Abstract

The industrial development of metal cutting processes in gear manufacturing aims at continuously increasing productivity, including increased tool reliability. Basically, the parameters that have an influence on the cutting processes should be known and possible to control.

Gear manufacturing is highly important for the automotive industry. The prevalent manufacturing method is gear hobbing with hobs consisting of solid Powder Metallurgical High Speed Steel (PM HSS) with Physical Vapor Deposited (PVD) coatings.

The hob teeth have to be reconditioned before wear reaches such levels that the gear quality becomes impaired. Such wear often results in a total breakdown of the tool. One crucial reason for this is that hobbing processes for the present often lack reliability; which makes it difficult for the gear manufacturers to predict the tool wear on the hob teeth and decide when the tool should be replaced in order to avoid severe damages. A consequence of catastrophic tool wear is that it leads to an instantaneously changed geometry of the cutting edge, which in turn implies that the machined gears do not comply with the stipulated properties on the machined gear products.

A single tooth milling test (STMT) with tools of PM-HSS in a conventional milling machine has been developed in this research project, aiming at characterizing the effect of tool preparation on the type of wear mechanism. The experience and conclusions from these tests may probably be transferred to real PM-HSS hob tooling (HT). The advantages of such a test, compared to a real gear hob test, are primarily the cost reductions and time saving aspects with respect to both the design and the manufacturing of the cutting teeth.

The research presented in this thesis is based on experimental investigations and theoretical studies of significant parameters, i.e. the surface roughness and edge rounding, contributing to the robust and reliable design of a PM-HSS cutting tool. The research work has in addition to, the development of the milling test method, also comprised development of measuring methods and a simulation model based on the Finite Element Model (FEM).

Keywords

Hobbing, single tooth milling test, TiN, High speed Steel (HSS), wear mechanisms, cutting force, cutting edge preparation, tool surface preparation, FEM cutting model.
Preface and acknowledgments

This thesis is a result of the work performed at the Royal Institute of Technology, (KTH), the department of Production Engineering in Stockholm, Sweden, within the “FFI Sustainable gear transmission realization project”. The most prominent gear-related manufacturing companies have participated in the project, together with the following academies: University of Uppsala (UU) Chalmers University of Technology (CTH) and KTH. The project is also supported by VINNOVA – the Swedish Governmental Agency for Innovation Systems.

A great number of analyses have been carried out together with the University of Uppsala. The analyses have been performed by using excellent measuring technology and equipments.

I wish to express my thanks for valuable suggestions and greatly encouraging support of my work to my supervisors Professor Mihai Nicolescu and Professor Bengt Lindberg. Secondly, special thanks to my colleague Julia Gerth (UU) for all our discussions and analysing work during the experiments. I am also grateful to her supervisors Professor Sture Hogmark (UU), Professor Urban Wiklund (UU) and Ph.D. Mats Larsson (Primateria AB). Further thanks to my project colleagues Mats Bagge (Scania AB), Sören Sjöberg (Sandvik AB), Ellen Bergseth, Matilda Teherl, Anders Berglund, Lorenzo Daghini and Andreas Archenti (KTH) for research discussions. I will also express my gratitude for all suggestions to Thomas Björk (Swerea Kimab), P.O. Söderholm, Ove Bayard, Mats Bejhem, Wenli Long, and Jan Stamer (KTH). I give my great appreciation to Bo Lindström (KTH) and Jan-Eric Ståhl (LTH) for having sent me their excellent literatures in metal cutting and for very valuable discussions. Finally, the companies in the research project are recognized for all delivering of materials and sharing their knowledge.

The present work had not been possible to realize without patience and support from my family, my wife Eva and my little daughter Emmalisa and my very little son Carljohan!

The author

Master of Science in Engineering, Tekn.Lic. P.O.E. Mathias Werner

“Prudentia et audacia”
# Table of contents

Abstract III  
Keywords III  
Preface IV  
Table of contents V  
Nomenclature, symbols and abbreviations. VI

1 **Introduction**  
   1.1 Project and research background 1.1  
   1.2 Aim of the thesis 1.3  
   1.3 Research questions 1.6  
   1.4 Delimitations 1.6  
   1.5 Outline of the thesis 1.7  
   1.6 Research methodology 1.9  
   1.7 Not appended research publications 1.9  
References in chapter 1 1.11

2 **Requirements for attaining reliable PVD coated PM-HSS tooth**  
   2.1 Requirements for gears and gear manufacturing 2.1  
   2.2 Characterization of work materials for power transmission components 2.4  
   2.3 Characterization of materials for the cutting tooth substrate 2.6  
      2.3.1 Powder metallurgical High Speed Steel (PM-HSS) 2.7  
   2.4 Coatings for PM-HSS cutting teeth 2.8  
      2.4.1 PVD- Titanium Nitride (TiN) and Titanium Aluminum Nitride (TiAlN) coatings 2.11  
   2.5 Industrial manufacturing of gears 2.12  
      2.5.1 Hob Tooling (HT) 2.14  
      2.5.2 Hobbing action 2.18  
      2.5.3 Chip formation generated by the HT tooth 2.19  
   2.6 Laboratory methods for cutting studies 2.20  
      2.6.1 Single tooth milling test 2.21  
      2.6.2 Single Tooth Milling Test action and kinematics 2.22  
      2.6.3 Chip formation in Single Tooth Milling Test 2.25  
   2.7 Tooth geometry 2.26  
   2.8 High Speed Steel tooth preparation 2.28  
   2.9 Tribological tooth design 2.28  
      2.9.1 The influence of the edge radius on the tooth wear 2.29  
      2.9.2 Tooth surface treatment 2.31  
   2.10 Conclusions 2.33  
References in chapter 2 2.34
3 Study of wear phenomena 3.1
3.1 Tooth substrates and coatings 3.1
3.2 Classification of tool failure 3.2
3.3 Contact conditions in Hob Tooling and Single Tooth Milling Test 3.7
3.4 Machined surfaces 3.12
3.5 Conclusions 3.15
References in chapter 3 3.15

4 Evaluation of the influence on tooth design 4.1
4.1 Influence of mechanical loads on cutting teeth 4.1
4.1.1 Cutting force in Single Tooth Milling Test 4.1
4.1.2 Load functions 4.3
4.1.3 Stresses on the tooth 4.4
4.2 Description of experiments 4.7
4.2.1 Specifications of tooth groups 4.11
4.3 Experimental results 4.12
4.3.1 Cutting force analyses in STMT 4.12
4.3.2 Calculated stresses on the rake face 4.24
4.3.3 Load functions 4.27
4.3.4 Measured edge loss volume 4.28
4.3.5 Measured second deformation zone 4.31
4.3.6 Use of vibration analysis for studying the influence of tooth preparations on tool wear 4.33
4.4 Analysis of wear pattern 4.36
4.5 Scratch testing of the coatings 4.46
4.6 Conclusions 4.50
References in chapter 4 4.52

5 Single Tooth Milling Test simulations 5.1
5.1 The aim of simulation 5.2
5.2 Procedure of the analysis 5.4
5.3 The yield criterion, flow rule and strain hardening model 5.6
5.4 A model for the Single Tooth Milling process 5.10
5.4.1 Tool – chip interface 5.10
5.5 Modelling of chip formation 5.14
5.5.1 Formulations for numerical modelling 5.14
5.5.2 Chip formation 5.16
5.5.3 Analysis of thermo-physical phenomena 5.17
5.5.4 Temperature and friction 5.23
5.6 Conclusions 5.27
References in chapter 5 5.28
6  Discussions  
6.1  
7  Conclusions  
7.1  Future work  
7.7
Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ALE</td>
<td>Arbitrary Lagrangian Eulerian (FEM formulation)</td>
</tr>
<tr>
<td>ASP</td>
<td>Registered steel trade mark of Erasteel</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>BUL</td>
<td>Built-up layers</td>
</tr>
<tr>
<td>D</td>
<td>Down (climb) milling</td>
</tr>
<tr>
<td>DIN</td>
<td>Deutsche Industrie Norm</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive X-ray Spectroscopy</td>
</tr>
<tr>
<td>EN</td>
<td>Euro Norm</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>HSS</td>
<td>High Speed Steel</td>
</tr>
<tr>
<td>HT</td>
<td>Hob Tooling</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LOM</td>
<td>Light Optical Microscope</td>
</tr>
<tr>
<td>PM-HSS</td>
<td>Power Metallurgical High Speed Steel</td>
</tr>
<tr>
<td>PVD</td>
<td>Physical Vapour Deposition</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>STMT</td>
<td>Single Tooth Milling Test</td>
</tr>
<tr>
<td>SS</td>
<td>Swedish Standard</td>
</tr>
<tr>
<td>U</td>
<td>Up (conventional) milling</td>
</tr>
</tbody>
</table>

Symbols

Physical terms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>AlCrN</td>
<td>Aluminium chrome nitride</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>Co</td>
<td>Cobalt</td>
</tr>
<tr>
<td>Cr</td>
<td>Chrome</td>
</tr>
<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>Mn</td>
<td>Manganese</td>
</tr>
<tr>
<td>Mo</td>
<td>Molybdenum</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorus</td>
</tr>
<tr>
<td>S</td>
<td>Sulphur</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>TiN</td>
<td>Titanium nitride</td>
</tr>
<tr>
<td>TiAlN</td>
<td>Titanium aluminium nitride</td>
</tr>
</tbody>
</table>
V         Vanadium
VC        Vanadium carbide
W         Tungsten (wolfram)
Wt %      percentage by weight
HB        Hardness in Brinell scale
HRC       Hardness in Rockwell C scale
HV        Hardness in Vickers scale
UTS       Ultimate Tensile Strength
σ         Stress (compressive or tensile)
τ         Shear stress
t         Time

**Machining terms**

A         Group of tooth in the pre-study
a_d       Depth of cut
a_r       Width of cut
B         Group of tooth in the pre-study
C         Group of tooth in the pre-study
D         Hob diameter
E         Group of teeth with various edge roundings
E_I       Primary deformation zone
E_II      Secondary deformation zone
E_III     Tertiary deformation zone
ER        Edge Radius
F_N       Normal force
F_R       Radial force (transformed from F_X and F_Y)
F_T       Tangential force (transformed from F_X and F_Y)
F_X       Measured force in x-direction
F_Y       Measured force in y-direction
f         feed
f         Feed / tooth
h_c       Chip thickness
R / t_c   Ratio edge radius / thickness of coating
R_a       Arithmetical mean deviation of the profile
R_k       Core roughness depth
R_pk      Reduced peak height
R_vk      Reduced valley depth
R_z       Mean maximum deviation
S         Tensile force
V_c       Cutting speed
Y         Group of teeth with various surface roughness
y_s       Height of stagnation point above reference plane
Forces and stresses acting on the faces of the tooth:

- \( N_{rf} \): Normal force acting on rake face
- \( N_{ffp} \): Normal force acting on primary flank face
- \( N_{ffs} \): Normal force acting on secondary flank face
- \( S_{rf} \): Shear force acting on rake face
- \( S_{ffp} \): Shear force acting on primary flank face
- \( S_{ffs} \): Shear force acting on secondary flank face
- \( S_{ffs(\text{resultant})} \): Resulting shear force of \( S_{ffp} \) and \( S_{ffs} \)
- \( N_{cd} \): Normal force acting on (rake face)
- \( S_{cd} \): Shear force acting on (rake face)
- \( N_{ad} \): Normal force acting on (primary flank face)
- \( S_{ad} \): Shear force acting on (primary flank face)
- \( N_{bc} \): Normal force acting on (secondary flank face)
- \( S_{be} \): Shear force acting on (secondary flank face)
- \( S_{bc1}, S_{bc2} \): Components of \( S_{bc} \)
- \( \sigma_{cd} \): Compressive stress on (rake face)
- \( \tau_{1cd}, \tau_{2cd} \): Shear stresses on (rake face)
- \( \sigma_{rf} \): Compressive stress on rake face
- \( \tau_{rf} \): Shear stress on rake face

Symbols, unique in Chapter 5

- \( \kappa \): Parameter as to kinematic hardening
- \( \chi \): Parameter as to isotropic hardening
- \( \varepsilon \): Elastic strain
- \( d\varepsilon \): Increment of elastic strain
- \( \varepsilon^p \): Plastic (permanent) strain
- \( d\varepsilon^p \): Increment of plastic (permanent) strain
- \( \dot{\varepsilon}^p \): Rate of plastic strain
\( \dot{\varepsilon} \)  
Strain rate

\( \dot{\varepsilon}_0 \)  
Reference plastic strain rate

\( \sigma_n \)  
Normal stress

\( \tau_f \)  
Frictional shear stress

\( \mu \)  
Coefficient of friction

\( \lambda \)  
Constant of proportionality (plastic consistency)

\( \sigma \)  
Flow stress

\( E_A \)  
Activation energy

\( T_f \)  
Modified friction stress

\( k \)  
Shear stress of chip material

\( m \)  
Thermal softening behaviour

\( Q \)  
Plastic flow potential

\( R \)  
Universal gas constant

\( T \)  
Work piece temperature

\( T_{\text{amb}} \)  
Ambient temperature

\( T_{\text{melt}} \)  
Melting temperature

\( v_s \)  
Sliding velocity

\( v_0 \)  
Small velocity compared with \( v_s \)
1 Introduction

In this introductory chapter the background of the thesis is described, as well as the research project in which the presented studies have been carried out. The current situation in the gear manufacturing industry is characterized by a lack of design parameters for reliable tool design. Therefore, significant development concepts for tool reliability enhancement are evaluated, and constitute the motives behind this research. The formulation of the goals and the structure of the thesis are outlined at the end of this chapter.

1.1 Project and research background

The industrial development of gear manufacturing by cutting methods aims to, with limited tool reliability, continuously increase productivity in the production process [1]. Therefore, the factors that have an influence on the cutting processes should be known and controlled. Another important aim is to create cutting processes that are resource saving by using reliable tools in an optimal way. At the same time, the lowest possible energy consumption, and other environmental factors in the manufacturing processes have to be taken into consideration.

"FFI sustainable gear transmission realization" is one of the research projects for which resources have been provided by the Swedish Automotive Industry together with the Swedish Governmental agency for Innovation Systems (VINNOVA). In this project the research is outlined through Work Packages (WP) as shown in Figure 1.1. These WP take into consideration demands on the gear components [2], [3], [4] with respect to design and function, work materials [5], and a robust manufacturing process that is focused on a reliable cutting process and process planning [6]. This thesis presents the research work performed in WP 4 (robust design and manufacturing) and WP 5 (cutting tools) with a focus on a reliable cutting process [7] and [8].

Initially, a careful investigation was completed to identify the research needs within the Swedish gear production industry. The investigation was carried out by means of interviews and visits to all companies participating in the project. This investigation was followed by a detailed study of hob tools, from a selection from the participating project companies, with respect to tool wear [9] [10]. The results of this study formed the baseline for the
research presented in this thesis and the outline of the research goals for establishing the framework of the development of a reliable gear cutting process. [11]

Figure 1.1: Outline of the project structure in the “FFI sustainable gear transmission realization” project

The manufacturing of transmission components constitutes one of the most sophisticated processes within the automotive industry. An overall goal within this process is the reduction of production expenditures, and one step in this direction is to reduce the lead time. It is then possible to optimize production lines to achieve the required process accuracy and high productivity through the smooth flow of material.
Robust and reliable tool design requires advanced technical knowledge of the mechanical properties of the cutting tool and of the tool wear mechanisms that affect tool performance [10] and [12]. The concept of reliability can be referred to the possibility of achieving a robust design, resulting in the optimized machinability of the work material [13].

The research presented in this thesis is based on experimental investigations and theoretical studies of significant factors, assumed to contribute to the robust and reliable design of a powder metallurgical high speed steel (PM-HSS) cutting tool, to which a Physical Vapor Deposited (PVD) has been applied. Both theoretical and experimental research has been carried out, in studies involving the development of a milling test method, measuring methods and simulation of the effect of preparations of HSS cutting teeth by means of the Finite Element Method (FEM).

1.2 Aim of the thesis

The research presented in the thesis lies at the confluence of several scientific disciplines and attempts to unify the tribological studies and the treatment of cutting phenomena into an integrated framework. The thesis casts in new light the influence of tooth micro-properties on the performance of the cutting process. This approach, which forms the central part of the thesis, is an original contribution to a research area that considers the tribo-system, tooth micro-geometry - tooth coating- tooth substrate –work material under large compressive and shear loads created during chip formation.

One major aim of this thesis is to develop a test method, the single tooth milling test (STMT) method using PM-HSS tools in a conventional milling machine, for the purpose of characterizing the effect of tool preparation on wear mechanisms. The conclusions of the experimental results may eventually be transferred to real PM-HSS hob tooling (HT). If this assumption is valid, the advantages of such a test, compared to a real gear hob test, are primarily the cost reductions and time saving aspects with respect to both the design and the manufacturing of the teeth [1].

Another aim is to investigate and identify the effect of major tool design factors and their individual impact on a reliable tooth micro-design in the intermittent gear cutting process, as illustrated in Figure 1.2. Generally, the
term machinability refers to the ability of a work material to be machined by a tool considering both technical and economical aspects. Machinability has to be good in order to be able to meet the demands, made on the machined surface and to contribute to a profitable economy in the machining process.

In order to evaluate the various tribological parameters it is also very important to consider the distribution of mechanical/thermal loads on the tool [14], an issue that is also addressed in this thesis.

![Figure 1.2: Overall concept and phases to design reliable tools based on tribological and physical parameters.](image)

The process of designing reliable tools is an iterative process that involves:
1. selecting properties of substrate, coating and work material,
2. specifying requirements for surface preparation
3. assessing the effect of tooth micro-geometry
4. optimization of the design parameters
5. achieving reliable processes for a competitive production
The detailed characterization of the micro-geometries has been completed by using simplified load distributions, dynamic conditions in intermittent machining and tool wear, all of these factors being associated with machined surface properties (Chapter 3 and 4). The interface tool-chip is a complex zone where thermo-mechanical phenomena are characterized by high gradient temperature variations coupled with high strain rates. These conditions make it difficult to measure accurately the thermal and mechanical stresses. As many of the results are affected by inherent errors due to measurement systems, a STMT model was developed to verify and explain phenomena related to friction, heat and load distribution.

This research was conducted over a period of five years, with a period of three years for licentiate including preliminary studies that were parts of a previous research project performed by the author.

The preliminary studies have been valuable sources for the development and evaluation of new concepts in tooth design. The structure of the thesis has followed a rigorous scientific methodology with carefully experiment design that resulted in a large amount of measurement data. The only way to deal with both the scope of the subject and the depth of the individual constitutive elements in the research work was to write a monographic thesis.

The road map that describes the author’s original contributions as presented in the thesis, begins with a pre-study that had the aim of identifying the state-of-the-art in the research of the gear cutting process and at the industrial implementation level. An important part of this preliminary research was to recognize the main causes for lack of cutting tool reliability in gear manufacturing. This led to a selection of critical design parameters to be studied in laboratory conditions.

Based on the process characteristic criteria and tooth design requirements at micro level, the Single Tooth Milling Test method has been developed and adapted for measurements of load, vibration and machined surfaces.

The experiments were then designed to facilitate a realistic evaluation of tooth preparation with respect to machinability criteria such as tool wear, cutting forces, and machined surface properties.
The results were then analyzed through a combination of methods that comprised SEM and LOM, dynamometry and vibration analyses, mechanical testing, hardness and micro-hardness. Methods of evaluating tool wear on the flank and rake faces, surface roughness and chip formation based on Quick stop and scratch test techniques have been integrated in the evaluation framework.

Theoretical load functions have been inferred to evaluate the force measurements. The functions were specially adapted for STMT.

In order to understand and appreciate the effect of some parameters that could not be measured, a FEM model has been developed. The model was especially designed to analyze the STMT and explains the mechanical and thermal distributions on the tooth under the influence of edge preparation.

1.3 Research questions

The research questions in this thesis are related to the tribo-system involving the substrate and coating interacting with the chip and the contribution of the micro-geometry in chip formation [7]:

- Is it possible to develop a laboratory test method for analyzing the influence of edge and surface preparation on the wear mechanisms that gives a similar wear pattern as the wear of hobbing tools?

- To which extent do the micro-geometrical parameters have a significant effect on the design of a reliable PM-HSS tools?

- How do the tooth cutting edge and surface characteristics influence the development of tool wear and the machined work piece’s surface?

1.4 Delimitations

The results presented correspond to the developed STMT. The substrate of the teeth was made of high alloy PM-HSS, ASP 2030, and coated with TiN. The work material in the experiments was an ISO reference steel 20NiCrMo52-2 SS 2506.
1.5 Outline of the thesis

In this work, a hypothesis is formulated in order to put the preliminary observations and knowledge in the research area to the test, so that they may be proved or disproved, and thus contribute to the newly acquired knowledge as presented in the conclusion.

One or several hypotheses can be made from observations that can be formulated using established theories, and experiments are carried out in order to verify their validity and make deductions. In the deductive method, earlier theories and research on a certain phenomenon are the bases for new hypotheses that will be tested and verified.

A hypothetical-deductive method has been applied in the present research work. The objective of this method is to prove hypotheses with respect to parameters that contribute to reliable tools.

The hypothesis to be tested is:

Uncontrollable wear tendencies are largely caused by the micro design properties of the tool surface and the cutting edges.

This thesis is produced as a monographic work consisting in 7 chapters. In addition, three papers are appended at the end of the thesis.

This introductory Chapter 1 is succeeded by Chapter 2 “Requirements for attaining reliable PVD coated PM-HSS tooth” with a theoretical presentation of the Hob Tooling (HT) process. In addition to this, the developed “Single Tooth Milling Test” method (STMT) is also presented. This method has been used in the evaluation of an optimization of the “tribological tooth micro-design” (tooth design) with respect to the functional surfaces and the active cutting edges of the tooth. Chapter 2 also includes such theories and characterization of work and tool materials, PVD coating, tool geometry and tool preparation, common to both HT and STMT.

In Chapter 3 “Study on wear phenomena on HT tooth and STMT” analyses of both HT and STMT are presented. These analyses have been the bases of more in depth studies on the possibility of optimization in tooth design.
In Chapter 4 the chosen tooth design parameters that have been tested with the STMT method are evaluated, including laboratory analyses and theories that support the actual observations. An analytic reflection on the conditions of mechanical loading and wear mechanisms on a STMT tooth is also presented, which is necessary to take into consideration in order to evaluate an optimized tooth design. The analytic reflection has been used to correlate the experimental results that are the bases of the evaluation of a reliable design of the tooth.

Chapter 5 presents a computational Finite Element Model (FEM) that has been performed in order to correlate actual tooth design parameters with the experiments in an effective way.

Chapter 6 presents discussions and Chapter 7 conclusions on the results of this thesis and proposals for further research.

The first article appended has the title, “Tooth micro geometry studies in single tooth milling tests with PVD coated HSS inserts” and the purpose of the article is to characterize the tribosystem of tooth substrate-tooth coating-chip/workpiece for various tooth’s micro-geometries and surface preparations.

The second article has the title “Single Tooth Milling test simulations” and present the theoretical model developed for studying the effect of micro-geometry on stress distribution on the tooth.

The third article has the title “Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test” The main goal of this study was to verify that the wear mechanisms in the developed single tooth milling test correspond with the wear mechanisms obtained in real gear hobbing.

The forth article with the title “Development of cutting force measurement system for gear hobbing” presents the theoretical and experimental studies of a dynamometer fixture to be integrated in a hob-machine.
1.6 Research methodology

The presented results have been obtained in experiments that were primarily aimed at determining the significant parameters for reliable tooth design. The subsequent selection was based on an enlarged test matrix, presented in Chapter 4, consisting of relevant tooth design parameters, with focus on tooth surface roughness and edge rounding.

A previous work by the author includes the Licentiate Thesis “Investigation on PM HSS Milling Inserts” [1]. The thesis gives an account of the development of a simplified testing method, which by means of single tooth milling reproduces the actual wear mechanisms that occur on cutting tools in the industrial hobbing processes.

Within this research project, FFI sustainable gear transmission realization, research results have been presented in the form of journal papers, conference papers and project reports, partly stating the need for research on the manufacturing of transmission components, and partly compiling a survey on the reliability of hobs used under industrial conditions.

A wireless device for measuring forces in HT has also been developed. The device can be used for evaluating the tooth design when applied to the hobbing process [15].

1.7 Not appended research publications

A selection of various previously published reports, articles and Technology Licentiate thesis, related to this project, and written by the author or co-authors.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>
References in chapter 1


2. Requirements for attaining reliable PVD coated PM-HSS teeth

This chapter presents a review of the research results on tool materials, work materials, tool geometries and kinematics of Hob Tooling (HT) and Single Tooth Milling Test (STMT). The two processes, HT and STMT, are presented with respect to the kinematics and the chip formation mechanism, respectively. It is important to consider both processes with respect to their similarities and differences. This is critical to the final design and the realization of sustainable tooth surfaces and edge geometries. The consequence is that with a laboratory method, the evaluation of tool designs can be effectively performed and reliable tools may be manufactured for hobbing.

2.1 Requirements for gears and gear manufacturing

The primary function of the vehicle transmission and the driveline is to safely and effectively transfer the power from the engine to the driving wheels. In addition, the transmission must allow for the torque and the rotational speed to be adapted to the driving situation. Not only is the gear ratio of interest when optimizing gear systems, but also strength, noise, energy loss, weight, cost etc. These factors determine the selection of material and manufacturing processes for the gears, and influence the design requirements for tolerances, geometries and surface finish.

Developments within the automotive industry, with focus on the production of high quality transmission components, have resulted in a demand for a more effective and reliable gear manufacturing process [1].

Requirements are related to the ability of a gear to perform satisfactorily under the conditions of loading for which it was designed and thus incorporate all mechanical property requirements.

Key design considerations require an analysis of the type of applied loads, either time-continuous or intermittent, and the desired mechanical properties, such as bending fatigue strength or wear resistance, all of which define the requirements of the strength and the heat treatment. Consideration must be given to the loads acting on the gear teeth, with tooth bending and contact stresses, resistance to wear, and fatigue problems being paramount. An overview of the requirements for automotive gear manufacturing is illustrated in Figure 2.1.
Numerous factors influence the mechanical properties of materials including:

- Microstructure, as a function of retained austenite percentage, grain size, carbides (size, type, distribution).
- Defect control, as a function of residual compressive stress, dislocations, surface finish, geometry.

Functional characteristics of a gear are affected by individual errors of the gear, as generated during the manufacturing process. Only precise pitches and correct involutes transmit perfect rotary motions at constant angular velocity as in the case of cylindrical gears. The inspection of geometrical characteristics and machined gear surfaces on flank faces demonstrates the surface properties after at hobbing process machined with the slightly used cutting teeth (broken line) and the severely used cutting teeth (solid line) of a gear, presented in Abbot curves in Figure 2.2. The machined surface comprises a regular waviness as well as smeared work material. The latter is both larger and more frequently observed on surfaces machined with a severely worn tool (a) than a slightly worn tool (b) in Figure 2.3.
Figure 2.2: Gear wheel surfaces machined with slightly used cutting teeth (broken line) and severely used cutting teeth (solid line)[2].

Figure 2.3: The machined surface comprises a regular waviness as well as smeared work material. The latter is both larger and more frequently observed on surfaces machined with a severely worn tool (a) than a slightly worn tool (b).
2.2 Characterization of work materials for power transmission components

Case-hardened steel material represents a major group of work materials used in power train manufacturing. The structure of the case-hardened steel is often pearlite-ferrite structure, illustrated in Figure 2.4. Generally, the upper tensile strength (UTS) of these work materials for gears is around 600 MPa [3] at 20°C, with a hardness of 120-190 HB. However, the material contains other constituents such as carbides, nitrides or oxides causing abrasion of the cutting edge during machining. High toughness of the work material, large fracture elongation and work hardening contribute to the generation of high temperatures during the chip formation [4]. High temperatures reduce the strength of the PM-HSS tooth and, in addition, facilitate chemical reactions that create the risk of forming inter-metallic phases between tooth and work material. This phenomenon contributes to accelerate adhesive wear on the rake face of the tooth.

![Figure 2.4: Cross-section LOM micrographs of case hardening steel. This steel was used in the STMT experiments revealing a typical pearlite-ferrite structure.](image)

In Figure 2.5 the relationship between stress and strain for typical pearlite-ferrite steel during dynamic-mechanical tests is illustrated at both low and high elongation rates. The tests were carried out on case hardening steel commonly used in power transmission components (ISO reference steel 20NiCrMoS2-2 with a hardness of 180 HB) subjected to tension loads at nominal elongation rates of 0.001 s⁻¹ (one test), 1 s⁻¹ (two tests) and about 400 s⁻¹ (two tests). It has to be noted that solely data up to the neck formation are presented in the graphs below.
Figure 2.5: The stress as function of the strain at indicated nominal elongation rates. The test specimens have a nominal length of 8 mm and a nominal waist thickness of 2 mm. If higher elongation rates are desirable, the application of a compressive load is recommended since the strains up to the neck formation are relatively smaller at faster tension loads.

The steel material used in the machinability investigations was annealed in stages first at 900°C for 1½ h and after that at 610°C for 3 h. The chemical composition according to the charge analysis of the melt is presented in Table 2.1 and is within the standard limits for this type of material. The most common standard reference designations of this steel material are listed in Table 2.2.

Table 2.1: Chemical composition (ISO reference steel 20NiCrMoS2-2)

<table>
<thead>
<tr>
<th>Chemical composition (Wt%) work material</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>N</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>97.701-98.611</td>
<td>0.2</td>
<td>0.24</td>
<td>0.86</td>
<td>0.009</td>
<td>0.013</td>
<td>0.039</td>
<td>85ppm</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 2.2: Standard reference designations of case hardening steel (ISO reference steel 20NiCrMoS2-2)

<table>
<thead>
<tr>
<th>Case hardening steel</th>
<th>EN 10027-1</th>
<th>SS</th>
<th>AFNOR</th>
<th>BS</th>
<th>DIN</th>
<th>ASTM / SAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>20NiCrMo2-2</td>
<td>2506</td>
<td>20 NCD 2</td>
<td>805 A 20</td>
<td>21NiCrMoS2</td>
<td>8620</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Characterization of materials for the cutting tooth substrate

There are some primary properties of tool steels that make them attractive to machining operations. These properties are toughness and brittleness, wear resistance, and heat resistance. These three properties are inherent to the tool steel and interact with each other. Hardness is another property of tool steel that is developed through the heat treating process. Hardness is the steel’s ability to resist compression, indentation or deformation. Hardness is directly related to the compressive strength.

Large variations in the mechanical and thermal load pattern among various machining applications give rise to the need for a number of tool materials with a wide range of physical properties. The most important method of meeting the requirements of wear resistance in a given application is to choose an optimal combination of flexural strength (or bend strength), hot hardness and toughness. Wear resistance is the steel’s ability to resist erosion. Wear resistance in tool steel is achieved by the presence of carbides. Chromium, molybdenum, tungsten and vanadium are the four carbide-forming elements commonly found in tool steels. On the other hand, large quantities of carbides will give rise to a brittle steel.

For a given tool material there is a relationship between the temperature and the strength/hardness. An increased cutting process temperature decreases the strength of the tool material especially if the process temperature is higher than the tempering temperature (roughly 550°C).

The fracture criterion of materials is in case of brittle tool materials related to their sensitivity to various types of defects.

The interaction between the tooth and the work material results in wear and frequent formation of an adhesive bond of the work material to the tooth surface, that is dependent on temperature. This adhesion and cold welding may lead to adhesive wear and damage to the edge line. Adhesive wear makes heavy demands on the toughness of the tooth material and therefore requires adequate surface preparation. Therefore, increased hot hardness of the tooth material results in a reduction of the adhesive wear, as cutting speed and temperature can be increased, which in turn will also accelerate diffusion or other types of chemical reactions.

As previously mentioned, a tooth material has to have a number of characteristic properties so that it can work in a specific application. The demands stated above result in certain technical limitations of the tooth material, for instance limitations with respect to hard phases in the tooth substrate. By means of powder metallurgy it is possible to reduce these limitations.

2.6
2.3.1 Powder metallurgical High Speed Steel (PM HSS)

PM-HSS materials exhibit several advantages as a result of the refined, homogeneous microstructure as compared to their cast counterparts:

- No macro segregation.
- Improved strength, toughness and ductility at the same hardness.
- Isotropic properties give less distortion at hardening of tools.
- Improved grinding properties.
- Improved hot workability and thus higher hardness at temperatures below 560°C, which gives greatly improved wear resistance.
- In many cases, a large increase of lifetime for cutting tools.

The structure of PM HSS is composed of hard carbides embedded in a martensitic substrate, presented in Figure 2.6. The carbides give the steel its wear resistance and the matrix accounts for its toughness and thermal stability. The distribution and the shape of the carbides influence the toughness of the PM HSS. Therefore it is desirable to control these factors through the composition of the substrate in order to attain an optimal combination of properties. In high-alloy PM HSS substrate there is carbide content of about 25%.

![Figure 2.6: The structure of PM HSS ASP steel](image)

Carbon is the most important alloying constituent because it determines both the wear resistance – through the influence of the amount and types of carbides – and the mechanical properties – through the influence of the substrate microstructure. High carbon content gives greater hardness and consequently higher thermal stability and formation of more complex carbides that contribute to an appropriate wear resistance. Molybdenum and tungsten are added to form hard carbides and give an increased secondary hardening in the tempering phase during the heat treatment.

Vanadium forms vanadium carbides (VC) and binds carbon in stable carbides. Vanadium increases the wear resistance without noticeably reducing the toughness. Many PM HSS tools are distinguished by a high ratio between carbon and vanadium resulting in a very hard martensitic substrate. If this ratio is increased the result will be a wear resistant PM HSS that is nevertheless more difficult to grind and more brittle. Chrome, existing in all PM HSS in a
concentration of about 4%, forms unstable carbides and increases the tempering capacity and plays an important role in the secondary hardening during the heat treatment. Cobalt does not form carbides but exits loosely in the substrate as a binder. Cobalt contributes mainly to an increase in the thermal resistance which makes higher cutting speeds possible.

The majority of PM HSSs for cutting tool applications have a hardness of about 62-68 HRC. The toughness of PM HSS makes it possible to produce complicated tooth shapes that can resist high static and dynamic cutting forces. PM HSS materials have properties characterized by a very high ultimate bending strength, a low brittleness ratio and a high ultimate toughness.

The limitation of PM HSS as a material for cutting teeth lies in the fact that the temperature must not exceed roughly 550°C. Cutting data leading to higher cutting temperatures will rapidly result in softening of the steel, followed by a collapse due to severe permanent deformation.

2.4 Coatings for PM HSS cutting teeth

In order to attain the desirable manufacturing capacity and reliability it is highly important that the design of the cutting teeth is robust and reliable. Since a great number of cutting teeth in today’s gear production are made of coated PM-HSS materials, an optimization of the properties of these kinds of materials requires a tooth design that considers the characteristics of both the current Physical Vapor Deposited (PVD) coating films and of the work materials which are suitable for gear wheel manufacturing [5]. The coating films properties in intermittent machining such as hobbing are characterized by [6]:

- the adhesion between the tool surface and the coating that relates to film flaking and/or abrasive wear,
- the oxidation effect on coating and,
- the influence of the film thickness on tool wear.

