Experimental simulation of gear hobbing through a face milling concept in CNC-machine

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Experimental simulation of gear hobbing through a face milling concept in CNC-machine

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Abstract

High-speed steels are the main material for cutting tools especially for producing gear boxes in the automotive industry. Cutting performance of high speed steel depends on their resistance to wear, their toughness and resistance to tempering at operating temperature. In this project, tool-life and wear type of cutting tools made of powder metallurgy high speed steel (PM-HSS) were investigated up to a flank wear width of 0.30 mm in different steels and cutting speeds. Hardness and cutting speed had a significant effect on tool-wear, tool-life and chip formation.

More rake face wear was occurred by harder materials because of higher thermo-mechanical loading. Three indicators were used for representing tool life and to show the relation of cutting speed and hardness with cutting performance. Difference of tool life between the softest and the hardest steels was about two times. By increasing cutting speed in every work-material more number of passes was obtained. The required data were obtained experimentally by a 3-axis milling machine. This test method facilitates simulation of gear hobbing wear type in a less time-consuming way, compared to the other methods which have the same kinematics of real hobbing.

List of acronyms

PM: Powder Metallurgy
HSS: High Speed Steel
C-IA: Carburizing steel- Isothermally Annealed
B-SA: Bearing steel- Spheroidized Annealed

QL: Quenched & tempered Low

QH: Quenched & tempered High
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1. Introduction

1.1 Background

Rough machining is a vital step to produce cylindrical gears for automotive transmission industry. Cutting metal is a process that is associated with complicated kinematics of cutting tools and work-piece material, chip formation and wear mechanism of the tools. Besides, economical machining depends on cutting tools material and geometry, cutting speed, cutting fluid and work material. Typically, gears for automotive transmission are made of case hardened steel. Recently, manufacturers intend to replace case hardening by induction hardening in order to increase productivity, reduce CO₂ emission and obtain desired hardness after induction hardening. For this aim, evaluation of used cutting tools with respect to tool life, wear type and wear mechanism is necessary. In addition, application of different cutting speed in different steels is an important parameter in hob-design for high-speed dry machining. Therefore, a test method of one tooth milling can be very attractive to reproduce wear type of gear hobbing.

1.2 Aim and motivation of this thesis

The major aim was to reproduce wear type of gear hobbing by performing one tooth milling tests and evaluating the used inserts. Additional aims were:

1) Understanding of tool-life, wear type and wear mechanism of used-cutting tools in face milling

2) Comparing wear type and tool life between different steels

3) An attempt to implement a chip study to frame roughly relevant cutting speeds.

Motivations of the project were based on the benefits of this test, compared to actual gear hobbing as can be seen below:

1) Accessibility since gear hobbing machines typically exist only in production plants.

2) Reduced costs for both design and production of test specimens (inserts) because gear hobbing machine and hobs are very expensive.
3) Duration of wear tests by real hob is very long (several weeks).

Therefore, a test method of one tooth milling can be very attractive to reproduce wear type of gear hobbing.

1.3 Method

Single tooth milling tests, using a PM-HSS insert in a climb face milling machine was performed.

The work was divided in three parts:

1. Chip collection tests to frame, roughly relevant cutting speeds in subsequent tool life tests.
2. Tool life tests with different cutting speeds and work-piece materials. A flank wear of 0.30 mm was used as wear-out criteria.
3. Evaluation of used inserts by LOM and SEM microscopy to characterize the wear type. The tool wear of end-of-life tested cutting tool was studied for different work-piece materials.
2. Literature survey

2.1 Gear manufacturing

Manufacturing gears especially cylindrical gears are important in automotive transmission industry. Rough machining of gears is an important step for producing helical gears. There are different methods for rough machining such as milling, hobbing, broaching, shear cutting, shaping and rack cutting. Selection of machining process depends on the type of gears that should be produced [1].

2.1.1 Milling

Milling is an intermittent machining operation for cutting and removing metals. This method is usually used for rough machining of gear teeth, especially helical gears. The basic differences between milling and other machining are:

- The intermittent cutting that happens when the cutting edge engages the work-piece and leave it successively
- The size of the chips is quite small
- Thickness of the chip is varying [1].

During milling, the metal is cut by movement between rotating multi-edge tool and the work-piece. Milling cutter has several cutting edges that are responsible for removing the metal. A certain amount of metal is removed by each cutting edge and rotation of the spindle. The important parameters in milling are cutting speed (V), feed rate (f), depth of cut (d), etc. The schematic of milling operation can be seen in Figure 1.
2.1.2 Hobbing

Gear hobbing is the most frequently used-method to cut the gear teeth and produce helical gears. This technique is associated with complicated kinematics of cutting tools and work-piece material, chip formation and wear mechanism of the tools [2] [3] [4]. In fact, cutting process is connected to several factors such as feed rate, cutting speed, properties and geometry of the cutting tools and the work-piece material. Hob is a cutting tool with a lot of cutting teeth that are set in the cylindrical body of hob. During cutting, hob and gear rotates in a synchronized manner and hob moves downward at the same time [5]. The cutting tooth enters into the work-piece material and generates gears by removing a chip. Each tooth of the hob has a defined cutting edge that forms a specific geometry of the chips. Therefore, different wear is produced at each hob tooth. Figure 2 shows the kinematics for axial gear hobbing. Axial gear hobbing is the leading method for manufacturing cylindrical gears. As can be seen in Figure 2, work-piece and hob are moved in relation to each other and parallel to the work-piece axis. \( v_c \) is cutting speed and the moving path per work-piece revolution is called axial feed \( (f_a) \) [2] [3].

