER-treatment of the inserts was as well one thing that was tested in the familiarization test.

Table 5: *Geometries of inserts for familiarization tests.*

	Chamferwidth [mm]	Chamferangle [°]	ER-treatment	Clearance angle [°]
UVM 2703 BR	0,05	-5	1	15
UVM 27030N	0,05	5	1	15
UVM 2703 BL	0,05	5	2	15

The toughness tests were decided to be started at a low feed, to see if the insert broke. The feed was then increased step by step until the insert broke. In conventional tests it is common that the insert is replaced after each feed, but since the number of inserts was limited, it was decided to not replace them.

The cutting data that was to be used for the life tests was decided according to the conclusions made in the reference tests. After discussions it was decided to test two sets of data. One high and one low data set. The thought was that the high data should give rise to more crater wear, while the low data should make the flank wear as significant as possible. Focus was put on those specific wear types since they were the most common, and their behavior is well known.

The datasets were tested on a R390 tool, both with GC1010 and GC1030, to verify that they were reasonable. The data chosen is given in table 6 below.

Table 6: *Data sets for life tests in familiarization.*

	f_z (mm)	V_c (m/min)	a_e
High data	0,16	220	65%
Low data	0,07	180	25%

With those sets as qualitative factors, the dispersion due to cutting data was reduced which should increase the accuracy in the results from the different geometries. Since there will be less factors to vary, the number of tests will also be decreased, which implies lower economical costs since the number of edges used in the tests will be decreased.

Both the toughness test and the life test were to be performed in the same manner. Because of this, one test order was then created with help from Modde, both for the toughness tests and the life tests. A schedule was then created to see the exact run order for the tests. This run order is presented in Appendix A. In this schedule some reference tests are also included. This was done to be able to detect dispersions in the material, if there were any. The scheduled reference tests were as well measured, while some non measured reference tests also were included. Those tests were only to be driven to breakage, and the life was noted.

The points of measure were also decided according to the conclusion for the reference tests. It was decided that the life test should be run for 1m and then measured. Measurements were to be made at 1, 3, 5 and 7 meters and on odd numbers up to breakage to give sufficiently much data for the analysis.

As mentioned in the conclusions for the reference tests it would be good to run each test to one measure point before changing insert and then run that insert to its next measure point. This was unfortunately not possible in the familiarization tests since the cutting data was changed for each insert, and this would have been too time consuming in the machines' aspect.

5.2 Testing / Analysis

The test was started with the toughness tests. The inserts were in work for one meter before the feed was increased for the inserts. This showed that the toughness of the inserts could be considered enough, since a feed that is not in the range of the tool's future working area was used.

The life tests were then done, and it was quite early found that the change in speed gave too much dispersion in the out coming data. It was then decided to put the two datasets even closer to each other, for what reason the high data set was maintained at a speed of V_c=200 m/min instead.

A first investigation was then performed on the test data for flank wear and crater wear. The condition number then became 3.2 for the flank data and 2.99 for the crater data. Looking at the summary of fit plot in figure 44 it can be seen that for the flank data a quite good model is built, while it is quite bad for the crater data. The model for crater data was refined, but again, too few data points were most probably the reason for the bad model.