In most cases the cutting performance of a tooth is not optimal, which causes large variations in tool life. The main reason for this is that important tribological properties and parameters of the cutting teeth are not standardized. Creating and standardizing a system of measurement of the tribological properties of the teeth results in an improved machining performance and guarantees quality and process trackability [7].
Aiming at an improvement in the efficiency of cutting processes, the cutting speeds have increased over the years. This implies a larger stress, a higher temperature and increased wear of cutting teeth. The primary purpose of coatings of hard materials is to reduce the wear mechanisms like adhesion, abrasion, diffusion and oxidation on the surface of the substrate. [8] [9] [10].

The excellent hardness of PVD coatings, typically about 2200-3200 HV, protects the tooth against mainly abrasive wear. The PVD coating is also resistant to wear due to its relatively low affinity to chemical elements in the work material that obstruct the welding mechanism, which is a necessary condition for adhesive wear.

The stresses in PVD coatings applied on PM HSS teeth in gear cutting are normally compressive and vary between 1 – 5 GPa in magnitude.

The kinematics of gear manufacturing consist of complicated chip formation mechanisms and cause relatively high stresses in the cutting tooth’s substrate and PVD coating. Therefore, experiments in “fly hobbing” were designed in order to carry out a quantitative study of the chip formation on teeth and the fatigue behaviour of substrates and PVD coatings [11].

One of the main advantages of PVD coating is that the coating process temperature between 160°C and 600°C makes it possible to coat materials with a low thermal resistance. Furthermore, this method introduces internal stress in the coating which, on the one hand, limits the coating-thickness to a range between 3 - 6 μm but on the other hand makes it harder and thus more wear resistant [12].

The tooth geometry combined with the surface compressive stress results in stresses in the interface. The ratio between the radius of the cutting edge and the thickness of the coating is crucial to the stress magnitude in the interface. An increased ratio will decrease the stress in the interface. All kinds of irregularities generally give rise to local stress fields that may imply adverse effects on the adhesiveness of coatings. Examples of such irregularities are droplets, pores, contaminations, and topographic variations. Therefore, the topography of cleaned surfaces and the edge radius are two important factors to be controlled in order to avoid too early a collapse due to separation of the coating [13].

The tooth surface to be coated often diverges from an ideally smooth surface because of inherent surface irregularities. This deviation from the ideal surface results in cohesive coating failures linked to a surface irregularity. Figure 2.7 illustrates the coating failure linked to a droplet site.

An equally distributed thickness of the coating on both the rake face and the flank face leads in most cases to an improved cutting performance [14][15][2].
Thermal phase transformations in the PM HSS tooth’s substrate, during the tooth surface treatment, may also decrease the adhesion of the coatings. If the tempering temperature of the steel is locally exceeded during e.g. the grinding of the substrate before applying the coating, the substrate will undergo a phase transformation down to a certain depth, formatting a zone of impaired substrate material. The subsequent coating on this zone has then no proper support from the substrate to carry loads.

Excessive temperatures during the cutting process may also result in flaking of the coating film, in turn leading to a brittle fracture of the coating and the subsequent rapid wear of softened substrate material.

In many cases the tooth surface has to be prepared before PVD. Generally, the surface preparation is attained by a grinding process. The industrial grinding processes will more or less always produce burrs. Such irregularities under a hard and brittle coating will act as starting points for cracking. They will certainly break nearly instantaneously when being subject to external stress, and leave areas with unprotected substrate. Therefore it is, yet again, vital to consider the importance of edge preparation as an essential condition for achieving reliable cutting teeth [16][17].

Figure 2.7: Cohesive coating failures linked to a droplet site.
2.4.1 PVD- Titanium Nitride (TiN) and Titanium Aluminium Nitride (TiAlN) coatings

The properties of hard coatings are determined by their chemical composition and structure, which depend on the conditions of their deposition. By changing the deposition conditions, properties such as chemical composition, morphology, structure, texture, residual stresses and thus micro-hardness, the thermal expansion coefficient and oxidation resistance can be altered within certain limits.

Hardness is a very significant property, as being related to the abrasive wear resistance and therefore a matter of vital importance to the rate of wear. The stresses in the coating layer must be taken into consideration in the design of the edge radius in order to attain a robust tooth edge.

Coatings with PVD TiN were first used on High Speed Steel teeth because it could be applied below 500 °C, the temperature at which PM HSS starts to soften.

Today, Titanium Nitride (TiN) is the most utilized material for cutting teeth coatings. The coating material is a compound of titanium and nitrogen. Due to the high interaction between the metal and nitrogen atoms, this compound is highly thermodynamically stable, and thus resistant to diffusion and less disposed to adhesion. Therefore, the resistance to crater wear is high and the TiN coatings are characterized by a high level of toughness. The characteristic colour of TiN is goldish yellow.

Titanium Aluminium Nitride Coatings TiAlN coatings represent a further development of TiN. The TiAlN coating system was developed in order to improve the oxidation resistance, hot hardness and wear-protection properties. TiAlN coatings also have a higher oxidation resistance with a comparatively higher level of hardness than TiN. TiAlN is a metastable coating system, in which aluminium has superseded titanium by 20–60 atom %. Depending on the composition, these layers range from brown (low Al-contents) to black-violet (high Al-contents). With increasing Al-contents, the oxidation resistance of the TiAlN coating is increased. However, despite its improved oxidation resistance as compared to TiN coatings, this coating fails above approx. 800°C where the oxidation of the coating material begins and considerably affects the properties of the coating. The TiAlN coatings are deposited as monolayers, multilayers or gradient layers.

AlCrN coatings are also a further development of TiN [18]. Besides increasing the aluminium contents, another means to further improve the oxidation resistance and high-temperature properties of TiAlN coating systems is the adding of small amounts of oxide formers such as Cr, Y or Si. One example of this tendency is the AlCrN coating system. In comparison to the conventional TiAlN coating, the
AlCrN coating system has proved to have a higher resistance to abrasive wear as well as higher hot hardness and improved resistance to oxidation [19].

Coatings are poor heat-conductors and act as a thermal barrier to the heat generated by the metal cutting process. [20]. Low thermal conductivity of the coating film raises the cutting edge temperature rapidly, resulting in melting and/or softening of the edge, as the softening temperature of the substrate material (high-speed steel) of hobs is low (773K to 823K) [21].

However, in the present thesis, the TiN coating has been chosen for the evaluation of the tooth preparation in the STMT process, because this coating shows clear and distinct proof of the existence of a correlation between tool design and the occurring wear mechanisms. Experiments that have been performed with coatings of TiAlN as well as AlCrN are more difficult to analyze after a short running time [1].

The wear resistance properties often refer to the parameters specified by the standard VDI 3824/1, including:

- Coating technique
- Film thickness [µm]
- Oxidation temperature [°C]
- Thermal resistance
- Abrasive wear resistance
- Adhesive wear resistance (against steel)
- Diffusion wear resistance (against steel)
- Corrosion resistance of the substrate

2.5 Industrial manufacturing of gears

The research work in this thesis aims at making a contribution to the development of reliable High Speed Steels (PM HSS) teeth for use in soft machining.

The variety of machining processes used in the manufacturing of gears includes turning, hobbing, shaping, gear milling, broaching and several specialized processes as primary machining methods, illustrated in Figure 2.8. Shaving, grinding, honing, coroning and lapping are used as refining operations to improve accuracy and surface finish.

The industrial development of gear manufacturing by cutting methods is directed towards continuously increasing productivity, which is linked with tooth reliability in production. Basically, the factors that have an influence on the properties and behaviour of the cutting processes should be known and possible to control.
Another important goal is to develop cutting processes that are resource-saving and to make reliable teeth in an optimal way. At the same time, the type of work material has to be taken into consideration, as well as the lowest possible energy consumption, and other environmental factors [22].

Manufacturing of gears is divided into four process steps:

- The process of producing the gear in a soft state turning.
- The process of producing the gear in a soft state gear cutting.
- The process of producing the hard state gear (heat treatment).
- The process of producing the finished part.

![Simplified process description for gear manufacturing with focus on gear cutting with hob teeth. It is to be noted that in some processes the finishing, prior to the heat treatment, is carried out by means of a so-called shaving tool.](image)

There are several manufacturing options, see Figure 2.9 for an overview, to bring the gear into a soft state and these methods can be grouped into the following classes:

- **Metal removal methods**: Hobbing (HT), shaping, gear milling and broaching.
- **Non-metal removal methods**: Sintering, gear rolling and forging.

The largest amount of gears for automotive applications is produced today by hobbing. As a consequence, in this thesis the focus will be on hob machining that brings the part into a gear by a metal removal process in a soft state. The tool costs are very high in hobbing and the tooth has to be reconditioned before the gear surface quality deteriorates through the wear on the hobs. The problem for gear manufacturers is that today’s hobs lack reliability with respect to tool wear, making it difficult to predict the correct time for reconditioning. An improved tooth design, taking into account the tribological phenomena, would in many cases increase tool reliability and performance considerably [23].
2.5.1 The Hob Tooling (HT)

Hobbing is an industrial method for cutting teeth in spur gears, helical gears, worm gears, and many special forms. Usually, hobbing machines are not applied to cutting bevel and internal gears. Tooling costs for hobbing are lower than those for broaching or other methods. Therefore, hobbing is even used in low quantity production or even for a few pieces. On the other hand, hobbing is a fast and accurate method (as compared to milling, for example) and is therefore suitable for medium and high production volumes. The shape of the work piece sometimes limits the use of hobbing. Some of the advantages to using the HT are:

- High accuracy in a wide range of gear sizes.
- Flexibility with respect to production quantities.
- Adaptability to work materials with higher-than-normal hardness.
Hobbing is also suitable for cutting gears in hardened steel (sometimes as hard as 48 HRC), although the hob tooth wear generally increases rapidly as a function of the work piece hardness. Normal practice should result in a production of an acceptable number of parts before a necessary tooth sharpening, provided that the hobs are robust and reliable with a predictable wear rate. A successful gear hobbing on hard work material depends to a large extent on attaining a rigid mounting of both the hob and the work piece [12].

The rotating hob generates the gear teeth in a synchronously rotating work piece. The basic profile motion in relation to the generated gear (viewed from the centre shaft of the gear) is illustrated in Figure 2.10. The harmonization of these two rotational motions is normally attained by Numerical Control steering.

![Figure 2.10: The hob in position and action relative to the gear blank](image)

The kinematics of the process can be described by the unrolling of a gear wheel on a worm wheel. In this case the gear wheel is the work piece while the worm wheel is the tool. In order to produce a metal chip the hob is equipped with axial gashes. The hob tooth also has clearance angles in the circumferential direction. Geometrical parameters for hobs correspond to those for cylindrical worms such as the lead angle $\gamma_0$ and number of starts (entries of the worm). The number of tooth gashes on the hob circumference is identical to the number of hob blades, which for instance determines the blade pitch $\varepsilon$, an illustration is presented in Figure 2.11.
Hobbing is an intermittent process characterized by a discontinuous chip formation with complex and periodically varying cutting kinematics, resulting in a varying chip thickness along the engagement zone, and a different cutting volume on every tooth. This demands a tooth design that is optimized with respect to the cutting conditions and to each zone along the cutting edge of the hob. In conventional hobbing (up-cut hobbing) the directions of feed and rotation of the tooth are the same while in climb hobbing (down cut hobbing) the directions are opposite. The chip formation in gear hobbing demands one or several transversal motions of the tooth, besides the individual rotary motions of the tooth and the work piece.

In case of climb hobbing, the maximum thickness of the chip, in the cutting direction, is formed at the tip of the cutting edge, in the beginning of the cutting engagement. The chip thickness decreases continuously with the increasing cutting path, i.e. the mechanical stress on the cutting edge reaches its peak value at the beginning of the engagement. In case of conventional hobbing the chip thickness develops in the opposite way, i.e. from a minimum to a maximum chip thickness at the end of the cutting path [24].

In the DIN 3968 standard there are requirements on dimensional errors on single-start hobs. This normalization is universally recognized to be valid for hobs used in cylindrical gear manufacturing. Hobs are divided into 5 different classes (AAA, AA, A, B, C and D) of accuracy even though in reality only the (AAA, AA and A) classes are actually commercialized [25].
The DIN 3968 does not consider the tolerances for special profiles such as those with protuberance or with semi-topping. Therefore this standard covers only standard hobs. Generally, however, multi-start hobs are considered in the same manner as single-start hobs as far as manufacturing tolerances are concerned. Also, there is no standard specifying the micro geometry, particularly with respect to the cutting edges and the functional tooth surfaces, i.e. surfaces in contact with the work material.

Hobs for gear manufacturing can be divided into three categories according to their mechanical configuration. The whole body of solid hobs consists of High Speed Steel or metallic carbide. Hobs with inserted blades and hobs with adjustable teeth are particularly suitable for the manufacturing of gears with large diameters and standard modules. The three categories according to their mechanical configuration are:

- Solid hobs.
- Hobs with inserted blades.
- Hobs with adjustable teeth.

Gear shaving is a finishing operation that removes small amounts of metal from the flanks of the gear teeth. Shaving improves the finish of the tooth surfaces and can eliminate load concentration on the tooth, reduce gear noise, and increase load-carrying capacity [26].

Hardening is the normal process to change the state of a gear from soft to hard. The hardening of gears can be carried out by means of case hardening, which is a thermo-chemical heat treatment method for optimizing the mechanical properties of steel parts, and wear resistance. During the process, the geometrical properties of the soft gear changes due to the transformation in the hardening process from one metallurgical phase to another. Heat treatment methods are often divided into the following groups [27]. The “peripheral zone hardening” ensures that the hardening process is limited only to the upper portion of a component:

- Case-hardening is technically used more often than other methods to improve the wear resistance of steel surfaces and is used in mass production as well as in single part production.
- Nitriding is in contrast to case hardening a “lower distortion” heat treatment. Apart from the advantage of a wear resistant surface, nitriding also implies an improvement in the fatigue strength and resistance against corrosion.
In many types of gear manufacturing it is sufficient to limit the hard state abrasive machining processes, such as grinding, honing, to the hardened flanks of the gears.

Hard machining methods are only applied to the pre-machined surfaces of the gears. It must be ensured that the hard finishing process very precisely removes the allowance on the heat treated flanks.

### 2.5.2 Hobbing action

The gear hobbing process is characterized by complicated kinematics, chip formation as well as difficulties in describing tooth wear mechanisms and cutting forces [28]. The hob geometry and basic process kinematics for generating an involute tooth flank are illustrated in Figure 2.12.

Each gear gash is produced by penetrations of the HT teeth, lined up on one or more starts on the cylindrical body of the hob, into the work piece material in the subsequent generating positions.

![Figure 2.12: The hob shape (blue colour) and basic process kinematics to generate an involute tooth flank](image)

Chips can be removed in gear hobbing with different cutting kinematics and tool helix directions with respect to the flank inclination of the work piece. Because the ratio between the hob diameter and the radial cutting depth is very large in hobbing and because the center of the tool lies outside the circumference of the blank, the resulting kinematics corresponds to either down or up milling.

Considering the process kinematics of a hob with one start, each hob tooth penetrates into the next gear gash, in the same generating position and removes a chip with the same geometry as in the previous gear gash. By additional axial feed of the cutter, the tooth gaps are formed over the entire blank.
Attempts to describe analytically the chip formation in gear hobbing, which is dependent on the tool, gear and cutting data, have been carried out by numerous researchers [29][30][31][32][33][34][35][36][37]. Sulzer [38] developed for the first time a computer program to calculate numerically the chip cross-sections at successive hob revolving positions, in every generating position during the cutting of a gear, considering all gear, tool and manufacturing process data.

### 2.5.3 Chip formation generated by the HT tooth

The HT tooth generates the gear profile in a process called “involute generating”. This means that each of the successive hob teeth removes segments of material between the gear teeth. The shape of the produced chips varies depending on the position of the tooth, and the chip can be removed by either two flank edges or one flank edge together with the head edge of the tooth. Maximum chip thickness and chip length can be calculated by using Hoffmeister’s equations. [27].

An unsuccessfully performed chip formation process is exemplified in Figure 2.13. The removed work material resulted in clamped chips between the hob teeth and following that, in this example, the tooth breaks down.

![Figure 2.13: Illustration of compressed and clamped chips between the hob teeth, which has resulted in a tool break down.](image)

In the engagement phase, the chip formation starts successively at the leading edge, the trailing edge and the head edge of a hob tooth, which penetrates into the gear blank. The material removal during the successive positions is dominated by intense flow obstruction, due to the collision between chip segments. The obstruction of the chip flow in this region exerts a remarkable effect on the tooth wear propagation.

The hobbing kinematics makes it difficult to establish an analytical approach to estimating process parameters, such as the chip geometry in the individual generating positions, tooth wear and cutting forces.
2.6 Laboratory methods for cutting studies

This research work examines the possibilities to reproduce the typical wear mechanisms found on hobs used in dry gear cutting by using the single tooth milling test (STMT). In the developed laboratory test method, HSS cutting inserts are used to replace hob teeth. A conventional face milling machine equipped with a dynamometer measuring cutting forces and torque was used.

The assumption is that the wear mechanisms are mainly controlled by the intermittent cutting process parameters, i.e. cutting speed, feed, etc. and only to a lesser extent by the complex kinematics specific to hobbing.

Certainly, the extent and rate of the wear will differ as the produced chip geometries are significantly different in the STMT and in gear hobbing. However, the reproduction of the correct wear mechanisms is more important as they allow studies of any influence from edge geometry and surface characteristics.

The results obtained in the milling test should then be transferrable to gear hobbing. Moreover, the simplified kinematics involved in the STMT also facilitates measurement and analysis of cutting forces, torque, vibrations which is highly desirable in the evaluation of cutting edge properties, tool wear and for the optimization of a reliable tribological tooth design.

The capability of the STMT to reproduce the wear mechanisms in hobbing was tested in a comparative study. Both surface and cross-sectional analysis were performed on teeth from worn hobs and inserts at similar cutting conditions (removed chip volume).

Extensive and detailed research is required to study the influence of different cutting edge geometries and various functional tooth surface properties. The purpose is to apply these research results to the hob tooth design in an industrial environment.
2.6.1 Single Tooth Milling Test

In order to investigate the possibility of analyzing the effect of a tooth’s geometry and its surface preparation on the wear mechanisms in a laboratory environment, a single tooth milling method has been developed that consists of a milling cutter with a single PM HSS tooth. The milling cutter is mounted on a common milling machine [39].

The type of cutting tooth used in the STMT is illustrated in Figure 2.14 which also shows the two cutting edges involved in the chip forming process, the primary and the secondary cutting edges.

![Figure 2.14: STMT tooth geometry](image)

The milling tests were performed in a vertical spindle machine equipped with a single tooth milling cutter (diameter 89 mm) and a magnetic table for clamping the work piece, as illustrated in Figure 2.15.

The tribological studies in this thesis focus on wear produced on the rake face and the primary cutting edge which is the one producing the machined surface. The secondary cutting edge is also of certain interest as its chip contact length is varying during the engagement. A schematic picture of the milling test set up is shown in Figure 2.15 where the rake angles (12°) and clearance angle (6°) are indicated. Both the rake angles and the clearance angle in Figure 2.15 refer to the tooth position in the milling cutter. The results are presented in Chapter 4.
2.6.2 Single Tooth Milling Test action and kinematics

In up milling (U) (conventional milling) the work piece is fed in the opposite direction of the rotation of the milling tooth, which means that the chip thickness increases from a minimum value close to zero to a maximum value near the end of the engagement, illustrated in Figure 2.16. The cutting tooth has to be forced into engagement, resulting in extremely high friction and high temperatures that often lead to a deformed hardened surface due to the high contact pressure between the work piece and the tooth. Another shortcoming is that the chip might easily get wedged between the tooth and the work piece, resulting in a tooth being broken. (U) type milling will increase tool flank wear.
In down milling (D) (climb milling), used in the STMT experiments in this research, the work piece is fed in the same direction as the direction of the milling tooth rotation, illustrated in Figure 2.16. The chip thickness decreases from its maximum value at the entrance of the engagement towards close to zero at the exit of the engagement. (D) type milling will increase the risk of tool breakage.

In down milling, whenever chips are welded on the cutting edge and whenever they come along to the next engagement of the tooth, they are cut into pieces in the following engagement without any damage to the cutting edge.

The directions of the cutting forces with respect to vibration risks are more favorable in down milling than in up milling, during the engagement as well as at the exit from the work piece, despite of the fact that the cutting forces in most cases are larger in down milling.

In STMT, as well as in HT, the ratio between the tool diameter and the cutting depth is large, i.e. the centre of the tooth holder lies outside the radial cutting depth which means that the maximum chip thickness is smaller than the feed per tooth.

The axial rake angle ($\gamma_a$) and the radial rake angle ($\gamma_r$) are two design angles that can be negative, neutral or positive. These angles are measured in planes that are parallel with or perpendicular to the axis of rotation of the tooth, respectively, as illustrated in Figure 2.17 with the actual set up of the STMT. The chip thickness varies depending on the way the milling tooth enters the work piece.
The tooth in the STMT experiments is mounted in the cutter with double positive rake angles. The positive axial rake angle contributes to a favorable removal of the chips by the tooth in the chip formation. Chips originating from the STMT process and HT, respectively, are presented in Figure 2.18.

Figure 2.18: Chips collected from the STMT process, and chip shapes from the HT process (beside the small gear wheel)
2.6.3 Chip formation in Single Tooth Milling Test

In the primary deformation zone (zone E₁) the work material is the subject of shearing and therefore separated as chips. In the secondary deformation zone (zone E₂) the chip slides on the tooth face and is sheared against the rake face of the tooth. Finally, in the tertiary zone (zone E₃) a new surface of the material is generated (or opens up) at the same time as the tooth’s flank face slides against the work piece, as illustrated in Figure 2.19

![Figure 2.19: The three deformation zones in the cutting process](image)

The width $\varepsilon_{II}$ of the secondary deformation zone and that of the tertiary zone, illustrated in Figure 2.20, highly influence the service life of the cutting tooth [40].

In the secondary shear zone, the tooth–chip interface is dominated by high friction for which explicit expressions do not exist, and it is further influenced by the presence of tooth wear. The shear strain rate is very large, to the order of $10^4$–$10^5$ s⁻¹.

As has been pointed out by Trent [4], the contact between tooth and work surfaces is so nearly complete over a large part of the total area of the interface that sliding at the interface is impossible under most cutting conditions. Over the areas of bonded contact, the tooth and work materials have effectively become one piece of metallic material, which is referred to as a condition of seizure. This area comprises a hydro-dynamically sliding layer.
Tribo-layer formation is an important phenomenon in the secondary deformation zone. This layer of work material welded onto the tooth rake face has been described in literature as ‘material transfer layer’, which transfers the work material from the chip onto the tooth surface [41] and [42].

2.7 Tooth geometry

The concept of ”tooth geometry” refers to the tooth design and dimensions. The geometry and its variations has a direct influence on the chip formation, which in turn affects the edge temperature, cutting forces, the surface roughness and the cutting performance as a whole.

Generally two types of tooth geometries are distinguished: the macro geometry and the micro geometry, respectively. The macro geometry refers to the basic shape of the cutting edge; for instance, in the case of indexable teeth, the geometry is defined by the current ISO or DIN codes. The micro geometry refers to the region around the edge, and comprises for instance the ground chamfer and the edge rounding as well as defects such as burrs and notches originating from manufacturing, within the range of measurement up to 10 µm.
The tooth geometry must meet the following two requirements:

- The macro geometry must give a correct machined shape and geometrical and dimensional tolerance and also make it possible to carry applied loads.
- The micro geometry must be adapted to the load to which the edge is subject to in its contact with the work material. Heavy demands should be made in order to avoid both an incorrect load distribution on the edge and chipping of the edge. A weak edge is illustrated in Figure 2.21. Sharp edges in combination with high intrinsic stresses in the PVD-coatings lead to chipping of the coating and edge wear.

![Figure 2.21: Illustration of a weak and sharp cutting edge with unpredictable coating thickness](image)

The tooth micro geometry has a direct influence on the cutting process and it is therefore of utmost importance for the machined surfaces [43][44][45].

The rake angles affect the radius of curvature of the chip when it is removed from the cutting zone. Normally, a negative rake angle decreases the radius of chip curvature and a positive angle increases it. A positive rake angle gives smaller cutting forces but a weaker edge that is more sensitive to, for instance, intermittent machining. The strength of the edge can also be improved by means of a reinforcing chamfer.
2.8 High speed steel tooth preparation

PM HSS milling teeth are primarily roughly machined in soft state and then ground to the final desired macro profile. In the manufacturing of PM HSS hob teeth, the rake face is in most cases ground (neutral rake angle) perpendicular to the pitch of the worm. Profiling implies that the teeth are ground to their final shape, as illustrated in Figure 2.22.

![Figure 2.22: A hob tooth after the finish shape](image)

Grinding is a sensitive process to optimize with respect to cutting data and machining temperatures. If the grinding depth and the feed are too large there is an impending risk that the PM-HSS tooth will be overheated resulting in a deteriorating softening by tempering.

The grinding process will leave burrs along the edge line of the tooth. To make the tooth coating possible it is necessary to apply a de-burring process following the grinding operations. Before coating there is a need for removing the fragments round the edge line; otherwise the strength of the coating will fail.

Residual stresses always occur in the substrate after the tooth grinding process. Residual compressive stresses improve the tool life while residual tensile stresses in some cases cause direct tool break-downs due to the acting compressive stresses of the PVD layer, when this has been deposited.

2.9 Tribological tooth design

Tribological tooth design aims at the edge preparation and surface treatments on the micro level. Correct tribological tooth design results in increased reliability, productivity and improved machined surfaces that meet the desired product specifications. Chipping is a typical wear symptom of an incorrect tooth design with respect to tribological criteria.
2.9.1 The influence of the edge radius on the tooth wear

When choosing cutting tools for a certain application, it has proved necessary to consider the micro geometry. The optimum micro geometry is determined by several parameters, such as the properties of both the tooth material and the work material, and the chip thickness. Teeth made of PM-HSS materials often lack edge preparations. Furthermore, micro geometrical defects are more frequently observed on cutting edges without an edge preparation. Some examples of preparations of cutting edges on PM HSS hobs have given promising results with respect to the wear resistance [46].

The performance of coated PM-HSS teeth is highly dependent on the preparation of surfaces and cutting edge rounding before depositing the coating, as well as the polishing of the coating in order to remove droplets that can be the subjects of concentrated loads [1].

The design of an optimal cutting edge radius (ER), is very important to the performance of the cutting process [1][47][48]. In addition to the STMT experiments that were carried out in the presented research, other researchers such as Rech carried out several fly hobbing experiments in order to analyze the behaviour of cutting edge preparations. The experiments are explained in detail in [49], and the article shows that also in gear hobbing the edge preparation of the hob is a necessity that can significantly prolong the service life of the cutting teeth.

An example of a model with a TiN coated PM HSS tooth is shown in Figure 2.23 with the maximum stress concentration at the edge, as a function of ER/tc. To avoid fracture in the edge and the coating, an optimized ratio ER/tc, i.e. the relation between the (ER) and the thickness of the coating (tc), must be taken into consideration in the tooth design [13][50].

![Figure 2.23: A model for TiN on PM HSS, maximum stress concentration at the edge as a function of ER/tc](image-url)
Depending on the chosen manufacturing technique, the geometry of the edge line will be curved approximately to an arc, which means that the edge rounding profile can also be micro-geometrically considered as an arc of a circle with the edge radius.

Hobbing and milling tests indicate that a sharp cutting edge is very sensitive to load concentrations in its first few engagements, but also that abrasive wear in a natural way generates blunted edges [40]. Both the tool life and its variation can be optimized by means of the edge radius and an adequate coating that protects the cutting edge from thermal shocks. The optimal edge radius and coating keep the cutting edge sharp enough to cut chips and at the same time prevent the edge from being subject to chipping. The increased life of a rounded edge is a result of the stabilization of the cutting edge. The high stresses that occur in the coating close to a sharp cutting edge will often lead to cracks in the coating. A rounded cutting edge on a tooth is more stable and can in a better way resist the dynamic loads which occur in an intermittent cutting process.

When the edge radius exceeds a certain value that is dependent on several parameters, e.g., the cutting data, the work material, the tooth substrate, the type of coating, the result is a drastic reduction in tool life.

Without an edge preparation, the wear will reach a severe state rapidly, while the preparation of the edge, e.g. edge rounding, contributes to both the strengthening of the edge geometry and protection against defects such as chipping [51].

The size and geometry of the cutting edge rounding will affect the chip formation, which is also affected by the position of the so-called stagnation point on the cutting edge, at a distance of \( y_s \) measured from the reference plane at the machined surface, as illustrated in Figure 2.24. The position of the stagnation point is proportional to the third deformation width \( \varepsilon_{III} \) [52].
In the down milling process the chip thickness decreases towards zero. The work material that is pressed against the tooth has to exceed the yield-point of the work material either on the rake face or on the flank face. These two situations are equally likely to occur, as stagnation zone is established. The position of the stagnation point, as well as the size and stability of the stagnation zone [52], can vary depending on the adhesive capacity of the cutting tooth and the degree of deformation hardening of the work material.

In down milling, as used in STMT, the chip thickness varies from a maximum value to a low value close to zero. This situation is also normally valid for hobbing in the case of down milling. This lower limit, the lowest theoretical chip thickness, is primarily dependent on the size of the edge radius of the cutting tooth. The tooth will smear the work material when the relationship between the chip thickness and the edge radius reaches a certain value without resulting in a proper chip formation.

**2.9.2 Tooth surface treatment**

In the case of a coating onto an infinite and perfectly flat and smooth surface, the coating adheres perfectly on the substrate. However, in reality the surfaces are neither infinite nor perfectly smooth. Therefore the coating on real surfaces generates compressive residual stress which results in a tensile “lift-off” stress illustrated in Figure 2.25 [13].
Figure 2.25: Lateral compressive stresses $\sigma$ are present in most PVD-coatings. These stresses in combination with surface irregularities cause tensile stresses that will generate a “lift-off” effect.

The surface roughness of the tooth and the dimensional accuracies of the micro geometries are issues that have been researched and discussed. It is difficult to find sufficient general conclusions in literature with respect to the direct influence of surface properties on tooth performance. The surface roughness of the teeth has in some applications proved to be very important for preserving the coating [53]. It has been pointed out in research reports that rake faces with a defined roughness cause a considerable reduction of the formation of built up layers and built-up edges [54].

The effect of roughness can be two-fold as the friction between the rake face and the chip has two origins. Firstly, the topography component of the friction coefficient is dominant and a rough surface will increase the friction coefficient. Then, once a layer of transferred work material has been formed, most sliding occurs at the interface between the work material and this layer, resulting in a decreased shear resistance. Components in the work material such as Si and Mn have also been found in regions that have been exposed to extreme compressive stresses and temperatures. These components have with oxygen from the environs been oxidized to tribo-layers with glassy structure [15][2][16].

The benefit of excessive polishing might seem to be significant for a reliable tool design [4][55][56][57]. However, the amount of layers mentioned above is reduced with decreased surface roughness.

The regions in Figure 2.26 represent initial, steady state (light, adhesive wear) and catastrophic tooth wear (severe, adhesive wear), respectively, and the influence of tooth surface preparation and coating is also indicated in [58][59].
2.10 Conclusions

To optimize the balance between production economy and gear quality, making a cyclic reconditioning scheme possible, the wear of the cutting teeth must be stable and predictable. Severe wear and non-predictable variations in tool life restrict the efficiency of the gear production of today. This restriction becomes even more evident as the industry aims to reduce the use of environmentally hazardous cooling lubricants by introducing dry machining, which contributes to higher mechanical and thermal loads on the teeth.

Experiments in industrial environments bring about an economic loss since a gear hobbing machine has to be taken out of the production line for rather a long period of time due to the time-consuming experiments. In addition, since industrial hobs are often borrowed, it is usually only possible to carry out non-destructive analyses, i.e. deeper analyses might be limited.

In order to investigate the possibility of predicting the wear mechanisms that occur on the hob tooth in real industrial gear hobbing, a single tooth milling method has been developed by using a PM HSS tooth. The tooth is mounted on a common milling cutter.

By means of the STMT method the substrates and coatings of the experimental teeth in this thesis have been evaluated with respect to an optimized tooth design and surface treatment, see Chapter 4.
References in chapter 2


2.35


2.37


3. Study of wear phenomena

In Chapter 2, an analysis of the research work performed on tool materials, work materials, tool geometries and kinematics as regarding HT and STMT was presented. This analysis shows very clearly the differences between the two processes with respect to kinematics and chip formation. However, considering the work and tool materials, cutting parameters and types of coating, it is interesting to analyze the wear mechanisms generated by the two processes. This may be important to the design and the realization of the tooth’s surfaces and edge geometry. The aim of this chapter is to evaluate whether or not the results from STMT could be applied to HT design. Chapter 4 presents the effects of varying surface roughness and edge radius on wear mechanisms.

3.1 Tooth substrates and coatings

PVD coated PM-HSS teeth with various surface roughness and edge geometries were tested in STMT [1], and evaluated with respect to tool wear mechanisms.

In the HT analyses, a reference hob was used, which was made of high alloy metallurgical powder HSS, ASP 2052 (of a core hardness of about 67 HRC) and coated with AlCrN, while the tooth substrate for the STMT experiments was made of high alloy metallurgical powder HSS ASP 2030 (also of a core hardness of about 67 HRC), and coated with TiN or TiAlN.

The mechanical properties of the coatings are stated in Table 3.1 and the chemical HSS composition is stated in Table 3.2.

Table 3.1: Mechanical properties of the coatings used on hobs and teeth

<table>
<thead>
<tr>
<th>Material (coating)</th>
<th>Hardness Mikro HV</th>
<th>Residual stress [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCrN (HT)</td>
<td>3200</td>
<td>-4.3 ± 0.3</td>
</tr>
<tr>
<td>TiAlN (STMT)</td>
<td>3000</td>
<td>-3.4 ± 0.3</td>
</tr>
<tr>
<td>TiN (STMT)</td>
<td>2300</td>
<td>-2.5 ± 0.3</td>
</tr>
</tbody>
</table>

As has been stated in Chapter 2, the chemical composition is related to the properties of the material. The two materials presented in Table 3.2 are relatively equal and they are utilized in hob manufacturing. In addition, ASP 2052 is also adapted to meet the requirements of increased wear resistance and hot hardness made on these types of tools by gear manufacturers.
Table 3.2: chemical composition of HSS substrate

<table>
<thead>
<tr>
<th>Material (substrate)</th>
<th>Nominal chemical composition [%, balance Fe]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASP 2052 (HT)</td>
<td>C 1.60 Cr 4.8 Mo 2.0 W 10.5 Co 8.0 V 5.0</td>
</tr>
<tr>
<td>ASP 2030 (STMT)</td>
<td>C 1.28 Cr 4.2 Mo 5.0 W 6.4 Co 8.5 V 3.1</td>
</tr>
</tbody>
</table>

Generally, when designing the tooth the following issues must be considered:

- The properties of the tool materials and the requirements on these with respect to the cutting operations in which the tools will be used.
- The macro geometry, i.e. the shape of the tooth.
- The micro geometry, i.e. the edge rounding and the surface roughness of the tooth before and after the depositing of the coating.