Hob is usually made of homogenous powder metallurgy high speed steel (PM-HSS) with a physical vapor deposited (PVD) coating by a hard ceramic phase such as (Ti-Al-N). HSS substrate is a better choice for cutting tools than cemented carbides because they are much tougher than the cemented carbides so the risk of cutting edge breakage is lower [6]. It is
possible to recondition and regrind hob teeth several times without changing the cutting geometry. Wear on the hobs should be stable and predictable in order to have an economical and efficient reconditioning with high quality of gears which eventually leads to increased productivity. However in real gear hobbing, there is a problem of intensive and non-predictable wear that occurs in cutting edges and restrict the productivity of gear manufacturing. This issue becomes more demanding when the industries intend to decrease the amount of harmful cooling lubricant by using dry machining, which generates more thermo mechanical loads on the cutting tools [6]. In fact, there is currently a trend towards dry hobbing and it is partially implemented at one of the major Swedish manufacturers of gears. Therefore, all of the cutting tests in this project were carried out in dry machining condition.

Figure 2. Gear hobbing kinematics [3][7]
The actual hob that is used as a reference hob for this project is made of PM-HSS, ASP2052, with bending strength of 4000 N/mm² for HSS substrate which is tougher than cemented carbide substrate [8]. PVD coating of the hob is made of AlCrN. Chemical composition of the hob is shown in Table 1. Length of the standard hob is 200 mm with a diameter of 100 mm. Rake angle is zero and clearance angle is (6°) [6][8][9].

Table 1. Chemical composition of reference hob, HSS ASP2052, Erasteel Company [9]

<table>
<thead>
<tr>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Co</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.60</td>
<td>4.8</td>
<td>2.0</td>
<td>10.5</td>
<td>8.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

2.1.3 Chip formation

Study of chips in dry milling and hobbing is important since most of the information for evaluation of cutting process such as cutting temperature; tool life and cutting speed are related to the chip geometry. During machining, movement of the tool against the work-piece removes the metal and produces chips. Chip formation is highly influenced by the mechanical properties of the work-piece material. Other effective parameters are rake angle and feed rate values. There are some other factors that become important for designing the cutting tool and chip formation such as cutting force, tool strength, temperature and vibrations during cutting. Therefore, chip formation becomes an important area for developing the metal cutting [10].

Different shape of chips is related to the mechanical load on the hob, gear geometry and axial feed. Mechanical load which is defined by maximum chip thickness has an important effect on tool-life. In hobbing, chips have three forms: one–flank, two-flank and three-flank. The form of the chips in hob affects the wear mechanism. Figure 3 shows the different geometry of the chip [11].
Behavior of cutting tools and wear mechanism depend on the work-piece features. From cutting point of view, mechanical properties of work-material are very important. The crucial mechanical properties that affect machinability are hardness, tensile strength and toughness. Thermal conductivity as a physical property has effect on machinability too. These properties are governed by chemical composition and microstructure of the steel [12]. To have a good machinability, hardness and toughness of work-material should be low [13]. However, as hardness decreases the toughness increases and vice versa. Consequently, the work-material with high toughness shows some problem during cutting such as poor surface texture, short tool –life and built-up edge. In order to solve this problem, hardness and toughness value should be in balance. Furthermore, high thermal conductivity is beneficial for cutting because the heat that is generated during cutting process can be conducted away from the cutting zone very fast [13].

2.2 Wear of cutting tools

2.2.1 General types of wear on cutting tools

Cutting of metals leads to high plastic deformation of the work-material, high temperature, and extensive friction at the interfaces of the tool, chip and work-material. Most of the
work of friction and plastic deformation is transformed to heat. Performance of cutting tool depends on its response to the above conditions [14]. High temperature and stresses during cutting generate blunted tools because of high plastic deformation of the tool and high stresses lead to tool failure. Typical types of wear on cutting tools are crater wear, flank wear, abrasive wear, built-up edge, depth of cut notching, and thermal cracks.

**Crater wear:** It usually happens on the rake face of cutting tools, during machining of soft steel at high speeds. It is basically occurred by chemical interaction between the rake face of the metal cutting insert and hot metal chip that flows over the tool.

**Flank wear:** It happens on the flank face of cutting insert because of abrasive effect from hard particles of the work-material. This mechanism usually occurs in machining of steels which have abrasive particles such as Fe$_3$C and non-metallic inclusions.

**Built-up edge:** It normally happens during machining of soft steels with low carbon content and nonferrous materials at low cutting speed and small feed rate.

**Depth of cut notching:** It typically happens at the depth of cut line because of oxidation of the tool material with the atmosphere or abrasion by hard and outer edge of the chip. It can lead to tool failure.

**Thermal cracks:** It happens when there is repeated heating and cooling with interrupted cutting such as milling, and generates temperature gradients at the cutting edge. It can cause unpredictable tool failure. Figure 4 shows different tool wear mechanisms [15].

