Fatigue Fracture Investigation of Cemented Carbide Tools in Gear Hobbing, Part 1: FEM Modeling of Fly Hobbing and Computational Interpretation of Experimental Results

Gear hobbing is a highly utilized flexible manufacturing process for massive production of external gears. However, the complex geometry of cutting hobs is responsible for the almost exclusive utilization of high-speed steel (HSS) as cutting tool material. The limited cutting performance of HSS, even coated HSS, restricts the application of high cutting speeds and restricts the full exploitation of modern CNC hobbing machine tools. The application of cemented carbide tools was considered as a potential alternative to modern production requirements. In former investigations an experimental variation of gear hobbing, the so-called fly hobbing was applied, in order to specify the cutting performance of cemented carbide tools in gear production. These thorough experiments indicated that cracks, which were not expected, might occur in specific cutting cases, leading to the early failure of the entire cutting tool. In order to interpret computationally the reasons for these failures, an FEM simulation of the cutting process was developed, supported by advanced software tools able to determine the chip formation and the cutting forces during gear hobbing. The computational results explain sufficiently the failure mechanisms and they are quite in line with the experimental findings. The first part of this paper applies the verified parametric FEM model for various cutting cases, indicating the most risky cutting teeth with respect to their fatigue danger. In a step forward, the second part of the paper illustrates the effect of various technological and geometric parameters to the expected tool life. Therefore, the optimization of the cutting process is enabled, through the proper selection of cutting parameters, which can eliminate the failure danger of cemented carbide cutting tools, thus achieving satisfactory cost effectiveness. [DOI: 10.1115/1.1511172]

1 Introduction

The application of High Speed Cutting (HSC) was proved to be the most powerful manufacturing strategy, considering the increase in productivity and the achievement of the desired cost efficiency. However, in spite of the evolution of highly sophisticated CNC hobbing machining tools, the claim for HSC in gear manufacturing has not yet been attained. The main reason for this is the almost exclusive utilization of High-Speed Steel (HSS) as the hobbing cutting tool material, as a consequence of its complex geometry. The application of the coating technology in HSS hobs improved significantly the cutting performance of the tool. Nevertheless, the upper cutting speed limit of HSS, even coated, is up to 100–150 m/min, which is low for modern production requirements. In addition, dry cutting is not applicable for coated or uncoated HSS tools, which is not in agreement with the current world-wide environmental trends. Even in cases, where dry cutting with coated HSS tools is applied, the selection of the permitted cutting parameters restricts the efficiency, the exploitation and the cutting possibilities of the hobbing machine tools.

The most promising alternative material for cutting hobs comes from the evolution of cemented carbides, which are widely used in massively produced cutting inserts. Despite the complex geometry of hobbing tools, their construction by cemented carbides is nowadays possible. The increased cost of cemented carbides tools is quite amortized by the doubtless wear superiority when compared to HSS. However, the brittleness of hardmetals may cause fatigue failures in an early stage, due to the discontinuous chip production occurring in gear hobbing. Such phenomena were thoroughly detected in special cutting experiments [1,2]. These failures yield to a poor exploitation of the wear performance of cemented carbide tools, since their appearance makes the entire hobbing tool out of order. Brittle fatigue failures are normally caused by high stress levels occurring at various cutting tools and usually are consequences of wrong selection of cutting parameters.

This paper illustrates a quantitative analysis of the stresses course in hobbing tools, aiming at interpreting the early tool fatigue failures computationally. In order to accomplish this task, special well-proved software tools were used, which render the chip formation mechanisms and calculate accurately the cutting force components. Finally, the development of a parametric FEM simulation of the cutting teeth yields the description of the tools stress field, for various cutting cases and technological parameters. The stress results are compared to existing mechanical properties of the tool materials, explaining in this way quantitatively their fatigue expectations. As it will be presented, the computational results are in line with the experimental ones, proving the validity of the utilized analytical and FEM models. Furthermore, a
parametric analysis presented in the second part of this paper illustrates the effect of various cutting parameters on the prediction of the tool life, allowing the optimization of nearly every specific cutting case.

