MANUFACTURING SIMULATION OF BEVEL GEAR CUTTING
Simulation based Approach for Tool Wear Analysis

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Abstract: The transmission of torque or speed from one axle to a non parallel orthogonal axle is realised by bevel gears. Bevel gears are applied in helicopters, in marine, in rear axles of automotives and industrial drives. The manufacturing of bevel gears is generally performed in a complex CNC cutting process. Due to unpredictable tool wear in bevel gear cutting, unexpected production stops e.g. for tool changes occur. This leads to additional manufacturing costs. Currently it is not possible to analyse the bevel gear cutting process sufficiently, because of its complexity. Hence, the design of the cutting process happens iteratively in order to find the best process parameters for a high productivity and optimal tool wear. Thus, an exact knowledge of the tool wear behaviour is necessary. Hence, a manufacturing simulation for bevel gear cutting has been developed at WZL. This simulation enables a detailed analysis of the process and consequently of the tool wear. Within this report a new approach for the tool wear analysis is presented. Four different gear cutting processes have been analysed regarding tool wear. The introduced new characteristic value K_G, which is calculated by the simulation, has been compared to tool wear from cutting trials. All the presented investigations will be considered in a simulation-based tool life prediction model which will be developed within a project funded by the German Research Foundation (DFG).

1 INTRODUCTION

The transmission of torque or speed from one axle to a non parallel orthogonal axle is generally realised by bevel gears. Bevel gears are applied in helicopters, in marine, in rear axles of automotives and industrial drives as shown in figure 1.

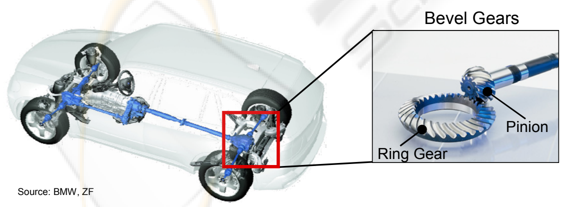

Figure 1: Exemplary automotive application of bevel gears.

The manufacturing of bevel gears is generally performed in a complex Computerized Numerical Control (CNC) cutting process.

Due to unpredictable tool wear and sudden failure of the cutting tools, unexpected production stops for tool changes occur and leads to a loss of productivity and hence to additional manufacturing costs. Thus, the productivity of the machining process depends significantly on the tool wear and tool life, see Chavoshi (2011). Currently it is not possible to analyse the bevel gear cutting process sufficiently, because of its complexity. Hence, the design of the cutting process happens iteratively in order to find the optimal process parameters. So an exact knowledge about the tool wear behaviour is necessary. These challenges and issues are presented in figure 2.

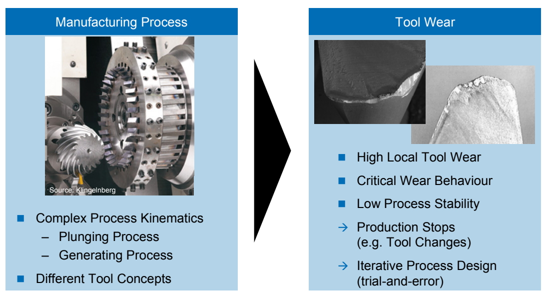

Figure 2: Challenges in bevel gear cutting.

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In order to provide a simulation tool for analysing and optimising the bevel gear cutting process a manufacturing simulation has been developed at WZL, as presented by Brecher (2010) and Rütjes (2010).

2 MODELLING AND SIMULATION METHOD

Within the manufacturing simulation a geometrical penetration is conducted as described by Klocke (2009), Rütjes (2010) and Brecher (2010). Before starting the calculation the workpiece, tool and kinematics have to be modelled.

At first the process kinematics are set. The kinematics of the bevel gear cutting process is presented in figure 3. Up to 6 CNC axis, like in the real cutting process, can be considered in the simulation. In figure 2 and table 1 the axis movements and positions of the bevel gear cutting machine are presented.