To minimize the effect of notching, tool material should be chemically inert and have high fracture toughness. Moreover, using optimized geometries, such as chamfered edges and circular insert that are able to spread the depth of cut over a wider area of the cutting edge is beneficial. Most of the effort to improve tools is focused on minimizing flank wear and preventing unwanted tool failure [15].
Figure 4. Tool wear mechanisms. (a) Crater wear on a cemented carbide tool produced during the machining of plain carbon steel. (b) Abrasive wear on the flank face of a cemented carbide tool produced during the machining of gray cast iron. (c) Builtup edge produced during low-speed machining of a nickel-base alloy. (d) Depth-of-cut notching on a carbide tool produced during the machining of a nickel-base super-alloy. (e) Carbide insert showing nose wear (tool-tip blunting) due to insufficient deformation resistance of the tool. (f) Thermal and mechanical cracks in a carbide insert after interrupted cutting of low-alloy steel [15]

2.2.2 Coating of cutting tools

Coating layer on high-speed steel tools improves the wear resistance of the tool and changes the contact condition between the chip and the tool face. PVD (physical vapor deposition) coating is usually used to protect the HSS-tools from adhesive and abrasive wear. It is a ceramic layer that has high hardness, good thermal and chemical stability. Oxidation resistance and low thermal conductivity of the coating layer maintains the tool against thermally induced wear which is very important in dry machining [4].

2.2.3 General damage mechanisms of coated HSS cutting tools

Flank wear is dominant wear mode on HSS cutting tools that used in turning, milling, drilling, sawing, etc. The wear out criterion is typically maximum width of flank wear. In gear cutting, there is no notch wear propagation since the depth of cut is varying and the
entire edge line is used for cutting. The largest wear in gear cutting usually happens close to the cutting edge, see Figure 5.

In dry cutting by coated tools, propagation of wear usually occurs by abrasive and adhesive wear and leads to slow removal of the coating layer. This mode of wear is fairly slow and predictable. Moreover, wear can develop by fatigue and separation of the coating layer along with early exposure of HSS substrate, which is an unpredictable wear.

Generally, wear on PM-HSS tools is controlled by the largest defect in both substrate and coating layer. Any types of defect such as pores, impurities, carbides, topographic variations, etc. in the interface of coating and substrate can cause local stress which is harmful for adhesion between coating and substrate. For instance, residual stress in the coating layer can cause crack and detachment of hard coating. Typically, PVD-coating layer has compressive stresses of about 1-5 GPa. Tool geometry, involving grooves, edges and ridges, interacts with residual stress and produces stress components which are detrimental for cutting tool. Therefore, it is important to control the defects to achieve high reliability of tools.

Furthermore, cutting temperature has a significant effect on wear propagation especially in dry cutting because phase transformation in the HSS substrate occurs by thermal loading. If the heat which is generated during cutting process increases excessively and reaches the tempering temperature of HSS substrate, usually above 500° C, then a brittle fracture will happen on the coating layer of the cutting tool and consequently HSS substrate will become softer which is harmful for tool-life. In fact, when the coating layer is to be removed by high cutting temperature and fragile fracture, HSS substrate will lose its protective layer and will be exposed to the thermal loading; consequently it leads to less tool-life and destructive tool-wear. Therefore, selection of the coating system and avoiding high temperature during cutting can improve tool-life and increase productivity [4].

In addition, cutting speed has an important role on chip formation and tool-wear. Crater wear is another type of wear which occurs at high cutting speed and high temperature. In fact, high cutting speed makes high temperature due to shear localization in the primary and secondary shear zones of the chip. Consequently the temperature gets closer to the melting point of the work-piece material and HSS substrate, which is harmful for tool life.
Therefore, the main factor for limiting cutting speed is tool-wear which is highly influenced by cutting temperature [16].

![Figure 5. Typical wear pattern of a metal cutting insert (a) and a hob tooth used for gear cutting (b). The studies of this investigation are concentrated to the area framed in (b). [4]](image)

### 2.3 Different experimental simulation for gear hobbing

Several experimental simulation tests have done so far to mimic hob milling in terms of wear mechanism, chip formation, etc. Their aims were to obtain more information about cutting condition, in order to improve hob and tool designing for high speed dry machining. Using one single insert in milling test, is a common method for gear hobbing simulation.

#### 2.3.1 Tests from KTH and Uppsala University

The aim was to reproduce the wear mechanism that is usually happened on the hobs during dry machining. In this method, one single cutting tooth was used in three-axis conventional milling machine. Cutting insert represents hob tooth. The insert is made of high speed steel (HSS) with PVD coating. The advantages of this method compared to using real hob is more economical, time consuming and higher accessibility to test specimens. Moreover, one cutting insert has more simple kinematic and geometry that makes analyzing and measurement of cutting force easier. It is assumed that wear mechanism is controlled by interrupted cutting process such as cutting speed, feed rate and to less extent by geometries and kinematics of hobbing. Although the rate and amount of wear is different from real hobbing because the geometry of chips from milling is different from hobbing, the wear
mechanism is close to the real gear hobbing [7]. A schematic picture of the milling test to simulate hobbing is shown in Figure 6.

