Influence of Gear Design on Tool Load in Bevel Gear Cutting

Fritz Klocke, Markus Brumme, Stefan Herzhoff*

*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Germany
* Corresponding author. Tel.: +49-241-80-28472; fax: +49-241-80-6-28472. E-mail address: s.herzhoff@wzl.rwth-aachen.de.

Abstract

During gear design, the tooth geometry is optimized towards the required running behavior. Pressure angle and tooth root radius of the gearset are among the influencing factors. As the tools in bevel gear cutting are specially designed for each gearset, the tool profile geometry is defined by the gear geometry. The objective of this work is to analyze the influence of the tool profile geometry on thermal and mechanical tool load during bevel gear machining. By means of a finite element based machining simulation the chip formation in bevel gear cutting of ring gears is calculated. The simulation results show a significant thermal and mechanical load maximum at the tool corner, where the maximal wear occurs. The variation of the tool profile geometry shows a high influence of the tool pressure angle and the tool corner radius on the tool load at the tool corner.

Keywords: Gear Cutting, Chip Formation, Machining Simulation, Tool Temperature, Tool Stress, Wear

1. Introduction and Challenge

Bevel gear cutting is a very productive machining process, especially in automotive applications. A machine kinematic in six axes is necessary to manufacture the gear geometry. In typical applications, the undeformed chip cross-section is L-shaped, spreading over two adjacent cutting edges including the tool corner as shown in Fig. 1.

In this multi-flank chip formation tools often reach the tool life due to excessive wear at the tool corner radius [1, 2, 3, 4]. This local wear limits the usable tool life in series production. Furthermore, tool wear related problems cannot be considered during the design phase of bevel gears. This would require a model for tool life prediction which considers the tool profile geometry, which is not available. A model for the prediction of tool corner wear in bevel gear cutting inherits high potential for process optimization.

Tool wear depends on the strength of the cutting edge as well as on the thermal and mechanical load on the cutting edge during chip formation. As the tool load cannot be measured locally, a finite element based machining simulation is used to model the process of chip formation in bevel gear cutting. The machining simulation is able to calculate the temperature and stress distribution along the cutting edge. This approach of tool wear prediction based on tool load is new for bevel gear manufacturing.

Fig. 1 Multi-Flank Chip Formation in Bevel Gear Cutting
2. Objective and Approach

The results described in this paper are part of a research project with the objective of developing a wear model to predict disproportionate tool corner wear in machining operations with multi-flank chip formation. As tool wear is the reaction of the tool to the thermal and mechanical load during chip formation the first step towards a wear model is the analysis of tool load, which is presented in this paper. The objective of this work is to analyze the influence of the tool profile geometry on thermal and mechanical tool load during bevel gear machining.

3. Design of the Simulation Model

The tool load can be described for example by the stress and temperature distribution along the cutting edge. As those values are difficult to gain by metrological means, a finite element based three dimensional machining simulation is used.

For machining simulation commercial software is used. The software is based on the finite element method and uses an implicit Lagrange approach with continuous new mesh generation.

Geometrical input values for the simulation are the geometry of workpiece and tool and the process kinematics. Furthermore the material behavior during deformation and the contact conditions between workpiece and tool have to be defined. As result, the geometry of the deformed chip is calculated. For the chip formation, stress and temperature distribution of tool and workpiece as well as the status and history of deformation can be analyzed.

The tool and workpiece geometries are based on an industrial process for milling of bevel gear ring gears (face milling). In automotive applications the pinion is usually machined in a generating process with a curved tooth profile, while the ring gear has a straight tooth profile. Therefore a profile milling process can be used for the ring gear. In the face milling variant all gaps are cut one by one. Usually a face cutter head equipped with carbide stick type blades is used as tool. The gear profile is divided into two L-shaped parts for concave and convex flank. Both are cut by separate blades.

In Fig. 2 characteristic values are shown for the description of the tool geometry and the geometry of the undeformed chip cross section used in the simulation model. The shown geometry and listed values represent a typical cutting condition in bevel gear cutting in the middle of the plunge cycle at the concave flank of a ring gear. This geometry is used for the simulation evaluated in Fig. 3 and Fig. 5 and as starting point for the tool profile geometry variation.