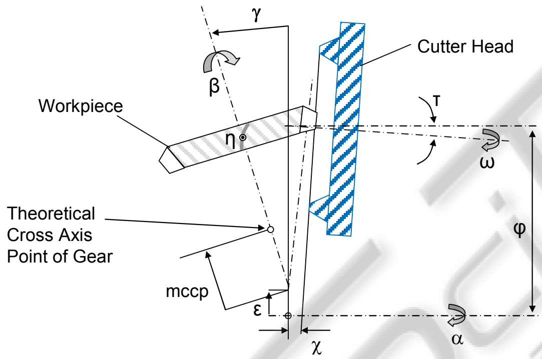

Figure 2: Scheme and axis movements of a bevel gear cutting machine.

Table 1: Axis movements of the cutting machine.

Mccp	Machine center to cross axis point
Cradle Angle	α
Modified Roll	β
Angular Motion	γ
Radial Motion	φ
Horizontal Motion	ε
Vertical Motion	η
Helical Motion	χ
Tool Rotation	omega

For example the axis movement for the depth position χ of the tool during the cutting process is calculated by formula 1:

$$\begin{aligned}\chi = a_\chi + b_\chi\cdot(\alpha-\alpha_m) + c_\chi\cdot(\alpha-\alpha_m)^2 \\ + d_\chi\cdot(\alpha-\alpha_m)^3 + e_\chi\cdot(\alpha-\alpha_m)^4 + f_\chi\cdot(\alpha-\alpha_m)^5 \\ + g_\chi\cdot(\alpha-\alpha_m)^6 + p_\chi\cdot(\omega-\omega_m) + q_\chi\cdot(\omega-\omega_m)^2 + \\ r_\chi\cdot(\omega-\omega_m)^3 + s_\chi\cdot(\omega-\omega_m)^4 + t_\chi\cdot(\omega-\omega_m)^5 + \\ u_\chi\cdot(\omega-\omega_m)^6\end{aligned} \quad (1)$$

Here a series expansion up to the sixth order is realised for the mean cradle angle α_m. The variables a_γ to u_γ represent the coefficients. E.g. the coefficient a_γ is a constant value therefore a positioning of the cutter, whereas b_γ is linear depending on the mean angle α_m which is time-dependent.

In the simulation the workpiece and the tool envelope are modelled as 3D clouds of scattered points. With these points a mesh is generated of triangles for the workpiece and the tool. The modelling of the workpiece can be described in three steps, see figure 4. At first the cross section of the gear flank is defined by 4 points.

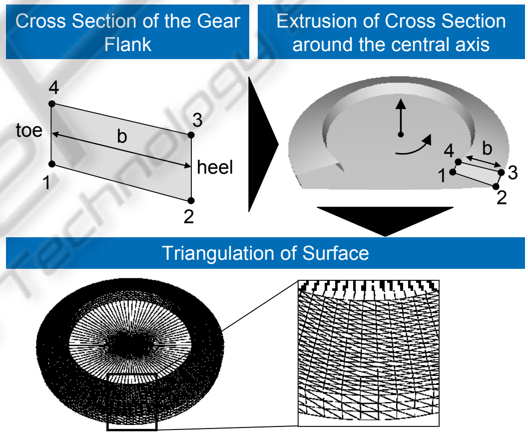

Figure 4: Modelling and triangulation of workpiece.

With the 4 points the gear width b and the toe and the heel of the bevel gear are defined. The heel is the face with the largest diameter respectively the largest distance to the central axis and the toe is the face with the smallest diameter. In order to get the blank body of the gear the cross section is rotated around the central axis. Finally this extruded body is getting triangulated as described by Rütjes (2010).

Finally the tool envelope is modelled by an extrusion of the tool profile depending on the process kinematics, see figure 5. Like the workpiece the tool is meshed by triangulation as well.

The data for workpiece, tool and process kinematics can be imported in the software from a ASCII file in the neutral data format. This data format is a common one in gear industry and developed by Klingelnberg (2008).

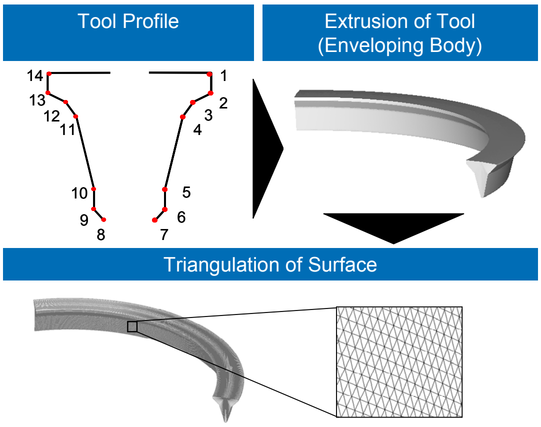

Figure 5: Modelling and triangulation of tool.