Figure 6. Schematic picture of the milling test with cutting and feed force components indicated. The direction of the cutting movement coincides with the direction of the cutting force, $F_c$, while the tool is fed in the opposite direction (climb milling) [7].

### 2.3.2 Fly hobbing and flute hobbing

Fly hobbing is an experimental simulation that is carried out in a five-axes milling machine and can promote efficiency of the gear hobbing studies. The aim of this test is to evaluate the performance of the tool in gear hobbing by investigation on the effect of cutting edge preparation on the wear resistance of PM-HSS hobs. The abrasive flow machining technology was used to prepare cutting edge and the final results show that this process is efficient. In this method, a single cutting tooth is used to mimic the work of hob in roughing zone. The benefits of this process are, duration of the test is short, and SEM analysis of the cutting tooth is feasible to have a better study about the wear types and consequently improves the hob design [6]. Kinematic of a hobbing operation and a fly
hobbing can be seen in Figure 7. However, by this method it is difficult to provide enough information about the most harmful zone for tool because in real hob a lot of cutting teeth are responsible in this zone and they remove different amount of work-piece. So, to identify which teeth have weaker wear resistance it is necessary to develop a quick testing method which is called flute-hobbing and is explained in the following part.

Figure 7. Kinematic of a hobbing operation and of a fly hobbing operation [6]

Flute hobbing is a new method that is faster than fly hobbing and can increase the efficiency of experimental simulation for real gear hobbing. The kinematic of this method is based on a standard five-axis milling machine which is similar to the real gear hobbing. There is special software that provides the geometry of each chip during the test. The relation between the geometry of the chip and wear of the tooth indicates where the worst wear is happened and facilitates to recognize the critical tooth of the hob in order to develop this part of cutting zone. Differences between flute hobbing and real hobbing are
the number of flute and cutting conditions. Flute hobbing has one single tooth while real hobbing has a lot of flutes. Cutting conditions like feed per revolution and machining time is different because one flute cannot do the same work as a real hob. In flute hobbing the calculation of cutting speed is easy while feed per revolution measurement is demanding because there is just one tooth. Moreover, feed rate affects chip thickness and to obtain the thickness similar to real hobbing, it is crucial to select the proper feed rate although it is impossible to achieve chips as thick as in real hobbing. As a consequence, the feed rate in flute hobbing is less than real hobbing. The substrate and coating material of the tool are the same in both cases [8]. Kinematic of a hobbing and a flute hobbing operation is shown in Figure 8.

Figure 8. Kinematic of a hobbing operation and of a ‘flute hobbing’ operation [8]
3. Experimental work

3.1 Principal and kinematic of the test

In this project the milling concept, proposed for gear hobbing simulation to reproduce the wear type of gear hobbing process. Dry face-milling tests were done by using a three-axis milling machine (VLLF-550 CNC machine) at Swerea KIMAB AB and a five-axis milling machine (Hermle) at KTH. The milling cutter was made of a spindle on an axis vertical to the surface of work-piece. The milling machine was climb milling (down-milling) in which the thickest part of the chip was formed at the entrance of the cut and decreased to zero at the exit. In our cutting test, the effective rake angle was 6° and clearance angle was 5° see Figure 9.

Figure 9. Dry face-milling set up during running at KTH workshop

3.2 Materials

3.2.1 Cutting tool materials

Cutting tools were circular inserts made of powder metallurgy high speed steel (PM-HSS, Erasteel ASP2030) with a PVD coating layer of TiAlN. They were provided by ALESA AG Company. The choice of circular insert was the capability of them to produce different
range of chip thickness and to minimize the effect of notching by spreading the depth of cut over a wider area of the cutting edge. The inserts had similar chemical composition with the reference hob (ASP 2052). Chemical composition of HSS substrate can be seen in Table 2.

Table 2. Chemical composition of HSS ASP 2030 as the insert substrate [%wt.] (from Erasteel company)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Co</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></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>

Geometry of cutting tool was $\phi 12 \times 4.76 \times 5.5 \text{ mm}^3$ which means each insert had a diameter of 12mm. The insert holder was provided by ALESA AG Company as well. The diameter of the holder or milling head was 100 mm ($D=100 \text{ mm}$), see Figure 10. To figure out the difference between appearances of unused and used tools, see Figure 11.

Figure 10. A circular cutting tool mounted in the holder that is used in the cutting test
3.2.2 Work-piece materials

Four steels were used as work-piece materials. They were provided by two companies, Gerdau-Sidenor and Ovako. Their denominations and heat treatment is shown in Table 3. They were selected from different hardness to see the effect of hardness on tool-life and wear mechanism. These steels can be divided to three groups according to their carbon content:

1) Case-hardening (0.15-0.21 % C)
2) Induction hardening (0.3-0.54 % C)
3) Ball bearing steel (0.97-1 % C)

***C = Carburizing steel

QL = Quench & tempered Low

QH = Quench & tempered High

B = Ball bearing steel

IA = Isothermally Annealed

SA = Spheroidized Annealed
Table 3. Proposed steels, heat treatments and denominations

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>18CrMo4</th>
<th>35CrMo4</th>
<th>50CrMo4</th>
<th>100Cr6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short name</td>
<td>C</td>
<td>QL</td>
<td>QH</td>
<td>B</td>
</tr>
</tbody>
</table>