### 3.2 Classification of tool failure

One critical issue is that industrial hobbing processes of today often lack reliability, which makes it difficult for the users to predict the hob teeth wear and thus enable recondition of the tool before too severe a damage occurs. A PM-HSS hob tooth has to be reconditioned before wear reaches such a level that the gear quality becomes impaired or tool failure occurs.

A consequence of using STMT [1] is that the kinematics are considerably simplified as compared to HT, a fact that facilitates the analysis of the effect of various cutting edge and tooth surface preparations on the wear mechanisms.

In this chapter, contact conditions between the tool and chip are presented. The contact area estimations are not sufficient for evaluating the stresses on the contact surface, the contact areas have nevertheless to be measured for this purpose. The contact area is divided into three zones.

The first zone represents the sticking friction region; the second zone the so-called flow zone region and the third zone the sliding friction region.
The first zone starts at the primary edge of the tool and extends a small distance along the chip side of the insert. The third zone extends over a short distance before the chip loses its contact with the tool and leaves the rake face of the insert. In between these two regions the second zone is located. The third zone can be characterized by a constant coefficient of friction, according to the Coulomb model. The behavior of the flow zone is better described as an extremely viscous liquid. The first zone can be characterized by a constant frictional stress equal to the shear flow stress of the chip material. The extent of the sticking region is thus a result of the friction value in the sliding region. [2].

However, the boundaries between the different zones are not always well defined and it can therefore be hard to locate them, especially the boundary between the second and third zone. Investigations made by [3] show that the flow zone region has a characteristic structure, consisting of equi-axed grains of very small size.

The flow zone region and the sliding friction region are connected to each other. Since the boundary between the zones is sometimes difficult to detect it is often better to measure them together as one zone. The major part of this zone will then be represented by the flow zone, and only a small portion can be associated with the sliding friction region.

It is only possible to measure wear after the machining process has stopped. Consequently, the measured wear traces represent the final and maximum tool-chip interface. No reliable online measuring method is available at this time.

The tool-chip interfacial friction can be characterized by different methods and parameters. In this research work the tool-chip contact length and contact area are used.

The classification of tool failure mechanisms is of importance of the evaluation of tooth designs.

The dominant mechanisms of tool wear are adhesion, abrasion, tribo-chemical reactions, surface fracture, and diffusion.

Adhesion describes the capability of two materials to interact as a compound. During the chip formation, high pressures and temperatures prevail which imply a number of chemical reactions. There are various interactions that may take place between the work piece and the tooth, one of which is like cold welding.

Due to plasticity and the close contact between the work material and the tooth, several phenomena can take place, such as an atomic interaction, a diffusion process, an electrical polarization.

3.3
The coefficient of friction is defined by the ratio between the tangential force needed for moving the two materials, and the normal force that presses the materials together. Due to the conditions in the plastic flow area, the coefficient of friction is not behaving as a classic coefficient of friction. The adhesion process also includes transport of micro-welded material from one surface to the other.

Another wear mechanism is abrasion. Particles in the work material can exert a grinding effect on the surface of the cutting tooth.

Tribo-chemical reactions are caused by the friction in the cutting process. In some reactions the work material and oxygen from the environs can interact. By means of these reactions the surface of the tooth can change its tribological properties.

The surface fracture does not necessarily occur immediately, but after too heavy loads have been applied to the tooth. After some time, crack formation and material fatigue takes place which can lead to the erosion of particles.

Another wear mechanism is diffusion. Due to the reactive circumstances during the cutting process, atoms can diffuse from the work material into the tooth, a process that is high enhanced by high temperatures.

One wear mechanism or a combination of mechanisms can cause a certain type of wear, which can be described as the resulting geometrical wear. Examples of wear types are illustrated in Figure 3.1. For instance, crater wear can be caused by adhesion, abrasion or diffusion. Tooth failure caused by a wear type is in most cases associated with the properties of the tooth surfaces and the cutting edge being in contact with the work piece and the chip. A wear pattern is dependent on the mechanical and thermal loads acting on the cutting tooth. For a tooth to present a stable and predictable performance, the wear type must be uniformly distributed on the tooth surfaces and gradually developed over time.

![Figure 3.1: Typical wear types on a PVD Coated PM-HSS hob Tooth](image-url)
In the preliminary HT study of this research work, wear has been observed on eight various PM-HSS hobs, temporarily picked out from the production lines at seven Swedish gear manufacturers. The aim of the study was to identify wear mechanisms and to recognize the common problems associated with these tools in order to facilitate the development of more reliable tools. Since the tools had to be reinstalled, the analyses were carried out with non-destructive methods.

Apart from edge chipping, wear was principally located on the rake face of the teeth in the HT process. Five of the eight hobs presented wear due to the occurrence of one or several craters on the rake face. The shape and the position of most of the craters gave the impression that wear was dominated by a large amount of discrete fractures rather than being continuous, illustrated in Figure 3.3. The fractures were related to “isolated” defects that resulted in a significant reduction of wear resistance [3].

For a reliable evaluation of the effects of the tooth’s surface roughness and edge geometry on wear, illustrated in Figure 3.2, it is very important to identify the correct wear mechanisms occurring on both the STMT and HT teeth.

Figure 3.2: Sharp cutting HT edge with burr

In addition to the preliminary study presented above, a detailed analysis of the wear types was carried out. In the first stage, the wear on HT teeth is presented in Figure 3.3 (a) and the wear on STMT teeth is presented in Figure 3.3 (b). The wear is generated by limited edge chipping and thermal softening of the tooth material on the rake face. This reduces the load bearing capacity of the coating, which often results in failures, such as cracking and brittle fracture. Once the coating has been lost, a large crater on the uncoated area will rapidly develop, as severe adhesive wear together with the detrimental effect of increased temperatures influence the tooth substrate.
Figure 3.3: Representative SEM pictures of the cutting edge of, (a) worn HT tooth and (b) a STMT tooth after 60 min of machining time.

The cutting conditions in intermittent cutting, such as down milling, involve a significant load impact that is followed by a load that varies with the chip thickness and ends in a high thermal load where the tool acts as a plough in the work piece as the chip thickness is nearing zero.

The hob tooth is relatively cool when it enters the work piece engagement, then it is heated as the chip is formed and then finally cooled down before entering the next cycle. This means that the cutting cycle involves both mechanical and thermal shocks that affect the tooth integrity.

Fatigue wear is often caused by a combination of temperature fluctuations and fluctuations of mechanical loads, and results in many cases in cracking and degradation of the cutting edges. Examples of fatigue wear on teeth close to the cutting edge are presented in Figure 3.4 (a) from the HT process and in Figure 3.4 (b) from the STMT process.

Figure 3.4: Enlarged areas indicated in respectively (a) HT tooth (b) STMT tooth. The inserted enlargements clearly show cracks close to the free edge of the coatings.
There was a difference between the cutting speeds employed in the STMT pre-study (160 m/min first, followed by 120 m/min finally) and in the HT reference-study (150 m/min) [1]. (The reference hob had been used in a gear production line at a Swedish gear manufacturer). Cutting data from the two processes are presented in table 3.3 below. However, it should be noted that a cutting speed of 120 m/min in STMT was sufficient for generating relevant wear in the evaluation of the influence of surface roughness and edge geometries.

<table>
<thead>
<tr>
<th></th>
<th>Cutting speed [m/min]</th>
<th>Feed tooth [mm/rev]</th>
<th>Depth of cut [mm]</th>
<th>Max chip length [mm]</th>
<th>Max chip thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HT</strong></td>
<td>150</td>
<td>0.27</td>
<td>7.1</td>
<td>25</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>STMT</strong></td>
<td>120 or 160</td>
<td>0.25</td>
<td>8 resp. 3</td>
<td>27</td>
<td>0.25</td>
</tr>
</tbody>
</table>

An initial wear, often involving tip blunting through minor fractures and chippings, is followed by a gradually increasing, steady-state wear dominated by abrasive and adhesive wear. Gradual tip blunting is one of the reasons for a successively increasing edge temperature, and eventually, a situation of accelerated wear resulting in edge fracture or in severe permanent deformation.

### 3.3 Contact conditions in Hob Tooling and Single Tooth Milling Test

The characteristics of both substrate material and coating film will control the way the cutting parameters affect the contact conditions. The abrasive wear and the chipping of the cutting edge depend on the hardness of the coating film. The adhesion influences to a large extent the flaking of the coating and therefore the chipping of the tooth. At higher cutting speeds, the oxidation wear has a predominant role due to the rise in temperature in the cutting zone. This is connected to the thermal conductivity of the coating film; lower coating thermal conductivity contributes to a rapid increase of the cutting edge temperature resulting in softening of the edge.

It is complicated to analyze the real contact area because it varies in most cases during each engagement and also depends on the edge geometry of the tool and the state of the contact between the tool and the chip, which in turn is affected by the occurrence of wear. One method to estimate the contact area on the rake face consists of a chemical analysis at a number of points in a line along the rake face in the chip direction. This is illustrated in Figure 3.5. Adhered material was found on the rake faces of the teeth. Work material sticks to the tooth in the area where the chip is separated from the tooth rake face.
Figure 3.5: The SEM picture shows an example of a spectral analysis line of the chemical composition of the adhered work material represented in 13 points (marked in red) in a line along the rake face orthogonally from the cutting edge. The distances between the points are 30 μm. The diagram shows an example of the chemical composition of the adhered work material on a STMT tooth surface on the rake face (point 1 is the closest to the primary cutting edge). The tooth is PVD coated with a TiN coating.

The chemical properties of the tool material and the affinity of the tool material and coating film to the work piece material decide the rate of the diffusion wear. Work material is often smeared on the tool surfaces. Results are presented for the HT process in Figure 3.6 (a), and for the STMT process in Figure 3.6 (b). Layers of adhered material occur mainly on the rake face of the tool, and often result in the formation of built-up layers [1].
Figure 3.6: Is a close up of the rake faces revealing patches of adhered material on (a) a HT tooth, (b) a STMT tooth.

The amount of adhered material increases with machining time. The formation of built-up layers (BUL) takes place under high pressure and high temperatures. An analysis in SEM-EDS clearly shows this phenomenon, and apart from the coating elements, the formed layers show traces of components from the work material. This can be found on the teeth of the HT, as illustrated in Figure 3.7, as well as on the STMT teeth, as illustrated in Figure 3.8, and presented in the pre-study of this project [1]. Oxidation (normally a glassy structure) is a common mechanism in the interface between the rake face and the chip, at the end of the contact length.

In the cutting process a fresh metal interface is continually generated at a very high pressure and temperature. The interface and its environment probably promote diffusion and chemical reactions between the tool and the work piece [5].

Various types of very hard particles are present in most work piece materials, and their hardness can often be compared to that of the tooth substrate and the coating, which generates an abrasive effect on the tooth.
Rake face on worn hob tooth, PVD AlCrN-coating

Figure 3.7: EDS-analysis of glassy layers on a worn HT tooth and the adhered work material.

Rake face on worn cutting insert, TiAlN-coating

Figure 3.8: EDS-analysis of glassy layers on a worn STMT tooth and the adhered work material.
The origin of heat in the secondary deformation zone is associated with the friction between tool and chip. By applying a coating to the tool substrate, the temperature of the tool can be lowered through improved contact conditions and the adhesive effect is also reduced on the tooth surfaces. In Figure 3.9 general thermal load distribution in a PM-HSS tooth is illustrated with the maximum located some distance from the cutting edge on the rake face. A significant thermal influence on the tool substrate is noticed. The mechanical properties of the substrate material are heavily altered.

![Figure 3.9: General temperature distributions in a PM HSS metal cutting edge during the chip formation in a turning process.](image)

Wear and edge failure involve changes of the geometry of the tooth. This affects the cutting capability which in turn implies different loads on worn and sharp edges. An edge that gradually loses material during a continuous wear process will lose its cutting capacity correspondingly [6] and [7].

Chippings and crater wear are special types of wear on the cutting tooth of a hob. These two wear types are closely associated and often occur together. As described above, high temperatures prevail in the tool during the cutting process. The heat generated during the process of material removal generates wear on the tooth surfaces by adhesion and diffusion. Because of the conductivity of the materials, the heat affects and increases the flank wear. These wear types affect the quality of the machined surface and the endurance time.

In recent literature it is stated that the edge geometry and the tool surface roughness, prior to and after the application of the coating, are matters of vital importance to defects in the coating, in the hob steel substrate, or in the interface between them. These defects, in turn, are the cause of unpredictable wear of the cutting edge [8].

3.11
3.4 Machined surfaces

The condition of the cutting edge (impaired by wear mechanisms) affects the machined surface quality. This phenomenon is illustrated in Figure 3.10 (a) with an example of a severely worn tooth and in Figure 3.10 (b) with an example of a slightly worn tooth.

![Figure 3.10: The machined surface comprising regular waviness as well as smeared work material. The latter is greater and more frequently observed on surfaces machined with (a) severely worn tooth, rather than (b) slightly worn tooth.](image)

The surfaces machined in HT with a slight wear and severe wear, respectively, are presented in Figure 3.11. The effect on the surface quality of greater wear of the cutting edges is apparent. The bearing ratio curve for the surface machined with the severely worn hob is less flat (i.e. it has a higher $R_s$ value) and both $R_{pk}$ and $R_{vk}$ values are higher, as compared to the same parameters of the surface machined with the slightly worn hob tooth. The $R_s$ and $R_z$ values are also increasing with the wear of the tooth. The same observation is valid for the machined surfaces in the milling tests, illustrated in Abbot curves in Figure 3.12. Measurements were done on surfaces machined after the tool had been used for 1 and 60 minutes.

A detailed cross-section is presented in Figure 3.13, where a local heavily deformed area of the work piece surface has been smeared over the work surface by a severely worn tooth. The smeared work material is not a homogeneous part of the machined surface on the work piece, and therefore this surface will not comply with stipulated properties.
Figure 3.11: Gear wheel surfaces machined with slightly used hob teeth (broken line) and severely used hob teeth (solid line).

Figure 3.12: Surfaces machined with ground STMT tooth after approximately 1 min (grey) and 60 min (black). Error bars indicate scatter between different tests.
In hobbing, the work material that is not removed by a worn edge will instead be removed by the subsequent edge or edges in contact with the work piece, as stated above. It is also possible that – due to damage – several edges in succession do not remove any material, resulting in accumulated chip thickness that the next intact and engaged edge has to take charge of, resulting in increased thermal as well as mechanical loads on these teeth that in turn increase the rate of the wear propagation.

The cutting edge geometry can be affected by the work material that is attached to the edge due to the formation of layers and built-up edges. Built-up edges are generally a means for the cutting process to adjust itself to the prevailing circumstances and they increase the rake angle. However, since BUE is a dynamic process, BUE material will be smeared on the work surface.
3.5 Conclusions

Adhesion is a common wear mechanism on the interface between the tooth and the work material, as is oxidation caused by high temperatures and the presence of air. Various types of very hard particles are present in most work piece materials, and they are often comparable to the tooth substrate and coating with respect to hardness and have therefore an abrasive effect on the tooth. Fatigue wear is often caused by a combination of temperature fluctuations and fluctuations of mechanical loads, and results in many cases in cracking and breaking of cutting edges, an illustration of the tooth wear process resulting in total tool break down is presented in Figure 3.14.

![Figure 3.14: Tool wear process](image)

The work material that has not been removed by a worn edge will instead be smeared on the machined surface of the work piece. This will occur in both HT and STMT. It is also possible that – due to damage – a succession of edges do not remove the desirable amount of work material in HT, which results in an accumulated chip thickness that the next intact and engaged edge has to take charge of. The result will be an increase in both thermal and mechanical loads on these teeth which in turn will increase the rate of the wear propagation.

References in chapter 3


4. Evaluation of the influence on tooth design

In this chapter the selected tooth design parameters for preparation of the PVD coated teeth have been tested by the Single Tooth Milling Test (STMT) method. The evaluation in this investigation, including analyses and theoretical interpretations which support the actual observations, is based on the mechanical load conditions and the type of developed wear after a constant machining time.

4.1 Influence of mechanical loads on cutting teeth

The evaluation of important parameters of tooth design, which was carried out in STMT experiments, has been expanded into deeper analyses of the influence on cutting teeth of edge rounding and surface preparation on wear characteristics. The analyses have been carried out quantitatively, based on laboratory experimental studies by means of STMT. Qualitative analyses are also presented so as to support the actual observations. In addition to these studies, the wear pattern on the cutting teeth has been investigated and qualitatively evaluated.

Before presenting and discussing the experimental results, the analysis of mechanical loading on the tooth-chip interface has to be considered. In the next section a force model will be examined that considers the forces acting on the cutting tooth in an explicit manner. The relationships between the parameters are very complex and the main goal is to identify an optimized tooth design by means of quantitative as well as qualitative analyses.

4.1.1 Cutting force in Single Tooth Milling Test

The cutting force varies with changes in the tooth micro-geometry design and with the modification of tooth micro-geometry caused by wear. The cutting force components in the shear zone and on the chip/tool interface gives an indication of energy transferred in the cutting process and generated heat. Therefore, an accurate measurement of the cutting force is essential so as to optimize the tooth design. A systematic analysis of the relationship between tooth characteristics and cutting force components has been carried out and the results were related to the contact area at the interface between chip and rake face, as well as to the wear patterns. In intermittent machining, both the magnitude and the direction of the cutting force vary with the chip thickness. One advantage of using the STMT method is that the effect of each of the tooth characteristics can be studied separately. In the STMT experiments, a force sensor measured the components $F_x$ and $F_y$ of the force acting on the tooth, in a x- and y-coordinate system.
The mechanical loads on the tooth are influenced by the angles at which the tooth is mounted in the holder. For practical reasons, it is more convenient to carry out force analyses based on the tangential and radial force components, which generally are associated with the cutting force component and the feed force component, respectively. While the cutting force can be measured accurately, the same cannot be said of the contact area (tooth/chip), which is usually ill-defined. Surveillance of this area during machining is not possible. When the tools are examined after use, worn areas, deposits of smeared work material and small irregularities, as well as discoloration due to oxidation or carbonization of cutting fluids can usually be observed. The deposits may be on the worn areas, or in adjacent regions, and the boundaries of the worn areas are often difficult to observe.

The vectors $F_T$ and $F_R$ in Figure 4.1 represent the tangential and radial force components acting perpendicular to and parallel with the rake face, respectively. $F_T$ and $F_R$ are vectors in a Cartesian coordinate system that form the radial rake angle $\gamma_r$ (12°) with the $F_X / F_Y$ – dynamometer system. The axial rake angle $\gamma_a$ (6°) in Figure 4.1 refers to the inclination of the rake face. In Figure 4.1, the engagement angle $\phi$ represents the relative positions of the cutting tooth and work piece, in the coordinate system $X_0 / Y_0$.

Figure 4.1: Illustration of the Kistler force components $F_X$ and $F_Y$ momentarily acting in the x-and y-plane at engagement angle $\phi$ and the tangential and radial force components $F_T$ and $F_R$, respectively.
The measured force components $F_x$ and $F_y$ are transformed to force components $F_T$ and $F_R$ in the $F_T / F_R$-system, according to Eq. 4.1 and Eq. 4.2, where $\gamma_r$ is the radial rake angle, as illustrated in Figure 4.1.

\[
F_T = F_x \cos \gamma_r - F_y \sin \gamma_r \tag{4.1}
\]

\[
F_R = F_x \sin \gamma_r + F_y \cos \gamma_r \tag{4.2}
\]

4.1.2 Load functions

Load functions describe the relationships between the force components acting on the tooth faces. Load functions contribute to attaining a good understanding of the load situation around the cutting edge [1].

The loads that act on the tooth are projected force components in the $x-y$ plane. The loads are combinations of tangential and radial force components as stated in the previous section. Each of these force components gives rise to both compressive and shear stresses on each face of the cutting tooth.

The tangential force component $F_T$ causes a compressive stress on the rake face and shear stresses on the two flank faces, while the radial force component $F_R$ generates a compressive stress on the primary flank face and shear stresses on the secondary flank face and the rake face.

The force components $F_T$ and $F_R$ cause normal forces ($N$) and shear forces ($S$), acting on the rake face ($rf$), the primary flank face ($ffp$), the secondary flank face ($ffs$), as formulated in Eq. 4.3 and Eq. 4.4.

\[
F_T = N_{rf} + S_{ffp} + S_{ffs} = N_{rf} + S_{ff}(\text{resultant}) \tag{4.3}
\]

\[
F_R = S_{rf} + N_{ffp} + S_{ffs} \tag{4.4}
\]

where for example $N_{rf}$ represents the part of $F_T$ that acts as normal force on the rake face, and $S_{ffp}$ refers to the shear force on the primary flank face.

The load function describes the ratio between $F_T$ or $F_R$ and can be calculated as demonstrated in Eq. 4.5.

\[
\phi_{RT} = \frac{F_R}{F_T} \tag{4.5}
\]
4.1.3 Stresses on the tooth

As stated in Section 4.1.2 the tangential and radial force components cause both normal forces and shear forces on the tooth. The representation of stresses below is done with reference to Figure 4.2a and Figure 4.2b where a local coordinate system W, U, Z has been introduced.

With reference to the shape in Figure 4.2a and Figure 4.2b, there are in principle three faces of the tooth that are affected by \( F_T \) and \( F_R \), viz. the rake face and the two flank faces. These faces are principally subjected to the following forces:

The contact area between the work material and the flank face in the UZ-plane is \( a \times d \), and the following forces are acting on this area:

A normal force \( N_{ad} \) and a shear force \( S_{ad} \).
The contact area between the rake face and the chip in the WZ-plane is \( c \times d \), and the following forces are acting on this area:

A normal force \( N_{cd} \) and a shear force \( S_{cd} \).

The contact area between the machined work piece and the flank face in the UW-plane is \( b \times e \), and the following forces are acting on this area:

A normal force \( N_{be} \) and shear force \( S_{be} \) (in Figure 4.3a and Figure 4.3b the shear force is decomposed in two components \( S_{be1} \) and \( S_{be2} \)).

**Figure 4.3a:** Forces acting in the UW-plane (dotted vectors are forces on the tool underside)

**Figure 4.3b:** Forces acting on the tool underside
In order to calculate the stresses on the tooth faces it is necessary to determine the components of $F_T$ and $F_R$ acting on each face. There are six force components to be solved by six equilibrium equations of moments and force components. Referring to Figures 4.3a and Figure 4.3b, two of these equilibrium equations are established in Eq. 4.6 and Eq. 4.7.

\[ F_T = N_{cd} + S_{ad} + S_{be1} \] (4.6)

\[ F_R = N_{ad} + S_{cd} + S_{be2} \] (4.7)

The following equations show, as an example, how the stresses on the contact area $c \times d$ can be calculated when the stress distributions are known.

\[ N_{cd} \cos \gamma = \int_{0}^{c} \int_{0}^{d} \sigma_{cd}(U, W) dU dW \] (4.8)

\[ N_{cd} \sin \gamma = \int_{0}^{c} \int_{0}^{d} \tau_{1cd}(U, W) dU dW \] (4.9)

\[ S_{cd} = \int_{0}^{c} \int_{0}^{d} \tau_{2cd}(U, W) dU dW \] (4.10)

It is to be noted that in case of two shear forces acting on the same area, the shear stress has to be composed as $\sqrt{\tau_{1cd}^2 + \tau_{2cd}^2}$.

If the stress distributions are not known the stresses must be calculated as average values.

Regarding the possibilities to determine the components $S_{ad}$, $N_{ad}$ and $S_{be}$, and calculate stresses, the following quotation from Trent [2] can be applied: “Where a worn surface is generated on the clearance face of a tool (‘flank wear’) both compressive and shear stresses act on this surface. Although the contact area on the flank is sometimes clearly defined, it is very difficult to arrive at values for the forces acting on it, and there are no reliable estimates for the stress on the worn flank surface”. The implication of this statement is that the forces on the rake face are approximated with $F_T$ and $F_R$, respectively, and the stresses on the rake face will be calculated according to Eq. 4.11 and Eq. 4.12.

\[ \sigma_{cd} = F_T \frac{\cos \gamma a}{c \cdot d} \] (4.11)
\[ \tau_{cd} = \frac{\sqrt{F_T^2 \sin^2 \gamma + F_R^2}}{c \cdot d} = \frac{F_T \sqrt{\sin^2 \gamma + \varphi_{RT}^2}}{c \cdot d} \]  \quad (4.12)

Where \( \varphi_{RT} \) is the load function according to Eq. 4.5.

### 4.2 Description of experiments

The STMT experiments have been carried out to collect data that should be used to characterize the effect of the micro-geometry on the tribo-system represented by tool-chip/work piece. For this purpose a number of direct and indirect methods have been used, as illustrated in Figure 4.4. STMT experiments with running times of up to 29.5 minutes machining time have been performed for deeper analyses.

The results of the force measurements and the estimations of the contact areas have been the basis for studying the influence of the tooth design on the loading on the tooth. Certain delimitations have been necessary since the contact areas on the two flank faces, primary and secondary, have not been measured, which principally is due to the fact that these contact areas are growing during the machining time, resulting in a loss of volume that is more complicated to take into consideration in the load calculations.

Initially in the pre-study, the 60 minutes experiments were used to collect these wear observations, but it was noticed that the experiments with 29.5 minutes running time were enough to attain relevant wear observations. It was also found that the types of wear, which can be related to the micro-geometry and surface roughness of the tooth edge, take place at the beginning of the STMT, and an initial wear could be identified as soon as a few chips had been formed.

Figure 4.4 explains the structure of the experiments in a more detailed way.

Out of the tests with a running time of 29.5 minutes, 13 records of the measured force, torque and vibrations have been sampled, each with a sampling time of about 10 seconds. During each sample period the metal chips of the cutting process were taken out, and the wear was characterized.
Figure 4.4: Layout of experiments and test setup
Various direct and indirect methods have been used to characterize the mechanical load and wear mechanisms as developed in the tribo-system tool-substrate-tool coating-chip/workpiece (see Figure 4.4). The basic characteristics of the tribo-system tool-chip interface are:

- The contact area
- The friction force
- The normal force
- The chip velocity
- Heat flux rate
- Wear type

A Kistler dynamometer mounted on the spindle was used to measure the torque and force components in x-, y- and z- directions with a sampling frequency of 16384 Hz. The signals were then transferred through the Kistler amplifier to the data processing system. Vibration was measured during the experiments by a three-component accelerometer mounted on the spindle.

The cutting force acting on the tooth-chip interface determines the compressive and shear stress distributions and is one of the factors that control the wear through the design of the tooth. Measurements of cutting force components show that the characteristics of the tooth preparations affect the \( F_T \) component with respect to both the edge rounding and the surface roughness. In these investigations, the path of the cutter has been assumed to be sinusoidal. Several empirical models of the tangential cutting force have been proposed; however, in this research work, the tangential force component is defined in Eq. 4.6. This component depends on the chip thickness, which is defined as a sinusoidal function according Eq. 4.13.

\[
h_{ch}(\phi) = f_z \sin(\phi) \quad (4.13)
\]

where \( h_{ch}(\phi) \) is the chip thickness, \( f_z \) is the feed per tooth and \( \phi \) is the engagement angle. The tooth entry and exit angles are determined by the cutter diameter, and the radial depth of cut, \( a_r \).

The radial cutting range \((35^\circ)\) has been determined from Eq. 4.14

\[
\phi_r = \phi_{out} - \phi_{in} \quad (4.14)
\]

The amount of recorded force component samples from each 10 seconds sampled time can therefore be estimated roughly as \( 10 \times 16384 \sim 160,000 \) values.

A qualitative and quantitative analysis of the correlation between wear and cutting forces will help in optimizing the tool design. The qualitative analysis explains how the cutting force varies during the tooth engagement period with respect to
the type of tooth preparation and the tool wear, respectively. When a worn surface is generated on the clearance face of a tooth, both compressive and shear stresses are acting on this surface. Although the contact area on the flank is sometimes clearly defined, it is very difficult to evaluate the forces acting on it.

Regarding the quantitative analyses, the force values during three engagements are illustrated in Figure 4.5 (in this example the force component refers to the x-direction).

Figure 4.5: Principle of force measurements in x-direction. The engagement angles $\phi_{\text{in}}$ (55°) and $\phi_{\text{out}}$ (90°) represent the relative positions of the cutting tooth during the engagement phase in the coordinate system $X_0 / Y_0$. 
4.2.1 Specification of tooth groups

In order to investigate the influence of the surface roughness and the rounding of the cutting edge on the tooth performance, the teeth were divided into two groups.

The teeth in the group denoted Y are classified with respect to the tooth surface roughness grade \( (R_a) \), starting from tooth type Y1 with the finest surface roughness to tooth type Y5 with the roughest surface. These teeth had no significant edge radius (ER), and can be considered practically sharp.

The teeth in the E group are classified with respect to the ER, all being polished to the same surface roughness as the tooth type Y1. Tooth type E1 has the smallest ER, and tooth type E3, the largest ER. Tooth type Y1 can be considered to be part of the E group, regarding surface roughness, and ER = 0, and it is therefore denoted as tooth type E0.

The average values of each interval of the surface roughness values have been applied as a basis for the presented graphs in this chapter. The classification of teeth is summarized in Table 4.1, Table 4.2, and Figure 4.6.

**Table 4.1: Specification of the specimens of groups E**

<table>
<thead>
<tr>
<th>Specimen (tooth No.)</th>
<th>E0</th>
<th>E1</th>
<th>E2 *</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge radius ER (µm)</td>
<td>0</td>
<td>15</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Surface roughness Ra (µm)</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
</tr>
</tbody>
</table>

*In the pre-study this is denoted as tooth type C*

**Table 4.2: Specification of the specimens in groups Y**

<table>
<thead>
<tr>
<th>Specimen (tooth No.)</th>
<th>Y1*</th>
<th>Y2</th>
<th>Y3 **</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge radius ER (µm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Surface Roughness Ra (µm)</td>
<td>&lt; 0.10</td>
<td>0.10</td>
<td>0.25</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15</td>
<td>0.30</td>
<td>0.60</td>
<td>0.80</td>
</tr>
</tbody>
</table>

* In the pre-study this is denoted as tooth type B

** In the pre-study this is denoted as tooth type A, and generally corresponds to the surface roughness of a rake face on HT teeth.
4.3 Experimental results

This section describes the experiments that were carried out under the conditions described above. A more detailed description of the experiments can be found in [5]. The main aim of the experiments was to evaluate the performance of tooth preparations in STMT.

4.3.1 Cutting force analyses in STMT

The objective of the first part of this section is to introduce a new approach so as to help understand qualitatively the influence of the tooth preparations on the experimentally obtained cutting force that was observed. Analyses of both the time and frequency domains of the cutting force are presented.

If the assumption above, that chip thickness variation follows a sinusoidal path, is valid, then the variation of the cutting force is also varying according to a sinusoidal function Eq. 4.15 (see Eq. 4.13)

\[ F_T = K_s w h_{ch} = K_s w f_z \sin(\phi) \]  

where \( F_T \) is the cutting force [N], \( K_s \) the specific cutting force, [N/mm\(^2\)] and \( w \) is the width of chip, [mm].

Since the cutting force is different from zero during the tool engagement period, and zero outside this period, the variation can be represented by multiplying the cutting force by a rectangular window function, \( W(\phi) \), defined as Eq. 4.16 (see Figure 4.7).
Thus, the force component $F_T$ expressed by Eq. 4.15 can be written as Eq. 4.17

$$F_T = K_s w f_c \sin(\phi) W(\phi) \quad (4.17)$$

The qualitative analyses of the cutting forces can also give some information on the friction condition on the rake face of the tooth. The friction force components vary in the STMT due to the variation of the chip thickness and the variation of the apparent situation of friction. In order to study the friction conditions and force during an engagement, a smoothing function has been applied to all force components in order to remove high frequency components.

The variations of the $F_T$ and $F_R$ components on teeth of type Y1, Y5, E1 and E3 respectively, after a machining time of 1 minute and 29.5 minutes, respectively, are illustrated in Figure 4.8a-b. The amplitudes of the force components has been changed after 29.5 minutes due to the effect of wear, which is exemplified in Figure 4.9a-b for the E1 and E3 tooth types. The energy also increases during this machining time as a result of the enhanced work done by the cutting tooth that is required for formation and removal of chips.
Figure 4.8a: Representation of the $F_T$ component on tooth type Y1 after 15 minutes and after 29.5 minutes, respectively.

Figure 4.8b: Representation of the $F_R$ component on tooth type Y1 after 15 minutes and after 29.5 minutes, respectively.
Figure 4.8c: Representation of the \( F_T \) component on tooth type Y5 after 15 minutes and after 29.5 minutes, respectively.

Figure 4.8d: Representation of the \( F_R \) component on tooth type Y5 after 15 minutes and after 29.5 minutes, respectively.
Figure 4.8e: Representation of the $F_T$ component on tooth type E1 after 15 minutes
and after 29.5 minutes, respectively.

Figure 4.8f: Representation of the $F_R$ component on tooth type E1 after 15 minutes
and after 29.5 minutes, respectively.
Figure 4.8g: Representation of the $F_T$ component on tooth type E3 after 15 minutes and after 29.5 minutes, respectively.

Figure 4.8h: Representation of the $F_R$ component on tooth type E3 after 15 minutes and after 29.5 minutes, respectively.
The analyses of cutting force components show that the maximum values of cutting forces do not change significantly with machining time or with change in edge radius or surface roughness.

Figure 4.9: Representation of the $F_T$ and $F_R$ components on tooth type Y1 vs Y5 and E1 vs E3 after 15 minutes and after 29.5 minutes, respectively.
The results presented above demonstrate that the areas under the force variation during one revolution vary with both machining time and micro-geometry. Therefore, in the subsequent section, a comparative study is presented regarding the areas under the force component curves, illustrated in Figure 4.10 and Figure 4.11. These areas correspond to the mechanical energy spent during a revolution to form the chip.

Figure 4.10: Energy and variation interval values after 15 minutes machining time. (a) Energy T1 (tangential force) as function of edge radius, (b) Energy T1 (tangential force) as function of surface roughness, (c) Energy R1 (radial force) as function of edge radius, (d) Energy R1 (radial force) as function of surface roughness
Figure 4.11: Energy and variation interval values after 29.5 minutes machining time. (a) Energy $T_2$ (tangential force) as function of edge radius, (b) Energy $T_2$ (tangential force) as function of surface roughness, (c) Energy $R_2$ (radial force) as function of edge radius, (d) Energy $R_2$ (radial force) as function of surface roughness

Evaluation of the energy functions demonstrates the variation interval as a function of increased surface roughness and decreased edge radius. The increasing of energy can be noticeably correlated to the end sequence of the tooth engagement during a revolution. An explanation is that chip forming with a worn edge in down milling increases the ploughing effect at the exit of engagement. In addition these analyses show that the higher the edge radius values are, the better the edge is preserved. This means that for edge radius of 30 µm, the variation of energy during a revolution is much less than that corresponding to sharper edges.
The spectral analysis of the tangential force component illustrates the main frequencies excited by the cutter and the effect of tooth preparation on the wear, presented in Figure 4.12.