When the modelling is finished a penetration calculation can be conducted. During the geometrical penetration calculation the bodies of workpiece and tool envelope penetrate each other in compliance with the kinematics. The penetration is realised by ray-tracing as described by Akenine-Möller (2002). The calculated penetration volume can be interpreted as the undeformed chip geometry resulting from the cutting process, see figure 6. With this undeformed geometry different characteristic values can be calculated. It has to be mentioned that the penetration calculation is a geometrical calculation, i.e. that no plastic deformations are considered.

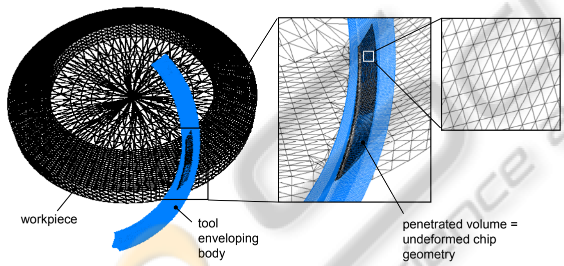

Figure 6: 3D penetration calculation of triangulated surfaces.

In order to accelerate the penetration calculation bounding-boxes and Binary Space Partitioning (BSP) Trees are used as depicted from Akenine-Möller (2002). A further approach to accelerate the simulation is the calculation of the penetration by General-purpose computing on graphics processing units (GPGPU) as published from Wienke (2011) where OpenCL, CUDA, PGI Accelerator are used in combination with graphics processing units (GPU) in order to increase the performance.

3 CALCULATION RESULTS

3.1 Characteristic Values for Process Analysis

The chip thickness h_{cu} and the working length l_e are characteristic values, besides the cutting forces, for description and analysing the bevel gear cutting process according to Klocke (2009) and Ruetjes (2010), see figure 7. The chip thickness represents the thickness of the undeformed chip at a certain point on the cutting edge. The working length represents the cutting path i.e. the contact length between the tool and the workpiece during the cutting. By means of these calculated characteristic values a first analysis of the tool wear behaviour and a process optimization is partly possible.

Current investigations from Klein (2007), Klocke (2009) and Rütjes (2010) show that also the characteristic values like the working rake angle γ_e and relief angle α_e have a significant influence on the tool wear. Especially the flank wear of the tool is not only influenced by the chip thickness h_{cu} and the working length l_e, but also by the geometry of the cutting edge. The cutter geometry, in turn, is determined by the rake and relief angle of the cutter. These angles are defined in the German Standards DIN 6580 (1985) and DIN 6581 (1985).

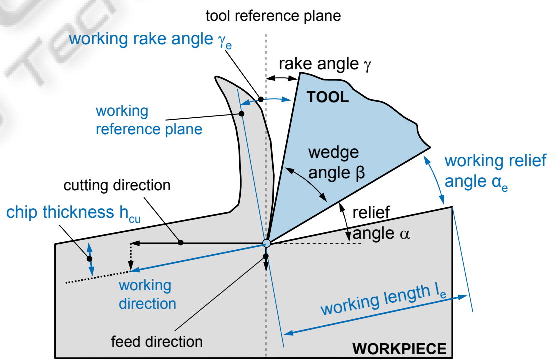

Figure 7: Calculable characteristic values.

As a conclusion it can be stated that there is partly the possibility to analyse the tool wear by means of the current characteristic values. But there is no approach for a prediction of tool wear in bevel gear cutting.

3.2 Gradient of Characteristic Values

In industrial application there are different tool concepts. One of the concepts are the alternating half profile blades. They are separated into outside and inside blades, see figure 8. Both blades are defined as a blade group. One blade group cuts the contour of one gap including gear root and flanks. The outside blade cuts the concave flank and the inside blade cuts the convex flank of the gear gap. From this typical two-flank chips are cut. The removed material on the flanks respectively the chip thickness $h_{cu,flank}$ depends inter alia on the chip thickness on the tip $h_{cu,tip}$ and the pressure angle δ_{OB} or δ_{IB} of the tools:

$$h_{cu,flank} = h_{cu,tip} \cdot \sin(\delta) \quad (2)$$

Besides the concept of alternating blades there is the concept of full profile blades, where one blade group consists of only one full profile blade. This type of blades has a theoretical rake angle of $\gamma = 0°$. The full profile blades cut both flanks (inside and outside) at the same time. Thus, typical three-flank chips are cut, as shown in figure 8 below right. The advantage of this concept is the increased productivity due to the possible increase of the number of blade groups in the cutter head.

