Continuous Generating Gear Grinding

A report on new possibilities in the process design and analysis of continuous generating gear grinding.

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IN ORDER TO IMPROVE LOAD CARRYING CAPACITY AND NOISE BEHAVIOR, CASE HARDENED GEARS USUALLY ARE HARD FINISHED [1]. ONE POSSIBLE PROCESS FOR THE HARD FINISHING OF GEARS IS THE GENERATING GEAR GRINDING, WHICH HAS REPLACED OTHER GRINDING PROCESSES IN BATCH PRODUCTION OF SMALL AND MIDDLE GEARS DUE TO THE HIGH PROCESS EFFICIENCY.

DESPITE THE WIDE INDUSTRIAL APPLICATION OF THIS PROCESS, ONLY A FEW SCIENTIFIC ANALYSES EXIST. THE SCIENCE-BASED ANALYSIS OF THE GENERATING GEAR GRINDING NEEDS A HIGH AMOUNT OF TIME AND EFFORT. ONE REASON IS THE COMPLEX CONTACT CONDITIONS BETWEEN THE TOOL AND GEAR FLANK, WHICH CHANGE CONTINUOUSLY DURING THE GRINDING PROCESS. THIS COMPLICATES THE APPLICATION OF THE EXISTING KNOWLEDGE OF OTHER GRINDING PROCESSES ON GENERATING GEAR GRINDING. THE COMPLEX CONTACT CONDITIONS LEAD TO A HIGH PROCESS DYNAMIC THAT IS A CHALLENGE FOR THE DESIGN OF MACHINE TOOLS, CONTROL ENGINEERING AND PROCESS DESIGN.

The knowledge of cutting forces and their time-dependent behavior is necessary to describe and optimize the process dynamic. However, the determination of the cutting forces during generating gear grinding is not readily possible. Until now, no scientific analysis exists which systematically describes the influence of the process parameters on the cutting forces during generating gear grinding.

STATE OF THE ART
Generating Gear Grinding

One of the most efficient processes for the hard finishing of gears in batch production of external gears and gear shafts is the continuous generating gear grinding. The generating gear grinding is used for the hard finishing of gears with a module of \( m_a = 0.5 \text{ mm} \) to \( m_a = 10 \text{ mm} \) [2], [3]. By the application of new machine tools the process can be used for grinding of large module gears (up to \( d_a = 1.000 \text{ mm} \) [4].

The cylindrical grinding worm, whose profile equates a rack profile in a transverse section, hobs with an external gear (fig. 1, left). The involute is generated by continuous rolling motion of grinding worm and workpiece by the profile cuts method [3], [5]. Profile cuts method in the generating processes means the profile form is generated by a finite number of profiling cuts. Due to the closed grinding worm no generating cut deviations, known from the gear hobbing, occur in generating gear grinding.

In comparison with other gear grinding processes, the stock removal rate in generating gear grinding is very high. In most cases it is only limited by the reachable gear quality [3]. In generating gear grinding, multiple points of the grinding worm are always in contact. The number of contact points change continuously during the tool rotation (fig. 1, right).

The contacts on the right and on the left tool flank are equal by an even
number of contact points. This leads to a consistent distribution of forces. By an uneven number of contact points, the distribution of forces will also be uneven. This leads to an inconsistent distribution of the cutting forces. In the example in fig. 1 on the line of contact of the left tool flanks the forces are split in two contact points. On the right tool flank the cutting force is increased, because only one point has contact. This fact can lead to a higher stock removal at this contact point and to a higher excitation. The consequence can be the appearance of profile form deviations that reduce the reachable gear quality. Scientific publications of Meijboom [9] and Türich [10] describe this relation theoretical. Publications, e.g., in [6, 7, 8], and the existing doctoral thesis of Meijboom [9], Türich [10] and Stimpel [11] show the influence of several parameter on the process results, but several technological correlations have not been analyzed or verified in trials yet.

Current Challenges
Due to limited scientific studies the technology users, grinding tool suppliers, and machine tool manufacturers face two main challenges. On the one hand the process design and optimization is based on the know-how of the process user. In cases where no sufficient experience (e.g., new gear geometry, no grinding tools) exists, cost-intensive trials have to be carried out to find a favored and robust process design. For this purpose several iterations are usually necessary. In order to reduce the number of needed iteration loops, the technological connections must be analyzed in detail in the future.

On the other hand the increasing demand of high volume of wind turbine gears leads to a higher demand of large module gears [12]. Until today most of these gears were manufactured by profile gear grinding. However, in recent years the increasing demand of large module gears led to the usage of the more productive generating gear grinding [4, 12]. The scaling of existing processes to large module gears is not easily possible. First of all, by the high workpiece weights and the higher mass inertia, the process dynamic becomes one of the greatest challenges. Therefore, knowledge of the process forces is important for process and machine tool design. An approach to meet these existing
challenges will be given by the research activities introduced in this paper.