Heat treatment

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quench &amp; tempering I</td>
<td></td>
<td>▪ QH-T1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quench &amp; tempering II</td>
<td>▪ QL-T2</td>
<td>▪ QH-T2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealing</td>
<td>▶️ C-IA</td>
<td></td>
<td></td>
<td>▼️ B-SA</td>
</tr>
</tbody>
</table>

Length of each bar of work-piece was 500 mm (L=500 mm). Heat treatment before rough machining was categorized in two groups: annealed and quenched-tempered. Hardness of the steels can be seen in Table 4.
Table 4. As-delivered hardness of work-piece materials

<table>
<thead>
<tr>
<th>As-delivered Hardness</th>
<th>Quench &amp; tempering I</th>
<th>Quench &amp; tempering II</th>
<th>Annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QH-T1</td>
<td>QL-T2</td>
<td>C-IA</td>
</tr>
<tr>
<td></td>
<td>345 HB</td>
<td>287 HB</td>
<td>157 HB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QH-T2</td>
<td>200 HB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>315 HB</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Cutting tests

To observe the effect of cutting conditions on the work-piece and tool and also investigate about wear mechanism and tool-life, different methods were used:

- Observing the cutting tools by Light Optical Microscope (LOM) microscope in the workshop and laboratory of Swerea KIMAB AB
- Observing the tools by SEM in Swerea KIMAB AB
- Chip collection from the cutting test and observe them in LOM
- Make the resin samples from chips in metallography laboratory of Swerea KIMAB AB to observe their microstructure before and after etching.
- Preparing metallographic specimens from as-delivered steel bars by grinding, polishing and etching to observe the microstructure of the steels before cutting tests see Figure 12 and Figure 13.
Figure 12. Observation of cutting tools mounted in the holder by LOM microscope at Swerea KIMAB AB workshop

Figure 13. Observing cutting tool by loupe at KTH workshop
In this project, face-milling tests were done by using one single insert mounted in the holder. Figure 14 shows milling cutter and work-piece set up during running in Swerea KIMAB AB. For face-milling test, cutting data were set according to the hardness of work-piece. However, some cutting data were common for all of the tests as can be seen below:

- Radial depth of cut \((a_e) = 10\) mm.
- Vertical depth of cut \((a_p) = 1\) mm.
- Feed per revolution \((f_i) = 0.6\) mm/rev
- Length of each passage in the test was 500 mm, which was equal to the work-piece length.
- Cutting speed, \(20 \leq V_c \leq 200\) m/min
- Diameter of the insert holder \((D) = 100\) mm.

Figure 15 represents the schematic of the milling operation. Other than mentioned common cutting data, there were specific cutting data such as rotation per minute \((n)\) and feed per minute \((V_f)\) which were calculated by Equation 1 and Equation 2. As the diameter of the insert holder \((D)\) and feed per revolution \((f_i)\) are constant, the values of rotation per minute \((n)\) and subsequently feed per minute \((V_f)\) depends on cutting speed \((V_c)\). The relationships between the cutting data are shown as below.

**Equation 1: Rotation per minute**

\[
n = \frac{V_c \times 1000}{\pi \times D}
\]

\(n:\) rotation per minute [rpm]

\(V_c:\) cutting speed [m/min]

\(D:\) diameter of the insert holder = 100 [mm]
Equation 2: Feed per minute

\[ V_f = f_r \times n \]

\( V_f \): feed per minute [mm/min]

\( f_r \): feed per revolution = 0.6 [mm/rev]

\( n \): rotation per minute [rpm]

Figure 14. Dry face-milling cutter and work-piece during running test at Swerea KIMAB AB
Two main test methods were used for this investigation:

1) Tool-life test
2) Chip collecting test

### 3.3.1 Tool-life test

The purposes of this test were:

- a) Obtain relevant data about tool-life
- b) Provide a basis for selection of cutting speed
- c) To verify the expected tool-life and wear-mechanism

Tool-life test is a long-time test which in; milling cutter cuts the surface of work-piece and finishes each passage consecutively. This process is repeated several passes until a wear-out criterion has been reached. In the tests, the wear-out criteria was either flank wear width of 0.3 mm, or if the cut generated a bad surface on the work-piece or if an increased noise was noted. Two different cutting speeds, high and low, were used for each work-piece, except B-SA. The aim was to reproduce wear type of gear hobbing and understand
the effect of cutting speed and hardness of work-material on tool wear. For observing the progression of wear, the insert was observed in LOM every five passes, and its flank wear was measured.

3.3.2 Chip collecting test

The aims of the tests were:

a) To frame the cutting speeds in the tool life test

b) A study of color and shape of the chips

c) To verify the relation between work-piece hardness, cutting data and chip formation

In this test, different cutting speeds, from low to high, were used for cutting of work-piece. Chips were collected to observe in LOM microscope. Chips of the same work-piece were compared to each other regarding color, curl and thickness to figure out the effect of cutting speed on cutting process. Moreover, chip criteria between different steel were investigated to understand how carbon content and hardness affect chip formation.