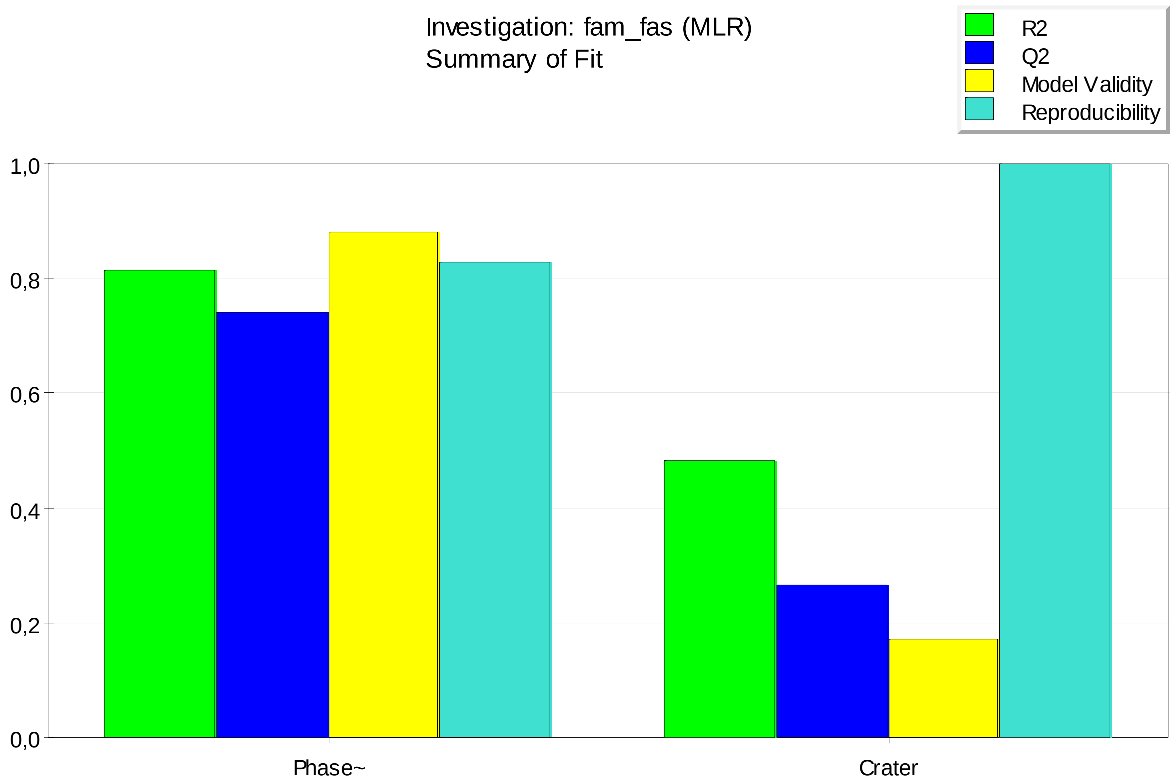


Figure 44: *Summary of fit plot, familiarization test.*

Again, the flank wear was studied closer since the behavior of it is well known. The model showed a result that is shown in figure 45, as expected. The results are based on the insert that was replicated the most, the UVM 2703 BL with low cutting data. As for the reference tests, eq. (2) presented in chapter 4 on p. 28 is used to normalize the values, with W_{max} set as the failure criterion 0,35.