4. Machining Simulation

In the pre-processor of the simulation a finite element mesh for tool and workpiece is generated. During chip formation the workpiece is exposed to strong deformation which results in a bad aspect ratio of the elements causing numerical instabilities. In areas with high strain, the mesh is therefore rebuilt continuously during simulation. For the machining simulation a fine mesh is only used in the deformation zones and for the chip.

A constitutive material model is used to describe the deformation behavior of the workpiece. The material model is implemented according to the theory of Johnson and Cook [5]:

\[
k_f = (A + B \cdot \varepsilon^m) \cdot (1 + C \cdot \ln(\varepsilon/\varepsilon_0)) \cdot (1 - (\theta_f - \theta_m)/\theta_0)^n\]

where \(k_f\) is the flow stress, \(\varepsilon\) the plastic equivalent strain, \(\theta_f\) the melting temperature and \(\theta_0\) the initial temperature. The material parameters for the used 16MnCr5 are listed in table 1:

| parameter | \(\varepsilon_0\) [1/s] | A [MPa] | B [MPa] | C [-] | n [-] | m [-] |
|-----------|-----------------|---------|---------|-------|-------|-------|
| value     | 1               | 560     | 400     | 0.022 | 0.2   | 1     |

This material is typically used in gear manufacturing. As in bevel gear cutting no segmented chip formation occurs, further modifications of the material law, as presented in [6], are not necessary. A more detailed presentation of the simulation model is published in [7], where the tool load is analyzed for one tool geometry. In this paper, the simulation model is used to conduct a geometry variation for analysis of the influence of tool pressure angle and tool corner radius on the tool load.
4. Simulation Results

The simulation model has been used to calculate characteristic key values for the thermal and mechanical tool load in bevel gear cutting. Furthermore a variation of tool profile geometry has been done, which results are described in this section.

In tool load analysis, two reasons for uneven load distribution have to be distinguished. At first, an uneven chip shape will result in uneven load acting on the cutting edge, as discussed in [7]. Secondly, the shape of the cutting edge will influence the load occurring in the inside of the tool as well. For example, a force at the tip of the tool will result in a three dimensional stress distribution throughout the tool. Hence, the analysis of the external load at the tool is not sufficient to qualify the tool load. Therefore internal load types, for example cutting edge temperature or stress state along the cutting edge, are analyzed in this paper.

For the presentation of the results, thermal and mechanical load values are considered separately. At first, the internal load state is analyzed for one simulation, based on:

- temperature distribution along the cutting edge
- thermally affected volume of the cutting edge
- equivalent von Mises stress along the cutting edge
- mechanically affected volume of the cutting edge

Afterwards, key values for the volumetric internal load distribution are derived by calculation of the product of the affected volume and the temperature or von Mises stress. Based on the volumetric key values the influence of the tool profile geometry on the tool load is shown.

4.1. Thermal Tool Load

In Fig. 3 the temperature distribution and the thermally affected volume of the cutting edge are shown. In order to determine the temperature data, the cutting edge is separated into different sectors. For each sector, the maximum nodal temperature is chosen as the sum of the volumes of all elements of the FE-net, whose temperatures have exceeded \( \vartheta = 323 \) K. The temperature of \( \vartheta = 323 \) K has been chosen to define a thermal effect, as the simulation starts at room temperature of \( \vartheta = 293 \) K.

In the upper diagram of Fig. 3 the thermal load over the unrolled cutting edge is shown. The x-axis represents the unrolled cutting edge, starting at the flank cutting edge and ending at the end of the tip cutting edge. On the one hand, the diagram shows the temperature distribution after a cutting time of \( t_c = 3 \) ms in the cutting edge and at the bottom of the chip. On the other hand, the volume \( V_{50} \) of the cutting edge, which exceeded a temperature of \( \vartheta = 323 \) K, is shown. The lower diagram of Fig. 3 shows the development of the maximal temperature along the cutting edge as mean value for the three sections of the tool over the cutting time \( t_c \).