Various cutting speed that were used for different work-materials is shown in Table 5. In addition, a small piece from cross-section of each work-material was cut for observing the microstructure of steels before cutting.
Table 5. Cutting test data

<table>
<thead>
<tr>
<th>Cutting speed [m/min]</th>
<th>Feed per revolution [mm/rev]</th>
<th>Work-material</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.6</td>
<td>C-IA</td>
</tr>
<tr>
<td>180</td>
<td>0.6</td>
<td>C-IA</td>
</tr>
<tr>
<td>160</td>
<td>0.6</td>
<td>C-IA</td>
</tr>
<tr>
<td>140</td>
<td>0.6</td>
<td>C-IA</td>
</tr>
<tr>
<td>120</td>
<td>0.6</td>
<td>C-IA</td>
</tr>
<tr>
<td>100</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T2, B-SA</td>
</tr>
<tr>
<td>90</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>80</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>70</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>60</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>50</td>
<td>0.6</td>
<td>C-IA, QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>40</td>
<td>0.6</td>
<td>QL-T2, QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>30</td>
<td>0.6</td>
<td>QH-T1, QH-T2, B-SA</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>QH-T1</td>
</tr>
</tbody>
</table>

3.4 Study of wear mechanism

An overview study of used cutting edge was done in LOM microscope by observing flank face, rake face and cutting edge. A detailed study of wear with focus on initiation of wear
was carried out with SEM microscope. All of SEM studies were carried out on un-etched insert. Backscattered mode (BS) and secondary electron mode (SE) were used in SEM.
4. Results

4.1 Tool-life test

Number of passage is one indicator for tool life test. The more number of passes indicates longer tool life. Regarding this criterion, the results of tool life tests represented that the work-materials with lower hardness had better machinability, with less harmful effect on cutting tool performance that led to more number of passes. But harder work-materials had more adverse effect on cutting tools; hence low number of passes was obtained. As can be seen in Figure 16, carburizing steel that had the lowest hardness was the best work-material for machining and tool-life, with 55 passes. The hardest work-material (induction hardening steel) was the most demanding one to cut and made the lowest value for tool-life, with 9 passes. For each work-material, by increasing cutting speed, more number of passes was obtained. As an example, in carburizing steel, three cutting speeds of 150, 180 and 200 m/min were used then 40, 45 and 55 passes had been reached respectively.

![Hob milling simulation tool life](image)

Figure 16. Result for tool life test regarding to number of passes
4.2 Chip collecting test

Color and curl of the chips were used as the indicators for cutting speed and temperature. By LOM study, it was observed that when hardness of work-material and cutting speed increased, diameter of the curl became smaller while length of the chip increased. Because higher cutting speed generated more cutting temperature, chips absorbed more heat and showed more thermal expansion that caused more twisting in their shape, see Figure 17 and Figure 18. Further, thickness of the chips was measured regarding to cutting speed. By increased cutting speed and hardness of the work-material, chips became thinner with the same behavior as it was observed for the curl see Figure 19 and Figure 20.

![Figure 17. Effect of hardness on chips curl and diameter](image-url)
Figure 18. Cutting speed vs. diameter of the curl
Figure 19. Effect of cutting speed and hardness on curl and thickness of the chip, (a) [V=70 m/min-157 HB], (b) [V= 200m/min- 157 HB], (c) [V=20 m/min - 345 HB], (d) [V=90 m/min- 345 HB]
Figure 20. Cutting speed vs. chip thickness

For every work-material, when cutting speed increased, a transition of the chip color occurred so that they became darker due to higher cutting temperature, see Figure 21. When cutting speed increases, cutting temperature becomes higher and close to the melting point of the work-material, so the color becomes darker. Considering different work-piece materials at one cutting speed, the transition of the chip color were governed by both hardness and carbon content of the work-piece but mostly influenced by carbon content, see Figure 21.
Chip collection tests

<table>
<thead>
<tr>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
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</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Chip images" /></td>
<td><img src="image2" alt="Chip images" /></td>
<td><img src="image3" alt="Chip images" /></td>
<td><img src="image4" alt="Chip images" /></td>
<td><img src="image5" alt="Chip images" /></td>
<td><img src="image6" alt="Chip images" /></td>
<td><img src="image7" alt="Chip images" /></td>
<td><img src="image8" alt="Chip images" /></td>
<td><img src="image9" alt="Chip images" /></td>
</tr>
</tbody>
</table>

(345 HB)

| ![Chip images](image10) | ![Chip images](image11) | ![Chip images](image12) | ![Chip images](image13) | ![Chip images](image14) | ![Chip images](image15) | ![Chip images](image16) | ![Chip images](image17) | ![Chip images](image18) |

(315 HB)

| ![Chip images](image19) | ![Chip images](image20) | ![Chip images](image21) | ![Chip images](image22) | ![Chip images](image23) | ![Chip images](image24) | ![Chip images](image25) | ![Chip images](image26) | ![Chip images](image27) |

(287 HB)

| ![Chip images](image28) | ![Chip images](image29) | ![Chip images](image30) | ![Chip images](image31) | ![Chip images](image32) | ![Chip images](image33) | ![Chip images](image34) | ![Chip images](image35) | ![Chip images](image36) |

(200 HB)

| ![Chip images](image37) | ![Chip images](image38) | ![Chip images](image39) | ![Chip images](image40) | ![Chip images](image41) | ![Chip images](image42) | ![Chip images](image43) | ![Chip images](image44) | ![Chip images](image45) |