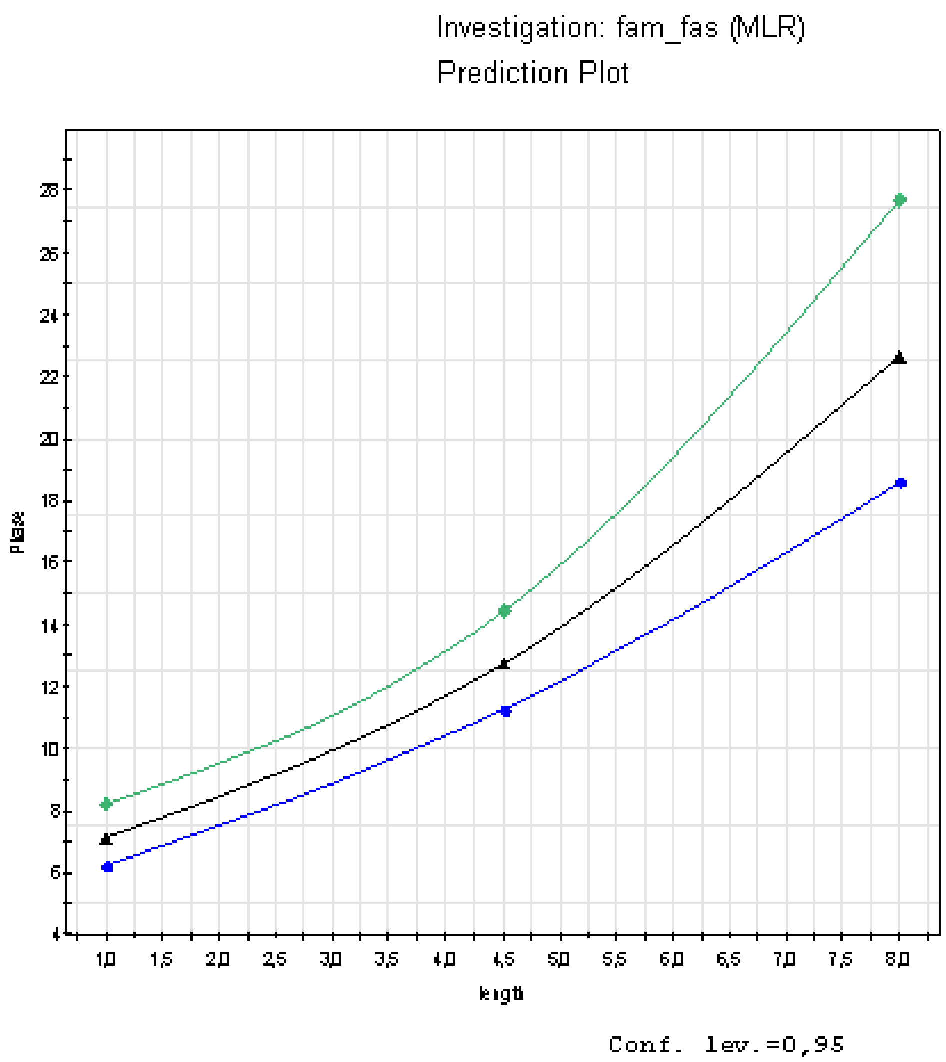


Figure 45: *Flank wear [%] as a function of length [m].*

5.3 Conclusions

It had been seen during the familiarization tests that the crater wear was very commonly the wear type that made the insert worn out. It can be explained with the fact that the GC1010 is very sensitive to crater wear, but anyhow it is a very important point of further investigation.

It was seen clearly in the familiarization test that the existence of a crater had influence on the life of the insert, but the lack of crater data made the model unfitted. In the coming tests it is very important to look on when the crater starts and how it develops. The flank wear was in this test the main wear type measured. The fact that the flank wear had the most points of measure is neccesarily not similar to that the flank wear is the most important wear type. This was studied further in the upcoming tests. Maybe it is to be shown that the fixture of measure is the most important part in the tests since it can help getting more accurate results.

The lack of center points for the tests was also concluded one of the reasons to the bad models. Due to this, an extra insert type was ordered for the upcoming screening tests.

The ER-treatment of the inserts was said to be unexplored, since the test data was unable to predict anything about it. Inserts with different ER-treatment was therefore ordered for the screening tests as well.

One interesting issue that was found during the familiarization was that tendencies were seen that a positive edge broke faster than a negative one. This can probably be explained by the fact that the cutting forces are too big, and therefore breaks the weaker positive edge before the stronger negative one.

6 Screening tests

After completion of the reference- and familiarization tests, the screening tests were to be done. Those tests were the final ones, and the purpose was to find factors that influenced the life of the insert to a large extent, as well as further investigate interesting issues found during the earlier tests.

6.1 Test Planning

The first thing that was done was to inspect the inserts that was used. It was then explored that the inserts with the brushed ER were in too bad condition to be used. Those tests were therefore not done. Using them would have jeopardized the results more than giving an accurate result. Due to this, new inserts were ordered to be able to do full tests.

Tests were to be done using both GC1010 and GC1030 grades. For the GC1030 grades a full factorial design was used for the screening. This design was then run one time, and then replicated two times. The test order for the first experiments can be seen in table 7 while the replicated test order can be seen in
table 8.

Table 7: *Outline for screening test 1 with GC1030.*

Exp No	Run Order	Chamfer width [mm]	Chamfer Angle [°]	Clearance angle [°]
28	1	0,05	5	15
29	2	0,05	-5	15
30	3	0,15	-5	15
31	4	0,15	5	15
32	5	0,05	-5	5
33	6	0,15	-5	5
34	7	0,15	5	5
35	8	0,05	5	5
52	9	0,1	0	10

Table 8: *Outline for screening test 2 with GC1030.*

Exp No	Run Order	Chamfer width [mm]	Chamfer Angle [°]	Clearance angle [°]
36	1	0,05	-5	15
37	2	0,05	5	5
38	3	0,05	-5	5
39	4	0,15	-5	15
40	5	0,15	-5	5
41	6	0,05	-5	15
42	7	0,05	5	15
43	8	0,15	-5	5
44	9	0,1	0	10
53	10	0,15	5	5
45	11	0,15	5	15
46	12	0,15	-5	15
47	13	0,05	5	15
48	14	0,05	5	5
49	15	0,05	-5	5
50	16	0,15	5	5
51	17	0,15	5	15
54	18	0,1	0	10

For the GC1010 grades a reduced full factorial design had to be used since all inserts needed to complete a full factorial design was not available. The tests were as before outlined with Modde, and the tests on the inserts that were not available were taken away. The results of the planning of the first test in GC1010 can be seen in table 9 and the run order for the second test can be seen in table 10.