2 Chip Geometry and Cutting Force Components in Gear Hobbing

The principles of gear hobbing are presented in Fig. 1. This gear manufacturing method, where each gear tooth is produced by successive penetrations of the tool teeth in the individual Generating Positions (GP), is of complicated kinematics, and it is difficult to be modeled. In addition, based on the tool position during each penetration into a gear gap, a number of revolving positions are used to describe the corresponding generating position. A decisive factor that determines the tool behavior is the chip formation mechanism, which is also complicated, due to the complex cutting kinematics. Therefore, each chip type is responsible for certain cutting force components that contribute to the overall cutting loads. This behavior is described by the chip forms that are inserted in the bottom part of the same figure for various generating positions.

Mathematical models that quantify the chip formation for each individual generating position are nowadays well established and widely used [3–10]. These models are further used to predict the course of the cutting force components that exhibit a remarkable influence to the tool lifetime. The simulation of gear hobbing, with the aid of the FRSWEAR model, yields the chip dimensions for each revolution of every generating position, considering the manufacturing, geometrical and technological specification of the cutting tool, the workpiece and the cutting kinematics [11–13]. In this paper a new module for the FEM Simulation of gear hobbing has been added to FRSWEAR model. The structure of this new module FRSFEM is presented in Fig. 2. The above mentioned data are interactively inserted using a modern software environment, enabling the mathematical description of gear hobbing kinematics for specific cutting cases. The unreformed chip cross sections over the development of the cutting edge are then determined for every generating position. The cutting force components can be determined at this stage, as they depend on the undeformed chip dimensions and on experimentally determined constants [14–17]. Using these cutting forces, the critical stresses occurring in gear hobbing tools can be determined. Besides these outputs, the FRSWEAR model is able to predict the progress of the tool wear and to propose proper hob tangential feed amounts, in order to achieve an even wear progress over the successive cutting teeth [18]. The whole software has an open and modular structure, offering a user-friendly graphical interface with interactive communication for data input and results output.

Typical outputs of the FRSFEM model for a specific generating position of a certain manufacturing case are presented in Fig 3. On the left part of this figure the entire penetration of the specific cutting tooth into the examined generating position is shown. The model assumes special coordinate systems for the tool, which is rotating and moving following the tool paths, as shown in the figure. The discretization of this generating position in various revolving positions is evident in this graph. The diagram in the middle of the same figure illustrates the unreformed chip distribution over the development of the cutting edge for the successive revolving positions. The number of the revolving positions is also a variable parameter, depending on the required computational accuracy. The cutting force components calculated in the tool coordinate system are also presented in the right part of Fig. 3. These loads are overall values and they are composed of the elementary forces produced by the chip dimensions along the cutting edge. All these results are stored in proper files for every generating position that is required to form a gear gap.

Despite the fact that the complicated hobbing kinematics can be treated analytically with the aid of the FRSFEM model, the experimental procedure is laborious. The reason is that each cutting tooth cuts a certain generating position and penetrates to every workpiece teeth for each workpiece revolution and subsequently, owing to the axial feedrate repeats the same procedure. Therefore, some of the cutting teeth cut generating positions with increased chip dimensions and they are subjected to high cutting loads and wear. Due to this reason, besides the problem of poor tool utilization, the experimental study of this cutting process becomes even
more difficult. On the other hand, the complexity of tools with complete geometry makes their dismounting from the machine tool spindle and the subsequent evaluation of the experimental status difficult.

For those reasons, in order to increase the experimental efficiency and to facilitate the evaluation of the test results, advanced experiments with one cutting tooth, the so-called fly hobbing, were used. In this manufacturing technique, the cutting tool is replaced with a cylindrical holder, on which one cutting tooth can easily be mounted and dismounted. The tooth geometry corresponds strictly to the DIN 3972 regulations [19]. This approach accurately simulates gear hobbing with tool having one origin. A variation of this method with two cutting teeth simulates complete tools with two origins. The aim of this procedure is the separation of each generating position from the others and the ability to study comprehensively their effect on the tool wear failure initiation and progress. Consequently, each tool cuts every generating position and this is taken into account in the present analysis, as it will be further explained.