(157 HB)

<table>
<thead>
<tr>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
</table>

![Chip images](image46) | ![Chip images](image47) | ![Chip images](image48) | ![Chip images](image49) | ![Chip images](image50) |

Figure 21. Chip color as an indicator for cutting speed and hardness of the work-material
4.3 Evaluation of used cutting tools

According to SEM observations, there were two types of wear on the cutting inserts: wear on the rake face and flank wear. On the rake face, close to the cutting edge, coating layer is removed completely and exposed HSS substrate is remained. The area above the cutting edge on the rake face is called depth of cut in which the coating layer (Ti-Al-N) is still remained and HSS substrate is not exposed however it became softer due to high thermal loading, see Figure 22. Maximum depth of cut and zero depth of cut which form respectively the thickest and the thinnest part of the chip is shown in Figure 23.

Figure 22. Overview of wear on depth of cut, the insert used for 345 HB [after 100 min at V=30 m/min].SEM-BS-mode.
The main difference of wear between soft and hard steel occurred on the rake face of the cutting insert. More wear happened on the rake face of the insert that used for harder steel as can be seen in Figure 24. In addition, a significant crater wear happened on the rake face of the insert that used for the hardest work-material, see Figure 25.

Figure 23. Rake face wear on cutting insert used for 157 HB [after 120 min at V=150 m/min]. SEM-SE-mode
Figure 24. SEM of rake face wear for the softest and the hardest, (a) and (c) [157 HB, after 120 min at V=150 m/min] (b) and (d) [345 HB, after 100 min at V=30 m/min]
Figure 25. Crater wear in cutting edge of the insert used for 345 HB [after 100 min at V= 30 m/min]

The widest flank wear (half-circle shape) occurred at the left side of the flank face, beside zero depth of cut, in which coating layer is removed completely and exposed HSS substrate remained. This part is called sliding side where cutting is finished and chips are ejected over the tool. Thermo-mechanical load is high at sliding slide, so instead of cutting and chip removal, all of the loads transfer to the tool and develop the flank wear, see Figure 26.
Figure 26. Flank wear on cutting insert used for 287 HB [after 75 min at V=50 m/min], SEM-BS-mode.

Inside the exposed HSS substrate, there are some white dots which are carbide particles from HSS tool. They are hard and abrasive and cause abrasive wear, which looks like scratches. Abrasive wear and carbide particles are shown in Figure 27 and Figure 28 respectively.
Figure 27. Abrasive wear appeared as scratches near exposed HSS on the insert used for 200 HB [after 195 min at V= 60 m/min], SEM-BS-mode.

Figure 28. Carbide particles from HSS on the exposed HSS substrate used for 287 HB after 75 min at V= 50 m/min, SEM-BS-mode.
5. Discussion

These milling tests succeeded to reproduce the wear of actual gear hobs due to the following reasons:

1) The same wear type was achieved according to the reference hob from literature survey; cp. Figure 5 [4].

2) The tool life was on the same level.

On the rake face, close to the cutting edge, high thermal loading caused softening on HSS substrate and brittle fracture of the coating layer, which resulted in rapid wear of the tool. The other reason for this rapid wear can be poor toughness of the coating layer. Moreover, hardness of the work-material and cutting speed affected the rake face wear. With harder work-material and higher cutting speed, more thermal softening happened on the HSS substrate along with accelerated wear propagation, see Figure 29. According to Finn et al. [12] and Sandvik Coromant [13], hardness of the work-piece material has an important role in performance of the cutting tool and wear-mechanisms so that lower hardness and strength of the work-material is beneficial for machinability. Therefore, carburizing steel with minimum hardness caused better machinability, less detrimental effect on the cutting tools and longer tool life.

![Figure 29. Difference in rake face wear regarding to hardness of the work-material; (a) 160 HB [after 120 min at V=150 m/min], (b) 250 HB [after 75 min at V=50 m/min], (c) 350 HB [after 100 min at V=30 m/min]](image)

In addition, there is a risk of crater wear with higher hardness of the work-piece material as it happened on the insert used for the hardest work-material, cf. Figure 25. As the work-material was very hard and the cutting speed was too low (30 m/min), the tool required
more cutting force to remove the chip. Consequently, more heating was generated and chemical interaction occurred between the rake face of the tool and the hot chips that were flown over the tool which caused the crater wear. In this test, flank wear on the cutting insert was the largest and dominant wear type. It happened in sliding side of the tool where thermo-mechanical loading is too high and there is no cutting, so all of the loads and pressure transfer to the tool instead of removing chips and developed the flank wear. No notch wear developed on tools since the cutting inserts were circular and the entire edge line was involved in cutting. Therefore, using circular insert was beneficial to minimize the effect of notching by spreading the depth of cut over a wider area of the cutting edge, cp. Figure 30 and Figure 31.