Table 9: *Outline for screening test 1 with GC1010.*

Exp No	Run Order	Chamfer width [mm]	Chamfer Angle [°]	Clearance angle [°]
2	1	0,15	5	15
4	2	0,1	0	10
5	3	0,1	0	10
6	4	0,05	-5	15
7	5	0,05	-5	5
10	6	0,1	0	10
11	7	0,15	5	5

Table 10: *Outline for screening test 2 with GC1010.*

Exp No	Run Order	Chamfer width [mm]	Chamfer Angle [°]	Clearance angle [°]
13	1	0,05	-5	5
16	2	0,15	5	15
17	3	0,15	5	15
20	4	0,05	-5	5
21	5	0,15	5	5
22	6	0,15	5	5
23	7	0,05	-5	15
27	8	0,05	-5	15

The GC1030 was to be tested in steel, SS2541, and the GC1010 in a hardened steel, SS2541 55HRc. It was also decided due to former conclusions that the tests were to be run to one point of measure before the insert was changed and the next test was run to its next point of measure and so on. The proven importance of using the same measuring points was concerned. It was decided that measurements was to be made at 1m, 5m, and 7m and further every second meter until break criterion was reached.

As posted earlier, the cutting data is an unnecessary point of variation since this increases the dispersion in tests, and since the geometry of the inserts was the main point to study. Due to this fact, only one cutting data set was used, and it was chosen in an area where the tool to be developed was wanted to work properly. Consulting milling experts to choose the data resulted in the cutting data presented in table 11.

Table 11: *Cutting data for screening tests.*

	f_z (mm)	V_c (m/min)	a_e
GC1010	0,1	100	9mm
GC1030	0,1	220	9mm

6.2 Testing / Analysis

After planning the tests they were performed simultaneously in two machines. It was shown that the data chosen was pretty good, and that the familiarization tests and reference tests had filled their purpose to choose accurate data for the given screening.

Measurement data was noted as an average value of repetitive measures, which means that the measure was redone a couple of times and then the average of the measured values was taken. This to decrease the dispersion in measured data, especially for flank wear.

It was seen during the tests in GC1030 that the data achieved did not repeat as well as wanted, but it was also clear that the behavior of the wear was quite the same for every insert type. For example one type of insert was in work for approximately the same length before it was showing crater wear or before a chipping first occurred. The life of the inserts though did not repeat for all three repetitions. An increasing trend for the chamfer wear as well as the fact that the inserts with a larger chamfer width and a small clearance angle tend to get more flank wear can be seen.

After the tests were completed the analysis started in Modde. First of all, an analysis of the flank wear on the GC1030 tests was done. It gave a model with a condition number of 2.35 but the results were very bad, again most probably depending on the big dispersion in data due to uncertainty of measurement.

As mentioned earlier the crater start seemed to have something to do with the life of the insert. Taking the data for when a crater first was seen on the insert a good model was achieved. The summary of fit plot for crater start can be seen in figure 46.