**RESEARCH OBJECTIVE AND APPROACH**

The global research objective for the generating gear grinding at the WZL is the increase of process efficiency and process reliability in generating gear grinding by description of the technological correlations and cutting forces in a holistic process model. For this purpose several methods for process analysis of generating gear grinding have been developed and will be introduced in this report.

Up to now a verification of those techniques with generating gear grinding process is missing. So the aim of this report is to determine the existing cutting forces for a sample gear in trials for the first time and to analyze their connection to the process parameters and the appearance of profile form deviations. Simultaneously, for the sample gear the same process design will be analyzed using a manufacturing simulation. The results of the grinding trials, the analogy trials, and the simulation will be compared. With these results verification for the sample gear will be possible. This report provides information about the technological interactions in generating gear grinding.

**METHODS FOR THE PROCESS ANALYSIS**

In the following section the new research methods for the process analysis will be described and some examples for the results of those methods will be shown. The methods for the investigation of the generating gear grinding are a manufacturing simulation and an analogy trial for the generating gear grinding.

*Simulation of Generating Gear Grinding*

The remarks given in the state of the art show that the process results are influenced by a multitude of parameters. The exact connections and interactions are not described in detail until now. This complicates the process optimization and design of generating gear grinding. An investigation of the process with a manufacturing simulation can be an advantage to reduce the high effort of time and workpieces for the process optimization.

For the analysis of generating gear grinding an existing, verified manufacturing simulation (SPARTApro) for gear hobbing was modified. Gear hobbing and generating gear grinding are based on the same kinematics. By an increased number of normal sections, a continuous grinding worm can be approximated (fig. 2). By a comparison between the simulated key values and analytical calculated values, the necessary number of sections can be determined for the simulation of the generating gear grinding. Among other things, this number depends on the workpiece and tool geometry. For one example, the effect of the number of normal sections on the key values and the calculation time is shown in fig. 2.
Figure 3 shows some selected results of the manufacturing simulation for one sample gear. It shows two key values plotted graphically for the tool profile, and two key values for the evaluation of the process dynamic plotted for the tool rotation angle. The volume of penetration $V_{\text{D,Sum}}$ describes the accumulated chip volume along the tool profile. This key value enables an estimation of the tool load and wear behavior along the profile. In this example the load on both tool flanks is similar. However, the tool root flank cuts a higher chip volume than the tool tip flank. This uneven wear of the tool profile can lead to profile angle deviations at the workpiece because of the different local tool load.

The cutting depth $h_{\text{c,Max}}$ describes the maximum penetration at one point on the tool profile during the manufacturing. The analysis of this key value shows a different cutting depth at the tool tip and tool root flank. This shows the different chip formation mechanisms. On the right side of fig. 3, two selected key values to rate the process dynamic are shown. Usually a high correlation between penetration volume and process forces can be found [2]. Therefore, the penetration volume can provide a first indication for the process dynamic.

The volume of penetration $V_{\text{D}}$ describes the accumulated volume of the penetration between tool and workpiece plotted against the tool rotation angle. In this example the volume of penetration is very homogeneous. This can be an indication for a low process dynamic and a high machinability at these parameter settings.

A further indication on the excitation can be provided by the analysis of the difference of the penetration $\Delta V_{\text{D}}$. This key value describes the difference of the penetration between the left and the right tool flanks and is plotted for the tool rotation angle. The graph shows a homogeneous run for this example. So far a comparison of the theoretical results of the manufacturing simulation is missing. Therefore, generating gear grinding trials will be carried out.

**Analogy Trial Generating Gear Grinding**

In generating gear grinding the contact conditions between the grinding worm and the gear are complex. On one hand the penetration changes continuously and on the other hand the number of contact points between the gear and the tool is variable during one tool rotation. In order to investigate generating gear grind-
ing without the influence of these contact conditions a geometrical and kinematical model for the generating gear grinding is designed at the WZL: the analogy trial for generating gear grinding.

The principle of the analogy trial for generating gear grinding is shown in fig. 4. In the analogy trial the geometry and the kinematics have to be adapted to the situation in the generating gear grinding process.