![Figure 30. Typical wear pattern of a hob tooth used for gear cutting [4]](image-url)
Figure 31. Wear pattern on the milling insert used for cutting 287 HB, after 75 min at V=50 m/min

There are three ways to represent tool life: number of passes, minutes and gear tooth meter. Tool-life tests in terms of number of passes showed that increasing cutting speed was beneficial for having more number of passes. It is probably because of less adhesion and lower built-up-edge (BUE). When cutting speed rises, rotation per minute (n) is more, so tool needs less cutting force to remove the chips. Consequently, less adhesion and built-up-edge (BUE) is formed around the tool, which is better for performance of cutting tool. Especially cutting speed of less than 50 m/min like 30 m/min was too low and made bad sounds during cutting that was not favorable for surface of the work-piece. Difference of tool life between the softest and the hardest steels in terms of number of passes was about 2 times. The difference in cutting speed was about 3 times, from 50-100 m/min for the softest to 180-200 m/min for the hardest one.

Minutes of tool life indicates a descending trend in tool life by increasing cutting speed which is similar in actual gear cutting. Because higher cutting speed generates more heating that is harmful for performance of the tool. The result is shown in Figure 32. The only exception in diagram is, when cutting speed increased from 30 to 50 m/min for quenched and tempered steels (315 and 350 HB) that led to higher tool life. Cutting speed of 30 m/min was too low and a bad sound was heard during cutting. Therefore, it caused
built-up edge formation with unfavorable effect on the work-pieces surface. Thus, the results in diagram should be considered after 50 m/min. Among the work-materials, quenched and tempered one with medium hardness (250 HB) was the most demanding for cutting. Moreover, it had the least tool life among quenched and tempered steels at the same cutting speed (50 m/min).

Figure 32. Minutes of tool life vs. cutting speed

According to Gerth et al. [7], the extent and rate of the wear from simulation test by milling are different from real gear hobbing due to different chip geometry. However, this project was successful to reproduce the wear rate close to the actual hobbing. There are some indicators such as length of the gear tooth or total volume of removed work-material that can verify the wear rate. There was a reference hob, according to an oral communication [17], to compare the tool life and wear rate in terms of gear tooth meter or volume of removed work-material. Basically, in real gear hobbing, each edge of the hob
removes a certain volume of the work-material and finally generates the gear tooth. For the above reference, the gear root is assumed as a rombohedric shape, see Figure 33. Then the volume of the removed work-material was gained as can be seen in the following calculation.

\[ V = \frac{11 + 2}{2} \times 9 \times 1\times 10^4 = 94.5 \times 10^4 \text{ (mm}^3) \]

In this milling test with using one cutting edge, total volume of removed work-material after cutting carburizing steel, was calculated by Equation 4.

\[ V = a_x \times L \times (a_p) \times N \]

\[ V = 10 \times 500 \times 1 \times 55 = 27 \times 10^4 \text{ (mm}^3) \]
The difference of the results between real hobbing and this milling test is about 3 times which is fairly good for one cutting edge.

In other words, reference hob [17] generates the gear tooth of 10 meter and this milling test succeeded to produce the gear tooth of about 3 meter after cutting the softest work-material (carburizing steel) at cutting speed of 200 m/min, see Figure 34. Again, the difference is about 3 times that is reasonable for one single cutting edge. Therefore, this one tooth milling test was able to mimic the wear rate of the tool and tool life was on the same level.

Figure 34. Length of produced gear tooth by one single cutting edge

On the other hand, some parameters were different between this milling test and actual hobbing, such as geometry of the tool and chip formation. Moreover, the simulation tests were carried out in dry cutting process while real hobbing usually has cutting fluids. CNC-machine at KTH workshop was new-brand and more advanced than milling machine at
KIMAB, so that during running the tests, less sound were heard that indicates less vibration and more stability of the machine that leads to more reliable results.
6. Conclusions

- The one tooth milling test was able to reproduce wear type and tool life on dry cutting.

- The edge line was the most critical part of the cutting tools which caused degradation in performance of the tools.

- Dominant wear mechanisms were brittle fracture of the coating on the rake face and flank wear at the end of cut due to poor toughness of the coating layer.

- During cutting, thermo-mechanical overload on the HSS substrate caused soft substrate and initiation of removal coating along the cutting edge, and then it propagates on the rake face in the chip flow direction and leads to rapid wear.

- Flank wear of the cutting edge was life limiting with the reference 160 HB steel. With the harder steels a transition to rake face wear was observed. The reason for that is higher thermo-mechanical load on the rake face at higher cutting speeds.

- Higher cutting speed led to higher tool life. Possible reason can be less adhesion and built up edge formation on the cutting edge at high speed. In other words, a cleaner cut was generated at higher speeds.

- More curl and thinner chip were formed at higher cutting speed and higher hardness of the steel because more heat is generated when cutting speed or hardness of work-material is increased. This heat transfers to the chips and causes more thermal expansion and more curl in the shape of the chips.

- Color transition of the chips was an adequate indicator for cutting speed, although the color is highly influenced by work-material. In particular the carbon content has a strong influence on the oxidation and the resulting color of the chips.

- Annealed steels as the work-materials caused longer tool life compared to quenched and tempered ones because they had less hardness than quenched ones.
7. **Future work**

- Investigation of the “sudden death” phenomena of the HSS cutting tools and probability of sudden edge failure at high cutting speeds

- Further investigations of work-materials heat treatment and microstructure effect to optimize gear hobbing and other machining operations.

- Modify the test set-up so that it can test actual forged ring blanks for gear production.

- Microstructure characterization of the chips to figure out how the microstructure is connected to the chip formation process
8. References


[17] Pertti Nikka at Volvo powertrain