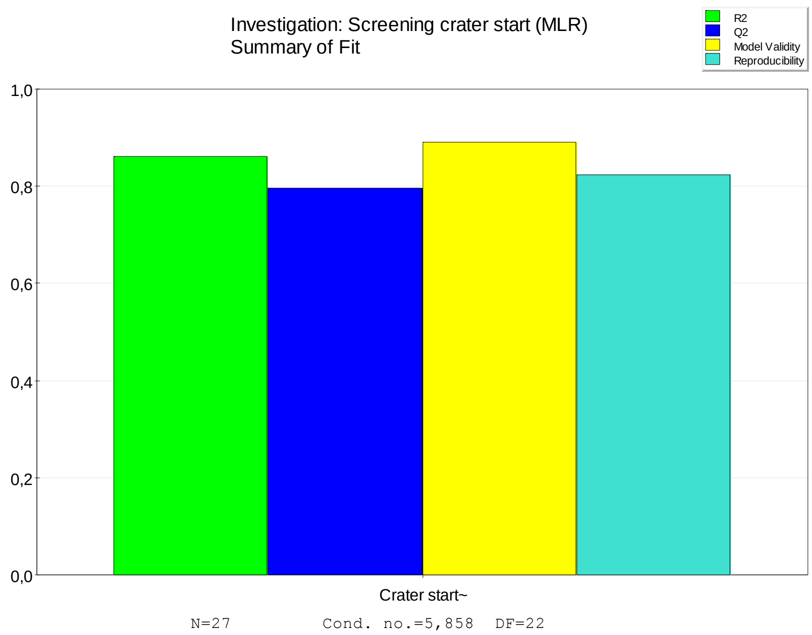


Figure 46: *Summary of fit plot for crater start in screening.*

Optimizing the Q_2 value gave the coefficient plot that can be seen in figure 47 for the crater start data. Even if there are two non significant coefficients, the model was better handling them as well.

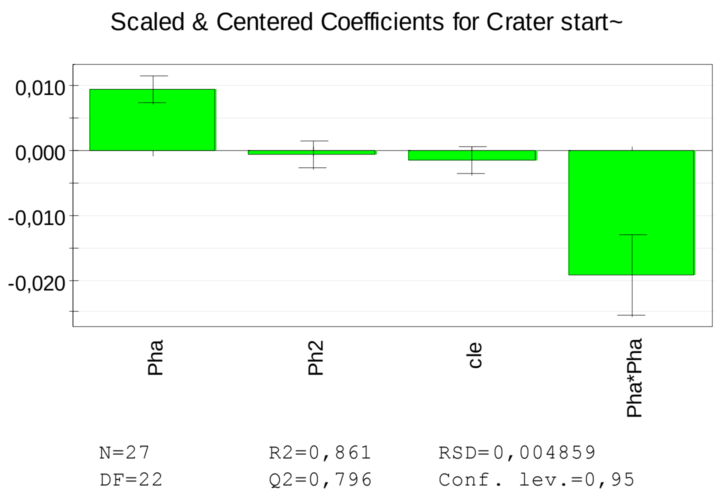


Figure 47: *Coefficient plot for crater start in screening.*

The most important result for the crater start investigation was the influence of the chamfer width. The chamfer angle and clearance angle changing did not affect the behavior. It was also seen during the tests that the dispersion in the results seemed to correlate with the size of the clearance angle.

The analysis of the GC1010 test gave very bad results, this mostly because the tests were too few, and therefore the models built on flank wear, crater wear, life and the crater start could not be fitted.

6.3 Conclusions

The GC1010 tests can be concluded as unfulfilled. Mostly because of the lack of data, which though once again points on the very important fact of having a good test, where it can be secured that data can be achieved. It was also seen that the crater was hard to measure due to the specific color of the GC1010 coating.

The insert that is the center point for GC1030 seemed to be a really good insert. There were many things pointing at this, among them that the crater started the latest on those inserts, and also that the life of those inserts was the longest. This suggests a maximum, which is good in an optimization point of view.

The model did though show tendencies that an increased chamfer width tended to increase the flank wear. It also pointed on a tendency where the clearance angle had influence on the flank wear in the way that a medium clearance angle was the best to reach as low flank wear as possible.

Again, the dispersion in life gave bad models. The main reason to this was again seen to be the replicates. There are too many uncertainties for example in the material or in the production of the inserts, that cannot be seen in three replicates but need many more. This to see whether an insert breaks because of material, the geometry of the insert or if it is totally random.

7 Discussion

This chapter aims to discuss the results that were the outcomes of the tests as well as looking on probable reasons to why the results differed the way they did. The discussion also brings thoughts about further studies to the surface.

The known methods to measure the wear of an insert is good in a point of view; the customers' view. The customer is always interested in the total life of the insert, and not what happens until the insert breaks. Therefore most of the known measurement methods are developed to focus on the life of the insert.

It is obvious when looking at the results of this project that those test methods are not the best when aiming to build knowledge about the geometries and the wear types of the inserts. The lack of a method where the measurement methods are accurate and the focus is on the phenomena during the insert life contributes in much to the bad models achieved in many tests. This maybe implies that the break criterions used must be changed. For example it can be good to have different criterions, such as when chipping first occurs or as later to be read, when the crater starts.