In one point the involute can be approximated by a circle with the local radius of curvature $\rho$ \[13\]. For the analogy trials the contact conditions at the pitch circle $d$ are approximated. The influence of the curvature along profile height can be unintended for gears with a high number of teeth. The diameter of the workpiece in the analogy trial $d_{\text{Wst}}$ equals the double radius of curvature at the pitch circle. This diameter depends on the number of teeth $z$, the module $m_n$, the helix angle $\beta$ and the pressure angle $\alpha_n$. The rack profile of the grinding worm can be approximated in the investigated contact point by a face wheel with a conic working surface.

Beside the workpiece and the tool geometry, the chip geometry in the analogy trial has to be comparable to the chip geometry in generating gear grinding. Therefore the cutting length $l_{\text{cut}}$ and the chip thickness $h_{\text{cut}}$ as well as the stock removal rate $Q'_{\text{W}}$ have to be equal.

Furthermore, the kinematics of the chip formation and the velocities must be fitted to the situation in generating gear grinding. During chip formation the lateral sliding speed, the axial feed speed $v_{\text{ax}}$, and the cutting speed $v_c$ interfere with each other. The cutting speed in generating gear grinding and the analogy trial are the same. The lateral sliding speed $v_{\text{sl}}$ can be calculated by the rotational speed $n_{\text{Wst}}$ of the workpiece and the synchronization requirement. The axial feed speed $v_{\text{ax}}$ can be adjusted according to the generating gear grinding process as the product of rotational speed $n_{\text{Wst}}$ and axial feed $f_a$.

In the analogy trials the cutting force can be determined by a dynamometer that is integrated in the flux of forces. Furthermore, the surface structure changes and the form deviations of the analogy workpiece can be analyzed and can be used to determine the tool wear behavior and performance. For
further information a full description of the analogy trial design can be found in [8].

In previous investigations using the analogy trial the influence of the workpiece geometry, respectively the radius of curvature and of the process parameters were analyzed. Based on the results of the measured cutting forces a first calculation model for the cutting forces in generating gear grinding was developed. Using a biquadratical ansatz function the run of the cutting forces can be calculated with a few restrictions especially in the area of exponential wear behavior (fig. 5).

A correlation between the measured forces in the analogy trial and the cutting force in generating gear grinding is missing. To verify the analogy trials generating gear grinding trial have to be carried out. The results will be shown in this paper.

GENERATING GEAR GRINDING TRIALS

For the measurement of the cutting forces in generating gear grinding, the verification of the analogy trials and a comparison between the theoretical analyses with SPARTApro generating gear grinding trial have been carried out. The experimental design and approach as well as the results will be described in the following section.

Experimental Design and Approach

In the first part of this section the experimental design and approach will be described in detail. Therefore, the workpiece and tool geometry as well as the machine tool are introduced. Furthermore, the experimental approach and the design of experiments are described.

Machine Tool, Workpiece, and Tool Geometry

The trials are carried out with a spur gear with a number of teeth of \( z = 22 \) and a normal module of \( m_n = 5.96 \, \text{mm} \). The material is 20MoCr5. The gears are case hardened with a surface hardness of 61 HRC and a case hardening depth of \( \text{CHD}_{500HV} = 1.4 \, \text{mm} \). Further information concerning the gear geometry is shown in fig. 6.

The generating and profile gear grinding machine LCS150 from Liebherr-Verzahntechnik, which is available at the WZL, is used for the trials. As a tool a grinding worm made from corundum with a grain size F80 (average grain diameter 185 mm) from Burka-Kosmos is used.

The grinding worm is dressed by a flank dresser and a fixed tip dresser. The dressing process will not be analyzed in the trials. Therefore, the dressing parameters, which can be taken from fig. 6 are not modified during the trials.

Experimental Procedure and Design of Experiments

For the force measurement in the generating gear grinding process a force measurement device has to be integrated in the machine tool. Therefore, a rotating dynamometer from Kistler is integrated in the flux of forces.

The dynamometer is mounted on the grinding worm arbor at the main bearing side. In order to integrate the dynamometer the grinding worm is half as long as usual (\( L_0 = 100 \, \text{mm} \)). With the dynamometer forces in three direction of space can be measured. Furthermore, the torque along the grinding wheel axis can be measured. The complete experimental setup can be seen in fig. 7. The workpiece is clamped by a hydrostatic extension mandrel and is additionally centered by an
The anvil block. The anvil block is not shown in the figure.

The grinding worm has a reference profile with a module of \( m_n = 5.96 \) mm and a tool pressure angle of \( \alpha_n = 20° \). All trials are carried out with a number of starts of \( z_0 = 1 \) and \( z_0 = 3 \).

For the trials the axial feed \( f_a \), the cutting speed \( \nu_c \) and the stock \( \Delta s \) are varied. In order to determine the interactions between all process parameters are varied with the full factorial method. The axial feed ranges from \( f_a = 0.1 \) mm to \( f_a = 0.5 \) mm. The cutting speed ranges from \( \nu_c = 35 \) m/s to \( \nu_c = 60 \) m/s. A higher cutting speed cannot be adjusted due to safety reason of the tool.