Figure 4.12: Spectral analysis of the $F_T$ signal produced by the E3 type of tooth after 1 minute machining time (blue) and 30 minutes machining time (red).

The effect of edge rounding on the teeth of E-type can also be identified from the $F_T$ signature. Both the amplitude and the mechanical energy generated by of the $F_T$ component increases with cutting time, as presented in Figure 4.12. The difference between the teeth of type Y1 and type E3 is that the latter has been designed with an edge radius, as compared to the Y-type, according to Table 4.1. Even a small edge radius contributes to a more robust cutting behavior during the 30 minutes engagement process, with a decreased variation of the cutting force amplitudes.

Figure 4.13: Mechanical energy (non-dimensional) conversed by the E3 type of tooth

4.21
Analyses of the mechanical energy conversed by the teeth of the E3 type, during the machining time are illustrated in Figure 4.13. In this figure, the mechanical work, and therefore also the energy required for the chip formation increases with machining time due to the growth of wear.

By plotting the tangential force and the radial force components in a locus diagram, the influence of surface roughness and tool wear on the force components can be studied. This result is demonstrated in Figure 4.14 for the teeth types Y1 and Y5, respectively. An increase in the area, described by the tangential force component as a function of the radial force component, is evidently a result of the changing surface roughness from Y1 type to Y5 type.

![Figure 4.14: Locus of $F_T$ as a function of $F_R$ for two types of teeth, Y1 (blue) and Y5 (red), respectively.](image)

The values of force components presented in the following quantitative analyses are the average maximum force values recorded during a 10 seconds sampling period after a machining time of 29.5 minutes.

The relationships between the force components and the edge radius and the surface roughness, respectively, are illustrated in Figure 4.15, based on the force measurements.

Both the edge geometry and the surface roughness seem to have some influence on the magnitude of the force components. The radial force component and the tangential force component have relatively small fluctuations, as can be seen from Figure 4.15. These fluctuations are more obvious in the qualitative analyses concerning the cutting engagement.
The following section presents the maximum compressive and shear stress on the rake face during a revolution. Each value represents the 10 s average after a 30 minutes machining time.

**Figure 4.15:** The tangential and radial force components as functions of the edge radius (left) and the surface roughness (right). Force components in x- and y-directions are also presented together with formed chips, respectively.
4.3.2 Calculated stresses on the rake face

The interface chip/tooth on the rake face and its size determines the stress distribution on this area. An example from STMT of the contact area on the rake face is illustrated in Figure 4.16.

![Figure 4.16: Contact zone on STMT rake face](image_url)

The values of contact areas presented in this section are the maximum measured contact areas on rake faces measured after 29.5 minutes’ machining time. There were no significant differences between measured areas for each type of tooth after a machining time of 15 minutes or 29.5 minutes, respectively. However, there were area differences between the types of teeth, as illustrated in Figure 4.17.

![Figure 4.17: The contact area between the chip and the cutting edge as a function of the edge radius (ER) and the Surface roughness (Ra)](image_url)
An increased edge radius leads to an increased curvature of the chips, which in turn results in a decreased contact area. A decreased surface roughness reduces the adhesive and the ploughing frictional component as well as the attraction between the chip and the rake face. However, an increased surface roughness gives rise to increasing chippings of the edge (the loss of edge volume is presented later in this chapter). The edge geometry and the chip formation are also affected. The decreasing contact areas on the teeth type Y1, Y2 and Y3 can be related to the increasing loss of edge volume (and losses in rake face area). This is also very significant for the teeth of type Y4 and Y5, but on these teeth the effect of the friction condition is more clearly perceived in that the contact area increases in spite of a considerable loss of edge volume. An increased surface roughness will also probably promote the formation of so-called oxidized layers at an early stage. These layers form at high pressures and temperatures.

As has been explained in Section 4.1.3, the stresses that can be approximately calculated are the compressive and shear stresses on the rake face according to Eq. 4.11 and Eq. 4.12, presented in Figure 4.19 and Figure 4.20. Trent [2] suggests that the mean value of the stress is estimated by dividing the respective force component by the contact area, though Trent does point out that there can be a substantial error in this estimation due to the poor accuracy in the measured contact area. This concept has been applied to the presented calculation of stresses. The stresses are essential to the evaluation of the performance with respect to the tooth preparations. The calculation procedure is illustrated in Figure 4.18.

![Figure 4.18: Calculations of stresses on the tooth rake face](image)
The compressive and shear stresses are presented in Figure 4.19 and Figure 4.20. Naturally, the variation of the stresses is strongly dependent on that of the contact area since the force components $F_T$ and $F_R$ are nearly constant. The shear component of the tangential force $F_T$, as a consequence of the positive axial rake angle, contributes to the shear stresses in addition to those caused by the radial force component $F_R$ and the shear stresses in Figure 4.20 refer to the resultant shear stress, as in Eq. 4.12.

The left graphs in Figure 4.19 and figure 4.20 show a relationship between the stresses and the edge radius. The reason for this is mainly a decreased measured contact area on the rake face.

It is to be noted that the part of the surface which lies on the edge rounding has not been included in the estimation of the contact area, only the plane part of the rake surface. This omitted part is an important area that carries a large share of the stresses, especially compressive stresses that are a crucial loading on a cutting edge. The reason for omitting this part of the area is that the boundary towards flank face is complex to define. An alternative would be to estimate the area on the edge rounding by starting from the position of the stagnation point which would add approximately $5 – 20 \%$ to the plane part of the area, corresponding to a variation of the edge radius from sharp edge to $ER = 30 \mu m$.

The possible corresponding effect on the shear stresses of the surface roughness might be depending on the contact area, the variation of which is discussed above.

As $\sigma_{rf}$ and $\tau_{rf}$ are based on the measured contact area between the chip and the rake face, the calculated stresses might be too high since other tooth contact areas that participate in carrying the force components are not considered.
Trent [2] states that the mean shear stress normally is between 30 and 60 % of the mean value of the compressive stress. It is to be noted that the calculated values above lie within this interval.

Figure 4.19: The compressive stress on the contact area between the chip and the tooth edge as a function of the edge radius (left) and the surface roughness (right)

Figure 4.20: The shear stress on the contact area between the chip and the tooth edge as a function of the edge radius (left) and the surface roughness (right)

4.3.3 Load functions

The load function can be expressed as the ratio between two quantities: either the radial and the tangential force component or the shear and the compressive stress. In both cases the load function gives information on the loading situation on the faces of the tooth.
Using the relationship between the stresses implies that the contact area is involved. Since the compressive stress on, for instance, the rake face is the crucial stress that should be kept as low as possible.

The first load function that is calculated in this thesis is $\varphi_{RT} = \frac{F_R}{F_T}$, in Eq. 4.5 as has been explained in Section 4.1.2. The results are presented in Figure 4.21.

![Load function $F_R / F_T$](image1)

![Load function $F_R / F_T$](image2)

Figure 4.21: The load function $\varphi_{RT} = \frac{F_R}{F_T}$ as a function of the Edge Radius (left) and the surface roughness (right).

The load function in Figure 4.21 has a minimum value corresponding to an edge radius of about 15 $\mu$m. A minimum value is also attained for surface roughness corresponding to a Ra value of about 0.25 $\mu$m.

### 4.3.4 Measured edge loss volume

In addition to the measurements presented in the previous sections two other quantities have been measured, (a) the loss of volume of the primary cutting edge of the tooth and (b) the second deformation zone in the chip ($\varepsilon_{II}$), as illustrated in Figure 4.23. The STMT teeth edges are measured and analyzed with the IF-Edgemaster. This measurement device is dedicated to the cutting tool industry, based on the Focus Variation technology, and make it possible to do profile roughness, surface roughness, contour analysis, form analysis, edge analysis. An example of form analysis is presented in Figure 4.22

Wear and destruction implies changes of the edge geometry. This affects the tool performance, which in turn changes the load distribution between worn and sharp edges.
The methods of analysis that are generally applied to evaluation of flank wear do not take into consideration the type of wear mechanisms, or the loss of edge volume. These methods are generally based solely on the area of flank face wear that has been affected during the edge degradation. However, this two-dimensional consideration generally does not give a correct description of the wear.

The graphs in Figure 4.24 indicate that the loss of edge volume has a relationship to the edge radius and the surface roughness, respectively. An increase in the edge radius has a positive effect on the loss of volume, while a rougher surface causes a greater loss of volume. These conclusions are supported by the observations that are illustrated in Figure 4.26.
The loss of volume that is the main reason for impaired edge geometry is the result of a combination of several different wear mechanisms, principally chipping. Chipping occurs, in principle, initially on a sharp edge, succeeded by an accelerated wear and degradation of the tooth substrate, illustrated in Figure 4.25.

The design that leads to a geometrically stable edge with the least geometrical change is found in the E group (E3), which also generates the best quality of machined surface. The largest geometrical change of the edge is found in the Y group, i.e. on tooth type (Y5) on the rake face. This group also generates a lower quality of machined surface, than, for example, tooth type E3, after 29.5 minutes’ machining time. The analyses of the machined surfaces indicate that a geometrically stable edge generates a machined surface with less smeared work material than an edge with increased chipping wear.

4.30
4.3.5 Measured second deformation zone

A significant part of the energy brought into the cutting process is converted into heat through permanent deformation and friction, located in three deformation zones. Each of the deformation zones has a certain geometric extension (volume). Within this volume there is an increase in temperature, which is related to the converted energy and the size of the zone.

The contact areas are important to the extent of the converted heat in the deformation zones. In most cases the cooling effect of the surrounding medium is probably less than the remaining heat, which is detrimental to the tooth [1].

In the 2nd deformation zone, that is defined by its width $\varepsilon_{II}$, the chip is sliding and sheared against the rake face of the tooth. The width of this zone was measured in micrographs of the chips, and the results are presented in Figure 4.27 as functions of the edge radius and the surface roughness, respectively.
An increased edge radius gives rise to a stagnation zone on the edge, which influences the shear process during the chip formation. The width of the second deformation zone has a tendency of increasing with an increased radius. The influence of the surface roughness on the second deformation zone is not as obvious, a fact that might depend on the extent and the distribution of the seized and the sliding regions that mainly involve the contact surface on the rake face.

Irrespective of the relative extensions between the seized and the sliding regions, it might be possible that the total contact area on the rake face has some kind of relationship to the magnitude of the friction and the width of the second deformation zone in the chip formation process. A rough estimation of the volume of the second deformation zone would be the product of the width $e_{II}$ and the contact area between the chip and the rake face. This product as a function of the edge radius and the surface roughness is illustrated in Figure 4.28. The left graph seems to show the same negative relationship to the edge radius as between the zone width and the edge radius.

Figure 4.27: The 2nd deformation zone as a function of the edge radius (left) and the surface roughness (right)

Figure 4.28: The product $e_{II} \times$ Contact area as a function of the Edge Radius (left) and the Surface roughness (right). The left graph seems to show roughly the same negative relationship to the edge radius as between the zone width and the edge radius.
4.3.6 Use of vibration analysis for studying the influence of tooth preparations on tool wear

In addition to the cutting force measurements, vibrations during the process by means of accelerometers are measured. The vibration measurements were performed in order to study the relationship between wear and tooth edge/surface preparation. Vibration signature analysis is shown to be an efficient method of analyzing the correlation between tool wear, micro-geometry and tribological properties at chip/tool interface. The STMT operation, as described in the previous chapters, was carried out in a 30 kW milling machine, at 420 rpm with a feed rate of 0.25 mm/rev. The axial depth of cut was 3.0 mm. A STMT cutter with 89 mm diameter was used. The work piece, a prismatic steel part, was mounted on the machine table by means of a magnetic fixture. Entrance and exit angles lead to a tool engagement period of 35°.

In order to interpret the obtained results, to identify the various sources of the dynamics of the machining system, the natural frequencies of the spindle have been identified by means of experimental modal analysis. The vibration signal recording system consisted of a three-component accelerometer screwed onto the spindle.

The vibration signal is synchronized with the force signal during the processing phase as shown in Figure 4.29.

![Figure 4.29: Synchronization between vibration signal (red) and force signal (blue).](image)
A typical signature during machining is shown in Figure 4.30. This corresponds to the interval of the tooth engagement, and will approximately be repeated for each spindle revolution. It is of interest to recognize the following three signature sections: the tool entrance, the in-cut, and the exit. The corresponding time intervals are approximately 5, 6 and 2.6 ms, respectively.

Figure 4.30: Vibration and tangential force component

Figure 4.31: Power spectrum of the vibration signal during the entrance phase

By analyzing the response signals from the experimental analyses, it was stated that the spindle’s natural frequency was 768 Hz.
In group Y, the amplitude increases from Y1 with the initially smoothest tooth surface to Y5 with the initially roughest tooth surface, as illustrated in Figure 4.32.

![Figure 4.32: FFT of the Y Group during the last run of a 29.5 Minutes Test](image)

In group E, the amplitude increases slightly from E1 with the initially smallest edge radius to E3 with the initially largest edge radius, as illustrated in Figure 4.33.

![Figure 4.33: FFT of the E Group during the last run of a 29.5 Minutes Test](image)
For both groups, the first marked frequency corresponds to the spindle rotation and the tooth pass frequency. In contrast to the E groups, a difference between the teeth can be observed in the Y groups at the location of the second and third marked frequencies in Figure 4.32 and Figure 4.33, respectively. The amplitudes of these frequency peaks increase more significantly with an increase in the edge wear of the tooth, as compared to an increased edge rounding and therefore a robust tooth design. Therefore the tooth design seems to have a great influence on the vibrations during machining, which can be correlated to the tooth wear and also the load situation on the teeth. More detailed wear analyses are presented later in this chapter.

4.4 Analysis of wear pattern

In order to investigate the wear types that occur during the STMT experiments, SEM micrographs of the teeth are taken before, during and after each experiment. The experimental results showed that the dominant tool wear and the main damages were flank wear and chipping. Damages observed on the rake surface, such as crater wear, were quite limited. Therefore the teeth are mainly worn as a result of initial chipping of both primary and secondary cutting edges followed by flank face wear. The exposed flank face on the PM-HSS teeth is in turn worn by a combination of mild adhesive and abrasive wear. Figure 4.34 shows the location of the examined areas on the tooth.

The wear on the tooth often results in a dramatic change in geometry and the tribological situation due to an altered surface topography. Often there are actual wear mechanisms observed in the early stages, even as soon as after a few engagements.

This change in the geometry of the tooth leads also to an altered chip formation which in turn gives rise to a distinctly unfavorable loading situation on the tooth with respect to mechanical as well as thermal loads. The consequence is accelerated wear that can result in very rapid tool break-down.

It is probably necessary to take into consideration both the actual loading on the tooth and the wear on the tooth, in the development of a reliable and robust tooth design of PVD coated teeth of PM-HSS.
Regarding the flank face wear of the teeth shown in Figure 4.35, a trend can be distinguished. With increasing edge radius, the size of the flank face wear gets smaller, from about 35μm to about 15μm. The reason for this could be the internal stress of the tooth coating which seems to decrease with an increase in the cutting edge radius, mainly due to edge strengthening, i.e. the risk of edge damages decreases with increased edge radius. These results are supported by the investigation results [3] and [4].

Figure 4.35 also illustrates the amount of chipping. The depth of flank wear on tooth type E1 is larger than that on the teeth with a greater edge radius. The flank wear on tooth type E2 is smoother with respect to both depth and width. There are only isolated occurrences of chippings of the cutting edge on tooth type E3. These chippings are not particularly deep, and the coating is mostly intact and therefore still protecting the tooth substrate. The amount of adhered material seems to decrease with increasing edge radii, a fact that most likely depends on an increased curvature of the chips and thus a decreased contact area.
Figure 4.36 shows the differences between the flank wear of the teeth with varying roughness. In contrast to the teeth with varying edge radius, the width of the flank wear does not change significantly and is therefore a severe wear phenomenon. The main difference within the group is the extent of local chippings that seems to increase with surface roughness. This is well supported by earlier results in the STMT pre-study [5], which also showed an increased risk of coating spallation next to deeper grooves on the surfaces.

A situation of severe flank wear involves a great risk of heat transfer into the tooth substrate, and results in a tooth break-down. The discussion on the extension of contact areas can also be applied to the amount of adherent material on the rake faces.
Figure 4.36: Flank Wear of the Y Group

The analyses of teeth with a surface preparation proved the importance of smooth tooth surfaces, and the influence of an omitted edge preparation is obvious since the initially sharp edges are considerably affected. The teeth types with a smoother rake face show a somewhat lesser amount of adherent material [5] than the teeth types Y4 and Y5. The teeth types Y4 and Y5 present more irregular flank wear and an increased number of deeper chippings, as compared to the teeth types Y1, Y2 and Y3, which might be explained by the unfavorable prerequisites for crack formation close to the edge due to grinding scratches.
In addition to the flank details of the E group shown above, Figure 4.37 underlines the connection of the cutting edge radius and the flank wear. Beginning with tooth type E1, the nose wear decreases from about 25μm to less than 10μm with tooth type E3.

The analysis of nose wear, i.e. at the interface between the primary and the secondary edges, shows that there is a trend towards a slightly increased wear on the teeth. This might depend on an increased thermal influence and a more complex stress pattern on the two adjacent edges. Tooth type E1 shows a flank wear with a somewhat more extended area. Tooth type E2 presents a declining tendency to edge chippings while tooth type E3, even at the nose region, shows a stable and robust edge with a coating that is largely preserved.
The analyses of the nose region on the teeth in group Y show how the combination of an initially sharp edge and a rough tooth surface contributes to an unstable edge that will be the subject of chippings. The type of wear that is illustrated on the teeth types Y2 and Y3 is a distinct flank wear, which is even more extensive in teeth types Y4 and Y5. In the nose regions the grinding scratches involve an even greater risk of chippings since the loading originates from both edges. According to the analysis of tooth type Y5 an edge fracture might possibly be due to a grinding scratch where a large part of the edge, being composed of both coating and substrate, has been removed along the scratch.

Initially, during the first few engagements, the loads act on a very small area of the sharp tooth, which is illustrated in Figure 4.39a. Parts of the edge are chipped out and the substrate will be uncovered, as illustrated in Figure 4.39b. The substrate is exposed to heat on a rapidly increasing contact area on the flank face, and it might be likely that a permanent deformation accelerates the wear even more due to the softening of the edge. The unfavorable tool geometry also results in an increased wear on the rake face, which in time will probably lead to crater wear. When the wear has advanced enough to leave the tool substrate unprotected by the coating...
on both the rake face and the flank face, as illustrated in Figure 4.39c, it is in most cases too late to recondition the tooth.

The scores or ridges that might remain after the grinding process, illustrated in Figure 4.40, are detrimental to the strength of the tooth and are in many cases the basis for the propagation of cracks. In case of irregularities left on the tooth surface when the coating is deposited, polishing then involves a strong reduction of the thickness of the layer on the higher areas of the surface, which greatly impairs the protection of the tooth substrate.

As for the surface roughness, irregularities and scores affect the tool reliability negatively. The defects that exist on tools with a rougher coating surface from the beginning carry a great part of the loads, which in many cases can result in the exceeding of the strength of the coating material. The region close to the edge will be the subject of chipping. Smoother surfaces contribute to the preserving of the original geometry of the tool.
Already after a few loading cycles the sharp edge will temporarily, during a number of engagements, be blunted. However, after a number of engagements the originally sharp edge, being the subject to an accelerating wear, will collapse.

Another scenario in case of edge treatment, with oversized edge radius, involves the unpredictable wear of the edge due to a widespread and unstable stagnation zone and a non-functioning shear process of the work material during the chip formation. This will result in a permanent deformation of the work material, i.e. a plastic deformation and thus a high thermal influence on the cutting edge which in turn will lead to increased edge wear.

An edge radius designed with respect to the cutting data and coating thickness, probably results in an intact edge and an intact coating as well as a functioning shear process during the chip formation.

An important phenomenon related to tooth wear, and influencing the chip formation, is the oxidized layers. By examining the rake face in SEM microscope, it was possible to study the formed oxidized layers, or how the work material adheres to the surface irregularities and chemically reacts to the tooth material, and also how the formation of oxidized layers is initiated.

Furthermore, by means of EDS (Energy Dispersive X-ray Spectroscopy) these oxidised layers could be analyzed and characterised. Marked areas indicate high concentrations of respective elements.
A selection of teeth analyses from the STMT pre-study are presented below so as to demonstrate the effect of surface roughness and edge rounding. The properties of these types of teeth are stated in the footnotes in Table 4.1 and Table 4.2. EDS analyses of the teeth of type A, type B and type C are presented in Figure 4.41, Figure 4.42 and Figure 4.43, respectively [5]. These teeth were used for 30 minutes in the STMT pre-study experiments, though it is to be noted that the teeth were PVD coated, but the oxidized layer formations are mostly influenced by the surface roughness and the edge radius.

Figure 4.41: EDS-analysis of oxidized layers on worn tooth type A, PVD coated with TiAlN and some adhered work material after 29.5 minutes machining time.

By examining the rake face of a worn tooth of type A from the EDS analysis, illustrated in Figure 4.41 it is possible to observe oxidized layers. These layers contain mainly Al, Mn and Si. A rough surface and a weak edge, initially sharp, affect the amount of oxidized layers that are formed on the contact area, on the rake face. In fact the teeth of type A in the STMT pre-study [5] show the same type of wear pattern as on the reference hob.
Figure 4.42: EDS-analysis of oxidised layers on worn tooth type B, PVD coated with TiAlN and adhered work material, about 400 μm from the cutting edge of type B after 29.5 minutes machining time.

Figure 4.43: EDS-analysis of oxidised layers on worn tooth type C PVD coated with TiAlN and adhered work material, about 500 μm from the cutting edge of type C after 29.5 minutes machining time.
The results of the EDS analysis of tooth type A show that there are great problems related to the adhesion of work material to the irregular tool surface. Polishing of the tooth surfaces on the type B and type C teeth proved to result in less adhesion, illustrated in Figure 4.42 and Figure 4.43.

The oxidised layer is located some 200μm from the cutting edge. The layer is very conspicuous on the teeth with a rougher surface, but barely visible on the polished teeth, and thus decreasing with increased surface smoothness.

The examination of the teeth in group C shows the influence of an edge radius, resulting in a decreased contact area and a decrease in the amount of formed oxidized layers, presented in Figure 4.43.

### 4.5 Scratch testing of the coatings

The purpose of the scratch testing is to determine differences in adhesion properties of the TiN layer on HSS substrate. Five samples are provided for measurements with the Scratch Tester. The samples concern five inserts with various surface roughness. For all measurements, a progressive scratch test (gradually increasing normal load) is used. In total, 2 series of measurements are performed; one by using a 50μm radius Rockwell-C indenter tip and one by using a 200μm radius Rockwell-C indenter. The Scratch Tester is designed and developed to characterize adhesion and scratch resistance properties of hard coatings. The normal load which can be applied with the Scratch Tester is maximum 200N.

The tests are divided into 2 series:
- Test series 1: 200μm radius Rockwell-C indenter
- Test series 2: 50μm radius Rockwell-C indenter

<table>
<thead>
<tr>
<th>For test series 1</th>
<th>For test series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Progressive Load</td>
<td>Type: Progressive Load</td>
</tr>
<tr>
<td>Begin load: 0.9N</td>
<td>Begin load: 0.9N</td>
</tr>
<tr>
<td>Final load: 75N</td>
<td>Final load: 30N</td>
</tr>
<tr>
<td>Scanning load: 0.9N</td>
<td>Scanning load: 0.9N</td>
</tr>
<tr>
<td>Scratch speed: 8mm/min</td>
<td>Scratch speed: 6mm/min</td>
</tr>
<tr>
<td>Scratch length: 4mm</td>
<td>Scratch length: 3mm</td>
</tr>
<tr>
<td>AE sensitivity: 7</td>
<td>AE sensitivity: 9</td>
</tr>
<tr>
<td>Indenter: Rockwell-C</td>
<td>Indenter: Rockwell-C</td>
</tr>
<tr>
<td>Material: Diamond</td>
<td>Material: Diamond</td>
</tr>
<tr>
<td>Radius: 200μm</td>
<td>Radius: 50μm</td>
</tr>
<tr>
<td>Serial number: F-288</td>
<td>Serial number: A-C052</td>
</tr>
</tbody>
</table>

4.46
The print-screens in Figure 4.44 and Figure 4.45 show the “Panorama Mode” of the CSM Instruments Scratch Tester. The optical image of the scratch is in-line with the recorded data (force, depth, friction and Acoustic Emission).

![Figure 4.44: Progressive scratch test on sample Y5 (scratch test serie 1).](image)

The normal load where the coating starts to “delaminate” from the substrate material is defined as the critical load. The critical load can be defined by using the optical video microscope image, Acoustic Emission data, Penetration depth data or frictional force. Figure 4.45 below shows a print-screen of a progressive scratch test on sample Y1.

![Figure 4.45: Progressive scratch test on sample Y1 (scratch test series 1).](image)

The position where the coating starts to show delamination from the substrate is in-line with the data of Acoustic Emission and Penetration depth. The “cracks”, which are formed by the coating delamination, and detected by the acoustic emission sensor.

The “peak” of the Acoustic Emission signal and the penetration depth signal are correlated to the optical image, where delamination is observed.
The following critical loads are detected on the scratches, which are performed with a 50 μm tip radius:

**Table 4.3: Critical load, by optical inspection performed with a 50μm tip radius**

<table>
<thead>
<tr>
<th>Critical load (N), by optical inspection (coating cracking):</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>10.300</td>
<td>8.928</td>
<td>7.907</td>
<td>4.666</td>
<td>1.543</td>
</tr>
<tr>
<td>Test 2</td>
<td>12.209</td>
<td>9.066</td>
<td>8.011</td>
<td>3.945</td>
<td>2.005</td>
</tr>
<tr>
<td>Test 3</td>
<td>11.074</td>
<td>8.886</td>
<td>7.287</td>
<td>5.242</td>
<td>1.890</td>
</tr>
<tr>
<td>Mean</td>
<td>11.194</td>
<td>8.960</td>
<td>7.735</td>
<td>4.617</td>
<td>1.749</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.960</td>
<td>0.094</td>
<td>0.392</td>
<td>0.650</td>
<td>0.234</td>
</tr>
</tbody>
</table>

The following critical loads are detected on the scratches, which are performed with a 200μm tip radius:

**Table 4.4: Critical load, by Acoustic Emission data performed with a 50μm tip radius**

<table>
<thead>
<tr>
<th>Critical load (N), by Acoustic Emission data:</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>10.331</td>
<td>8.969</td>
<td>7.978</td>
<td>7.413</td>
<td>2.347</td>
</tr>
<tr>
<td>Test 2</td>
<td>12.238</td>
<td>9.139</td>
<td>8.390</td>
<td>5.356</td>
<td>2.944</td>
</tr>
<tr>
<td>Test 3</td>
<td>11.074</td>
<td>8.886</td>
<td>7.349</td>
<td>5.889</td>
<td>1.557</td>
</tr>
<tr>
<td>Mean</td>
<td>11.214</td>
<td>8.998</td>
<td>7.905</td>
<td>6.219</td>
<td>2.087</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.961</td>
<td>0.129</td>
<td>0.524</td>
<td>1.068</td>
<td>0.690</td>
</tr>
</tbody>
</table>

The following critical loads are detected on the scratches, which are performed with a 200μm tip radius:

**Table 4.5: Critical load, by optical inspection performed with a 200μm tip radius**

<table>
<thead>
<tr>
<th>Critical load (N), by optical inspection (coating cracking):</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>61.247</td>
<td>44.494</td>
<td>46.046</td>
<td>29.507</td>
<td>22.726</td>
</tr>
<tr>
<td>Test 2</td>
<td>62.205</td>
<td>50.321</td>
<td>51.268</td>
<td>37.556</td>
<td>26.512</td>
</tr>
<tr>
<td>Test 3</td>
<td>52.929</td>
<td>48.527</td>
<td>50.083</td>
<td>37.344</td>
<td>27.672</td>
</tr>
<tr>
<td>Test 4</td>
<td>60.843</td>
<td>50.107</td>
<td>44.460</td>
<td>30.193</td>
<td>22.997</td>
</tr>
<tr>
<td>Mean</td>
<td>59.306</td>
<td>48.362</td>
<td>47.964</td>
<td>33.650</td>
<td>25.915</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>4.290</td>
<td>2.700</td>
<td>3.233</td>
<td>4.398</td>
<td>3.009</td>
</tr>
</tbody>
</table>
The measurements that are performed on the TiN coated samples prove that the Scratch Test is very well suited to characterize the adhesion properties of hard coatings. The accuracy in depth and force measurement (thanks to active force feedback and profile scanning) in combination with the large normal load range (up to 200N), makes the Scratch Test a suitable quantitative method for evaluation of the adhesion properties of hard coatings.

The two test series (one by using a 50 μm radius Rockwell-C tip and one by using a 200 μm radius Rockwell-C tip) show that the adhesion of the TiN layer to the HSS substrate is highly dependent on the substrate roughness. The critical load (normal load where the coating starts to show adhesion failure) is detected by using the integrated optical video microscope and the Acoustic Emission data. A strong correlation between these critical loads is obtained, both for the 50 μm tip tests and a 200 μm tip tests. The sample with the highest substrate roughness (Y5) has the lowest critical load value (meaning that a relatively small load is required to “break” the coating/substrate adhesion). The sample with the lowest substrate roughness (Y1) has clearly has the highest critical load value (meaning that a relatively high load is required to start coating delamination).

Although the differences when using a 200 μm radius indenter are more significant than when using a 50 μm radius indenter, both test series show the same trend (the larger the substrate roughness is, the worse the adhesion is – also the opposite: the smoother the substrate roughness, the better the adhesion properties).
4.6 Conclusions

The evaluations of important parameters for tooth design, which was carried out in STMT experiments, has been expanded into deeper analyses of the influence on cutting teeth of edge rounding and surface preparation.

Initially in the pre-study, the 60 minutes experiments were used to collect these wear observations, but it was noticed that the experiments with 29.5 minutes running time were enough to attain relevant observations.

Both the edge geometry and the surface roughness seem to have some influence on the magnitude of the force components. The radial force component and the tangential force component have relatively small fluctuations, as can be seen from Figure 4.15. These fluctuations are more obvious in the qualitative analyses concerning the cutting engagement.

The values of contact areas presented in this section are the maximum measured contact areas on rake faces measured after 29.5 minutes’ machining time. There were no significant differences between the measured areas for each type of tooth after a machining time of 15 minutes or 29.5 minutes, respectively. However, there were area differences between the types of teeth.

An increased edge radius leads to an increased curvature of the chips, which in turn results in a decreased contact area. In the surfaces with Ra exceeding 0.4 µm there will probably exist an increased amount of formed so-called oxidized layers at an early stage.

It is to be noted that the part of the surface that lies on the edge rounding has not been included in the estimation of the contact area, but only the plane part of the rake surface. This omitted part is an important area that carries a large share of the stresses, especially compressive stresses that are a crucial load on a cutting edge. The reason for omitting this part is that the boundary towards flank face is complex to define.

The possible corresponding effect on the shear stresses of the surface roughness might be dependent on the contact areas.

The loss of edge volume has a relationship to the edge radius and the surface roughness, respectively. An increase in the edge radius has a positive effect on the loss of volume, while a rougher surface causes an increased loss of volume. There are only isolated occurrences of chippings of the cutting edge on tooth type E3.

An increased edge radius gives rise to a stagnation zone on the edge, which influences the shear process during the chip formation. The width of the second
deformation zone has a tendency of increasing with increased radius. The influence of the surface roughness on the second deformation zone is not as obvious, a fact that might depend on the extent and the distribution of the seized and the sliding regions that mainly involve the contact surface on the rake face.

Regarding the flank face wear of the teeth, a trend can be found. With increasing edge radius, the size of the flank face wear becomes smaller, from about 35μm to about 15μm.

A situation of severe flank wear involves a great risk of heat transfer into the tooth substrate, which results in a tooth break-down.

The scores or ridges that might remain after the grinding process are detrimental to the strength of the tooth and are in many cases the basis for the propagation of cracks. In case of irregularities left on the tooth surface when the coating is deposited, polishing then involves a strong reduction of the thickness of the layer on higher areas on the surface, which greatly impairs the protection of the tooth substrate.

The main difference within the Y group is the extent of local chippings that seems to increase with surface roughness.

The qualitative analyses of the cutting force can also give some information on the friction condition on the rake face of the tooth. The friction is determined by the relationship between the radial and the tangential cutting force components. The friction force components vary in the STMT experiments due to the variation of the chip thickness and the variation of the friction coefficient. In order to study the friction conditions, a smoothing function has been applied to all force components in order to remove high frequency components. The results of the EDS analysis show that the surface roughness is related to the adhesion of work material to the irregular tool surface. Polishing of the tooth surfaces proved to result in less adhesion.

The scratch testing shows that the adhesion of the TiN layer to the HSS substrate is highly depending on the substrate roughness. A strong correlation between the critical loads is obtained, both for the 50 μm tip tests and a 200 μm tip tests. The sample with the highest substrate roughness (Y5) has the lowest critical load value (meaning that a relatively small load is required to “break” the coating/substrate adhesion). The sample with the lowest substrate roughness (Y1) has clearly the highest critical load value (meaning that a relatively high load is required to start coating delamination).
References in chapter 4


5. Single Tooth Milling Test simulations

Many essential characteristics of the machining process such as tool wear, cutting forces and machined surface roughness can be evaluated experimentally. However, serious difficulties relate to the measurement of thermal and mechanical stress distributions mainly due to limited possibilities to access the tool-chip interface. Numerical methods can then be used together with experimental procedures to improve the accuracy of cutting process characterization. In this chapter, the effect of micro-geometry on HSS teeth wear is analyzed by means of a Finite Element Method (FEM) model.

The method used to predict this effect is by comparison of the thermo-mechanical distributions produced by various combinations of micro-geometries. Developing a consistent model requires data from the experiments that have been performed in intermittent machining. Data on the material behavior at elevated temperatures and high strain rates are important to the model input. Part of this information was lacking at the time of establishing the model, and therefore the presented model is not complete but must be regarded as an attempt to evaluate tooth preparations. The main purpose here is to describe how the new knowledge from the Single Tooth Milling Test (STMT) experiments and the simulation can complement each other and contribute to a better understanding of factors affecting reliable tooth design.

In the first section 5.1, a description of the objectives and benefits of an FEM analysis is given, including the delimitations that are associated with such an analysis. Section 5.2 contains an outline of the procedure and prerequisites for the modeling. Strain, strain rates, stresses, yield criterion in a hardening model are discussed in Section 5.3. The last two sections address the modeling for STMT.

5.1
5.1 The aim of simulation

One of the main objectives of this thesis is to study the effect of edge rounding and surface roughness on thermal and mechanical stress distribution.