The chippings' break criterion itself is an interesting issue to discuss because of the fact that a chipping above 0.35 mm is seen as a worn out insert, while the chipping itself is like to break a cracker, you never know exact how it breaks.

The crater wear has been seen as one of the factors that most contributes to a worn out edge. Therefore, the machined length when the crater starts to form would be of interest to maximize through further studies.

The number of repetitions in a test with inserts is also very important. It has been said that it is impossible to know the life of an insert exact, due to the many unpredictable factors affecting, such as material impurities, uncertainties in the production of the insert etc. With many repetitions the pattern for such unpredictable events probably will be discovered, and it will then be able to distinguish the normal tests from those where unpredictable factors has affected the test results in any way.

The results achieved with Modde are very interesting and the knowledge built about the computer program and its usefulness in this type of tests is though valuable. To be able to use the program for a specific application the specific application has to be evaluated.

Looking at the differences of the insert life in the repetitions it is easy to conclude that there are too many uncertainties in different unknown factors, as mentioned. By searching those factors, and try to measure them, they suddenly become known. One of those factors might be the fact that the ER of them varied much. Both the width and height of the ER and as well the look of it might affect the results in a larger extent than first thought.

8 Results and recommendations

This last chapter handles the most important results achieved during the work with the tests and the analysis of them. It also leaves some recommendations for further studies on the topic. The aim of the work; to give inputs to the optimization tests is also delivered.

What has been seen in the performed tests is that the lack of repetitions gives unsecure data where it is impossible to determine whether the dispersion depends on that the tests are bad, i.e. that it is impossible to get a good result, or if the unknown factors affects some of the results, and that it would have been able to find good results. It was first thought that three replicates should give an accurate result, but it has not been proven, why a recommendation of at least five replicates is given.

The crater wear has been seen as the one wear type that to the largest extent affects the life of the insert. The crater starts, where after it reaches the edge, where after chipping occurs. The chipping is a very random event. It can, when it occurs; either break the whole edge, or remain on a value measured as an intact insert.

A reduction of the dispersions in the tests should be made. From what is seen in the tests in this project the test order is very important. The tests should be rotated as much as possible, that said, the best would be to run the insert to one point of measure, change to the next insert in the test and then run in to its next point of measure. Further should the data points to measure be the same for every test; the best would be if it is on beforehand decided on which lengths measurements should be made.

Toughness tests without looking at the behavior until breakage do not give sufficiently much data for research of the geometries why the toughness only should be tested to see if it is sufficient.

Looking at the geometries an optimization should be made on the factors chamfer width and clearance angle. Those are important factors among others affecting the crater start and life of the tests.

In further tests, the center points of the tests will also play a large role. It is therefore important to order enough of inserts to complete the whole test that is to be outlined in Modde, so that every data point is fulfilled.

The tests performed did also show some interesting tendencies that is an option for further studies. The tendencies that were shown were

- that increased chamfer width tends to increase the flank wear.
- that the clearance angle had influence on the flank wear in the way that a medium clearance angle was the best to reach as low flank wear as possible.
- that a positive edge broke faster than a negative one.

The tendency that a positive edge breaks before a negative one can maybe be explained by the fact that the cutting forces are too big, and therefore breaks the weaker positive edge before the stronger negative one. Therefore measurements of the cutting forces when machining are recommended.

A good way of looking at the life of an insert is to look at it in two parts. The first part has a breaking point when the crater starts, and depends heavily on the chamfer width. The second part is the life until the insert breaks according to the old criterions. With this fact in hand, it is able to predict a shortest life for the insert, namely when the crater starts. This is a more predictable event, which is also good in a customer point of view. The customer normally changes all inserts in a tool at the same time, no matter of how they look, and with a predictable life the process becomes safer. Tendencies can also be seen that an increased clearence angle increases the dispersion in insert life which should be further investigated.

All in all, Modde is a good program to use for data handling of test data of this type, as long as the measurements and the tests are performed in a good manner by a person that knows what he or she is doing. Optimizing the life of the insert until the crater starts by looking at the chamfer width, as well as minimize the dispersion of the length of the second part of the insert life, by looking on the clearance angle, an optimized insert according to insert life is feasible.