After the first millisecond of cutting time an even temperature distribution along the cutting edge is established, as shown in the lower diagram of Fig. 3. For explanation of this behavior two influencing factors have to be considered. At first, the flank cutting edge has the first contact to the tool and is therefore affected by the thermal conditions of cutting for the longest time. The end of the tip cutting edge is the last part of the tool to get in contact with the workpiece. Secondly, the temperature difference of two bodies is the driving force for heat transfer. The temperature at the bottom of the chip is shown in Fig. 3 as dotted line. It shows that the temperature at the tooth root part of the chip is higher than the temperature at the tooth flank part. The temperature difference between tip cutting edge and tooth root chip is larger compared to the temperature difference at the flank cutting edge and the tooth flank chip. Both factors combined explain the even temperature distribution at the beginning of the cut. From there on, a significant temperature maximum occurs in the region of the tool corner, as shown in the upper diagram of Fig. 3.

The thermally affected volume along the cutting edge \( V_{50} \) shows a maximum at the tool corner. At the tip cutting edge the thermally affected volume is higher than at the flank cutting edge.
For explanation, the contact area between chip and tool is analyzed, through which the heat transfer occurs. In orthogonal cutting the contact area corresponds to the chip thickness. Therefore, the different chip thickness of \( h_o = 0.12 \text{ mm} \) at tip cutting edge compared to \( h_s = 0.06 \text{ mm} \) at flank cutting edge explains the different thermally affected volume \( V_{S\vartheta} \) at tip and flank cutting edge. At the tool corner the chip thickness increases from \( h_s = 0.06 \text{ mm} \) to \( h_o = 0.12 \text{ mm} \), but the simulation results show a higher contact area between chip and tool compared to the tip cutting edge. This is due to the multi-flank chip formation, where, especially at the tool corner, the chip is forced into a bigger radius. The resulting higher contact area leads to more thermal energy per unit length of the cutting edge being transferred into the tool at the tool corner, compared to tip and flank cutting edge. This is the explanation for the higher thermally affected volume. The increasing temperature maximum at the tool corner during cutting process shows, that in this area of the tool a lower heat flow to the inside of the tool occurs, compared to flank and tip cutting edge.

4.2. Influence of Tool Profile on Thermal Tool Load

For the variation of tool profile geometry the tool pressure angle \( \alpha \) and the tool corner radius \( r_c \) have been varied. Comparing different tool profile geometries, the maximal temperature does not differ significantly. For all the simulations, the resulting temperature at the tool corner is higher than at the tip and flank cutting edge. However, the heat flow towards the inside of the tool is different for different tool profile geometries. This can be shown by calculating the product of thermally affected volume and temperature, which has been defined as:

\[
V_o = \sum_i V_i \theta_i, \text{ if } \theta_i > 323K
\]

In this equation, \( V_i \) is the volume of one tetrahedral element and \( \theta_i \) is the average temperature of its four nodes. For the calculation only elements are considered, whose average temperature has exceeded \( \theta = 323 \text{ K} \).

Fig. 4 shows the product of thermally affected volume and temperature at the three different parts of the cutting edge across the range of tool profile geometry variation.

The product of thermally affected volume and temperature corresponds to the heat energy in the cutting edge, neglecting the heat capacity and the density of the material. Both are temperature dependent, but material constants and thereby equal for the different tools.

At the tool corner the product of thermally affected volume and temperature is significantly higher than at tip and flank cutting edge for all tool profile geometries. The variation of tool profile geometry shows a high influence of the tool profile geometry on the product of thermally affected volume and temperature at the tool corner and a minor influence at the tip and flank cutting edge. In all cases, the product of thermally affected volume and temperature increases with decreasing tool pressure angle \( \alpha \) and tool corner radius \( r_c \). The influence of the pressure angle \( \alpha \) is bigger than of the tool corner radius \( r_c \).