The results will facilitate understanding of:

- The surface requirements before depositing the coating film.
- The mechanical conditions which are necessary to strengthening the edge.
- The mechanical and thermal conditions at the chip-tool interface needed for the reduction of friction in the secondary deformation zone and also for reducing the emergence and propagation of notch wear.

In addition, the gained knowledge could be further applied to the design of the micro-geometry of a hob tooth for improving the hob performance in gear machining. The machining cost of gear transmission components represents an important part of the total production costs. The shape of the chip in machining is the result of several combined influences, such as the properties of the work material and of the tool material and its geometry, as well as the cutting parameters.

The optimization of the machining process and the integrity of the surface as well as the product performance demand a thorough understanding of the tribo-system tooth substrate-tooth coating-chip/workpiece. This understanding comprises knowledge of the effect of the micro-geometry of the cutting edge and the tooth preparation on stress distribution. The state of the tooth edge affects the properties of the work piece surface and gives rise to residual stresses and influences surface integrity as well as the cutting temperatures, which in turn have an effect on tool life. Models, analytical or numerical, contribute to the comprehension of the thermal and mechanical conditions on the interface between the chip and the rake face of the cutting edge.

Establishing models for metal cutting in order to describe phenomena such as friction, temperatures, and high rates of large strains is an extensive task to accomplish. In recent years a great deal of work has been put into developing analytical models for this purpose.

An alternative method for establishing machining models, that have better applicability, is the implementation of numerical models, for instance a Finite Element Method (FEM) [1]. These models can predict the geometry of the chip as well as residual stresses and deformation in the work material. In addition, it is also possible to make these models predict the forces acting on the tool that are related to cutting parameters, the geometry of the cutting edge and tooth surfaces and properties of the materials. Up to now it has been presumed that a cutting edge
is perfectly sharp in the simulation models. The fact that all edges in practice are more or less blunt has been in many cases neglected, i.e. the effect of an edge preparation has not been considered. [2].

In this thesis the modelling of the STMT process aims at improving the comprehension of the mechanical and thermal load conditions on the tooth. Modelling of machining processes aims in many cases at the prediction of forces and temperatures. Deformation of work material is distinctive in that it occurs at highly elevated temperatures at normal cutting speeds and there is an appreciable variation of the material properties with respect to temperatures. The influence of high temperatures is twofold in so far as they can give rise to an altered flow stress in the work material as well as exert a vital influence on the rate of tool wear. In addition to these influences, elevated temperatures can also generate thermo-deformed layers in the machined surface. All this demonstrates the necessity of taking the influence of temperatures into consideration in the analyses of the cutting processes.

Flow stress in a material is defined by the stress that causes an incremental increase in plastic deformation, given strain, strain rate and temperature. In many cases, the history of the material, like for instance its hardness, also has an influence on the flow stress.

There are at least two methods for estimating the flow stress in the machining process, one of which is a direct machining test. Another method is based on compression or torsion tests at high speeds. Irrespective of method, it is necessary to meet certain conditions in the flow stress test, including a high strain, a high strain rate and a high temperature in order to analyze the cutting process.

Forces that are necessary to the deformation of a material sample under tension, compression or shearing are measured in conventional tests. The tests are carried out at temperatures and strain rates that are similar to those in the process being simulated. Such deformation rates in machined materials can amount to $10^5 /s$ in the primary deformation zone. Figure 5.1 presents the results from a tensile test of a work material made of steel 20NiCrMoS2-2 at low and high strain rates.

The model presented in this chapter is based on a thermo-elasto/plastic model for the chip and work piece where the strain hardening data is extracted from a stress-strain diagram obtained in experiments performed on the case hardening steel from STMT at different strain rates, as illustrated in Figure 5.1. Since the chip formation is characterized by a high strain rate, the values in the simulation model were chosen from the red curve in Figure 5.1.
5.2 Procedure of the analysis

As mentioned above, the work piece is modelled as being an elasto / plastic material. The plastic deformations are focused on the primary and secondary deformation zones. These are rigid regions characterized by a very small value of the effective strain rate in comparison with that in the material to be deformed. The physical properties of the work and tool materials are presented in Table 5.1.

<table>
<thead>
<tr>
<th></th>
<th><strong>Work piece</strong></th>
<th><strong>Tool</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>20NiCrMoS2-2</td>
<td>ASP 2030</td>
</tr>
<tr>
<td>E-modulus (GPa)</td>
<td>210</td>
<td>240</td>
</tr>
<tr>
<td>Hardness (HV)</td>
<td>190</td>
<td>840</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>7.8</td>
<td>8.1</td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td>Specific heat (J/kg°C)</td>
<td>450</td>
<td>420</td>
</tr>
</tbody>
</table>

Figure 5.1: Stress-strain diagram for work piece material, steel 20NiCrMoS2-2.
The work piece is modelled as a 3D rectangular plate consisting of 8-node linear brick, reduced integration with hourglass control illustrated in Figure 5.2. The bottom nodes of the work piece have both vertical and horizontal constraints, while the nodes on the right edge and on the edge situated above the cutting zone are unconstrained.

The body of the milling tool is constrained on the interior boundaries by a rigid connector. This is a special kinematic constraint, which can be attached to one or several boundaries. The effect is that all connected boundaries behave as an assembly connected by a common rigid body.

The necessary degrees of freedom for representing this assembly are those needed to make the rigid body move.

The tooth clamped on the cutter’s post is modelled by a 10-node modified quadratic tetrahedron. The interface between tooth and chip is represented by contact nodes, as can be seen in Figure 5.3. The effects of the boundary conditions were reduced by choosing the dimensions of the work piece large enough to maintain steady-state cutting for a certain time. The cutting was completed before reaching the left edge.
5.3 The yield criterion, flow rule and strain hardening model

A plasticity model is formulated in terms of:

- A yield criterion
- A flow rule defining the inelastic deformation
- An evolution law defining the hardening i.e. the change of yield and flow stresses as the inelastic deformation occurs

The limit of elasticity is defined by the yield criterion for any possible combination of stresses. To attain the steady state geometry of the chip flow, a thermo-elasto-plastic cutting simulation connected with isotropic strain-hardening was carried out [3]. The basic assumption of the total strain, decomposed into an elastic part, $\varepsilon^e$ and a permanent or plastic part, $\varepsilon^p$ will be made according to Eq. 5.1.

$$\varepsilon = \varepsilon^e + \varepsilon^p$$

(5.1)
The total stress $\sigma$ at time $t$ can be modelled as a function of the total strain $\varepsilon$ at time $t$, by means of the flow theory of plasticity, which describes the behaviour of the elasto / plastic material, as a function of the stress and strain history. This history of the material is usually taken into consideration through two parameters, $\kappa$ and $\chi$ which are controlled by a specific evolution law [4].

It is generally accepted as an experimental fact that yielding (i.e. the state of stress at which the plastic flow is initiated) can occur only if the stress satisfies the general yield criterion, Eq. 5.2.

$$F(\sigma, \kappa, \chi) = 0$$  \hspace{1cm} (5.2)

where $\sigma$ denotes Cauchy’s stress matrix with all the nine components of stress, illustrated in Figure 5.4. Where $\kappa$ represents kinematic hardening parameters and $\chi$ an isotropic hardening parameter.

![Figure 5.4: Cauchy’s stress matrix [5]](image)

This yield criterion can be illustrated as a surface in an n-dimensional space of stress with the position and the size of the surface dependent on the momentary values of the parameters $\kappa$ and $\chi$, presented in Figure 5.5.
Figure 5.5: Yield surface and normality criterion in a two-dimensional stress space

It is demonstrated that basic behaviour that defines the plastic strain increments is related to the yield surface. If $\varepsilon^p$ denotes the component of the plastic strain tensor, the rate of plastic strain is assumed to be given by Eq. 5.3.

$$\dot{\varepsilon}^p = \dot{\lambda} \frac{\partial F}{\partial \sigma}$$

(5.3)

In Eq. 5.3, $\dot{\lambda}$ is a constant of proportionality, often called the ‘plastic consistency’ parameter. If this condition is met, the plastic strain rate components are normal to the yield surface in the space of nine stress and strain dimensions. The expression in Eq. 5.3 also formulates the flow rule, which specifies the inelastic or plastic strain rate vector as a function of the state of stress. During plastic deformation the following condition has to be satisfied, Eq. 5.4.

$$\dot{F} = 0 \quad \text{and} \quad \dot{\lambda} > 0$$

(5.4)

while the condition in Eq. 5.5 must be met during elastic loading and unloading

$$\dot{F} \neq 0 \quad \text{and} \quad \dot{\lambda} = 0$$

(5.5)
These conditions lead to a general constraint form

\[ \dot{F} \dot{\lambda} = 0 \]  \hspace{1cm} (5.6)

known as ‘the normality principle’. The plastic flow rule potential is defined as

\[ Q = Q(\sigma, \kappa) \]  \hspace{1cm} (5.7)

The particular case of \( Q = F \) is known as associative plasticity. When this relation is not satisfied the plasticity is non-associative. The satisfaction of the normality principle for the associative case is essential for proving so-called upper and lower bound theorems of plasticity as well as uniqueness [6].

In many machining models, the Johnson and Cook flow stress model is adopted [7]. This model describes the flow stress as a function of strain, strain rate and temperature.

\[
\bar{\sigma} = (A + B \varepsilon^p)(1 + C \ln(\dot{\varepsilon} / \dot{\varepsilon}_0))(1 - [(T - T_{amb})/(T_{melt} - T_{amb})]^m)
\]  \hspace{1cm} (5.8)

where
\[ A \] represents the strength
\[ B \text{ and } n \] define the strain hardening
\[ C \] is the rate sensitivity
\[ m \] is the thermal softening behaviour
\[ \bar{\sigma} \] is the flow stress
\[ \varepsilon^p \] is the plastic strain
\[ \dot{\varepsilon} \] is the strain rate and
\[ \dot{\varepsilon}_0 \] is the reference plastic strain rate.
\[ T \] is the work piece temperature
\[ T_{amb} \] is the ambient temperature
\[ T_{melt} \] is the melting temperature of the work piece material.
5.4 A model for the Single Tooth Milling Process

A suitable model for the single-tooth milling process should take into consideration the ability of the work material to work-harden. Since the chip material is considerably harder than the work piece material, it is correct to assume a stress situation where the material adjacent to the shear zone is brought to the yield point. In this zone the material will be strain-hardened.

In the present single-tooth milling model, the flow stress data was obtained from the experimental tests.

5.4.1 Tool – chip interface

The contact and the friction at the interfaces between the tooth and the chip, and the tooth and the work material, determine the required cutting power, the machining quality and the tooth wear. Contact and friction conditions highly important to the metal cutting process [8] are:

- adhesion,
- mechanical interactions of surface asperities,
- ploughing of one surface by asperities on the other,
- deformation and/or fracture of surface layers such as oxides, and
- interference and local plastic deformation caused by agglomerated wear particles, trapped between the moving surfaces.

The microscopic mechanisms that to varying degrees influence the generation of friction are also presented in Figure 5.6.
Figure 5.6: (a) adhesive friction, (b) ploughing friction, (c) deformation and fracture of oxides. (d) trapped wear particles.

These mechanisms exist to a varying extent in the friction at the interfaces chip – tooth and tooth – work piece during the cutting process. The coexistence of adhesive and ploughing friction at the chip - tooth interface under many cutting conditions has been assumed by Zorev in a slide-stick friction model [9].

In the present model a constant coefficient of friction along tool – chip interface is applied to the analysis of all chip formation processes throughout the whole useful tool life.

It is important to pay regard to the contact between the tool and the chip when developing a reliable simulation model for cutting, since the friction force bears a strong relation to the chip formation process and affects the tool performance.

A typical stress distribution on the rake face is shown in Figure 5.7. The normal stress increases monotonously towards the tooth edge, while the shear stress at first increases but then reaches a nearly constant value.

Two distinct zones exist on the rake face: a sliding zone and a sticking zone. In the sliding zone, the normal stress is relatively small and dry friction prevails. On the contrary, in the sticking zone, the normal stress is so high that real and apparent areas of contact are equal and the shear stress is approximately constant.
The basis for the friction behaviour along the interfaces chip - tool and tool–work piece is Coulomb’s friction model. The conditions for sticking and sliding friction at the chip-tool interface are directly owing to the stress magnitude, with sticking occurring at high contact pressure. When this pressure is low, as it is away from the cutting edge, friction due to sliding will be predominant. Based on results from experimental research, Coulomb’s friction law is presumed to prevail in the sliding zone, i.e. a constant coefficient of friction has been applied to this zone, while an approximately constant frictional stress has been applied to the sticking zone. These assumptions with respect to frictional stresses can be expressed according to Eq. 5.9.

\[
\begin{align*}
\tau_f &= \mu \sigma_n \quad \text{for } \tau_f < k \quad \text{(sliding)} \\
\tau_f &= k \quad \text{for } \tau_f \geq k \quad \text{(sticking)}
\end{align*}
\]  

\( (5.9) \)

where \( \tau_f \) is the frictional stress, \( \sigma_n \) is the normal stress, \( \mu \) is the coefficient of friction, and \( k \) is the shear stress of the chip material.

The friction model described above has been applied to most FEM cutting models, and by using it the constant frictional stress can be obtained from the flow stress of the chip.

However, the conditions of friction in the sliding zone are dissimilar from those prevailing in conventional tests of friction, and it is therefore very difficult to determine the coefficient of friction in the sliding zone. The lower part of the chip constitutes a freshly formed surface that is the subject of high strain hardening. Since the chip is plastically deformed its hardness can be twice as high as that of the work piece. This varying hardness may result in changes in the coefficient of friction.
Frictional stresses can be determined by means of other methods, e.g. in machining tests and tests that are specially designed for this purpose [10]. Such tests might result in accurate and usable information on frictional stresses.

On the non-perfectly sharp cutting edge of the tooth a stagnation point of the flow exists. The material above this point is flowing into the chip, and the material below the point is flowing back into the work piece.

The sliding velocity, and thus also the frictional stress, will move in reverse motion at the stagnation point. Since the position of this point is not known in advance, applying the friction boundary conditions requires the use of special numerical techniques. This problem is often encountered in metal forming, such as ring compression, rolling, and forging.

Out of a number of methods, Chen and Kobayashi [11] suggested a modified form of the friction stress according to Eq. 5.10.

\[
T_f = \tau_f \left[ \frac{2}{\pi} \tan^{-1} \left( \frac{|v_s|}{v_0} \right) \right] \tag{5.10}
\]

where \(T_f\) is the modified friction stress, \(\tau_f\) is the friction stress, \(v_s\) is the sliding velocity of the work material at the tooth – work piece interface, and \(v_0\) is a small positive number compared to \(v_s\).

Figure 5.8: Illustration of the stagnation point an edge rounded tooth

The minimum thickness of the uncut chip is practically equal to the height of the stagnation point \(h_C\), where the separation of the material flow takes place, the
upper part is flowing into the chip and the lower part is flowing under the tooth to become a part of the machined surface, as illustrated in Figure 5.8.

### 5.5 Modelling of chip formation

There are several formulations available for numerical modelling, Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian (ALE). The Lagrangian and ALE formulations supply approaches to the chip separation in the chip formation process. The Lagrangian formulation tracks discrete material points.

#### 5.5.1 Formulations for numerical modelling

The physical partial differential equations are generally formulated either

- In a material coordinate system, fixed to the material in its reference configuration and following the material as it deforms (Lagrangian formulation).

  or

- In a spatial coordinate system, with coordinate axes fixed in space (Eulerian formulation).
The Lagrangian formulation
The Lagrangian formulation makes the properties of an anisotropic material independent of the current spatial orientation of the material. Structural mechanics and other fields of physics handling a possibly anisotropic, solid material are therefore most adapted to being simulated by means of material coordinates.

Eulerian formulation
On the other hand, if the purpose is the simulation of the physical state at fixed points in space, an Eulerian formulation is usually more suitable. A basic drawback of the pure Eulerian formulation is that it cannot manage domain boundaries that move, since physical quantities are related to fixed points in space; while the set of spatial points, inside the domain boundaries, changes with time.

Therefore, to allow moving boundaries, the Eulerian equations must be rewritten so as to describe all physical quantities as functions of some coordinate system in which the domain boundaries are fixed. The finite element mesh offers one such system: the mesh coordinates.

Mesh coordinate system
In the mesh coordinate system, the domain is fixed, and there is a one-to-one map from the mesh coordinates to the current spatial configuration of the domain. The mesh coordinate system can be defined arbitrarily and separated from both the spatial and the material system. The natural choice is to let the mesh coordinate system, at least initially, coincide with the geometrical coordinate system. This is the immediate result of the way in which meshes are created, and implies that points in the domain are identified by their position in the original geometry.

As the domain — and the mesh — deforms, the map from mesh coordinates to spatial coordinates may show increasing incongruity. The simulation can be stopped at any time and a new mesh created in the current configuration of the domain with all quantities mapped to the new mesh. When the simulation is restarted, points in the domain are internally identified by their new mesh coordinates, which coincide with the spatial coordinates at the time when the simulation was stopped. Therefore, the geometry and mesh coordinates of a given point will differ after a remeshing operation, illustrated in Figure 5.9.
Conceptually, all three frames always exist, but all or some of them may point to the same actual coordinate system. It is the actual coordinate system that decides the notation of the independent variables.

### 5.5.2 Chip formation

The chip separation is performed along predetermined lines of elements on the moving path of the cutting edge, by deleting elements ahead on the cutting edge when element failure criteria, such as shear failure criterion, are reached. The failure criterion is usually defined arbitrarily because of the difficulty of obtaining the required basic experimental data. In addition, the number and size of deleted elements affects the produced chip thickness, and fine elements improve the simulated result but, at the same time, increase the calculation time and cost considerably. ALE is very suitable to the cutting conditions in which a rounded or chamfered-edge cutting tool is used.
5.5.3 Analysis of thermo-physical phenomena

The modeling design makes it possible to carry out the simulation from the initial chip formation till reaching a steady state, which is attained by two analysis steps, viz. the very chip formation and the steady-state of the chip formation. During the chip formation step, a coupled thermo-physical analysis is carried out. In the current model analysis, it has been assumed that most of the plastic deformation is converted into heat energy, and that part of this heat energy enters the tooth.

In this model, the work piece is fixed and the tool is rotating in an anti-clock wise direction. As mentioned above, a “Moving mesh” method is implemented based on the ALE method. When the mesh deformation becomes larger, the quality of the mesh created by the smoothing equations becomes impaired. Based on the quality of the mesh elements, the simulation is stopped and the re-mashing of the model is performed. In order to simulate the chip separation, illustrated in Figure 5.10 and Figure 5.11, the moving mesh boundaries are constrained in both x- and y- directions.

![Simulated von Mises stresses on a sharp edge in the first sequence (2ms) of the engagement during one revolution](image)

Figure 5.10: Simulated von Mises stresses on a sharp edge in the first sequence (2ms) of the engagement during one revolution.
The objectives of this chapter are to provide an understanding of the effect of edge preparation and of surface roughness (micro-geometry) in STMT simulations, illustrated in Figure 5.10 and Figure 5.11. The simulation section is divided into two parts; firstly, the effect of the edge radius on the plastic deformation is analyzed and later the thermal phenomenon related to surface finish is studied.

The edge geometries used in simulation are illustrated in Figure 5.12 where the meshed tools are represented.

Figures 5.13a-c show the von Mises stress in STM model for three different edge radii, 0µm, 60µm and 80µm for a constant surface roughness value with a friction coefficient (0.36), which is kept constant during simulations. These figures represent the interaction tool-chip during the first two milliseconds of the engagement. As in the experimental study presented in chapter 4, the milling type in simulations is down milling, i.e. the chip thickness has its maximum value at the beginning of the engagement.
However, there is a transitional period from the tool entering the work piece to the largest contact area being reached. This is well demonstrated by representing the contact area on the rake face of the tooth, shown in Figure 5.14. During the first part of the engagement (1.5 ms) the contact area is continuously increasing until reaching a relatively constant level before decreasing again to zero at the end of engagement. This conclusion is valid for all edge radii.
Figure 5.13b: Simulation of STMT with edge radius 60µm in the first sequence (2ms) of the engagement of a revolution.

Figure 5.13c: Simulation of STMT with edge radius 80µm in the first sequence (2ms) of the engagement of a revolution.
The compressive force acting on the rake face is represented for all three edge radii values in Figure 5.15. By examining Figures 5.14 and 5.15, two important conclusions can be drawn: (1) the contact area corresponding to the maximum compressive force has an inverse relationship to the edge radius, and (2) the compressive force corresponding to the maximum chip thickness increases with the edge radius. Furthermore, it can be noticed from these figures that a better choice of edge radius is 60 µm as it gives a moderate compressive force and a relatively large contact area.

![Figure 5.14: contact area development at the rake face during the first sequences during one engagement.](image)

![Figure 5.15: Cutting force, compressive component at the rake face during the first sequences during one engagement.](image)
This also becomes apparent by studying the results in Figure 5.16, where the friction force on the rake face is represented. In the transitional period of the engagement (1.5 ms), the energy spent in friction is similar for all the three edge radii. As the chip thickness reaches the maximum value, the tooth with 60 µm edge radius has the minimum friction energy. The tooth with 80 µm exceeds the one with a sharp edge due to the increasing effect of the compressive force.

\[ J \]

\[ \text{Figure 5.16: Friction energy in the first sequence (2ms) of the engagement of one revolution.} \]

Stress components during the first phase of the engagement on the cutting edge from the FEM simulations are presented in Table 5.2.

<table>
<thead>
<tr>
<th>r[µm]</th>
<th>Von mises max [Pa]</th>
<th>σ_{xx} [Pa]</th>
<th>σ_{yy} [Pa]</th>
<th>σ_{zz} [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.11x10^{10}</td>
<td>2.15x10^{9}</td>
<td>5.00x10^{9}</td>
<td>2.55x10^{9}</td>
</tr>
<tr>
<td>60</td>
<td>1.00x10^{10}</td>
<td>2.72x10^{9}</td>
<td>4.33x10^{9}</td>
<td>2.59x10^{9}</td>
</tr>
<tr>
<td>80</td>
<td>4.63</td>
<td>1.88x10^{10}</td>
<td>1.21x10^{10}</td>
<td>1.71x10^{10}</td>
</tr>
</tbody>
</table>
The plastic deformations of the chip during the engagement are illustrated in Figure 5.17. The figure shows that most of the part of the chip in contact with the tooth is in a plastic deformation state, which increases during the engagement time.

![Figure 5.17: Distribution of the plastic strain on the chip, time evolution.](image)

### 5.5.4 Temperature and friction

Temperature predictions are used to estimate the tool’s useful life or a change in the mechanical properties of the work piece. Both of these considerations are important to the economical operation of the process, as well as safety and performance of the machined product.

In machining there are two sources of heat generation; one is located in the shear zone and is initiated by plastic deformation, and the other is produced to overcome the friction resistance. Part of the heat produced in the shear zone is carried away by the chip. For a cutting force $F$ and a cutting speed $V_c$ the total energy expanded per unit width of cut is $FV_c$. The energy $E_{sh}$ converted in the shear zone is [5] Eq. 5.11

$$E_{sh} = FV_c - F_f V_c \frac{h}{h_c} \quad (5.11)$$

where $F_f$ in Eq. 5.12 is the friction force, $h$ is the uncut chip thickness and $h_c$ is the actual chip thickness. If the angle between the resultant force acting on the tool and cutting force is $\lambda - \alpha$ it follows that the friction force $F_f$ is

$$F_f = F \frac{\sin \lambda}{\cos (\lambda - \alpha)} \quad (5.12)$$

5.23
and the rate of heat generation per unit area $\dot{Q}$ in the shear zone in Eq. 5.13

$$\dot{Q} = FV_c \left(1 - \frac{\sin \lambda \sin \phi}{\cos(\lambda - \alpha) \cos(\phi - \alpha)}\right)w$$

(5.13)

where $\phi$ is the shear angle and $\alpha$ is the rake angle and $w$ is the width of cut. The rate of heat generation is proportional to the strain-rate at any point in the shear zone

$$\dot{Q} = k \dot{\gamma} w$$

(5.14)

where $k$ is the shear flow rate, and $\dot{\gamma}$ is the strain rate.

In the secondary deformation zone, the frictional heat generation $\dot{Q}_f$ at a point a distance $x$ from the cutting edge is

$$\dot{Q}_f = \tau_{ch} V_x$$

(5.15)

where $\tau_{ch}$ is shear stress on the tool / chip interface and $V_x$ is the sliding velocity of the chip and

$$\tau_{ch} = \frac{F_f}{hW}$$

(5.16)

The STMT simulations have been performed for various tooth surface roughness (contact conditions), illustrated in Figure 5.18 and Figure 5.19. For a coefficient of friction, $\lambda = 0.42$ the temperature distribution in the work piece are shown in Figure 5.18.

*Figure 5.18: Heat development in a work piece in the first sequence (2ms) of the engagement of one revolution.*
Reducing the coefficient of friction to 0.36, illustrated in Figure 5.19a, is followed by a drop in the maximum temperature to 420°C. The figure shows that the heat concentration with the maximum temperature is located at a distance away from the cutting edge, and the temperature is relatively low due to a smaller friction force.

Figure 5.19a: Simulation of STMT with a smooth surface (min roughness) in the first sequence (2ms) of the engagement of one revolution.

Figure 5.19b shows that increasing the surface roughness (medium roughness) will increase the temperature, and as a result the maximum temperature is located closer to the edge. For the surface roughness that corresponds to a rough tooth surface, the maximum temperature after 2 ms is about 700°C.
Figure 5.19b: Simulation of STMT with a medium rough surface (medium roughness) in the first sequence (2ms) of the engagement of one revolution.

Figure 5.19c shows temperature distribution on a rougher surface (max roughness) and indicates that the maximum temperature is both higher and located closer to the edge than on the smoother tooth surfaces.

Figure 5.19c: Simulation of STMT with a rough surface (max roughness) in the first sequence (2ms) of the engagement of one revolution.

During the first phase of engagement of one revolution, the energy increasing is significant for all three types of simulated surfaces. After 4 ms, the energy dissipation is lower for the smoother surface roughness, while the rougher surface shows high increase in energy dissipation, which also corresponds to an increasing temperature.
The greater the surface roughness, the higher the friction coefficient, which results in an increased chip thickness ratio, which in turn results in an accumulation of heat energy that leads to a higher temperature in the tooth.

5.6 Conclusions

The objective of the model was to explain the thermo-physical phenomena on the tooth-chip interface and to compare the simulation results to the experimental results from a qualitative point of view. The model takes into consideration the von Misses yield criterion and an isotropic strain hardening and makes use of a special technique to separate the chip from the work material. This technique is based on the ALE method.

The model shows a good agreement with the observed phenomena in the STMT experiments, even if the model not completely contains a true representation of the work piece material.

The simulation model helps to explain and validate some of the experimental results presented in chapter 4. Temperature measurements are difficult to perform in milling and therefore the effect of tooth preparation on the heat generation is difficult to assess experimentally.

Two important conclusions can be drawn from the mechanical analyses; (1) the contact area corresponding to the maximum compressive force has an inverse relationship to the edge radius, and (2) the compressive force corresponding to the maximum chip thickness increases with the edge radius. An optimal value for the...
edge radius can be selected by considering the friction energy, contact area and the compressive force.

The greater the surface roughness, the higher the friction coefficient, which results in an increased chip thickness ratio, which in turn results in an accumulation of heat energy that leads to a higher temperature in the tooth.

References in chapter 5
6. Discussion

The purpose of this thesis was to develop a basis for a Single Tooth Milling Test (STMT) method and a model for identifying and investigating some critical factors affecting tooth design, and the individual influence of these factors on the tooth wear behavior during the cutting process.

The theories presented in this thesis prove that the tooth design from a micro-geometric perspective and with consideration of the load condition on the tooth is important to consider in the development of a robust and reliable design of a PM-HSS cutting tool. Most of the previously performed research work has been focused on the improvement of the strength of the edge i.e. from a macro-geometric perspective. Although the results have been of great use to the gear manufacturing industry, they have not yet concluded in an optimized tooth design. One reason for this is the complexity of establishing criteria for a reliable tooth design, taking all relevant factors into consideration, for instance the interaction between the design parameters and varying mechanical and thermal loads that are influenced by the friction properties at the interface between the chip and the tooth edge.

The presented STMT has demonstrated that the micro parameters of the tooth design, the surface roughness of the tooth and the edge rounding, strongly affect the chip formation process, the machined surface and the tooth wear. Furthermore, it has been shown that the ratio between the edge radius and the coating thickness has a great effect on tooth wear, which has also been stated in other research works for continuous cutting.

The developed FEM model also illustrates the influence of edge rounding on the mechanical load distribution on the tooth and the chip. The presented FEM model is intended to support the experimental results and demonstrate the advantages of a certain tooth design. The model has to be further developed in order to take into consideration the complexity of the chip formation in milling operations as well as the varying friction phenomena on the chip – tool interface.

The presented results have been obtained in experiments that are primarily aiming at determining the influence of parameters, which are vital to the tooth design in contributing to an edge strengthening effect.

As a further development of the pre-study, an enlarged test matrix was established, consisting of relevant tooth design parameters i.e. edge
rounding and removal of defects from the tooth surfaces. It has been demonstrated that this enlarged test matrix has been successful in the identification of cross-correlated effects, i.e. between tooth design parameters and machinability factors. These results from STMT clearly illustrate that the tooth design parameters must be considered, in the manufacturing of cutting PM-HSS teeth.

The presented results also demonstrate that the behavior and intensity of tooth wear varies with the tooth edge radius and the surface roughness, given the same cutting conditions. This could be explained by the influence of cyclic thermal and mechanical loads during each engagement in the intermittent cutting process, correlated to the actual design parameter. It has been shown that severe flank wear due to chipping also leads to an unfavorable chip formation situation, resulting in an uncontrolled and accelerated wear process due to increased thermal and mechanical loads.

The configuration of the tooth set-up, the positioning and the diameter of the milling cutter are factors that influence the stability of the cutting process. If this is not done in an appropriate way, the process might become unstable.

The scientific contribution of this thesis is primarily that the presented results of the STMT studies comprise both technical analyses of the cutting process and tribological analyses of the surfaces in contact. It has also been demonstrated that this combination of analyses has made the interpretation of cross-correlation effects possible.

The design of PM-HSS tools must be adapted to different applications and the performance of the teeth optimized by using modern substrates and coatings. The evaluation of the influence of tooth preparations on the cutting process under laboratory environments was conducted by means of a combination of measurements of forces, vibration and wear as well as analyses of the machined surface. This interaction of tribology and traditional cutting studies, which has been carried out in this thesis, satisfies a great demand.

The evaluation of the developed STMT was initiated with wear analyses including a survey of the tooth wear on industrial hobs (HT), whose substrate consisted of ASP 2052 coated with AlCrN, and STMT with tooth substrate 2030 coated with TiN.
The two powder metallurgical HSS steels, APS 2030 and ASP 2052, common coated tools in the industry, were used in this study. Since the mechanical properties of the two HS steel grades are very similar, the choice of substrate materials is not considered to have any significant influence on the results. Likewise, two coatings used in this study are frequently used on teeth and they have similar, although not identical, properties and performances. This difference should be noted but it is not considered to influence the validity of the results.

The STMT proved to generate the same detrimental mechanisms as those occurring in dry hobbing. As is also the case in the hobbing process, the wear in the milling tests is mainly located at and around the cutting edge. There are distinct signs of edge chippings, indicating that the wear is discrete and discontinuous.

Already on unworn teeth with sharp edges, both on HT and STMT teeth, it is evident that the coating does not completely cover the boundary between flank and rake side. Cutting edges in the Y group in the STMT have not been exposed to any edge treatments, i.e. they are extremely sharp with grinding burrs still present on some parts. In other words, the edges do not have an optimized micro-geometry for the coating depositing.

As most of the PVD coatings, the TiN coating is the subject of relatively high compressive intrinsic stresses. When deposited on a sharp cutting edge, the local stress concentration is rapidly increasing as the coating thickness increases, i.e. when the ratio between the edge radius and the coating thickness decreases. When the stress reaches a certain value, the coating will crack and leave the cutting edge unprotected, illustrated in Figure 6.1. The weakened edge will then be subjected to continuous flank wear and, even more serious, discontinuous edge chippings. The wear appears to propagate by the removal of coating fragments – of more or less unaffected thickness – from the free edge of the coating. These cohesive coating failures are spurred by the intrinsic compressive stress in the coating and the intermittent cutting process.
Figure 6.1: Poor edge coverage, cohesive coating failure on a HT tooth with TiAlN coating, probably due to high compressive stresses corresponding to large coating thickness.

However, it should be emphasized that the extent and rate of wear should not be interpreted as a comparison between HT and STMT. The comparison between them concerns solely in the mechanisms of wear. It was concluded that a milling time of 29.5min was sufficient for the experiments.

Consequently, the benefit to performance of polishing is not easy to observe in cutting forces or in detrimental mechanisms. The varying amount of adhered work material as an effect of different surface roughness is clearly perceivable.

Initially the topography (ploughing) component of the friction coefficient is dominant and a rough surface will increase the friction on the rake face. Once a transferred layer of work material is formed most sliding occurs at the interface between the rake face and this layer, which provides the least shear resistance.

The building up of oxidized transfer layers indicates that the sheared zone is no longer the interface between the chip and the tooth surface but rather the interface between the chip and the transfer layers. A rough surface promotes the building up of such layers and, once formed, they constitute a probable thermal barrier in the contact zone.

The machined surfaces show differences. The great deformation of work material being smeared over the surfaces, when machined by a severely worn tooth, is probably the result of temporary built up edges or layers on the tooth and loss of edge volume, which results in a changed edge geometry.
The STMT experiments as well as the analyses of the load situations on the cutting teeth and the presented FEM model have been carried out at KTH. The tooth wear has been documented at the University of Uppsala and at Swerea Kimab AB.
7. Conclusions

This thesis presents the research performed to develop the laboratory STMT method and its application for studying the tooth micro-geometry influence on the tribo-system, tooth substrate-tooth coating-chip/work piece. The results will be used to design reliable PM-HSS hob teeth.

Development of STMT method

The advantages of using the developed single tooth milling test (STMT) method in a conventional milling machine is that the kinematics are considerably simplified as compared to hob tooling (HT), a fact that facilitates the analyses of the effects of cutting edge radii and tooth surface preparations on wear and the wear mechanisms. These parameters have been considered to have a considerable effect on the performance of PM-HSS teeth. In the experimental design, edge radius and surface preparation have been chosen as independent variables.

Characterization of micro-geometry effect on STMT tribo-system

For the evaluation of the effect of edge radius and tooth preparation in STMT, two experimental methods have been considered. First method used the cutting forces and vibration and the second used the tool wear. The tooth wear is evaluated using both direct and indirect methods. The experimental investigations show, for instance, that both the edge geometry and the surface roughness have some influence on the radial and the tangential force components, even if the force components have relatively small fluctuations.

The contact area between the chip and the rake face, which affect the STMT tribo-system behaviour, has been estimated by SEM, and was characterized by analyzing the chemical composition of the contact area chip/tool.