3 FEM Modeling and Mechanical Properties of the Cutting Teeth

In order to determine the stress field occurring in gear fabrication using gear hobbing, modern CAE calculations were performed. The reason for selecting FEM software to compute the stresses and strains is the complicated tool geometry and process kinematics, as well as the highly variable cutting force components. Taking into account the volume of the involved parameters, a parametric approach was used, in order to produce a flexible and reproducible model. The cutting teeth modeling strategy is presented in Fig. 4. The model was built in parametric terms, by

Data : m=5mm, d₁=125mm, z₁=1, b₁=0°, n₁=12, z₂=30, t₁=11mm, s₁=4mm/rev, Climb hobbing, 16MnCr5N
means of the APDL (Ansys Parametric Design Language) module of the ANSYS FEA® code. The entire geometry of the cutting tool is standardized by DIN 3792 norm, as a function of its module and diameter. Therefore, the modeling routine was written in terms of such parameters, considering also the tool clearance angles and thickness. Owing to the complex teeth geometry, a bottom up modeling strategy was utilized, as it is presented in the middle diagram of the same figure. Hereby keypoints, lines, areas and volumes were determined sequentially, forming in this way a 3-D solid model.

This model consists of six volumes, in order to perform a finer meshing near the tool-workpiece contact areas and a coarser net away from these regions. This way, the available computer resources are properly allocated, thus increasing the accuracy of the FEM calculations. The nodes density was also set as a variable parameter for optimization purposes. The optimized model consists of $2 \times 10^9$ eight-noded brick elements, performing in this way a mapped meshing (see the right part of Fig. 4). More elements in a denser mesh did not manage to increase the computational accuracy, whereas the CPU solution time was unacceptably increased. The cutting force components explained in Fig. 3 are properly distributed to the rake nodes, using a special APDL routine that takes into account the chip compression ratio, besides the geometric location of each node [20]. The model is pure elastic, so that it requires only the tool elasticity modulus and Poisson's constant.

The above-mentioned mechanical properties of the finite elements are also variables, allowing the applicability of the model for HSS and cemented carbide tools. In the present analysis the mechanical properties of ISO-P 40 cemented carbide were used in the model. Figure 5 summarizes the static and fatigue properties of this material. The left diagram of this figure exhibits the bulk hardness of cemented carbides versus their cobalt content [21]. Further calculations of the present analysis correspond to experimental data performed by using fine-grained P 40 cemented carbide. For this reason, the Vickers hardness for this material was found from this diagram to be 1430 HV. This value, besides the resistance of this material to plastic deformation, may be used to determine its static stress limit, considering that this value for brittle materials equals to the one third of their pyramid hardness [22,23]. On the other hand, the right diagram of the same figure illustrates the fatigue limits for cemented carbides, also as function of their cobalt content [21]. For fine-grained P 40 hardmetal the value for continuous endurance, i.e., $10^8$ loading cycles, equals to 83 N/mm$^2$.

The static and the fatigue stress limits can be used to elaborate the Woehler diagram for the specific material, as it is illustrated in the diagram in the middle of Fig. 5 [24]. Considering the purpose of the present analysis, the abscissa of this diagram was reasonably transformed from loading cycles to number of successive cuts. When the level of the occurring stresses is known, this diagram can be used to determine the number of loading cycles, i.e., the number of successive cuts, which a certain tool made of P 40 hardmetal is expected to develop a fatigue failure mechanism. This is also a great tool to examine the FEM model sufficiency. When the number of cuts required to cause tool failures in a
specific cutting case, is experimentally determined, the stress level that yields from the Woehler diagram must be in agreement to the FEM calculations.