The chip thickness h_{cu} is the most common characteristic value for the analysis of the cutting process according to Rütjes (2010). A higher pressure angle δ results in a higher chip thickness on the flank. The chip thickness itself depends on the feed velocity per blade group.

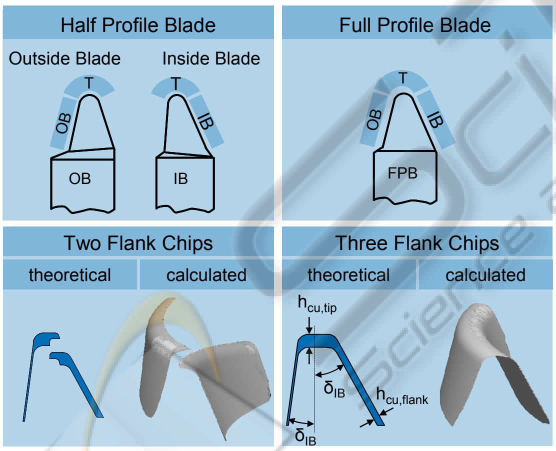

Figure 8: Cutter separation of blades.

Within the investigations of Klein (2007) regarding tool wear in bevel gear cutting, it became clear that especially the corner radius is critical regarding tool wear, e.g. chipping. This is caused by the multi-flank chip-formation at the corner radius. Here the material of the chip is compressed and squeezed, see figure 9. Thus, a simple analysis of the chip thickness in this area of the tool is not sufficient.

It becomes clear that the chip thickness h_{cu} is varying along the cutting edge l_s. Especially in the transition area of the corner radius between the flank (IB) and the tip (T) a gradient of the chip thickness $\Delta h_{cu}/\Delta l_s$ is visible.

The spatial compression of the chip is determined by the pressure angle of the tool as Klocke (2010) presented. In order to consider the compression and squeezing of the chip in the geometrical penetration calculation the gradient of the chip thickness can be used. The gradient represents the varying chip thickness along the cutting edge l_s. At the tool flank the gradient is zero due to the not varying chip thickness. This is plausible, because of the not existing compression of the chip material referred to the rake face respectively the working reference plane, see DIN 6581 (1985).

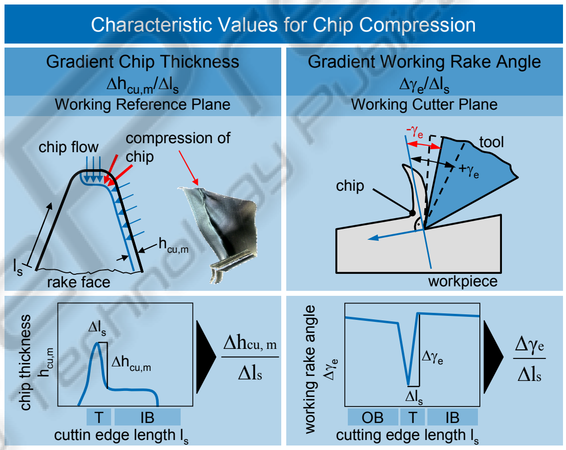

Figure 9: Gradient of chip thickness and rake angle.

A higher compression of the chip results in a higher thermal and mechanical load at the cutting edge and the risk of tool wear.

Due to the spatial chip formation and compression a consideration of only the working reference plane is not sufficient. Even the working cutter plane in which the chip flows orthogonal to the rake face has to be considered according to DIN 6581 (1985). Both planes take the working direction of the cutter into account. For the desription of the chip compression in the working cutter plane the gradient of working rake angle $\Delta\gamma_e/\Delta l_s$ can be used, see figure 10. This characteristic value represents the varying rake angle along the cutting edge and thus the varying chip formation and the chip compression along the cutting edge. A rapidly changing gradient in a small area of the cutting edge corresponds with a changing chip formation and a varying load during the cutting. This varying load has a negative influence on the tool wear behaviour. Hence, the gradient should have a minimum value.