9 References

Sandvik Coromant (1994) *Modern Metal Cutting,*Kullavik: Tofters Tryckeri AB

AB Sandvik Coromant (2007) *Milling – good practice*, Sandviken: AB Sandvikens Tryckeri

L. Eriksson, E. Johansson etAl. (2008) *Design of experiments, Principles and Applications*,Umeå: Umetrics AB

AB Sandvik Coromant (2010), C-2900:10 ENG/01, *Rotating Tools,*Sweden: Elanders

Sandvik (2011). *Sandvik Coromant* [Online] December 21, 2009
http://www.sandvik.com/sandvik/0110/internet/Sweden/SE03030.nsf

Sandvik Intranet:
Figure 1, 2, 3, 4, 5, 6, 7, 10, 13, 16, 17, 19 and 20 from Sandviks' Picture database:
http://webbasenet.coromant.sandvik.com/WebBaseNet/

Projekt PM (2009) [Document ID: **TM CTPM45514**] *Produktegenskapers inverkan på kundvärdet livslängd - Förutsättningar*

Third Wave Systems (2011). Minneapolis. *Third Wave Systems.* [Cited: Mars 26, 2011.] http://www.thirdwavesys.com/products/advantedge_fem.htm

Appendix A

T	a_e varies between 12 and 16 mm; Feed =0,16; Program: "the wedge"
L	a program with constant a_e during the process, but where it varies between flankdata and craterdata.

Test no:	Test type	Insert	Insert no.	H	Tool	Data
1	Reference	**R390 1030**	1		R390	T; Speed: 180
2	Toughness	**UVM 2703 BR**	2	*24,2*	1	T; Speed: 180
3	Toughness	**UVM 27030N**	1	*20,4*	2	T; Speed: 280
4	Toughness	**UVM 2703 BL**	1	*25,5*	1	T; Speed: 280
5	Toughness	**UVM 2703 BR**	3	*28,5*	2	T; Speed: 230
6	Toughness	**UVM 2703 BL**	2	*29,8*	1	T; Speed: 180
7	Reference	**R390 1030**	2		R390	T; Speed: 280
8	Toughness	**UVM 27030N**	2	*20,1*	2	T; Speed: 180
9	Toughness	**UVM 2703 BL**	3	*29,4*	1	T; Speed: 230
10	Toughness	**UVM 2703 BR**	4	*29,4*	2	T; Speed: 180
11	Toughness	**UVM 27030N**	3	*23,0*	1	T; Speed: 280
12	Toughness	**UVM 2703 BL**	4	*32,4*	2	T; Speed: 280
13	Reference	**R390 1030**	3		R390	T; Speed: 180
14	Toughness	**UVM 2703 BR**	5	*29,3*	1	T; Speed: 230
15	Toughness	**UVM 2703 BL**	5	*33,9*	2	T; Speed: 180
16	Reference	**R390 1030**	4	*27,5*	R390	T; Speed: 280
17	Reference	**R390 1030**	5		R390	L; Craterdata
18	Life	**UVM 2703 BL**	6	*27,5*	1	L; Flankdata
19	Life	**UVM 27030N**	4	*26,5*	2	L; Flankdata
20	Life	**UVM 2703 BR**	6	*27,1*	1	L; Craterdata
21	Life	**UVM 2703 BR**	7	*24,1*	2	L; Flankdata
22	Reference	**R390 1030**	6		R390	L; Flankdata
23	Life	**UVM 2703 BL**	7	*29,3*	1	L; Craterdata
24	Life	**UVM 27030N**	5	*24,4*	2	L; Craterdata
25	Life	**UVM 2703 BL**	8	*28,8*	1	L; Craterdata
26	Life	**UVM 2703 BL**	9	*32,1*	2	L; Flankdata
27	Reference	**R390 1030**	7		R390	L; Craterdata
28	Life	**UVM 27030N**	6	*24,2*	1	L; Flankdata
29	Life	**UVM 2703 BR**	8	*27,0*	2	L; Craterdata
30	Life	**UVM 27030N**	7	*21,9*	1	L; Flankdata
31	Life	**UVM 27030N**	8	*23,3*	2	L; Craterdata
32	Life	**UVM 2703 BL**	10	*25,5*	1	L; Craterdata
33	Reference	**R390 1030**	8		R390	L; Flankdata