Initially the model was used to calculate the cutting stresses for every generating position in cutting cases where experimental results were available. Taking into account that every generating position is subdivided in successive revolving positions, it was reasonable to solve the revolving position holding the bigger chip dimensions and consequently higher cutting loads. Figure 6 illustrates such a calculation for a certain generating position of a specific cutting case with climb and equi-directional hobbing, using a cutting tool with two starts. The upper left diagram shows the calculated revolving position of the examined generating position. The corresponding cutting forces on the tool rake face are applied in the model, and they are shown in the middle part of the same figure. It is obvious that the cutting force components are in agreement to the formation of the produced chip. The solution of the specific cutting case offers the deformation of the cutting tooth and it is shown in the bottom left part of the same figure. Finally, the von Mises stress distribution at the entire tool is presented in the right part of Fig. 6. As it was expected, the most fatigue risky region is the cutting tooth head, which fits to the experimental observations, as it will be explained. It is also obvious that the stress contours follow the distribution of the chip thickness and consequently the development of the cutting force components.

4 Correlation of Computational and Experimental Results

The FEM model was further used to calculate the course of the cutting stresses in every generating position of the cutting case presented before. The computational results are summarized in the left diagram of Fig. 7, which presents the maximum von Mises stresses in three endangered rake regions versus the successive generating positions. These regions are the transient regions between the leading and the trailing flanks to the tool head respectively and the middle of the tool head. The stress results indicate as the most hazardous region the trailing flank of the cutting tool. The variation of the stress course at this region is a result of the uneven chip dimensions per generation position and the collision between the chips produced at the flanks and the tool head respectively, a behavior which is experimentally and computationally detected [1]. As it was previously described, the experimental procedure was examined with the aid of fly hobbing with continuous axial feed. Therefore, the cutting tooth cuts in every generating position, and it is subjected successively every stress of the diagram. To evaluate the experimental results, a representative equivalent stress must be calculated, with respect to the fatigue theory for collective loads [24]. This stress level for the current cutting case corresponds to the horizontal line of the same diagram and equals to the 3100 N/mm².

The experimental behavior of cemented carbide tools of this cutting case are presented in the diagram at the right part of Fig. 7, which present the determination of the flank wear at the transient regions of leading and the trailing flanks versus the overall cutting width (OCL) of the work gear [1]. The experiment was terminated after the early failure of the cutting edge at the transient region, between the middle of head and the trailing flank, as it is illustrated by the micrograph of Fig. 7. The OCL can easily be turned into a number of successive cuts considering the transmission ratio, the cutting speed and the applied axial feed. For this case the OCL equals 85 mm that corresponds to 4050 successive cuts. The computational and experimental results are finally compared in the middle part of the same figure, using the Woehler diagram of the specific tool material. This diagram states that the achieved number of cuts corresponds to a representative equivalent stress of 2960 N/mm², whereas the computational one is about 4% higher. This difference is absolutely reasonable, considering expected arithmetical errors and other imponderable factors that cannot be included to the FEM model.

Similar results are presented in Fig. 8, which present the determination of the flank wear at the transient regions of hob versus the overall cutting width (OCL) of the work gear in a counter directional hobbing case [1]. For this case the OCL equals 710 mm that corresponds to 31950 successive cuts. The comparison between the computational and experimental results states that the achieved number of cuts corresponds to a representative equivalent stress of 2450 N/mm², whereas the computational one is about 6% higher.

The method was further applied for other cutting cases, which were also experimentally examined. Hereby, Fig. 9 illustrates typical chips for two variations of the same cutting case of climb hobbing, i.e., the equi- and the counter-directional one. Each part of this figure illustrates chip developments for two different representative generating positions, per cutting case. For each of these chip diagrams a smaller adjacent diagram illustrates the regions of the tool rake that is subjected to cutting load components.
for specific revolving positions. The relationship between these diagrams is obvious. For example in the upper left pair of diagrams, the examined revolving position produces a chip that starts from the upper part of the trailing flank, passes the tool head and terminates at the one third of the length of the leading flank. Consequently, the model is subjected to cutting load components at the same regions.