Besides the aspect of chip compression and the so caused tool load further characteristic values for analysing the cutting process can be used. The entire working length l_e describes the contact length, which the cutter is in contact with the workpiece under consideration of the working direction, see figure 10. So the working length is an approach for the description of the thermal and mechanical load on the cutting edge. A higher working length results in a higher temperature respectively friction and thus in higher loads on the cutting edge.

Additionally the working relief angle α_e can be used for the analysis of the tool load. The working relief angle influences the thermal stress on the cutting edge. Thus the gradient $\Delta\alpha_e/\Delta l_s$ is a useful characteristic value for the alternating thermal stress along the cutting edge. The higher the gradient the higher the alternating thermal stresses on the relief face of the cutter. Hence, a minimum value of the gradient is desirable.

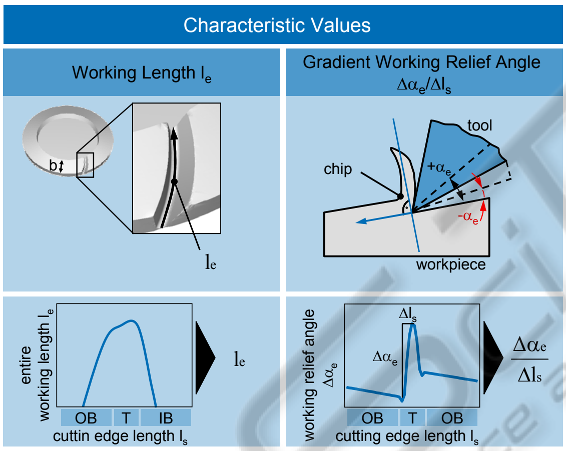

Figure 10: Working length and gradient of relief angle.

In order to integrate the presented characteristic values in only one value the new characteristic value K_G is introduced:

$$K_G = l_e \cdot \frac{\Delta h_{cu}}{\Delta l_s} \cdot \frac{\Delta \alpha_e}{\Delta l_s} \cdot \frac{\Delta \gamma_e}{\Delta l_s} \qquad (3)$$

A high K_G value results in a higher tool load and thus in higher tool wear. With the new characteristic value K_G a first qualitative comparison of different processes and so of the tool wear is possible. From this an optimization of the process is feasible and a first approach for a qualitative tool wear prediction model is realised.

In the future the characteristic value with the tool wear model has to be modified by weighting in order to enable a quantitative evaluation and prediction of the tool wear.

4 TOOL WEAR ANALYSIS

Bevel gear drives consists of a pinion and a ring gear. The pinion is positioned at the input driving side and the ring gear at the output side of the rear axle drive train. In general both parts are manufactured in a process using cutter heads which are equipped with stick-type blades. Here the face-milling process, as described by Klingelnberg (2008), is used for manufacturing. The plunging process is mostly used for the manufacturing of the ring gear whereas the generating process is used for pinion manufacturing.

Following different case-studies regarding tool wear of stick type blades in industrial application will be presented. Here the tool wear behaviour in plunging and generating process with different tool concepts is compared to the new characteristic value K_G. In this report the focus is on the discontinuous face milling process with tungsten carbide tools in dry cutting.

4.1 Tool Wear Analysis of Plunging Process

In figure 11 the tool wear of two full profile blades are presented. They are used for plunging process 1 and 2 for ring gear manufacturing. In process 1 a cutting velocity of $v_c = 200$ m/min and a feed ramp of $f_{BG} = 0.15 – 0.06$ mm per blade group was used. The cutter head with an outer diameter $D_a = 231$ mm. was equipped with 7 carbide tools. The characteristic value K_G was displayed in the diagram over the unrolled cutting edge length l_s which is separated into the outside blade (OB), the tip area (T) and the inside blade (IB). The maximum tool wear occures at the corner radius of the outside blade (OB) to the tip area (T). In the simulation the characteristic value K_G has its maximum at the same tool area. Additional tool wear occurs at the corner radius of the inside blade (IB) and the tip area (T). In this area the tool wear is less than at the other corner radius. The same tendencies are calculated in the simulation. Thus, the correlation of the calculated value K_G and the real tool wear is good. On the one hand the maximum tool wear can be located by K_G, on the other hand the lower tool wear at the inside blade can also be calculated.