![Fig. 4 Thermal Tool Load for different Profile Geometries](image)

For an evenly loaded, straight cutting edge, it can be assumed, that the direction of heat flow into the workpiece is perpendicular to the cutting edge. Drawing the direction of heat flow as a vector towards the inside of the tool, in multi-flank chip formation the directions of heat flow coming from tip and flank cutting edge intersect. The smaller the tool pressure angle and the tool corner radius are, the closer the intersection is at the cutting edge. Considering the higher heat transfer into the cutting edge at the tool corner (see Fig. 3), the tool corner is exposed to higher heat flow, compared to the rest of the tool. This corresponds to the behavior of the product of thermally affected volume and temperature, shown in Fig. 4.

At the tool corner the effect of tool profile geometry is dominant. However, flank and tip cutting edge are affected as well. This can be explained by an enlarged contact area, not only at the tool corner, but also at the parts of tip and flank cutting edge, that are close to the tool corner.
4.3. Mechanical Tool Load

In Fig. 5 the distribution of the equivalent von Mises stress $\sigma_v$ and the mechanically affected volume of the cutting edge $V_{S\sigma}$ are shown along the cutting edge. The mechanically affected volume is the volume, which is exposed to stress over $\sigma_v = 500$ MPa. The stress of $\sigma_v = 500$ MPa has been chosen to define a mechanical effect, it could also be replaced by a critical load level of the cutting material.

For the machining simulation, a rigid model of the tool is used for performance reasons. To calculate the stress distribution, the nodal contact forces calculated by the simulation are transferred to an elastic model of the tool. Hereby the stress state along the cutting edge can be calculated. Due to the non-symmetrical (L-shaped) load on the tool and the shape of the stick type blade, a three dimensional stress state consisting of bending and torsion of the tool occurs. To evaluate this stress state the equivalent von Mises stress is calculated:

$$\sigma_v = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}$$

$\sigma_v$ is the equivalent von Mises stress and $\sigma_1$ to $\sigma_3$ are the principal stress components. The results of this calculation are shown in Fig. 5. At the flank and the tip cutting edge an even stress distribution occurs. The stress level at the flank cutting edge is higher than at the tip cutting edge. The maximal stress occurs at the tool corner, which is up to 50 % higher than the average stress level at the flank cutting edge. The difference of mechanical affected volume $V_{S\sigma}$ of the tool corner radius and the tip cutting edge is over 100 %. To what extent the stress maximum at the tool corner results from the external load, from the cutting process or from the geometry of the tool is subject to research.

Both, a high affected volume and a high stress, favor a failure resulting from crack initiation and growth. Therefore, the product of elemental volume $V_i$ and elemental stress $\sigma_{vi}$ is calculated as key value $V_{\sigma}$:

$$V_{\sigma} = \sum_i (V_i \cdot \sigma_{vi}), \text{ if } \sigma_{vi} > 500 \text{ MPa}$$

The product of mechanically affected volume and stress corresponds to the mechanical energy in the cutting edge. Fig. 6 shows the product of mechanically affected volume and stress as it results from the variation of tool profile geometry. At tip and flank cutting edge, the product of mechanically affected volume and stress decreases with increasing tool pressure angle $\alpha$ and tool corner radius $r_c$. At the tool corner the product of mechanically affected volume and stress decreases for increasing tool pressure angle $\alpha$ and decreasing tool corner radius $r_c$. The average level of the product of mechanically affected volume and stress is significantly higher at the tool corner radius, compared to the rest of the tool.

Mechanical and thermal load show a similar influence of tool profile geometry at tip and flank cutting edge. Both can be explained by a widening of the contact area not only at the tool corner, but also at tip and flank cutting edge.

The mechanical load at the tool corner decreases with increasing tool pressure angle $\alpha$ and decreasing tool corner radius $r_c$. The length of the tool corner cutting edge decreases with increasing tool pressure angle $\alpha$ and decreasing tool corner radius $r_c$. The bigger the tool corner becomes, the more of machined material under-
goes the high deformation in the area of the tool corner. Therefore, the mechanical load at the tool corner increases.

5. Summary and Outlook

The machining simulation gives the opportunity to calculate the thermal and mechanical tool load directly from the simulation of the chip formation. The presented simulation is based on the tool geometry and process kinematics for cutting a typical automotive ring gear.