The compressive and shear stresses were then estimated from the cutting force components measured by the dynamometer located on the spindle and the estimated contact areas on the rake face.

The stress distribution on the flank faces is, however, more difficult to evaluate since the wear mechanism (flank wear) continuously increases in this zone. Although the contact area on the flank is sometimes clearly defined, it is very difficult to measure the force components acting on it, and there is therefore no reliable estimation of the stresses on the worn flank faces. It is suggested that the
mean value of the stress can be estimated by dividing the respective force by the contact area, even if it has been pointed out that there can be a substantial error in this estimation due to the poor accuracy in the estimated contact area. This concept has been applied to the calculation of stresses. It is important to load comparisons between various tooth designs to be able to relate measured force values to the contact areas.

Most PVD coatings, even those based on TiN, involve rather high intrinsic compressive stresses, and when the coating is applied on a sharp cutting edge, the local stress concentration on the edge will increase. Therefore, when the mechanical stress exceeds the ultimate strength of the coated edge during the cutting engagement, the coating will crack at the sharp edges. On rough teeth with sharp edges an increased edge chipping was observed, already at an early stage. After 1 minute’s machining time, exposed substrate material was visible on the edge. There is an ideal value of the ratio between the edge radius and the coating thickness that minimizes the stresses on a coated edge.

Thus, sharp cutting edges become impaired due to both continuous flank wear and – what is more serious – discontinuous edge chippings, as a result of an early loss of the coating.

STMT experiments demonstrate that there is a strong correlation between the stress values and the edge radius geometry. This is explained by the distribution of the stress on the contact area on the rake face. It is to be noted that the part of the surface that consists of the edge rounding has not been included in the estimation of the contact area, only the flat area of the rake face surface is estimated. The neglected area carries a large share of the loads, a fact that influences especially the dominating compressive stress but also the shear stress on the edge. This means that the calculated load might be overestimated. The reason for neglecting this part of the area is that the boundary towards the flank face is too complex to define. An alternative would be to estimate the area on the edge rounding by starting from the position of the stagnation point which will add 5 – 20 % to the flat part of the area, corresponding to a variation from a sharp edge to an edge radius of 30 μm.

**Wear studies**

Wear on the cutting edges caused by chipping as well as flank wear aggravates with the machining time. Edge chippings and gradually propagating wear will
result in a change of the mechanical load on the tooth. The geometrical shape of the cutting edge that has been changed due to this wear will probably give rise to an increased temperature that in turn affects the HSS substrate, as a result of the removed protective coating, leading to an intensified and accelerating wear rate.

Regarding the flank wear of the teeth, a trend can be noticed. With increasing edge radius, the size of the flank wear becomes smaller, from about 35 μm to about 15 μm. An indirect cause for this phenomenon might be the possibly reduced internal stress in the tooth coating by an increased edge radius in relation to the coating thickness.

The depth of the flank wear and the intensity of chipping on the teeth with an edge radius of 15 μm were larger as compared to the wear values estimated on teeth with a larger edge radius. Teeth with an edge radius of 30 μm had only isolated occurrences of chipping on the cutting edge. A closer analysis proves that the propagation of wear is considerably more irregular for a sharp edge than it is on edges with increased radii. This demonstrates the fact that a carefully selected edge radius will result in considerably better tooth wear resistance.

Increased wear is to be found near the nose of all the examined tools, a fact that might be related to higher temperature effects in the nose, in combination with a certain temperature influence from the secondary edge.

By polishing the teeth before the coating deposition, defects such as burrs, grinding scratches and grooves are removed from the cutting edge, resulting in less edge chippings and flank wear as compared to teeth with rougher surfaces. The effect of polishing coated surfaces is also of vital importance since the irregularities in the surface will be removed, resulting in an improved load bearing capacity.

The edge wear increases as a result of rougher tooth surfaces, which means that the positive effect of polishing mentioned in the thesis is significant. It is also demonstrated that the extent of local chipping seems to increase with surface roughness. The scores or ridges that might remain after the grinding process are detrimental to the strength of the tooth and are in many cases the basis for the propagation of cracks.
Experiments also showed that on a surface with $R_a$ exceeding 0.25 μm there will exist an increased amount of so-called oxidized layers even at an early stage.

Loss of edge volume is related to the edge radius and the tooth surface roughness, followed by a corresponding wear. An increased edge radius reduces the loss of volume, while the rougher the tooth, the greater the loss of volume.

Most of the process energy is converted to heat and located in three deformation zones in the cutting process. The width of the secondary zone ($\varepsilon_{II}$) and the tertiary deformation zone ($\varepsilon_{III}$) are both of great importance for the wear of the cutting tool and they greatly influence the service life of the tool. In this thesis the measurements of $\varepsilon_{II}$ are presented. If the secondary deformation zone is represented by its width $\varepsilon_{II}$ this will be enlarged by an increased edge radius as well as by an increase in the tooth surface roughness, which can result in a rise in temperature. The extension of this zone is represented by the contact area along the interface between the rake face and the chip, and the product of the width and the contact area might represent the “volume” of the secondary zone.

**Cutting force studies**

The qualitative analyses of the cutting force can also give some information on the friction condition on the rake face of the tooth. The friction is determined by the relationship between the radial and the tangential cutting force components. The friction force components vary in the STMT experiments due to the variation of the chip thickness and the variation of the friction coefficient. In order to study the friction conditions, a smoothing function has been applied to all force components in order to remove high frequency components.

In addition, qualitative analyses of the cutting force have been performed. These analyses take into consideration the average value of maximum force and the effect of wear.

**Characterization of Coating adhesion**

The scratch testing shows that the adhesion of the TiN layer to the HSS substrate is highly influenced by the substrate roughness. A strong correlation between the critical loads is obtained, both for the 50 μm tip tests and a 200 μm tip tests. The sample with the highest substrate roughness (Y5) has the lowest critical load value.
(meaning that a relatively small load is required to “break” the coating/substrate adhesion). The sample with the lowest substrate roughness (Y1) has clearly the highest critical load value (meaning that a relatively high load is required to start coating delamination).

**Thermo-mechanical model**

A thermo-mechanical model of the STMT is developed in chapter 5. The model complements the experimental work and tries to give an understanding of the tooth preparation’s effect on the load and temperature distribution. The objective of the model was to explain the thermo-physical phenomena on the tooth/chip interface and to compare the simulation results to the experimental results from a qualitative point of view. The model takes into consideration the von Misses yield criterion and an isotropic strain hardening and makes use of a special technique to separate the chip from the work material.

The model shows a good agreement with the observed phenomena in the STMT experiments, even if the model is not completely representative of the work piece material.

Two important conclusions can be drawn from the mechanical analyses; (1) the contact area corresponding to maximum compressive force is inversely proportional to the edge radius, and (2) the compressive force corresponding to maximum chip thickness increases with the edge radius. An optimal value for the edge radius can be selected by considering the friction energy, contact area and the compressive force.

The higher surface roughness, the higher friction coefficient resulting in an increased chip thickness ratio, and an accumulation of heat energy that leads to a higher temperature in the tooth.

**Research questions**

The research questions that have been considered in this thesis, lead to the following summarized conclusions:
• Influences of edge and surface preparations on various tooth types as well as the intensity of wear mechanisms are possible to be studied by the STMT method and the results might be transferred to industrial hobs. The single tooth milling test was able to reproduce the wear mechanisms active on dry cutting hobs used in normal gear production. The dominating wear types are discrete failures in the form of edge chippings (flank wear) and cohesive coating failures on the rake face.

• A tooth surface roughness of $R_a 0.2 \, \mu m$ is often considered to result in a sufficient surface finish so as to attain a successful deposit of the coating and lead to a satisfying cutting process performance. These results are supported by the investigation results from the STMT and scratch tests. An optimal edge radius of $30 \, \mu m$ is often considered to be sufficient for a stable edge geometry resulting in an improved edge strengthening. A stable edge geometry retains its shape without any significant loss of edge volume. These results are also supported by the investigation results from the STMT.

• The analysis of the machined surfaces indicates that a geometrically stable micro geometry generates a machined surface with less smeared work material than an edge with increased chipping wear.

**Scientific and technological contributions**

Finally in this chapter the scientific contributions are summarized and these are are consistent with the scientific methodology formulated in the thesis:

• Mapping and identifying relevant research issues related to hob tool reliability in the Swedish gear production industry.

• Designing the theoretical and experimental methods for analysis and characterization of STM tribo-system created during chip formation
  - Development and implementation of STMT as an efficient method to study, in laboratory environment, the tooth micro-geometry influence on the STM tribo-system behavior.
  - Design of experimental work and selection of measurement methods and tools, micro-geometry significant features and cutting parameters.
  - Selection of measurement variables best correlated to the studied phenomena
- Development of a theoretical model, implemented as a 3D-FEM simulation, to study the thermo-mechanical behavior of STM tribo-system.
- Characterization of micro-geometry using cutting force, wear, scratch tests and micrographs.

- Development of an original dynamometer on a rotating fixture and a method for cutting force components evaluation based on piezo-electric effect modeling and NN (neural-network) calibration methods.

### 7.1 Future works

Evaluation of the cutting process by STMT should be correlated to the development of new work materials that might be even more difficult to machine than today’s materials. The new mechanisms of tribo-film formation, friction and wear must also to be examined.

The optimal behavior of coatings is dependent on the cutting parameters. Available as well as future tooth substrates and coating materials should therefore be the subjects of deeper analyses, preferably by means of the STMT, which should also be applied to the evaluation of the role of tribo-films, and also considered in the further development of the FEM model, with respect to the frictional conditions on the interface chip – tooth.

It is also of interest to validate the preparation of HT teeth in the hobbing processes, and develop a cutting simulation model for chip formation in hobbing.

A specially designed fixture is developed in this project for online measurements of cutting forces in gear hobbing, illustrated in Figure 7.1. However, validation of the system might be carried out when the calibration is completed, by performing actual machining tests on a conventional hobbing machine. Such a developed system might have a significant role in cutting force measurements and in the related analyses of the gear hobbing process.
Figure 7.1: (a) Direction and locations of applied force and (b) simulation output.
Tooth micro geometry studies in single tooth milling tests with PVD coated HSS inserts

Mathias Werner*, Thomas Björk** and Mihai Nicolescu*

*Department of Production Engineering, KTH, Stockholm, Sweden
**Swerea Kimab AB, Stockholm, Sweden

Submitted to publication and under review in International Journal of Machining and Machinability of Materials (IJMMM).

2012
Tooth micro geometry studies in single tooth milling tests with PVD coated HSS inserts

Mathias Werner*, Thomas Björk** and Mihai Nicolescu*

*Department of Production Engineering, KTH, Stockholm, Sweden
**Swerea KIMAB AB, Stockholm, Sweden

Abstract

Cutting tools can be made more reliable and robust by optimizing their micro geometry with respect to the tool surface roughness before and after coating, the adhesion of the coating to the substrate, and the cutting edge rounding. A single tooth milling method, STM, has been developed for experimental analyses of the effect of micro geometry on tool wear mechanisms. The purpose of this paper is to characterize the tribo-system consisting of tooth substrate – tooth coating – chip/work piece for various tooth micro-geometries and surface preparations. SEM micrographs of new and worn teeth have been evaluated in order to describe and characterize the relationships between micro geometry and the wear mechanisms.

The results acquired in STM can be further implemented to other applications, as for example the development of reliable hob teeth in gear manufacturing. The gear manufacturing industry has adopted hobbing as a very common method for the manufacturing of gears. The most frequently used type of hob have teeth consisting of a substrate of High Speed Steel (HSS) covered with a PVD coating. The damage of one tooth will normally require the replacement of the entire hob.

The conceivable superiority of STM test method over experimental methods in real gear hobbing – and even over the so-called “fly hobbing” tests – can be referred to the availability and the reduction of both design and production costs for the milling inserts, as well as time saving of the experiments.

Keywords: Single tooth milling, Hob, tooth micro geometry.

Introduction

The intensified global competition in the automotive industry gives rise to tough demands on enhancing the manufacturing performance by means of innovation of processes and product development. The powertrain is one of a vehicle's most complicated parts with gears being its central components.

Gear manufacturing with hobbing has to become a highly specialized area in order to produce gears with demands on reliable performance and high efficiency. A critical element to achieve the demands is the tooling used in the manufacturing process. In addition to the impact on the quality of the gears, the tooling affects both the production costs and the process reliability. Hobbing as a method for gear generation is widely used for manufacturing of spur gears, helical gears, worms and worm wheels and it is characterized by high accuracy and machining productivity. This type of metal cutting with hobs involves less forces on the cutting edge (less chip load on the teeth) compared to those on other gear milling processes [1]. The tooling cost for hobbing is lower than that for broaching and multiple-tool shaping heads. For this reason, hobbing is used in large-quantity production but even for just a few pieces.

The gear hobs are mainly made of high-alloy high speed steels (HSS). The advantage of HSS hobs resides in its strength to withstand cutting forces and the relatively low cost of the tools. Considering tool life, HSS perform very well in intermittent cutting applications. However, the cutting speed range of HSS is highly limited, which is the greatest disadvantage of HSS. Generally, powder-metallurgical HSS (PM HSS) tools and particularly hob teeth have to be designed in such a way that they can be
reconditioned without losing their service life. The reconditioning is done by a scheduled regrinding of the tool in order to optimize the relationship between part quality and production costs.

This means that regrinding must take place when the wear of the hob’s teeth is relatively small, which requires a good control of the hobbing process. Control of the hobbing process can be achieved partly by designing and producing reliable tools and partly at the process stages by controlling the hob’s wear mechanisms. However, current gear hobs lack sufficient prediction of wear which leads to reduced tool life mainly due to brittleness of the cutting edge. It should also be mentioned that the breakage of an individual edge makes it necessary to replace the entire hob. This is another reason for improving the reliability of PM HSS hobs.

There are many design parameters that must be considered for controlling the functionality of a hob. Less concern has been given to the design of a tooth’s micro-geometry with respect to tooth surface and its cutting edge radius. Previous studies on the effects of a tooth’s micro-geometry were mainly focused on the chip formation mechanisms and less on the underlying tribological phenomena. Therefore, the objective of this paper is to study the effect of the tooth’s micro-geometry on wear mechanisms.

The hob consists of a large number of cutting teeth arranged to generate specific gear blanks. Each hob tooth is designed in such a way that it can be reconditioned several times without losing its original geometry. The desired wear scenario is a controlled wear which makes a continuous tool reconditioning schedule possible. This schedule can then be applied to the tool to be used in the most economical way. The problem is that hobs, in general, do not show continuous wear behaviour, and therefore lack reliability. This makes it difficult to predict how many gears a hob should produce before it is reconditioned so as to avoid breakdown and to sustain the gear quality. In a previous study [2], the wear observed on almost all hobs was located on the rake faces and/or the cutting edges. The overall conclusion from the study was that the wear mainly propagates by discrete fractures which appear to be associated with local defects in the coating and/or substrate-coating interface. It was also suggested that high intrinsic stresses in the coating around the cutting edge leads to coating spallation, that subsequently accelerates the wear of the cutting edge.

Experimental testing of various tooth designs requires access to industrial equipment since hobbing machines often are not part of the equipment of production research laboratories. Tests in industrial equipment would imply production stops and high costs. An alternative solution would be to develop laboratory methods that reproduce the same hob wear pattern in laboratory environment.

Experimental results of the first author’s previous studies have demonstrated that the wear mechanisms in the single tooth milling (STM) experiments shows close similarities to the tooth wear in real gear hobbing [3]. As a consequence, the aim of this paper is to study the influence of preparations of the tooth surfaces on the tool wear mechanism in STM and to evaluate how various edge geometries contribute to the reliability of the tools. Arc Physical Vapour Deposited (PVD) TiN-coated Powder Metallurgic High Speed Steel (PM HSS) inserts with various surface polishing and edge rounding were tested in STM experiments and evaluated with respect to various observed parameters such as tool wear and tool degradation process. The laboratory results provide a preliminary estimate of feasibility and allow realistic conditions to be defined. As a result, tentative design of industrial gear hobs can be performed.

The conditions that distinguish the intermittent cutting processes from continuous cutting operations, always involve both mechanical and thermal shocks [4]. The development of PVD processes has made it possible to coat HSS materials with hard material, without the steels being subject to thermal effects. The improved performance of coated tools is the result of a combination of a tough substrate material and a wear-resistant surface coating. An improved performance of tool Substrates leads to increasing resistance of the tooth to both mechanical and thermal shocks, as illustrated in Figure 1 [5].
A surface can be characterized by its mechanical, physicochemical, topographic or structural properties. The combination of these characteristics defines the surface state, Figure 2 [5].

One objective of surface preparation procedure prior to and after the coating is to produce a homogeneous surface on the substrate. The possibilities to reproduce surface preparations are the prerequisite of robust and reliable tool designs.

The strength of PM HSS tools with hard ceramic PVD coatings is limited by the flaw formation. In order to attain reliable tooth designs it is necessary that knowledge of flaws formation in the coating, hob substrate and the interface in-between these are available. In recently published research results it is stated that the edge geometry and the tooth’s surface preparations, prior to and after the application of the coating, are matters of vital importance for the flaw formation, which causes wear growth in the cutting edge [2].

Since the performance and reliability of a PVD coated PM HSS tooth depends on the adhesion of the hard coating material to the substrate material, the influence of the micro-geometry on the wear mechanisms has also directly explained how the surface preparation affects the coating adhesion. In addition, the association between the tool loads, resulting from the material removal rates, and the substrate material preparation has also been studied.
Phenomenological aspects

The understanding and characterization of the tribo-system in STM, with particular attention paid to the tooth surface roughness, helps in reducing tool wear and in performing an efficient cutting process. To fully promote the coating protection, the adhesion between the substrate material and coating must be adequate. The coating have relatively low affinity to the elements in the work material which counteracts the welding mechanism that is a prerequisite for adhesive wear. Furthermore, by applying a coating, the tool temperature can be reduced due to improved contact conditions [6] and [7].

In addition to its mechanical properties, a coating must adhere perfectly to its substrate in order to act as an efficient protective layer against wear. This is the main reason for the deposition of coatings to be preceded by mechanical treatment, designed to modify the surface micro-geometry, in order to improve the adherence of the coating to the substrate. The principle of adhesion is complex and the fundamental mechanisms are intricate as they can include mechanical binding, electrostatic forces, diffusion, or chemical bonding [8].

Coating detachment never occurs suddenly and completely, they occurs rather as a result of the propagation of cracks, which gradually breaks the interfacial bonds, releases elastic energy and allows the dissipation of irreversible work at the head of the crack. The crack can propagate when the adhesion energy W is less than the strain energy release rate G (i.e.: \( W < G \)) [9].

On a coated tool, wear can either propagate by abrasive and mild adhesive wear leading to a slow and gradual removal of the coating, which is the desired mode of wear, or by fatigue and discrete detachment of the coating [10]. The two latter phenomena leave the substrate exposed prematurely which leads to an accelerated wear situation. A magnified view of tool wear area is illustrated in Figure 3.

![Figure 3 General overview of worn insert](image)

It has been shown that residual stresses in the coating influence fracture and delamination of hard coatings [11]. PVD coatings on HSS typically possess compressive stresses of the order of 1-5 GPa. On a perfectly flat and smooth substrate of infinite extent, these stresses would not generate any normal or shear stresses at the interface between the coating and the substrate; they would only act positively on the coating cohesion.

However, the tool surface that is to be coated is far from being that ideal, as it has a certain surface roughness and, of course, is not infinitely extended. The tool surface contains ridges, grooves and sharp edges, in combination with lateral compressive stresses that in turn generate stresses across the interface, Figure 4.
Initially, during the first few engagements, the loads act on a very small area of a sharp edge, which is illustrated in Figure 4a. Parts of the edge are chipped out and the substrate has been uncovered, as illustrated in Figure 4b. The substrate is exposed to heat due to friction on a rapidly increasing contact area on the flank face, and it is likely that a permanent deformation accelerates the wear even more due to the softening of the edge. The unfavorable tool geometry also results in an increased wear on the rake face, which in time will lead to crater wear. When the wear has advanced enough to leave the tool substrate unprotected by the coating on both the rake face and the flank face, as illustrated in Figure 4c, it is in most cases too late to recondition the tool.

Figure 4 wear propagation

In the PVD process, the demarcation line between the coating and substrate is sharp without any diffused layer in either side, indicating the mechanical nature of bonding.

When the substrate / coating-system is applied with an external stress acting on the tool, the coating detachment is facilitated in regions where the interface is already subject to high tensile normal stresses, i.e. along the coarse ridges and along the cutting edge of the tool. The ratio between the substrate radius and the coating thickness determines the magnitude of the interfacial stresses. An increased ratio reduces the maximum interfacial stresses. The surface topography and the edge radius are therefore two important factors that affects a premature failure due to discrete coating detachment. In general, all types of irregularities such as pores, impurities, carbides, topographic variations etc. in the interface will induce local stress fields and may have negative effects on the coating adhesion, Figure 5.
Thermally induced phase transformations in the HSS substrate can also reduce the adhesion of the coating [6]. If the tempering temperature of the HSS is locally exceeded during the grinding of the HSS surface, prior to the coating deposition, the material will undergo a phase transformation over a specific depth [12] and [13]. When coated, this altered material will constitute a weakened layer between the coating and the undamaged HSS which acts destructively on the adhesion of the applied coating. Furthermore, excessive temperatures in the cutting process can also lead to discrete coating delamination. HSS begins to show significant thermal softening for temperatures above 600 °C. This results in brittle fracture of the coating, and rapid wear of the exposed and more softened HSS.

The “industrial” grinding processes always generate defects on the micro-geometry such as burrs, micro-cracks and wrong surface textures. Burrs are initiated at the edges and in connection with the ridges on the ground surface. The burrs can be described as thin flakes of severely deformed material. When such burrs are present under a hard, brittle coating they will initiate cracking and will certainly be broken off almost immediately when being exposed to external stress, leaving areas of unprotected substrate. It is therefore important to remove these burrs from the substrate surface before depositing the coating.

**Experimental**

Extensive research was required to study the influence of cutting edge geometries and surface properties on tool wear. The laboratory test method, STM, has been developed by means of a conventional milling machine, using the single tooth milling cutter as illustrated in Figure 6. [3].

**Figure 5 Cohesive coating failures linked to a droplet site.**

**Figure 6 SMT milling cutter**
A consequence of the STM tests is that the kinematics is highly simplified, a fact that makes analyses of the effect of various cutting edge preparations possible. Besides the general aim of evaluating the micro-geometry with respect to the surface roughness and various edge radii of milling teeth, the purpose is also to transfer the laboratory results and the optimized micro-geometry design to gear hobbing tools and to verify them in industrial environment.

Poor micro-geometry design of cutting teeth can promote mechanical and thermal failures and may reduce dramatically the service life. Therefore, the aim of this paper was to verify how the surface roughness and the edge radius of PVD coated PM-HSS teeth affects tool life and wear mechanisms in the developed laboratory test method, called Single Tooth Milling test (STM test) in Figure 7.

![Figure 7. Test setup in single tooth milling method with conventional milling](image)

The experimental results might be applied to improve the performance of real hobbing teeth in gear production. A main objective is to correlate the surface roughness and the deburring process (including edge rounding) to various wear mechanisms, and to understand the influence of surface preparation, prior to coating, on adhesion and how this affects the reliability of the machining process. An conventionally produced and un-deburred sharp edge is illustrated in Figure 8 where typical burr can be noticed.

![Figure 8. Cross section of a coated sharp edge with burrs](image)

In STM operations, several tool wear mechanisms can initiate simultaneously. The dominant wear mechanism will depend on the cutting conditions, tool/work piece materials and tooth micro-geometry. A rigorous classification of failure and wear mechanisms with respect to different micro-geometries of teeth is important in order to evaluate the machinability of the STM process. Improving
tool life results in a progressive tool wear on the rake face and on clearance face. Most often the occurrence of wear on the clearance face (flank wear) is used to quantify tool wear.

As the purpose of the research was to study the effect of the micro-geometry of teeth on selected output variables that characterize the STM tribo-system, the combinations of tooth roundness and surface roughness were carefully planned. Disregarding the influence of the machine tool structure, the results of the machining process are determined by three sets of variables: (1) cutting parameters, i.e., cutting speed, depth of cut and feed rate, (2) cutting tool/work piece material properties and (3) the cutting tooth’s macro- and micro-geometry.

Cutting parameters were kept constant at values close to those used in real hobbing with the cutting speed optimized with respect to heat generation. Characteristic cutting parameters in the milling tests are presented in Table 1. A cutting speed of 120m/min, a table feed rate of 0.25mm/rev, an axial depth of cut 3 mm and a radial depth of cut 8 mm was used in the study. Climb milling was used in all tests. Another parameter that affects machining is the ratio $t_{\text{cut}}/t_{\text{offcut}}$, where $t_{\text{cut}}$ is the in-cut time and $t_{\text{offcut}}$ is the off-cut time. This ratio was also selected close to that used in real hobbing. As regards the second set of variables, the tool material ASP 2030 was the same in all the tests. The tooth macro-geometry affects the magnitudes and the nature of the thermal and mechanical stress in the primary shear zone and residual stresses in the machined surface. Figure 9 illustrates the macro-geometry.

A single insert cutter with a rake angle of 12° and a clearance angle of 6° has been used in the experimental studies. The inserts were designed with three various edge radii and the tooth surfaces were polished to five different grades of roughness, presented in Table 2 and Table 3, respectively. Both the rake and flank faces of the inserts were in advance prepared with a plane grinder and were manually polished. Furthermore, the inserts were polished after the coating so as to remove protrusive small drops resulting from the coating procedure.

![Figure 9 Illustration of the milling inserts used in the single insert milling test](image-url)
A vertical tri-axial Mazak CNC-controlled milling machine was used in the experimental single tooth milling tests. The milling cutter, especially designed for this purpose, Figure 10 illustrates the set-up in experimental tests with the work piece clamped on a magnetic table for holding it in a fixed position.

In order to investigate the influence of the surface roughness and the cutting edge rounding on the tooth performance, the teeth were divided into two groups. The teeth in the group denoted Y are classified with respect to the tooth surface roughness grade (R\text{a}), starting from tooth type Y1 with the finest roughness to tooth type Y5 with the roughest surface. These teeth had no significant edge radius (ER) and can be considered to be perfectly sharp.

The teeth in the E group are classified with respect to the edge radius, all being polished to the same surface roughness as the tooth type Y1. Tooth type E1 has the smallest ER, and tooth type E3, the largest ER. Tooth type Y1 can also be considered to be part of the E group, regarding the surface roughness and a sharp edge (ER \approx 0), and it is therefore denoted tooth type E0 in Table 3.

Table 1 Characteristic cutting parameters for the milling tests

<table>
<thead>
<tr>
<th>Cutting parameters used in single tooth milling method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed (v\text{c}) [m/min]</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>120</td>
</tr>
</tbody>
</table>

Table 2 Specification of the specimens in groups Y

<table>
<thead>
<tr>
<th>Specimen (tooth No.)</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge radius (ER [\mu m])</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Surface Roughness (Ra [\mu m])</td>
<td>&lt; 0.10</td>
<td>0.10</td>
<td>0.25</td>
<td>0.40</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 3 Specification of the specimens of groups E

<table>
<thead>
<tr>
<th>Specimen (tooth No.)</th>
<th>E0</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge radius (ER [\mu m])</td>
<td>0</td>
<td>15</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Surface roughness (Ra [\mu m])</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
<td>&lt; 0.10</td>
</tr>
</tbody>
</table>

Cutting tools

The substrate material of the inserts was powder metallurgical HSS (ASP 2030 from Erasteel) according to Table 4. The substrate consists of a fine-grain type of material with uniformly distributed small carbides. This homogeneous material, free from segregation, has a uniform structure as illustrated in Figure 11 where the microstructure of P/M processed ASP HSS tool is presented [14].
The most prominent properties of the ASP technique include improved toughness and ultimate strength due to the uniform carbide distribution and the absence of metallurgical defects. Improved dimensional stability in heat treatment resulting from the absence of segregation is also an advantage. Additionally, wear resistance can be improved by increasing the alloy content, without sacrificing toughness or grindability. In the ASP process, Figure 12, a melt of alloy steel is atomized in an inert gas to form spherical powder particles.

The PM ASP 2030 has good impact strength compared to other alternative harder cutting tool materials, which makes this type of material very suitable for tools used in interrupted cutting operations, (Figure 13).
PM ASP 2030 provides various combinations of wear resistance, hot hardness, and toughness. Tools of ASP 2030, protected with hard coating, present high wear resistance without losing the toughness of the HSS core material. Physical properties of the ASP 2030 material hardened at 1080°C and tempered at 560°C (3x1 hour) are presented in Table 5.

### Table 4 Chemical composition of the tooth substrate ASP 2030 material used in the tests

<table>
<thead>
<tr>
<th>Material (substrate)</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Co</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASP 2030</td>
<td>1.28</td>
<td>4.2</td>
<td>5.0</td>
<td>6.4</td>
<td>8.5</td>
<td>3.1</td>
</tr>
</tbody>
</table>

### Table 5 Physical properties of ASP 2030

<table>
<thead>
<tr>
<th>Temperature</th>
<th>20°C</th>
<th>400°C</th>
<th>600°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density g/cm³</td>
<td>8.1</td>
<td>7.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Modulus of elasticity, kN/mm²</td>
<td>240</td>
<td>214</td>
<td>192</td>
</tr>
<tr>
<td>Thermal conductivity, W/m°C</td>
<td>24</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>Specific heat, J/kg°C</td>
<td>420</td>
<td>510</td>
<td>600</td>
</tr>
</tbody>
</table>

### Tooth coating

The PVD coating of titanium nitride (TiN) used in the SMT tests on the inserts is commercially available. Its hardness and mechanical properties are presented in Table 6. TiN is one of the most frequently used PVD coating material. Crystallographically, it is characterized by a face-centred cubic lattice as shown in Figure 14. Its hardness can range from 1400 HV to 4000 HV depending on the deposition technique and conditions. Titanium nitride readily oxidizes at 500°C which significantly impairs its mechanical properties. This decomposition of the material, under conditions of extreme stress, restricts its utility [15].

![Figure 14 The face-centred cubic lattice of titanium nitride](image)
Table 6. Nominal mechanical properties of the coatings used on inserts in the tests.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TiN (Inserts)</td>
<td>29</td>
<td>2300</td>
<td>410</td>
<td>-2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Work piece material

The selected work piece material was a case hardening steel, ISO 20NiCrMoS2-2 with a pearlite-ferrite structure, a very common work material in the industrial production of transmission components. The elemental composition of the steel can be found in Table 7.

Table 7 Chemical composition of the work material

<table>
<thead>
<tr>
<th>Chemical composition (Wt%) work material</th>
<th>balance Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.2</td>
</tr>
<tr>
<td>Si</td>
<td>0.24</td>
</tr>
<tr>
<td>Mn</td>
<td>0.86</td>
</tr>
<tr>
<td>P</td>
<td>0.009</td>
</tr>
<tr>
<td>S</td>
<td>0.013</td>
</tr>
<tr>
<td>Al</td>
<td>0.039</td>
</tr>
<tr>
<td>N</td>
<td>85 Ppm</td>
</tr>
<tr>
<td>V</td>
<td>0.005</td>
</tr>
</tbody>
</table>

LOM Micrographs of metallographic cross-sections of the work material used in the laboratory tests are illustrated in Figure 15. The pearlite-ferrite structure is typical for case hardening steel.

Figure 15 Cross-section LOM micrographs of the work material used in the milling test revealing a pearlite-ferrite structure (a) and its distribution (b).

The main objectives for the experimental studies in STM were:

- Investigation and characterization of the tribo-system tooth substrate - tooth coating - chip for various micro-geometries and surface preparations of teeth.
- Characterization of wear mechanisms and phenomenological modelling of the wear process.
- Evaluation of obtained wear data, directly by Scanning Electron Microscopy (SEM) and indirectly by measurements of cutting forces and vibrations.
Results and discussions

The shape, morphology and the location of wear provide important information, that generally are needed so as to characterize the tribo-system tool - chip and the wear process. In order to investigate the wear types that occur for various tooth surface preparations, micrographs of the inserts were taken before and after each experiment. Micrographs at the same position and observation angles, at constant time intervals of a worn tooth were always taken in order to investigate the progress of wear in SMT.

The dominant observed wear during the experiments in single tooth milling was flank wear on the primary and secondary cutting edges. Damages on the rake surface, was quite limited. Therefore the teeth are mainly worn as a result of initial chipping of both the primary and secondary cutting edges, followed by flank face wear. The exposed flank face of the PM-HSS teeth is in turn worn by a combination of mild adhesive and abrasive wear. Figure 9 shows the location of the examined areas on the tooth.

The wear on the tooth often results in a dramatic change in geometry and tribological conditions due to an altered surface topography. Wear develops often in early stages, even as soon as after a few engagements. The altered geometry of the tooth leads also to a different chip formation which in turn gives rise to distinctly unfavourable loading situations on the tooth for both mechanical and thermal loads. The consequence is an accelerating wear that can result in a very rapid tool break-down. It is therefore necessary to take into consideration both the actual loading pattern and the wear on the tooth when designing a reliable and robust tool with PVD coated PM-HSS teeth.

The loss of volume that is the main reason for impaired edge geometry is the result of a combination of wear mechanisms, principally chipping. Chipping occurs, in principle, initially on a sharp edge, succeeded by an accelerated wear and degradation of the tooth substrate. Regarding the flank face wear of the teeth shown in Figure 16, a trend can be distinguished. With increasing edge radius, the flank wear gets smaller, from about 35 μm to about 15 μm. The reason for this is the internal stress in the tooth coating, which apparently decreases with an increased cutting edge radius, mainly due to edge strengthening, i.e. the risk of edge damages is reduced by an increased edge radius.

---

**Material:**

HSS ASP2030

**Cutting Parameters:**

- \(v_c\)  = 120 m/min
- \(a_v\)  = 3 mm
- \(a_n\)  = 6 mm

**Insert:**

- Substrate: HSS ASP2030
- Coating: TIN
- E Group: Increase in Edge Radius
- Y Group: Increase in Surface Roughness
Figure 16 Flank Wear of the E Group

Figure 16 also illustrates the frequency of chipping. The depth of flank wear on tooth type E1 is larger than that on the teeth with larger edge radii. The flank wear on tooth type E2 is smoother with respect to both depth and width. The existence of chippings of the cutting edge on tooth type E3 is only an isolated occurrence. These chippings are not particularly deep, and the coating is mostly intact and therefore still protecting the tooth substrate.

Figure 17 shows the differences between the flank wear of the teeth with varying roughness. In contrast to the teeth with varying edge radius, the width of the flank wear does not change significantly with roughness and remains at a severe wear level. The main difference within the Y group is the extent of local chippings that seems to increase with surface roughness. This is well supported by earlier results as presented in [18], which also demonstrated an increased risk of coating spallation next to deeper grooves on the surfaces.