In process 2, see figure 11 right, a cutting velocity of $v_c = 150$ m/min and a feed ramp of $f_{BG} = 0.16 – 0.10$ mm per blade group was chosen.

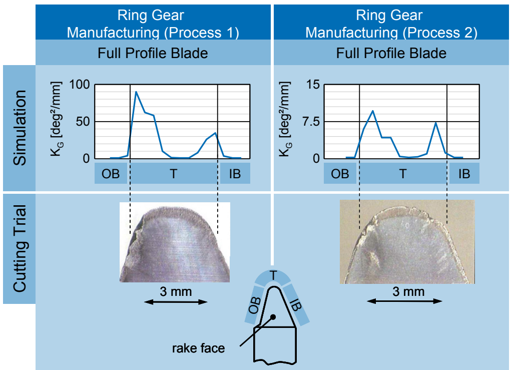

Figure 11: Tool wear analysis of full profile blades.

The cutter head with an outer diameter $D_a = 165$ mm was equipped with 14 carbide tools. Here the correlation between the tool wear from cutting trial and the simulation is also good. The maximum tool wear occurred at the corner radius of the outside blade (OB) and the tip (T). Even the tool wear in the corner radius of the inside blade (IB) can be determined by the simulation. In this example the tool wear is similar in both corner radii compared to process 1, where the amount of tool wear is very uneven. This tool wear behaviour is predictable with the simulation by means of the characteristic value K_G.

In addition to full profile blades there is the concept of alternating half profile blades. In order to show the good correlation between the cutting trial results and the simulation results the tool wear and the characteristic value K_G are presented in figure 12. Here (process 3) the focus is not only the localization of the maximum tool wear at the cutting edge but also the identification of the most critical blade regarding tool wear. The maximum value for K_G was calculated at the corner radius of the outside blade (OB). This correlates well with the occurred tool wear from the cutting trials. Even the lower tool wear of the inside blade (IB) was calculated correctly.

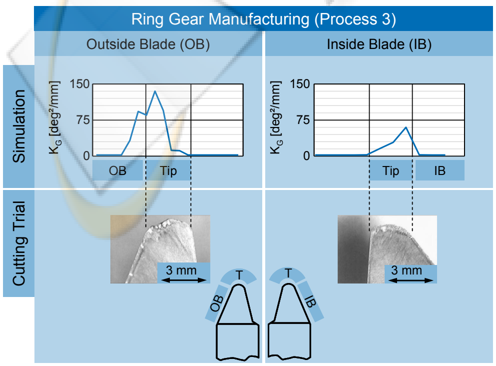

Figure 12: Tool wear analysis of half profile blades.

4.2 Tool Wear Analysis of Generating Process

Generally pinions are manufactured by a generating process. The tool and the workpiece are moving during the cutting depending on the process kinematics. In process 4 a feed ramp of $v_w = 8.72$ - 12.4 °/s and a cutting velocity of $v_c = 230$ m/min have been used. The outer diameter of the cutter head has been $D_a = 268$ mm and was equipped with 32 carbide full profile blades. In this process a generating from heel to toe is conducted. In figure 13 the occurred tool wear on the full profile blade is shown. It is visible that the maximum tool wear is located at the corner radius of the outside blade (OB). Here a chipping is observed. The tool wear at the inside blade is about 50% of the maximum wear.

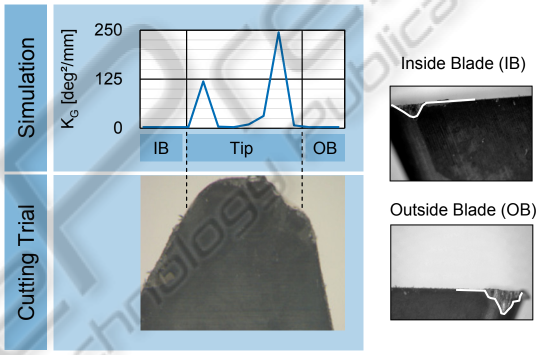

Figure 13: Tool Wear Analysis for Pinion Manufacturing with new characteristic value K_G.