The tool corner is exposed to significantly higher mechanical and thermal load described by the cutting edge temperature and the equivalent von Mises stress. Furthermore the thermally and mechanically affected volume at the tool corner is significantly higher, than at the other parts of the cutting edge. The mechanical and thermal load level is similar to the results of investigations of gear hobbing and gear skiving as presented in [8, 9]. High load and high affected volume correspond to a high wear rate of the tool in the machining process and should therefore be avoided.

The variation of tool profile geometry shows a high influence on the thermal and mechanical load at the tool corner and a minor influence on the load at tip and flank cutting edge. The tool load decreases with increasing tool pressure angle. The influence of the tool corner radius is different for thermal and mechanical tool load. While the thermal load decreases towards large corner radius, the mechanical load increases with increasing tool corner radius.

The results of the machining simulation show, that the tool geometry influences the tool load. Wear trials will be conducted with chip geometry similar to the machining simulation. Both results will be combined into a wear prediction model to help the development of industrial manufacturing processes. As the simulation times are very long and as bevel gear cutting tools are specially designed for a specific gear set, an implementation of a tool wear model into the cutting simulation, as described in [10], is not suitable in this case. Therefore an analytical model has to be developed, which will be implemented into the analysis software for bevel gear cutting [11].

As the tools in bevel gear cutting are specially designed for each gearset, the presented and proposed investigations will help to design gears not only optimized for the running behavior, but also for a good manufacturing process. Furthermore the results can be transferred to other manufacturing processes in which multi flank chip formation occurs, like gear hobbing and shaping of spur gears, broaching of internal gears or milling of chain wheels.

Acknowledgements

The investigations described in this paper were conducted as a part of a project sponsored by Deutsche Forschungsgemeinschaft (DFG) to design a wear model to predict disproportionate tool corner wear.

References

[1] Winkel O. Steigerung der Leistungsfähigkeit von Hartmetallwerkzeugen durch eine optimierte Werkzeuggestaltung. Dissertation RWTH Aachen; 2005.
[2] Klein A. Spiral Bevel and Hypoid Gear Tooth Cutting with Coated Carbide Tools. Dissertation RWTH Aachen; 2007.
[3] Bouzakis K-D, Lili E, Michailidis N, Friderikos O. Manufacturing of cylindrical gears by generating cutting processes: A critical synthesis of analysis methods. CIRP Annals – Manufacturing Technology, Vol. 57: 676-696; 2008.
[4] Klocke F, Schröder T, Klein A. Tool Life and Productivity Improvement through Cutting Parameter Setting and Tool Design in High-Speed Bevel Gear Tooth Cutting. Gear Technology May/June 2006: 40-49; 2006.
[5] Johnson GR, Cook WH. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. Engineering Fracture Mechanics Vol. 21: 31-48; 1985.
[6] Uhlmann E, Schulenburg M, Zettier R. Finite Element Modeling and Cutting Simulation of Inconel 718. CIRP Annals – Manufacturing Technology, Vol. 56: 61-64; 2007.
[7] Klocke F, Gorgels C, Herzloff S. Tool Load during Multi-Flank Chip Formation. Advanced Materials Research Vol. 223: 525-534; 2011.
[8] Bouzakis K-D, Friderikos O, Mirisidis I, Tsiafs I. Determination of Chip Geometry and Cutting Forces in Gear Hobbing by a FEM-based Simulation of the Cutting Process. Proceedings of the 8th CIRP International Workshop on Modeling of Machining Operations. Chemnitz, Germany, 49-58; 2005.
[9] Schulze V, Köhlewein C, Autenrieth H. 3D-FEM Modeling of Gear Skiving to Investigate Kinematics and Chip Formation Mechanisms. Advanced Materials Research Vol. 223: 46-55; 2011.
[10] Attanasio A, Ceretti E, Rizzuti S, Umbrello D, Micari F. 3D finite element analysis of tool wear in machining. CIRP Annals – Manufacturing Technology, Vol. 57: 61-64; 2008.
[11] Brecher C, Weck M, Klocke F, Rütjes U. Analysis of a bevel gear cutting process by manufacturing simulation. Production Engineering, Vol. 12/2: 107-110; 2005.