Figures 16 and 17: Flank Wear of the E and Y Groups

The analyses of teeth with various micro-geometry preparations gave evidence of the importance of smooth teeth surfaces, and the detrimental effect of the absence of an edge preparation is obvious since the initially sharp edges were considerably affected. The teeth with a smoother rake face showed a somewhat lesser amount of adherent material, than the teeth types Y4 and Y5 did. The teeth types Y4 and Y5 presented more irregular flank wear and an increased number of deeper chippings, as compared with the teeth types Y1, Y2 and Y3, which might be explained by the unfavourable prerequisites for crack formation in the shape of grinding scratches close to the edge.

The consequences of severe flank wear involve a great risk for heat transfer into the tooth substrate, eventually resulting in a tooth break-down.
Figure 18 Nose area studied after 30 minutes machining.

Figure 18 also enhances the connection of the cutting edge radius and the flank wear. Beginning with tooth type E1, the nose wear decreases from about 25 μm to less than 10 μm at tooth type E3. The analysis of nose wear, i.e. at the interface between the primary and the secondary edges shows that there is a trend towards a slightly increased wear on the teeth, compared to the primary edges. This might depend on an increased thermal influence and a more complex stress pattern on the two adjacent edges. Tooth type E1 shows a flank wear with a somewhat more extended area. Tooth type E2 presents a declining tendency to edge chippings while tooth type E3, even at the nose region, shows a stable and robust edge with a coating that is largely preserved.

The loss of edge volume has a relationship to both the edge radius and the surface roughness. An increase in the edge radius has a positive decreasing effect on the loss of volume, while a rougher surface causes a greater loss of volume. These conclusions are supported by the observations that are illustrated in Figure 19.

The design that leads to a geometrically stable edge with the least geometrical change is to be found on tooth type (E3), which also generates the best quality of the machined surface. The largest geometrical change of the edge is found in the Y group, i.e. on tooth type (Y5) on the rake face. This group also generates on the whole a lower quality of machined surface, than, for example, tooth type E3, after 29.5 minutes’ machining time. The analyses of the machined surfaces indicate that a geometrically stable edge generates a machined surface with less smeared work material than an edge with increased chipping wear does.
The analyses of the nose region on the teeth in group Y show how the combination of an initially sharp edge and a rough tooth surface contributes to an unstable edge that will be the subject of chippings. The type of wear that is illustrated on the teeth types Y2 and Y3 is a distinct flank wear, which is even more pronounced on teeth types Y4 and Y5. In the nose regions the grinding scratches involve a greater risk of chippings since the loading on these regions originates from both edges. On tooth type Y5 an edge fracture might possibly be caused by a grinding scratch. Large part of the edge, being composed of both coating and substrate, has been removed along the scratch.

Initially in the wear process, during the first few engagements, the loads act on a very small area of the sharp tooth, which is illustrated in Figure 4. Parts of the edge are broken, resulting in an uncovered substrate that is exposed to heat on a rapidly increasing contact area on the flank face. It is likely that a permanent deformation accelerates the wear even more due to the softening of the edge. The unfavourably changed tool geometry also results in an increased wear on the rake face, which in time will probably lead to crater wear. When the wear has advanced enough into the coating to make the tool substrate unprotected on both the rake and the flank faces, it is in most cases too late to recondition the tooth.

The ridges that might remain after the grinding process, illustrated in Figure 4, are detrimental to the strength of the tooth and are in many cases the basis for propagation of cracks. If there are irregularities left on the tooth surface when the coating has been deposited, polishing then leads to a strong reduction of the thickness of the coating on raised areas of the substrate, which greatly impairs the protection of the substrate.
In addition to surface roughness, irregularities and scores have a negative effect on the tool reliability. The defects that exist on tools with a rougher coating surface from the beginning carry a great part of the loads, which in many cases can result in too high stresses in the coating material. The region close to the edge will be the subject to chipping. Smooth surfaces help to preserve the original geometry of the tool. Another scenario with an oversized edge radius, involves an unpredictable wear of the edge due to a widespread and unstable stagnation zone and a non-functioning shear process of the work material during the chip formation. This will result in a permanent deformation of the work material and thus a high thermal influence on the cutting edge which in turn will lead to increased edge wear. An important phenomenon related to tooth wear, and influencing the chip formation, is oxidized layers. By examining the rake face in SEM microscope, it was possible to study the formed oxidized layers, or how the work material adheres to the surface irregularities and chemically reacts on the tooth material, and also how the formation of oxidized layers is initiated.

Conclusions

The paper introduces the STM as a method for studying the tribo-system tooth substrate - tooth coating - chip for various micro-geometries and surface preparations of the tooth. The evaluation of the influence of important parameters on the tooth design was carried out by means of STM experiments, followed by deeper analyses regarding the influence of edge rounding and surface preparation. The principal wear in the experiments in STM was characterized as flank wear on the primary and secondary cutting edges. As for the flank face wear, a trend can be distinguished. With increasing edge radius, the size of the flank face wear becomes smaller due to the simultaneously decreasing internal stress in the tooth coating. The loss of edge volume is related to both the edge radius and the surface roughness. An increase in the edge radius has a positive decreasing effect on the loss of volume, while a rougher surface causes an increased loss of volume. A situation of severe flank wear involves a great risk for heat transfer into the tooth substrate, which eventually might result in a tooth break-down. There is only isolated occurrence of chippings of the cutting edge on tooth type E3 with the largest edge radius. An increased edge radius leads to an increased curvature of the chips which in turn results in a decreased contact area. A surfaces roughness exceeding 0.4 μm, is favourable to the emergence of formed so-called oxidized layers at an early stage. An increased edge radius gives also rise to a stagnation zone on the edge, which influences the shear process during the chip formation. The width of the second deformation zone has a tendency to increase with increased radius. The influence of the surface roughness on the second deformation zone is not equally obvious, a fact that might depend on the extent and the distribution of the seized and the sliding regions that mainly involve the contact surface on the rake face. The scores or ridges that might remain after the grinding process are detrimental to the strength of the tooth and are in many cases the basis for the propagation of cracks. If irregularities are left on the tooth surface when the coating has been deposited, polishing results in a strong reduction of the thickness of the coating on raised areas on the substrate, which greatly impairs the protection of the tooth substrate. The principal difference within the Y group is the extent of local chippings that seems to increase with surface roughness.

References


ARTICLE II

Single Tooth Milling test simulations

Mathias Werner and Mihai Nicolescu
Department of Production Engineering, KTH, Stockholm, Sweden

Submitted to publication and under review in
ASME Journal of Manufacturing science and Engineering
2012
Abstract

The Single Tooth Milling test is a research laboratory method that has been developed to study the tribo-system tooth – chip/workpiece in various machining conditions. The tooth performance has been evaluated with respect to micro-geometry in terms of tooth’s edge rounding and surface roughness. The surface roughness effect on tooth performance has been evaluated with respect to coating adhesion to the substrate and the wear mechanisms. Various experimental methods have been use, in present research work, to investigate the tool-chip interface, including scanning electron microscopy, scratch tests, cutting force measurements and wear tests. Important factors affecting cutting tooth wear are thermal and mechanical load distributions on the tooth during machining. Due to the inherent difficulties to evaluate the tool-chip contact area, numerical methods have been introduced to estimate the temperature and mechanical load distributions on the tooth. The paper main focus is to present the results of 3D simulations of single tooth milling method. The experimental and simulation results will be used to control the wear mechanisms in industrial hobbing by optimizing design of teeth.

1 Introduction

In response to this intensified global competitive pressure, companies are struggling to enhance performance by innovating and adopting process and product improvements. This phenomenon is apparent in automotive industry where global leaders with superior production processes and better quality products intensify the competitive pressure. Regarding product innovations, they are relatively easy to copy; therefore they cannot be a permanent response to a new competitive challenge. On the other hand, innovations that improved processes account for a larger share of the total increase in labor productivity.

The powertrain is one of a vehicle's most complex parts with the gear being its central component. The gear manufacturing has to become a highly specialized area in order to produce parts with reliable performance and higher efficiency. A critical element to achieve these demands is the tooling used in the manufacturing
process. In addition to the impact on the quality of the gear’s teeth, the tooling is affecting both the production costs and process reliability. Gear generation method by hobbing, illustrated in Figure 1a is widely used for cutting teeth in spur gears, helical gears worms and worm wheels and is characterized by high accuracy and machining productivity.

The tooling cost for hobbing is lower than for broaching and multiple-tool shaping heads. For this reason, hobbing is also used in low-quantity production or even for a few pieces. The gear hobs are mainly made of high-alloy high speed steels (HSS). The advantage of HSS hobs resides in its strength to withstand cutting forces and the low cost of the tools. From the tool life point of view, HSS performs very well at intermittent cutting applications. But the greatest limitation of HSS is that its usable cutting speed range is limited. Generally powder-metallurgical HSS (PM HSS) tools and particularly hob teeth have to be designed in such a way that they can be reconditioned without losing their service life.

Control of the hobbing process can be achieved by understanding and controlling the tooth micro-geometry. However, current gears hob teeth lack higher predictability which leads to reduced tool life mainly due to brittleness of the cutting edge. It has also to be mentioned that the breakage of an individual edge makes it necessary to replace the entire hob. This is another reason to consider ways to improve the reliability of PM HSS hobs. There are many design parameters that control the functionality of a gear hob. Less concern has been given to design of tooth micro-geometry with respect to tooth surface and cutting edge radius. Previous studies on the effects of tooth’s micro-geometry were mainly focused on the chip formation mechanism and its mechanics and less on the underlying tribological phenomena. Experimental testing and validation of various tooth designs requires access to industrial equipment since hobbing machines often are not part of the equipment of production research laboratories. This situation would imply higher costs for tooling and for production stops. An alternative solution would be to develop research laboratory methods using pattern-based similarity methods. Single tooth milling (STM) method, the STM cutter illustrated in Figure 1b was developed as a research laboratory method for studying, understanding and characterization of the tribo-system with particular attention paid to the tooth surface roughness, with purpose for reducing tool wear and for performing an efficient cutting process.
A benefit of laboratory STM tests is that the kinematics is highly simplified compared to hobbing process (see Figure 2), a fact that makes it straightforward the analysis of the effect of various cutting edge preparations on the tooth performance. Besides the general aim of evaluating the micro-geometry with respect to the surface roughness and various edge radii of milling tooth, the purpose is also to scale up the laboratory results and optimized micro-geometry design to gear hobbing tools and later to verify them in industrial environment.

There are many facts that make the measurements, interpretation and comparison of the STM’s experimental data challenging. The friction conditions due to various tooth surface preparations affect the morphology of the contact area on the rake...
face which make difficult to interpret the measured tool wear, cutting force and tool temperature. There is also known as notorious demandingly to measure the contact areas and delimitate different regions characterizing the sticking and sliding zones. The purpose of the STM model is to analyze the nature of the STM tribo-system and reliably predict the effect of tooth’s edge radius and surface preparation on the stress and strain histories at any material point during chip formation. Developing a consistent model requires data from the experiments that have been performed in intermittent machining. This information concerns temperature and mechanical load distributions, both on the tooth and the chip, and also the shear zone characteristics. Data about the material behavior at an elevated temperature and high strain rates is also important to the model. The main purpose here is to describe how the new knowledge from the STM experiments and the simulation can complement each other and contribute to a better understanding of a reliable tooth design.

2 Simulation procedure

2.1 The STM model representation

One of the main objectives of the research work presented here is to study the effect of edge rounding and surface roughness on tooth performance, i.e. on tool wear resistance (see Figure 3), tool wear mechanisms, tool life, cutting forces, surface integrity and chip formation. The practical interest of the results lies in understanding:

- The surface requirements before depositing the coating.
- The mechanical conditions which are necessary to strengthening the edge.
- The mechanical and thermal conditions at the chip-tool interface needed for the reduction of friction in the secondary deformation zone and also for reducing the emergence and propagation of notch wear.
The machining cost of gear transmission components represents an important part of the total production costs. The nature of chip formation is determined by several combined influences, such as the properties of the work material and of the tool material and its geometry, as well as the cutting parameters. The optimization of the machining process and the integrity of the surface as well as the product performance demand a thorough understanding of the chip formation. This understanding comprises the knowledge of the effect of the micro-geometry of the cutting edge and the tooth preparation on the machinability. The state of the tooth edge affects the properties of the workpiece surface and gives rise to residual stresses that influences surface integrity and cutting forces as well as the cutting temperatures, which in turn has a strong impact on the tool life. Figure 3 illustrate the progressive wear of a sharp tooth in STM. Establishing models, analytical or numerical, contributes to the comprehension of the thermal and mechanical conditions on the interface between the chip and the rake face of the cutting edge. This understanding will result in the design of hobs with improved performance. Establishing models for metal cutting in order to describe phenomena such as friction, temperatures, and high rates of large strains is an extensive task to accomplish. In recent years a great deal of work has been put into developing analytical models for this purpose [1], [2] and [3].

An alternative method for establishing machining models that reflects better the nature tool-chip interface is the application of numerical programs, for instance the Finite Element Method (FEM). By means of such programs simulation models can be designed that predict the geometry of the chip as well as residual stresses and
deformation in the work material. In addition, it is also possible to make these models predict the forces acting on the tool which are related to cutting parameters, the geometry of the cutting edge and tooth surfaces and properties of materials. Up to now it has been presumed that a cutting edge is perfectly sharp in the simulation models. The fact that all edges in practice are more or less blunt has been in many cases neglected, i.e. the effect of an edge preparation has not been considered [4].

In the research work described in this paper, the modelling of the STM process aims at improving the comprehension of the mechanical and thermal load conditions on the tooth. Modelling of machining processes aims in many cases at the prediction of forces and temperatures distributions on the contact area. Deformation of work material is distinctive in that it occurs at highly elevated temperatures at normal cutting speeds and there is an appreciable variation of the material properties with respect to temperatures. The influence of high temperatures is twofold in so far as it can give rise to an altered flow stress in the work material as well as exert a vital influence on the rate of tool wear. In addition to these influences, elevated temperatures can also generate thermo-deformed layers in the machined surface. All this demonstrates the necessity of taking the influence of temperatures into consideration in the analyses of cutting processes.

A complete analysis of the metal cutting process demands analyses of the relation between metal flow and heat transfer, since materials generally have greater sensitivity at increased temperatures. Since appropriate material data are not available, the quantitative analysis of the machining process by means of FEM is limited.

Flow stress in a material is defined by the stress that causes an incremental increase in plastic deformation, given strain, strain rate and temperature. In many cases, the history of the material, like for instance its hardness, also has an influence on the flow stress.

There are at least two methods for estimating the flow stress in the machining process, one of which is a direct machining test. Another method is based on compression or torsion tests at high speeds. Irrespective of method, there is a need for attaining properties from the flow stress test including high strain, high strain rate and a high temperature in order to analyze the cutting process.

Forces that are necessary for the deformation of a material sample under tension, compression or shearing are measured in conventional tests. The tests are carried out at temperatures and strain rates that are similar to those in the process being simulated. Such deformation rates in machined materials can amount to $10^7$/s in the primary deformation zone. Figure 4 presents the results from a tensile test of a work material made of steel 20NiCrMoS2-2 at low and high strain rates.
The model presented in this research work is based on a thermo-elasto/plastic model for the chip and work piece where the strain hardening data is extracted from a stress-strain diagram obtained in experiments performed on the case hardening steel from SMTT at different strain rates, as illustrated in Figure 4. Since the chip formation is characterized by a high strain rate, the values in the simulation model were chosen from the red curve in Figure 4.

![Stress-strain diagram for work piece material, steel 20NiCrMoS2-2.](image)

**Figure 4: Stress-strain diagram for work piece material, steel 20NiCrMoS2-2.**

### 2.2 Model representation

A transient model that tracks the evolution of chip formation with time was implemented. Tool entry and exit behaviour as well as evolution of chip shape and contact in STM were modelled. The model requires special treatment for chip separation through frequent remeshing to manage severe deformation at the tool edge. Chip separation at the tool edge was modelled by a fracture criterion. The physical properties of the work and tool materials that were introduced in the model are presented in Table 1.
Table 1: Material physical properties

<table>
<thead>
<tr>
<th></th>
<th>Work piece</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>20NiCrMoS2-2</td>
<td>ASP 2030</td>
</tr>
<tr>
<td>E-modulus (GPa)</td>
<td>210</td>
<td>240</td>
</tr>
<tr>
<td>Hardness (HV)</td>
<td>190</td>
<td>840</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>7.8</td>
<td>8.1</td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>44</td>
<td>24</td>
</tr>
<tr>
<td>Specific heat (J/kg°C)</td>
<td>450</td>
<td>420</td>
</tr>
</tbody>
</table>

The workpiece is modelled as a 3D rectangular plate consisting of 50000 elements, 8-node linear brick with reduced integration and hourglass control as illustrated in Figure 5. The bottom nodes of the workpiece have both vertical and horizontal constraints, while the nodes on the right edge and on the edge situated above the cutting zone are unconstrained. To simplify the model kinematics, both the rotational and feed movements are generated at the centre of the cutter.

Figure 5: STM meshed model
The body of the milling cutter is constrained on the interior boundaries by a rigid connection. This is a special kinematic constraint, which can be attached to one or several boundaries. The effect is that all connected boundaries behave as an assembly connected by a common rigid body. The necessary degrees of freedom for representing the cutter’s assembly are those needed to make the rigid body move, i.e., translations in the x-y plane, and a rotation around the z-axis. Thus, both the cutting speed and feed rate are created at the cutter’s mass centre.

The tooth clamped in the cutter is modelled by 4-node modified tetrahedron elements. The interface between tooth and chip is represented by contact nodes as can be seen in Figure 6. The effects of the boundary conditions were reduced by choosing the dimensions of the workpiece large enough to maintain steady-state cutting for a certain time. The cutting was completed before reaching the left edge.

![Figure 6: Schematic representation of boundary conditions in STM simulation](image)
2.3 The yield criterion and flow rule

The work material was represented by a model formulated according to the following conditions:

- isotropic linear-elastic behaviour within the yield locus
- a stress state dependent criterion for the yield locus
- a strain rate dependent isotropic hardening rule
- a criterion for the onset of failure depending on the loading condition

The limit of elasticity is defined by the yield criterion for any possible combination of stresses. Flow stress in a material is defined by the stress that causes an incremental increase in plastic deformation, given strain, strain rate and temperature. To attain the steady state geometry of the chip flow, a thermo-elasto/plastic cutting simulation connected with isotropic strain-hardening was carried out. The basic assumption of the total strain decomposed into an elastic part, $\varepsilon^e$ and a permanent or plastic part, $\varepsilon^p$ is made according to Eq. 1. [5]

$$\varepsilon = \varepsilon^e + \varepsilon^p$$  \hspace{1cm} (1)

The total stress $\sigma$ at time $t$ can be modelled as a function of the total strain $\varepsilon$ at time $t$, by means of the flow theory of plasticity which describes the behaviour of the elastic/plastic material, as well as a function of the stress and strain history. In this paper the von Mises yield criterion with associated flow rule was implemented. It is demonstrated that basic behaviour which defines the plastic strain increments is related to the yield surface. If $\varepsilon^p$ denotes the component of the plastic strain tensor, the rate of plastic strain is assumed to be given by Eq. 2

$$\dot{\varepsilon}^p = \lambda \frac{\partial F}{\partial \sigma}$$  \hspace{1cm} (2)

where $\lambda$ is a constant of proportionality, often called the ‘plastic consistency’ parameter [6]. If this condition is met, the plastic strain rate components are normal to the yield locus $F$ in the space of nine stress and strain dimensions.
2.4 Tool – chip interface

The contact and the friction at the interfaces between the tooth and the chip and the tooth and the work material determine the required cutting power, the machining quality and the tooth wear. Contact and friction conditions considered important to the metal cutting process are [7]:

- adhesion,
- mechanical interactions of surface asperities,
- ploughing of one surface by asperities on the other,
- deformation and/or fracture of surface layers such as oxides, and
- local plastic deformation caused by agglomerated wear particles, trapped between the moving surfaces.

These mechanisms exist to a varying extent in the friction at the interfaces chip – tooth and tooth – work piece during the cutting. The coexistence of adhesive and ploughing friction at the tooth – chip interface under many cutting conditions has been assumed by Zorev in a slide-stick friction model [1].

In the present model a constant coefficient of friction along tool – chip interface is applied to the analysis of all chip formation processes throughout the whole useful tool life.

It is important to pay regard to the contact between the tool and the chip when developing a reliable simulation model for cutting, since the friction force bears a strong relation to the chip formation process and affects the tool performance.

A typical stress distribution on the rake face is shown in Figure 7. The normal stress increases monotonously towards the tooth edge, while the shear stress at first increases but then reaches a nearly constant value.

Two distinct zones exist on the rake face: a sliding zone and a sticking zone. In the sliding zone, the normal stress is relatively small and dry friction prevails. On the contrary, in the sticking zone, the normal stress is so high that real and apparent areas of contact are equal and the shear stress is approximately constant.
The base for the friction behaviour along the interfaces tool – chip and tool–work piece is Coulomb’s friction model. The conditions for sticking and sliding friction at the tool – chip interface are directly owing to the stress magnitude, with sticking occurring at high contact pressure. When this pressure is low, as it is away from the tool cutting edge, friction due to sliding will be predominant. Based on results from experimental research, Coulomb’s friction law is presumed to prevail in the sliding zone, i.e. a constant coefficient of friction has been applied to this zone, while an approximately constant frictional stress has been applied to the sticking zone. These assumptions with respect to frictional stresses can be expressed according to

\begin{align*}
\tau_f &= \mu \sigma_n \quad \text{for } \tau_f < k \quad (\text{sliding}) \\
\tau_f &= k \quad \text{for } \tau_f \geq k \quad (\text{sticking})
\end{align*}

where $\tau_f$ is the frictional stress, $\sigma_n$ is the normal stress, $\mu$ is the coefficient of friction, and $k$ is the shear stress of the chip material.
The friction model described above has been applied to most FEM cutting models, and by using it the constant frictional stress can be obtained from the flow stress of the chip. The conditions of friction in the sliding zone are dissimilar to those prevailing in conventional tests of friction, and it is therefore very difficult to determine the coefficient of friction in the sliding zone. The lower part of the chip constitutes a freshly formed surface that is the subject to high strain hardening. Since the chip is plastically deformed its hardness can be twice as high as that of the work piece. This varying hardness may result in changes of the coefficient of friction.

Frictional stresses can be determined by means of other methods, e.g. in machining tests and tests that are specially designed for this purpose [8]. Such tests might result in accurate and usable information on frictional stresses, but there are solely a few available experimental results that are applicable to special conditions.

On the non-perfectly sharp cutting edge of the tooth a stagnation point of the flow exists. The material above this point is flowing into the chip, and the material below the point is flowing back into the work piece.

The sliding velocity, and thus also the frictional stress, will move in reverse motion at the stagnation point. Since the position of this point is not known in advance, the applying of the friction boundary conditions requires the use of special numerical techniques. Out of a number of methods, Chen and Kobayashi [9] suggested a modified form of the friction stress according to

\[
T_f = \tau_f \frac{2}{\pi} \tan^{-1}\left(\frac{v_s}{v_0}\right) 
\]

where \(T_f\) is the modified friction stress, \(\tau_f\) is the friction stress, \(v_s\) is the sliding velocity of the work material at the tooth – work piece interface, and \(v_0\) is a small positive number compared to \(v_s\).
3 Results and discussions

3.1 Effect of cutting edge roundness on stress distribution

The objective of the simulation was to provide an understanding of the effect of edge preparation and surface roughness (micro-geometry) in STM. First, the effect of the edge radius on the plastic deformation is analysed and then the surface roughness effect on the temperature distribution and heat flow is discussed. The edge geometries used in simulation are illustrated in Figure 8 where the meshed tools are represented.

![Figure 8: Cutting Edge preparation with radii 0; 35; 60; and 80\(\mu\)m](image)

The chip separation is performed along predetermined lines of elements on the moving path of the tool edge, by deleting elements ahead on the tool edge when element failure criterion, such as shear failure criterion, are reached. The failure criterion is usually defined arbitrarily because of the difficulty of obtaining the required basic experimental data. In addition, the number and size of deleted elements affects the produced chip thickness, and fine elements improve the simulated result but increase at the same time the calculation time and cost considerably. ALE is suitable to the cutting conditions in which a rounded or chamfered-edge cutting tool is used. When the mesh deformation becomes larger, the quality of the mesh created by the smoothing equations becomes impaired. Based on the quality of the mesh elements, the simulation is stopped and the remeshing of the model is performed.

Figures 9a-c show the von Misses stress in STM model for three different edge radii, 0\(\mu\)m, 60\(\mu\)m and 80\(\mu\)m for a constant surface roughness value with a friction coefficient (0.36) which is kept constant during simulations. These figures represent the interaction tool-chip during the first two milliseconds of the engagement. The milling type in simulations is down milling, i.e. the chip thickness has its maximum value at the beginning of the engagement.
There is a transition period from tool entering the work piece until the largest contact area is reached. This is well demonstrated by representing the contact area on the rake face of the tooth shown in Figure 10. During the first part of the engagement (1.5 ms) the contact area is continuously increasing until reaching a relatively constant level before to decrease again to zero at the end of engagement. This conclusion is valid for all edge radii.
Figure 9b: Simulation of STMT with edge radius 60µm in the first sequence (2ms) of the engagement of a revolution.

Figure 9c: Simulation of STMT with edge radius 80µm in the first sequence (2ms) of the engagement of a revolution.
The compressive force acting on the rake face is represented for all three edge radius values in Figure 11. By examining Figures 10 and 11, two important conclusions can be drawn; (1) the contact area corresponding to maximum compressive force is inverse proportional to the edge radius, and (2) the compressive force corresponding to maximum chip thickness increases with the edge radius. Further, it can be noticed from these figures that a better choice of edge radius is 60 µm as it gives moderate compressive force and a relatively large contact areas.

**Figure 10:** contact area development at the rake face during the first sequences during one engagement.

**Figure 11:** Cutting force, compressive component at the rake face during the first sequences during one engagement.
This also becomes apparent by studying the results in Figure 12, where the friction force on the rake face is represented. In the transition period of the engagement (1.5ms), the energy spent in friction is similar for all the three edge radii. As the chip thickness reaches the maximum value, the tooth with 60 µm edge radius has the minimum friction energy. The tooth with 80 µm exceeds that with sharp edge due to the increasing effect of the compressive force.

![Figure 12: Friction energy in the first sequence (2ms) of the engagement of one revolution.](image)

Stress components during the first phase of the engagement on the cutting edge from the FEM simulations are presented in Table 2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.11x10¹⁰</td>
<td>2.15x10⁹</td>
<td>5.00x10⁹</td>
<td>2.55x10⁹</td>
</tr>
<tr>
<td>60</td>
<td>1.00x10¹⁰</td>
<td>2.72x10⁹</td>
<td>4.33x10⁹</td>
<td>2.59x10⁹</td>
</tr>
<tr>
<td>80</td>
<td>4.63</td>
<td>1.88x10¹⁰</td>
<td>1.21x10¹⁰</td>
<td>1.71x10¹⁰</td>
</tr>
</tbody>
</table>
The plastic deformations of the chip during the first 2ms of engagement are illustrated in Figure 13. The figure shows that most of the part of the chip in contact with the tooth is in a plastic deformation state, which increases during the engagement time.

![Figure 13: Time development of the plastic strain on the workpiece](image)

### 3.2 Effect of surface roughness on temperature distribution

Temperature predictions are used to estimate the tool’s useful life or a change in the mechanical properties of the work piece. Both of these considerations are important to the economical operation of the process, as well as safety and performance of the machined product.

In machining there are two sources of heat generation; one is located in the shear zone and is initiated by plastic deformation, and the other is produced to overcome the friction resistance. Part of the heat produced in the shear zone is carried away by the chip. For a cutting force $F$ and a cutting speed $V_c$ the total energy expanded per unit width of cut is $FV_c$. The energy $E_{sh}$ conversed in the shear zone is [3] Eq. 5.

$$E_{sh} = FV_c - F_f V_{ch}/t$$  \hspace{1cm} (5)
where \( F_f \) in Eq. 6 is the friction force, \( h \) is the uncut chip thickness and \( t \) is the actual chip thickness. If the angle between the resultant force acting on the tool and cutting force is \( \lambda - \alpha \) it follows that the friction force \( F_f \) is
\[
F_f = F \sin \lambda / \cos(\lambda - \alpha) \quad (6)
\]
and the rate of heat generation per unit area \( \dot{Q} \) in the shear zone in Eq. 7
\[
\dot{Q} = F V \left( 1 - \frac{\sin \lambda \sin \phi}{\cos(\lambda - \alpha) \cos(\phi - \alpha)} \right) w \quad (7)
\]
where \( \phi \) is the shear angle and \( \alpha \) is the rake angle and \( w \) is the width of cut. The rate of heat generation is proportional to strain-rate at any point in the shear zone
\[
\dot{Q} = k \dot{\gamma} w \quad (8)
\]
where \( k \) is the shear flow rate, and \( \dot{\gamma} \) is the strain rate.

In the secondary deformation zone, the frictional heat generation \( \dot{Q}_f \) at a point a distance \( x \) from the cutting edge is
\[
\dot{Q}_f = \tau_{ch} V_x \quad (9)
\]
where \( \tau_{ch} \) is shear stress on the tool / chip interface and \( V_x \) is the sliding velocity of the chip and
\[
\tau_{ch} = \frac{F_f}{h w} \quad (10)
\]
The STMT simulations have been performed for various tooth surface roughness (contact conditions) illustrated in Figure 14 and Figure 15. For a coefficient of friction, \( \lambda = 0.42 \) the temperature distribution in the work piece are shown in Figure 14.
Reducing the coefficient of friction to 0.36, illustrated in Figure 15a, is followed by a drop of the maximum temperature to 420°C. The figure show that the heat concentration with the maximum temperature is located at a distance away from the cutting edge, and the temperature is relative low due to smaller friction force.

Figure 15a: Simulation of STMT with smooth surface (min roughness) in the first sequence (2ms) of the engagement of one revolution.

Figure 15b show that by increasing the surface roughness (medium roughness) the temperature is increasing and the maximum temperature is located closer to the edge. For the surface roughness that corresponds to a rough tooth surface, the maximum temperature after 2 ms is about 700°C.
Figure 15b: Simulation of STMT with surface (medium roughness) in the first sequence (2ms) of the engagement of one revolution.

Figure 15c shows temperature distribution on a rougher surface (max roughness) and indicate that the maximum temperature is both higher and located closer to the edge than on the smoother tooth surfaces.

During the first phase of engagement of one revolution, the energy increasing is significant for all three types of simulated surfaces. After 4 ms, the energy dissipation is lower for smoother surface roughness, while the rougher surface shows high increase in energy dissipation, which also corresponds to increasing temperature (see Figure 16).
The higher surface roughness, the higher friction coefficient that resulting in an increased chip thickness ratio, resulting an accumulation of heat energy that leads to a higher temperature in the tooth.

**Conclusions**

The objective of the model was to explain the thermo-mechanical phenomena on the tooth/chip interface and to compare the simulation results to the experimental results from a qualitative point of view. The model takes into consideration the von Misses yield criterion and an isotropic strain hardening and makes use of a special technique to separate the chip from the work material. This technique is based on the ALE method.

The model shows a good agreement with the measured values in the laboratory SMTT experiments, even if the model is not completely representative of an intermittent milling process.

The simulation model helps to explain and validate some of the experimental results obtained in STMT experiments.

Temperature measurements are difficult to perform in milling and therefore the effect of tooth preparation on the heat generation is difficult to be experimentally assessed.

To design reliable teeth, it is necessary to obtain the thermal and mechanical load distribution on the contact area tool - chip. In the experimentally milling operation the evaluation of contact area is almost impossible to obtain with high accuracy, the main reason is the varying types of friction and contact conditions on the
contact area. However, the estimations of contact area only present contact area which represents the last micro seconds of the cutting engagement. Therefore is the simulation model also are of great value.

Two important conclusions can be drawn from the mechanical analyses; (1) the contact area corresponding to maximum compressive force is inverse proportional to the edge radius, and (2) the compressive force corresponding to maximum chip thickness increases with the edge radius. An optimal value for the edge radius can be selected by considering the friction energy, contact area and the compressive force.

The higher surface roughness, the higher friction coefficient that resulting in an increased chip thickness ratio, resulting an accumulation of heat energy that leads to a higher temperature in the tooth.
References

Birmingham, University of Birmingham; 1984.

Produktion, Lunds Tekniska Högskola, Lunds Universitet nr 84; 2010.


different tool edge geometries, Journal of Materials Processing Technology, 

2000.

2006.

chip tool contact for high speed cutting, International Journal of Machining 

[8] Iwata, K., et al. Process modeling of orthogonal cutting by the rigid-
plasticfinite element method, ASME Journal of Engineering Materials and 

Applications of numerical methods to forming processes. In: ASME 
Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test

J. Gerth\textsuperscript{a}, M. Werner\textsuperscript{b}, M. Larsson\textsuperscript{c}, U. Wiklund\textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a} Department of Engineering Sciences, Uppsala University, Box 534, S-751 21 Uppsala, Sweden
\textsuperscript{b} Department of Production Engineering, KTH, Stockholm, Sweden
\textsuperscript{c} Primateria AB, Uppsala, Sweden

Journal of Wear

Int. Journal of Wear
Vol. 267(12), pp. 2257-2268; 2009
Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test

J. Gerth a, M. Werner b, M. Larsson c, U. Wiklund a,∗

a Department of Engineering Sciences, Uppsala University, Box 534, S-751 21 Uppsala, Sweden
b Department of Production Engineering, KTH, Stockholm, Sweden
c Primateria AB, Uppsala, Sweden

1. Introduction

Gear hobbing is commonly used in the industrial production of cylindrical gears. A hob is a milling tool that has a large number of cutting teeth arranged in a spiral around the tool body. The most common type is made from a homogenous piece of powder metallurgical high speed steel (PM HSS) and protected by a PVD coating. In order to increase the reliability and tool life of these milling tools, further developments of the tool surfaces and cutting edges are necessary.

A single tooth milling test, using a HSS insert in a conventional milling machine, has been developed with the aim to reproduce the wear mechanisms seen on real HSS gear hobbing teeth. The benefits of such a test, compared to actual gear hobbing tests, are primarily accessibility and reduced costs for both design and production of test specimens (inserts).

The main goal of this study was to verify that the wear mechanisms in the developed test correspond with the wear mechanisms obtained in real gear hobbing. Once this was verified, the influence of surfaces roughness on the performance of TiAlN coated HSS inserts was evaluated by using the tool as delivered or after polishing the tool surfaces. Parameters considered were tool wear, cutting forces and the quality of machined surfaces. The polished inserts, yielded less adhered work material and reduced flank wear but no significant difference in cutting forces as compared to the unpolished inserts.

PM HSS coated tool edge with a hard ceramic PVD coating can be considered a ceramic composite with its strength limited by the largest defect. Thus, it is important to have good control of defects in both coating, steel substrate as well as in the interface between the coating and the HSS material to reach high tool reliability. Previous work has concluded that cutting edge geometry and surface roughness before and after coating deposition are crucial factors for the propagation of wear [1]. However, the development of reliable hobs requires more detailed studies of the influences of different surface characteristics as well as cutting edge geometries. Using hobs for such studies involves high production costs of tools (>1000 € per hob), expensive machine costs as a gear hobbing machine is required (>150 k€) and time consuming wear tests. This has led to the development of different alternative tests, often referred to as “fly hobbing” tests for modelling the real hobbing process [2–4].