A comparison of the real tool wear in generating process with the calculated characteristic value K_G is presented in figure 13, left. The calculation results correlate well with the tool wear from the cutting trials. Not only the location of the tool wear correlates well with the characteristic value K_G but also the amount of tool wear.

The presented results show that now it is possible to analyse the occurring tool wear with only one characteristic value. Thus it is not necessary any more to analyse the cutting process regarding tool wear by applying and analysing many different characteristic values, like the chip thickness or the working tool angles, which often do not correlate with the tool wear.

4.3 Case Study: Optimal Tool Concept

Within this report different tool concepts have been presented. Process 1 (full profile blades) and 3 (half profile blades) differ in the tool concept. But the manufactured geometry of the ring gear is the same.

Not only is the ring gear the same, but also the productivity. This means e.g. that the cutting and feed velocity is the same and the number of blade groups of the full profile concept is reduced to 50%. This reduction is possible, because the number of active cutting edges is the same for 14 half profile blades and 7 full profile blades.

Now it is interesting to know which concept is the best for the presented application. A comparison of process 1 (full profile blades) and process 3 (half profile blades) by means of the characteristic value K_G has been done, see figure 14.

The comparison of the calculated characteristic value K_G for the two processes shows that the maximum tool wear appears at the outside blade (OB) of the half profile blade concept. The value of K_G at the outside blade has approximately the double magnitude of the value of the full profile blade. The tool life of the full profile blade has been to L = 500 workpieces whereas the tool life of the half profile blades has been to L = 400 workpieces. Thus there is a good correlation between the characteristic value K_G and the tool wear but there is also a good correlation between K_G and the tool life of the different tool concepts.

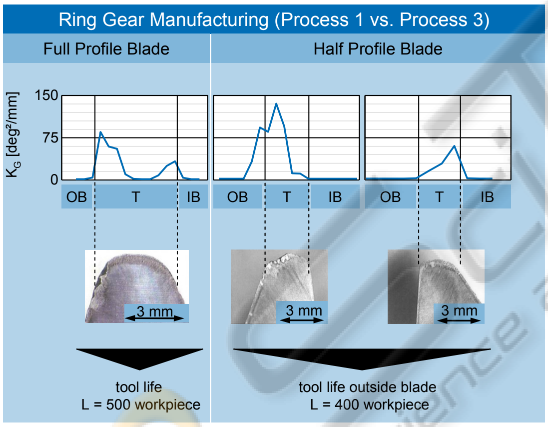

Figure 14: Comparison of different tool concepts

It can be stated that the manufacturing simulation including the calculation of the new characteristic value K_G allows for the first time analysing the bevel gear cutting process regarding the expected tool wear. In the future the quantitative prediction of tool life within a tool life model will be realised.

5 CONCLUSIONS

Within this report the manufacturing simulation for bevel gear cutting has been presented. At first the modelling of the workpiece and the tool are conducted. Under consideration of the process kinematics the simulation can be conducted. Within the simulation a 3D penetration calculation of workpiece and tool are carried out. From the penetrated volume the undeformed chip geometry can be calculated. With information from this penetrated volume different characteristic value like the chip thickness can be derived. With these values a first analysis of the cutting process regarding tool loads and wear is possible. Unfortunately, there is often no correlation between these values and the expected tool wear.

Currently a new characteristic value for the tool wear analysis is developed and implemented in the manufacturing simulation. This new value includes the gradient of different calculated characteristic values over the cutting edge like the gradient for the chip thickness $\Delta h_{cu}/\Delta l_s$. This gradient, for example, represents the compression and squeezing of the chip over the cutting edge. Thus, this value can be used for the analysis of the tool load at the cutting edge.

The comparison of the calculated new characteristic value and the tool wear from cutting trials show good correlations. The localization of tool wear as well as a qualitative comparison of different processes regarding the expected tool life is possible. E.g. the tool life behaviour of full profile blades and half profile blades correlates well with the simulation results.

In the future the new characteristic value has to be modified in order to quantify the expected tool life. This, for instance, can be applied for increasing the productivity of the cutting process and for optimising the process design regarding tool changes. Thus, the development of a tool life model for the bevel gear cutting process has to be realised. This tool life model has to be implemented in the manufacturing simulation.

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