The FEM simulation of the cutting tools, which corresponds to the aforementioned cutting cases, yielded results that are inserted in the diagrams of Fig. 10. The left diagram illustrates the von Mises stress distribution for equi-directional climb hobbing versus the successive generating positions. The critical regions are the same presented in Fig. 7. The experimental procedure indicated the generating position from 2 to 9, which correspond to the shaded region of the same diagram, as the most endangered ones. The level of the computational stresses explains quantitatively this statement, since their level more or less leads to a poor fatigue expectation. Identical results are presented for the case of counter directional climb hobbing in the right part of the same figure. For this cutting case the most endangered generating positions are from 6 to 15, which also fit to the experimental results [1]. The comparison between the experimental and the computational results presented, indicated that the developed model produced an adequate simulation of the hob cutting teeth. The evaluation of the calculated stress field managed to interpret the early fatigue failures of cemented carbide hob teeth computationally. The adequacy of the FEM modeling strategy was proved also by experimental results. The validation of the simulation, allows us to expand the calculations in further cutting cases without the need for additional laborious experimental work. In this way the tool lifetime can be predicted for every possible variation of tool-workpiece combinations, cutting materials and cutting conditions. For this purpose the second part of this paper presents a parametric analysis of such interactions, which may contribute to the op-

Fig. 7 Maximum Mises stresses at individual generating positions in fly climb and equi-directional hobbing and fatigue prediction of cutting tooth

Fig. 8 Fatigue prediction of cutting tooth in fly climb and counter-directional hobbing

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timization of every cutting condition. In this way, the doubtless wear performance of cemented carbide tools can be exploited, by avoiding cutting conditions that lead to unexpected early tool fatigue failures.

5 Conclusion

The experimentally detected early fatigue failures of cemented carbide hobs were examined in this work, with the aid of analytical and numerical software tools. The application of the FRSFEM model enabled the determination of chips and cutting force components for every generating position per cutting case. The FEM simulation of the hob tooth geometry produced a reliable solid model, able to calculate precisely the stress strain field occurring in gear hobbing with hardmetal tools. The model was used to interpret experimental results of such tools. Therefore, through the calculated stresses and the mechanical properties of the tool ma-

Fig. 9 Chips and cutting forces distribution at equi- and counter directional climb hobbing

Fig. 10 Critical generating positions for cutting tool cracks in climb and equi-directional hobbing

m=3.82mm, d₁=147mm, n₁=6, b₂=30°(le), z₂=24, t=9.7mm, sₐ=4mm/rev, Climb hobbing
Hardmetal ISO-P40 (US code C5), 16MnCr5 G
terial, we can estimate the expected tool life and the cutting conditions which will avoid the early fracture. The model allows us to create a database of optimal cutting conditions for a wide variety of tool-workpiece combinations.

Nomenclature

- **GP** = Generating Position
- **RP** = Revolving Position
- **HV** = Vickers Pyramid Hardness [daN/mm²]
- **TRS** = Traverse Rapture Strength
- **FEM** = Finite Elements Method
- **TF** = Cutting tooth Trailig Flank
- **LF** = Cutting tooth Leading Flank
- **H** = Cutting tooth Head
- **OCL** = Overall Cutting Length [mm]
- **s_A** = Axial feed [mm/rev]
- **t** = Cutting depth [mm]
- **v** = Cutting speed [m/min]
- **m** = Work gear and hob tool module [mm]
- **n_i** = Number of hob columns
- **z_i** = Number of hob origins
- **z_s** = Number of work gear teeth
- **d_2** = External work gear diameter [mm]
- **b_2** = Gear helix angle [°]
- **F_{ij}** = Force component at direction i of coordinate system j [N]
- **S_{eqv}** = Von Mises Equivalent Stress [N/mm²]
- **S_Y** = Yield Stress [N/mm²]

References