The common denominator for these tests is that a single cutting tooth is used.

This study examines the possibilities to reproduce the typical wear mechanisms found on hobs used in dry gear cutting by using a single insert face milling test. Cutting inserts are used to represent hob teeth. A conventional face milling machine equipped with a dynamometer measuring cutting forces and torque was used [5,6].

The assumption is that the wear mechanisms are mainly controlled by the intermittent cutting process, i.e. cutting speed, feed, etc. and only to a lesser extent by the complex kinematics and geometries...
surfaces, by scanning areas of approximately 0.041 mm², and to characterise the machined surfaces, by scanning areas of approximately 0.27 mm².

2. Experimental

The capability of the milling test to reproduce the wear mechanisms in hobbing was tested in a comparative study. Both surface and cross-sectional analysis were performed on teeth from worn hobs and inserts at similar cutting conditions. The worn hob teeth are compared to an insert that had been operating during 60 min in the milling test set-up. Also, the surface finish was measured on gears milled when the hob was slightly and severely worn, respectively. Surface and cross-sectional analysis were also performed on unused hob teeth and inserts in order to establish the initial conditions.

Milling tests were then performed to investigate the influence from surface roughness on the cutting process in terms of cutting forces, tool wear and finish of the machined surfaces. The cutting forces were measured continuously while wear was evaluated after 1, 30 and 60 min of cutting and surface finish only after 1 and 60 min.

Scanning electron microscopy (SEM) using a Zeiss DSM960A and a Leo 440 was used to image tool surfaces, tool cross-sections and machined surfaces. Chemical analyses on the tool surfaces were carried out using energy dispersive X-ray spectroscopy (EDS) with an EDAX equipment attached to the SEMs. An optical surface profilometer (WYKO NT 1100) was used to characterise the initial tool surfaces, by scanning areas of approximately 0.041 mm², and to characterise the machined surfaces, by scanning areas of approximately 0.27 mm².

2.1. Gear hobbing

The reference hob had been used in a production line for planet gears (module 2.025) at a Swedish gear manufacturer. Climb cutting was used, meaning that the tool feed and the cutting motion had opposite directions, see Fig. 1a. The tool generates the gear profile by a process called “enveloping”. This means that each of the successive hob teeth removes segments of material between the gear teeth. The shape of the chips produced varies between different generating positions of the teeth and both two and three flank chips are produced [3], c.f. Fig. 1b. In Table 1 characteristics of the hobbing process are presented, including cutting speed, feed, depth of cut (gear tooth depth) and maximum chip thickness and chip length as calculated using equations by Hoffmeister as presented in [7,8].

2.2. Milling test

The milling tests were performed in a vertical spindle face milling machine (Mazak) equipped with a single insert milling cutter (Ø 89 mm) and a magnetic table for the fixture of the work piece. The geometry of the cutting insert is presented in Fig. 2, which also shows the two cutting edges involved in the chip forming process; the primary and the secondary cutting edge. The wear studies focus on the primary cutting edge which is also the one producing the machined surface. A schematic picture of the milling test is shown in Fig. 3 where the rake angle (12°) and clearance angle (6°) are indicated. Characteristic parameters for the milling tests are presented in Table 2. Note that two different cutting speeds were used, 160 m/min when comparing milling and gear hobbing and 120 m/min in the study on surface roughness dependence. Climb milling was used in both studies.

Please cite this article in press as: J. Gerth, et al., Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test, Wear (2009), doi:10.1016/j.wear.2009.04.004

---

**Fig. 1.** During gear hobbing, the rotation of the hob and gear blank is synchronised and the tool is fed axially (a) resulting in the enveloping process that generates the shape of the gear teeth (b).

**Fig. 2.** Design of the cutting insert with the two working cutting edges indicated.

---

**Table 1**

<table>
<thead>
<tr>
<th>Gear hobbing parameters</th>
<th>Cutting speed ( v ) [m/min]</th>
<th>Feed/tooth ( f ) [mm/rev*]</th>
<th>Depth of cut [mm]</th>
<th>Maximum chip length [mm]</th>
<th>Maximum chip thickness [mm]</th>
<th>Feed direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.27</td>
<td>7.1</td>
<td>25</td>
<td>0.20</td>
<td>Climb hobbing</td>
<td></td>
</tr>
</tbody>
</table>

* The feed is given in mm per work piece revolution.
A KISTLER dynamometer mounted on the spindle above the cutting head allowed dynamic forces in three dimensions and the torque to be measured at a sample rate of 16 kHz. In this work mainly two forces are considered. The cutting force $F_c$ acting on the rake face orthogonally to the cutting edge and in the direction of the cutting motion and the feed force $F_f$ parallel to the direction of feed, see Fig. 3.

### 2.3. Materials

#### 2.3.1. Tool materials

The hob and insert substrate materials were high alloy powder metallurgical HSS, ASP 2052 and ASP 2030 (Erasteel Kloster designations), respectively. The two steels are of similar compositions, see Table 3, and heat treated to similar hardness levels (around 67 HRC) and impact strengths. The inserts were coated with a commercial PVD TiAlN coating and the hobs were coated with a commercial PVD AlCrN coating. Hardness and Young’s modulus of the coatings are measured using nanoindentation (Nanoindenter XP) are presented in Table 4. The residual stresses were measured on reference samples (polished and PVD coated HSS plates) and determined using a deflection technique where the HSS substrate is successively thinned until the residual stresses in the coating induce a curvature that can be accurately measured [9].

Two types of inserts were used; ground and polished. The ground inserts were prepared with a plane grinder on both rake and flank faces before being coated with the PVD coating. The rake and flank faces on the polished inserts were manually polished to a Ra value <0.01 µm prior to coating deposition. In addition, these inserts were also polished after coating deposition in order to remove protruding droplets from the coating surface.

### 3. Results

#### 3.1. Initial test edges

Surface parameters for the hob and for the two types of inserts, are presented in Table 6. The polishing of the coated surface that was performed on the polished inserts resulted in a quite high amount of cavities in the surfaces. In contrast, the coated surfaces of the ground inserts, which were left untreated, contained a high amount of protruding droplets, see Fig. 5.

No edge treatment was performed on the inserts and thus the cutting edges are very sharp, c.f. Fig. 6. On the ground inserts, burrs at the cutting edge could be found buried under the coating. Due to the sharp edges and the presence of burrs the coating coverage of the edge is poor. Even though the cutting edge of the hob is less sharp than on the inserts, cracking of the coating around the edge can be seen even on unused teeth resulting in poor coating coverage, see Fig. 7.

#### 3.2. Damage mechanisms of hob teeth and cutting inserts

The wear found on the ground cutting inserts agrees to a large extent with the wear observed on the hobs. The most striking feature of the severely worn parts of the cutting edges, both on the hobs and the inserts, is the exposed substrate material along the edge line, c.f. Fig. 8a and b.

In addition, for both tools the edge line is very uneven due to edge chippings spurred by the inadequate as-deposited coating coverage along the edge lines, c.f. Fig. 6a and b. This can be seen on the cutting insert already after 2 min of milling time, see Fig. 9. Coating detachment on the rake face close to the cutting edge is also a common wear mechanism as seen in both Fig. 8 and in cross-section in Fig. 10. Both tools show coatings whose thickness decreases quite abruptly from the full as-deposited thickness to almost zero thickness close to the cutting edge. This is evident from the enlarged cross-sections in Fig. 11a and b which also reveal cracks in the coatings close to the coating edges. Although different in appearance, both tools also show patches of adhered work material at irregularities further in on their rake faces, c.f. Fig. 12a and b.

---

**Table 2**  Cutting parameters used for the milling test.

<table>
<thead>
<tr>
<th>Cutting speed [m/min]</th>
<th>Feed [mm/rev]</th>
<th>Axial depth of cut (a) [mm]</th>
<th>Radial depth of cut (a) [mm]</th>
<th>Chip length [mm]</th>
<th>Maximum chip thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 or 1200</td>
<td>0.25</td>
<td>3</td>
<td>8</td>
<td>27</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Table 3**  Chemical composition of the insert and hob substrate materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Nominal chemical composition [%], balance Fe</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Co</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASP 2052 (hob)</td>
<td>1.60 4.8 2.0 10.5 8.0 5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASP 2030 (inserts)</td>
<td>1.28 4.2 5.0 6.4 8.5 3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4**  Mechanical properties of the coatings used on hob and inserts.

<table>
<thead>
<tr>
<th>Coating</th>
<th>Hardness [GPa]</th>
<th>Young’s modulus [GPa]</th>
<th>Residual stress [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCrN (hob)</td>
<td>30 ± 0.5</td>
<td>380 ± 64</td>
<td>-4.3 ± 0.3</td>
</tr>
<tr>
<td>TiAlN (inserts)</td>
<td>275 ± 3.6</td>
<td>360 ± 12</td>
<td>-3.4 ± 0.3</td>
</tr>
</tbody>
</table>

*Rough surfaces due to micro particles cause the large scatter.*

---

Please cite this article in press as: J. Gerth, et al., Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test, Wear (2009), doi:10.1016/j.wear.2009.04.004
3.3. Influence of surface topography on inserts

The main difference between ground and polished inserts is the amount of adhered material found on the rake faces of the tools. For ground inserts, work material sticks to the tool in the area where the chip is separated from the tool rake face, about 400 μm from the cutting edge. The extent of adhered material increases with milling time, *c.f.* the SEM pictures in Figs. 13a–15a and the EDS Fe map in Fig. 16. For polished inserts, hardly any such adherence was detected, *c.f.* Figs. 13b–15b and 17. Oxidised layers containing mainly Al and Si were detected on the rake face of both types of inserts, *c.f.* Figs. 16 and 17. On both type of inserts the layers are located some 200 μm from the cutting edge. The layer is very prominent on the ground inserts but barely visible on the polished inserts.

After 1 min of milling time both ground and polished inserts show exposed substrate material at the edge line. However, the ground insert show higher amount of edge chippings in the initial stage, *c.f.* Fig. 15. The cutting edge on both ground and polished inserts are then worn by edge chippings and flank wear with increasing time, see Figs. 14 and 15. Generally, slightly less flank wear is seen on the polished than on the ground inserts.

3.3.1. Cutting forces

During a single cut in milling, both the cutting and the feed forces show a fluctuating behaviour with the highest force occurring as...
the insert is engaged, see Fig. 18. During the cut the chip thickness steadily decreases towards zero, however the forces do not show a steadily decreasing trend but have severe undulations superimposed. This even continues for some time as the insert is disengaged at the end of the cut.

In Fig. 19 the peak values, at engagement, for the forces have been extracted at a roughly 1 min interval and a trend line has been fitted to the data of each of the four tests performed with the KISTLER dynamometer. Both types of cutting inserts were used during both a 30 and a 60 min test. All inserts show steadily increasing forces with time but the data do not allow any significant difference between the two surfaces to be deduced.

3.4. Machined surfaces

The effect of a degrading cutting edge is evident in Fig. 20 where surface roughness of machined gear surfaces milled with slightly and severely used hobs, respectively, are presented. The bearing ratio curve for the surface machined with the severely worn hob is less flat (i.e. it has a higher Rk value) and both Rpk and Rvk values are higher, compared to the same parameters of the surface machined with the slightly worn hob. The Ra and Rz values are also increasing with the wear of the tool. The same relation is valid for the machined surfaces from the milling tests. Measurements were done on surfaces machined after the tool had been used for 1 and 60 min. Surfaces machined with ground and polished inserts show similar surface characteristics, cf. Figs. 21 and 22.

The machined surfaces comprise a regular waviness as well as “tongues” of material that appear to have been smeared out on the surface. These “tongues” are both larger and more frequently observed on the surfaces milled with a severely used tool than on the surfaces machined with a slightly used tool, cf. Fig. 23. Cross-sections of the machined surfaces reveal that these “tongues” are heavily deformed material that has been sheared or ploughed by the cutting edge instead of being cut to become part of the rake, see Fig. 24.
Fig. 10. Cross-sections of (a) a worn hob tooth and (b) a cutting insert after 60 min of milling. The rake face is the upper horizontal sides in the pictures. Outlined areas are enlarged in Fig. 11.

Fig. 11. Enlargements of the areas indicated in Fig. 10a and b respectively (a) hob tooth (b) cutting insert. The inserted enlargements clearly show cracks close to the free edge of the coatings.

Fig. 12. Close-ups on the rake faces revealing patches of adhered material on (a) a hob tooth and (b) a cutting insert.

Fig. 13. SEM pictures of the rake face and cutting edge of (a) a ground insert and (b) a polished insert after 1 min of milling.

Please cite this article in press as: J. Gerth, et al., Reproducing wear mechanisms in gear hobbing—Evaluation of a single insert milling test, Wear (2009), doi:10.1016/j.wear.2009.04.004
Fig. 14. SEM pictures of the rake face and the cutting edge of (a) a ground insert and (b) a polished insert after 30 min of milling.

Fig. 15. SEM pictures of the rake face and the cutting edge of (a) a ground insert and (b) a polished insert after 60 min of milling.

Fig. 16. EDS maps of the rake face close to the cutting edge of a ground insert after 60 min milling time.
4. Discussion

Two different powder metallurgical HSS steels, commonly used in industry as coated tool substrates, were used in this study. Considering the close similarity in mechanical properties of the two steel grades and the rather low temperatures involved, the choice of substrate materials is not considered to have any significant influence on the results. Likewise, both coatings used in this work are coatings commonly used on tools and they present similar, although not identical, properties and performance. Also this difference should be noted but not considered important for the validity of the results.

The milling test succeeds in reproducing the damage mechanisms occurring in dry hobbing. As for the hobbing process, the wear is mainly located at and around the cutting edge. There are obvious signs of edge chippings, c.f. Fig. 8, indicating that the wear is discrete and discontinuous. Already on unused tools, both on hob teeth and inserts, it is evident that the coating does not completely cover the edges. As already mentioned, the cutting edges on the inserts have not been exposed to any edge treatments, i.e. they are extremely sharp with grinding burrs still present on some parts, c.f. Fig. 18.

Cutting force and feed force measured during a single cut in milling. The cut begins at zero time and it is finished 12 ms after that. Fig. 5. In other words, the edges do not have an optimised geometry for coating deposition. As most of the PVD tool coatings, the TiAlN comprises relatively high compressive intrinsic stresses, c.f. Table 4. When deposited on a sharp cutting edge, the local stress concentration is rapidly increasing as the coating thickness increases, i.e. when the ratio between edge radius and coating thickness ($R_e/t_c$) decreases [10]. When the stress becomes excessive the coating will crack and chip to relax the stress, leaving the cutting edge unprotected. Even though the hob teeth have a somewhat larger cutting edge radius, and that grinding burrs have been removed prior to coating, the same phenomenon can be seen on those, c.f. Fig. 6. The compressive stress measured in the AlCrN coating deposited on the
hob is even higher, above 4 GPa, and the cutting edge is too sharp also in this case.

The coating is thus easily removed from the cutting edge at an early stage, on hob teeth and inserts, cf. Figs. 5, 6 and 9. The weakened edge then wears through a continuous flank wear and, more importantly, by discontinuous edge chippings. The wear appears to propagate by the removal of coating fragments of more or less full coating thickness from the free edge of the coating, cf. Fig. 11. These cohesive coating failures are spurred by the intrinsic compressive stress in the coating and the intermittent cutting process. Finally, the fact that adherence of work material is also in common for the two different tools further reinforce the validity of the milling test to be used as a simulation method. It should however be noted that the extent and rate of wear is not being compared between hobs and inserts, only the mechanisms of wear.

The results are considered to be representative, but it should be noted that the number of tests used for this comparison is limited. From the gear hobbing process, worn teeth from two hobs were examined. In the milling test, five inserts were tested during different operating times. It was concluded that a milling time of 60 min were suitable for the comparison, although the wear mechanisms described above is generally valid for all.

Based on industrial experience a roughness of 0.2 µm is often referred to as a sufficient finish for successful coating deposition and performance. Ra = 0.2 has also been showed to be a threshold value regarding coating failures in scratch testing [11]. The two surfaces used in the present work certainly have different roughness but they can nevertheless both be deemed “sufficiently good” for use on cutting tools. Consequently, the gain in performance from polishing is not easily observable either in cutting forces or damage mechanisms. The adherence of work material is the only effect that is clearly different between the two surfaces. The effect of roughness can be two-fold as the friction between rake and tool has two origins. Initially the topography (ploughing) component of the friction coefficient is dominant and a rough surface will increase the friction coefficient and thus the feed force. On the other hand, once a transferred layer is formed most sliding occurs at the interface between the rake and this layer which provides the least shear resistance. Such behaviour has been reported frequently and the presence of Al, Si and O found here is also typical [12–14]. The benefit of excessive polishing is therefore equivocal. The difference in measured forces between the two tests with the same surface, e.g. the 30 and 60 min test with polished inserts is larger than the difference between the average levels of the polished and the ground inserts. Although this hint at the reproducibility of results it also indicates that the two surfaces were made too similar to function as demonstrators for a discriminating milling test. However, by polishing the inserts, defects such as burrs and grooves were removed from the cutting edge resulting in less edge chippings and flank wear compared to the ground inserts. This is beneficial as it most likely increases tool reliability, i.e. a polished tooth will give better means to predict tool life, an assumption that will be further investigated in future work.

Nevertheless, the fact that a clear trend is present in each individual force curve in Fig. 19 is encouraging. It shows that the experimental set-up is capable of detecting the small gradual changes in cutting performance that occur with increasing cutting

| hob tooth | 0.29 ± 0.04 | 3.1 ± 0.8 | 0.9 ± 0.1 | 0.3 ± 0.05 | 0.4 ± 0.1 |
| ground insert | 0.22 ± 0.04 | 4.3 ± 1.8 | 0.6 ± 0.1 | 0.4 ± 0.1 | 0.4 ± 0.2 |
| polished insert | 0.09 ± 0.02 | 2.9 ± 0.7 | 0.2 ± 0.06 | 0.1 ± 0.06 | 0.3 ± 0.1 |

Table 6 Average surface parameters obtained by scanning areas of about 0.041 mm² on the rake face on hob teeth and on ground and polished inserts.

Table 5 Hardness and chemical composition of the work materials.

<table>
<thead>
<tr>
<th>Work material</th>
<th>Hardness [HB]</th>
<th>Nominal chemical composition [%], balance Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>For inserts</td>
<td>155–185</td>
<td>0.17–0.23, 0.35–0.65, 0.15–0.25</td>
</tr>
<tr>
<td>For hobs</td>
<td>150–190</td>
<td>0.17–0.20, 1.10–1.25, 0.017–0.030, 0.15–0.40, 1.05–1.20</td>
</tr>
<tr>
<td>polished insert</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>ground insert</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

[For more detailed information, please refer to the original document.]
time. The small increase in forces is likely due to a combination of wear and transfer layers. Blunting of the cutting edge due to chipping and gradual wear lead to increasing forces. The building up of oxidised transfer layers indicates that the most easily sheared zone is no longer the interface between rake and tool surface but rather the interface between rake and transfer layer. The rough surface on the ground insert promotes the build up of such layers and, once formed, they constitute a thermal barrier in the contact zone. A higher temperature at the interface between the plastically deforming rake and the transfer layer will result in a reduction in friction.
between rake and tool which is measured as a lowered feed force. This process is supported by the higher coverage of transfer layers present on the ground inserts, cf. Figs. 13–17. In other words, there is reason for the forces measured for ground inserts to be initially higher than those on polished inserts due to higher roughness. But there is also reason for the increase in forces due to wear to be, at least partially, compensated for by reduction in friction due to temperature rise caused by transfer layers.

The fluctuations superimposed on the forces during a single cut as shown in Fig. 18 is likely due to vibrations in the tool holder and the machine itself. This testifies to an adequate combination of sensor sensitivity and sample rate to produce representative curves of force variations during a single cut. Apart from these fluctuations a sharp increase in forces is to be expected as climb cutting is used, i.e. the inserts engage at maximum depth of cut after which it decreases. Likewise, after the initial rise in force the forces reduce to close to zero.

The wear studies were made on two inserts for each milling time and surface finish (total of 6 polished and 6 ground inserts) and are considered to be representative. The machined surfaces do show differences but the differences are larger between new and used inserts than between polished and rough surfaces. This further strengthens the conclusion that the two surfaces are too similar to give a clear difference in performance.

The heavily deformed tongues of work material being smeared over the surfaces when machined by a severely worn tool, as seen in Fig. 24, are a result of temporary built up edges on the tool. These form and disintegrate in a repetitive manner, especially as the tool machines inhomogeneous work material. Such processes have been described before, as have their detrimental effect on the resulting finish of the machined surfaces [15].

5. Conclusions

- The single insert milling test was able to reproduce the wear mechanisms active on dry cutting hobs used in normal gear production. The dominating wear mechanisms are discrete failures in the form of edge chippings (flank wear) and cohesive coating failures on the rake face.
- The single insert milling test can be used to reproduce the wear mechanisms on hobs by using adequate cutting data translated to the milling operation.
- For all tools in this work the very sharp cutting edges constitute mechanically weak regions and often result in poor coating coverage at the very cutting edge.
- By polishing the inserts, defects such as burrs and grooves are removed from the cutting edge resulting in less edge chippings and flank wear compared to the ground inserts. It also leads to less work material sticking to the insert and, in the end, to a slightly improved surface finish of the machined surface.
- Despite these effects, polishing of the inserts did not result in a detectable reduction of cutting or feeding forces.

References

ARTICLE IV

DEVELOPMENT OF CUTTING FORCE MEASUREMENT SYSTEM FOR GEAR HOBBING

Abebayehu Seifu Alazar, Mathias Werner, Cornel Mihai Nicolescu
Department of Production Engineering, Royal Institute of Technology (KTH), SE-100 44 Stockholm
ABSTRACT
Increasing demands for high quality and high performance gear manufacturing are reflected in a need for a model based investigation of gear hobbing process. This paper presents the development of a system for online measurement of actual cutting force components during gear hobbing. Although there are a large number of well developed cutting force measuring systems for different machining operations available in the market, it is difficult to find a system tailored to the requirements of a gear hobbing process. Hence, a fixture containing piezoelectric dynamometer and telemetry device is developed. The fixture is designed taking the real machining circumstances into consideration. The telemetry system enables wireless measurement of cutting force while machining. Multiphysics finite element analysis and Artificial Neural Network (ANN) are used as tools for modeling, simulation, and calibration of the developed system. Final stage of this work includes conducting hobbing experiments to validate both the model and the force measurement system.

INTRODUCTION
Gear hobbing is a widely used manufacturing process to produce high quality and high performance gears. It is associated with complex process kinematics, tool wear mechanisms, and formation of chip. The demand for higher quality and reliable gears calls for a scientific analysis and investigation of number of process variables and parameters involved in the hobbing process.

A number of research works have been carried out in order to understand this complex process. The work of [1, 2] shows the kinematics of gear hobbing for one gear gap or tooth, while [3] deals with the mechanics and the measurement of force during hobbing. Different approaches have also been employed to determine and predict tool wear in gear hobbing. Study of the nature of chip formation [4], the influence of cutting edge preparation and coatings [5, 6], analyzing the nature and quality of the surface generated, are some of widely used ways of investigating tool wear. Many more approaches have also been experimented and discussed. Ultimately, the goal is maximizing the life of hobs, and thereby improving the overall performance of hobbing operation [7, 8].

Cutting force is an important and significant process parameter which requires detailed analysis. It has a direct influence on the generation of heat, and thus tool wear, quality of the machined surface and accuracy of the product. Due to complexity of hobbing process, theoretical calculation of force has become a difficult task and often produces unsatisfactory results. Therefore, experimental measurement of cutting force is necessary to obtain better results, which underlines the necessity of a system for measuring cutting force. Analysis of measured cutting force enables an
understanding of its contribution and impacts on the process, tool wear, and quality of gears being produced. In addition it can offer important practical foundations and reference value for cutting tool design, machine tool design, cutting tool wear and damage control [9]. As a result, improved performance of the hobbing process can be achieved through enhanced quality of products and optimized usage of the costly hobs.

Although there are a large number of well developed cutting force measuring systems for different machining operations available in the market, it is difficult to find a force measuring system tailored to the requirements of the gear hobbing process. This is a barrier in process optimization effort both in research and industry. Therefore, developing a reliable cutting force measurement system in gear hobbing would contribute to improved knowledge for researchers and the industry involved in this area.

Main objective of this research work is to develop a system for measurement of cutting force components in gear hobbing operation. It is divided into two parts: the first part, which is the focus of this paper, deals with design and manufacture of a special fixture, modeling and simulation, and calibration. For this purpose, a fixture that comprises dynamometer and telemetry device is designed. A finite element software and ANN are used as tools for modeling, simulation, and calibration. Different stages of the research work and the scope of this paper (the green region) is shown in Fig. 1 below.

Second part is future work that deals with validation of the developed system using a series of machining tests and experiments. When completed, this system is expected to provide useful data that will contribute to the ongoing research effort in tool design for gear hobbing operation.

SYSTEM DESCRIPTION

The system under development is a hobbing fixture that allows online measurement of cutting force during gear hobbing. The fixture is made of structural steel and it has base diameter of 165 mm and a height of 115 mm. Its geometry and other details were designed in such a way that it could be used on a conventional hobbing machine without any further modification or change. It is basically a support to work holding device to be clamped on the machine table. It rotates together with workholding device at selected rate with respect to the cutting tool (hob).

Three Kistler 3-component piezoelectric dynamometers of type 9017B are embedded in the fixture at distance of 2 mm from the base of the fixture. They are located at 120° apart from one another, as shown in Fig. 1(b). They have force measuring range of -2KN to 2KN in x, y, and z directions under a preload of 10KN.

MODELING AND SIMULATION

Finite element software is used for modeling and simulation. Direction of force changes continuously due to rotation of the fixture during machining. Therefore, the purpose of this simulation is to calculate and analyze the variation of applied force at different points. Force is applied from different directions during simulation. Output of this simulation is response of sensors in terms of volt/deformation readings, which is used for error calculation.

Since the applied force is not directed along the center of mass, it produces both force and moment of force simultaneously. Therefore, it is important to calculate the force produced along x, y, and z directions. ANN simulation is used to calculate the force components along x, y, and z. In addition, the ANN simulation provides a transformation matrix that is used for evaluation of error at various points. Then based on this computed error, compensation factor can be calculated for calibration. Figure 3 shows block diagram of analytical modeling and simulation.

Finite Element Simulation

A combination of Stress-Strain and Piezo models were used for finite element modeling and simulation. The piezoelectric phenomenon can be explained by using the following relations. The electrical condition of an unstressed piezoelectric medium under the influence of electric field is defined by the equation [10]:

\[ \delta = e E \] (1)
The mechanical condition of the same medium at zero field strength and application of stress is given by the following equation [10]:

\[ \varepsilon = \sigma \varepsilon \] (2)

Piezoelectricity involves the interaction between electrical and mechanical behavior of the medium. This interaction can be described by a linear relation between two electrical and mechanical variables in either stress-charge or strain-charge as [11]:

\[
\begin{align*}
\text{Stress charge:} & \quad \sigma = \varepsilon E - \varepsilon E \\
\text{Strain charge:} & \quad \varepsilon = E \sigma + dE
\end{align*}
\]

In the above equation the superscripts to the symbols denote the quantity kept constant under boundary conditions. Values of the constants depend on the direction of electric field, stress, strain and displacement.

The strain conditions at a point are completely defined by the deformation components - \( u, v, \) and \( w \) in 3D and their derivatives. The precise relation between strain and deformation depends on the relative magnitude of the displacement. Under the assumption of small displacements, the normal strain (\( \varepsilon \)) components and the shear strain (\( \gamma \)) components are related to the deformation as follows [11]:

\[
\begin{align*}
\varepsilon_x &= \frac{\partial u}{\partial x} \\
\varepsilon_y &= \frac{\partial v}{\partial y} \\
\gamma_{xy} &= \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \\
\varepsilon_z &= \frac{\partial w}{\partial z} \\
\gamma_{xz} &= \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\
\gamma_{yz} &= \frac{1}{2} \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)
\end{align*}
\] (5)

In the finite element simulation, range of loads representing the cutting force is applied at various selected locations from top side of the fixture. The corresponding response of each dynamometer is measured.

Several simulation runs are conducted by varying the locations and directions of applied force. This includes application of force from each \( x, y, \) and \( z \) direction at a time, combinations of two directions, and combination of all three \( (x, y, \) and \( z) \) directions. The purpose is to study the response of the sensors when load is applied from different directions. This allows analysis and understanding of contribution of force components when force is applied from different directions.

The model has two sub domains: solid, stress-strain sub domain for the main fixture and the Piezo Solid sub domain for the dynamometers. Structural steel is selected for the first domain and piezoelectric material type Lead Zirconate Titanate (PZT 5H) is selected for the second domain. Figure 4 (a) shows selected points of force application, labeled as \( p_1, p_2, \) and \( p_3 \). It also shows that force is applied along negative \( z \) direction at \( p_1 \); and (b) shows result of a simulation run.

Artificial Neural Network

A feed forward neural network is designed with linear activation function and no hidden layer. During the training phase of neural network analysis, extensive experimentation is performed to define the optimum and appropriate network parameters. The input/output relationship of the neurons in a given neural network can be expressed as follows [12].
\[ y_j = f \left( b_j + \sum_{i=1}^{9} w_{ij} s_i \right) \]  

Where \( y_j \) is the output, \( f \) is the activation function, \( b_j \) is the bias, \( w_{ij} \) is connection weight, and \( s_i \) is the input.

\[ \begin{bmatrix} \delta_{x1} \\ \delta_{x2} \\ \delta_{x3} \\ \delta_{y1} \\ \delta_{y2} \\ \delta_{y3} \\ \delta_{z1} \\ \delta_{z2} \\ \delta_{z3} \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \]

Where:  
\( [F] = \) force components = \( [F_x; F_y; F_z] \);  
\( [s] = \) dynamometer displacement readings; and  
\( [R] = \) resolved force matrix or transformation matrix

**CALIBRATION AND EXPERIMENTAL SET UP**

Any sensor calibration is normally carried out after having considered some basic aspects or parameters. Few of them are choosing the calibration range, the reference instruments, and the calibration method. Selection of parameters is done on the basis of the sensor characteristics (measurement range, required accuracy, influencing quantities). Depending on the method, sensors are calibrated either across the entire measuring range; at a single point, stepwise at several different points or, continuously [14].

Three Kistler charge amplifiers of type 5011 and three UNI-T UT50A voltmeters were used for initial stage of calibration. The amplifiers have one input channel and one output channel, where the input channel is connected to the sensor and the output channel is connected to the voltmeters. They are used to convert response of dynamometers to equivalent volt readings. After proper placement of the sensors at their respective position and right orientation, preload of 10KN is applied to each of them. Then tests are conducted in a similar way as the simulations runs. This is the initial stage of calibration process, which would help to determine the necessary parameters and conditions for the final calibration of the system.

Manual load application technique is employed using click-torque wrench. Its capacity ranges between 300 and 1200 Nm. Force is applied in the z-direction at selected points. Measurements are done three times and mean of readings are calculated for each test. The importance of repeating measurements comes in to picture with a situation of having varied readings due to very slight change of any of system parameters.

**RESULTS AND DISCUSSION**

A number of simulation runs are conducted to understand the behavior of the dynamometers and the system in general. The results reveal that the response patterns of the dynamometers vary based on the direction and point of force application. Similarly, initial stage tests are conducted in the lab in order to investigate how the dynamometers actually respond when force is applied at various locations.
Results from the simulation runs and observations of initial stage tests have shown good agreement. However, variations are also observed in some cases of test results. Figure 6 (a) shows the response of dynamometers when force is applied at point $P_1$ only in z-direction. The deformation reading increases linearly for each increment of applied force. It also shows the dynamometer ($S_1$) closer to the point of applied force has much higher readings of deformation as compared to $S_2$ and $S_3$. Since these two dynamometers are located symmetrically with respect to point of load application, they have almost similar deformation readings. Overlapping of plots of two sensors reveals this fact. Figure 6 (b) shows the response when equal magnitude of force is applied at point $P_1$ in x, y, and z-directions simultaneously. Application of same magnitude of force along the x, y, and z-directions has resulted in response of the dynamometers with different deformation readings unlike the readings in (a).

Figure 7. TEST RESULTS WHEN FORCE IS APPLIED IN Z-DIRECTION AT POINTS: (a) $P_1$, (b) $P_2$, AND (c) $P_3$

Figure 7 shows the response of dynamometers for tests conducted in the lab. (a), (b), and (c) represent the responses when force is applied in z-direction at point $P_1$, $P_2$, and $P_3$, respectively. The main purpose of this test is to study the pattern of response of each dynamometer in relation to the simulation results. Figure 7(a), (b), and (c) reveal that the dynamometers are responding in similar pattern at each point of force application, yet with some variation. Each test is repeated three times to ensure the repeatability of the measurements. The maximum variation of readings was found to be 13%.

Comparison of linearity of graphs is done for dynamometers closer to the points of load application. This means, $S_1$, $S_2$, and $S_3$, each from (a), (b), and (c), respectively. Their linear regression was found to be 0.997, 0.992, and 0.994 respectively. Some deviation is observed when the remaining graphs of each dynamometer, at each of load application point are taken in to account. There are many factors that contribute to this variation. The major factors are: dimensional and geometrical accuracy of the fixture itself and other structural parts, construction of test set up, and the method of force application. In addition, because of higher sensitivity of the piezoelectric dynamometers in use, very small change in any parameter of the system results in considerable amount of variation in output. This deviation is expected to be minimized to acceptable range when the calibration is completed.

The transformation matrix from ANN simulation will be used in the final calibration process for evaluation of the resulting cutting force components. Figure 8 below shows the percentage error when a single matrix is used to calibrate between different points of load application. In other words, it shows how the magnitude of error increases when a single matrix is used for calibrating at multiple points. Hence, it gives useful information to calculate how many matrices are required for calibration of different points within $360^\circ$.

In this particular case (Fig. 8), a matrix obtained at point $P_1$ ($0^\circ$) is used to calculate errors at different points between $0^\circ$- $45^\circ$. It is possible to observe that the percentage error increases sharply after $22.5^\circ$. This indicates that using the matrix up to this point ($22.5^\circ$) has only 5.4% error, whereas beyond this level might result in higher error. Thus considering 5.4% as minimum acceptable error, 16 matrices are required for one complete rotation of the fixture.
CONCLUSIONS

In this work a specially designed fixture is developed for online cutting force measurement in gear hobbing. Good results have been obtained from the initial stage of calibration process. Validation of the system will be conducted when calibration is completed. This will be done by performing actual machining tests on a conventional hobbing machine. This developed system will have significant role in cutting force measurement and related analysis of gear hobbing process. Moreover, if thermocouple is incorporated in the system, it could also be used to investigate the heat generated during hobbing.

REFERENCES