Three different stocks are analyzed: \( \Delta s = 0.08 \) mm, \( \Delta s = 0.10 \) mm and \( \Delta s = 0.12 \) mm.

The trial with an axial feed of \( f_a = 0.1 \) mm, a cutting speed of \( \nu_c = 60 \) m/s and a stock of \( \Delta s = 0.08 \) mm is the reference point. At the reference point additionally the tool pressure angle is varied with \( \alpha_n = 19.5° \) and \( \alpha_n = 21.5° \).

To reduce the influence of deviations caused by the heat treatment all trials are carried out on pre-ground gears. Therefore, a pre-cautious set of process parameter (low axial feed and in-feed) was chosen to remove the deviations and ensure a constant gear quality on all gears.

After this grinding step all pre-ground gears are measured geometrically to check the gear quality. A gear quality of class Q6 and better according to DIN 3960 [13] could be achieved. Furthermore, all gears are tested by nital etching to ensure that no grinding burn occurred due to the pre-grinding process. A thermal damage of the external zone on the gear flank could not be detected after the pre-grinding.

The reference point is used to analyze the influence of the dynamometer in the flux of forces on the process. Hence, the trial at the reference point is repeated with and without the dynamometer. The influence is evaluated via the measured power and the achieved gear quality. Before the trial the grinding worm is always dressed to avoid an influence of the tool wear on the force measurements. All trials are carried out without shifting.

Analysis of the Cutting Force Measurements

In the second part of this section the meth-
od for the cutting force analysis, the influence of the dynamometer on the process and the results of the trials will be described in detail.

**Approach for the Analysis of Cutting Force Measurements**

The cutting forces are measured by the dynamometer. Due to the rotation of the grinding worm and its shaft the measured forces are available in a rotating coordinate system. They have to be transformed into a non-rotating coordinate system. This new coordinate system equates to the machine tool coordinate system.

Afterward the forces are transformed in forces known from other grinding processes: the radial force $F_r$, the tangential force $F_t$ and a resulting accumulated force $F_{xy}$. Other forces like the normal force $F_n$ or axial force $F_a$ have not been analyzed yet and will not be examined in this paper. To ensure that the process results and the machine tool structure are not influenced by the dynamometer at the reference point a trial with and without dynamometer is carried out. The result of this comparison is shown in fig. 8.

The effective power $P_{\text{Spindel}}$ is nearly the same with and without dynamometer. As the forces are normally proportional to the power, the assumption can be made that the forces and therefore the process is not influenced by the dynamometer. Furthermore, the comparison of the achieved gear quality (profile measurement) measured after the trials with and without dynamometer shows no significant difference. The required gear quality can be achieved in both cases.

**Variation of Process Parameters**

**Axial Feed**

The penetration between workpiece and grinding worm increases with an increasing axial feed $f_a$ with a constant cutting speed. Thereby, the cutting length increases. The influence of an increasing axial feed on the cutting forces and the process result is shown in fig. 9.

The force in radial direction $F_r$ and the resulting force $F_{xy}$ increase with an increasing axial feed. Also, the value of the tangential force $F_t$ increases absolute. Furthermore, an increasing power at the grinding spindle $P_c$ can be detected. The increasing forces lead to an increasing tool wear which can be detected by an increasing profile form deviation. In spite of this the required gear quality can still be achieved. Due to the constant dressing parameters, the surface roughness is not influenced by the axial feed.

**Cutting Speed**

The productivity of the generating gear grinding can be increased significantly by an increasing cutting speed. Due to the higher workpiece revolutions per grinding worm rotation, a higher chip volume is chipped in the same time. The influence of an increasing cutting speed on the cutting forces is shown in fig. 10.

An analysis shows the effect for two different axial feeds. For both axial feeds the resulting force $F_{xy}$ and the tangential force $F_t$ decrease. The force in radial direction is constant. The effect can be explained by the strongly increasing energy stream. The power at the grinding
spindle increases because of the higher cutting speed. The higher power leads to a higher energy stream into the workpiece [2]. Both the gear quality and the surface roughness are not influenced by the increasing cutting speed.

**Tool Pressure Angle**

The flank sequence is an often-used approach to explain the appearance of a characteristic profile form deviation [9, 10]. A flank sequence with frequently changing contacts, mostly the change between an even and an uneven number of contacts, is often described as a reason for these deviations. The contact sequence can primarily be influenced by the tool pressure angle. The influence of the tool pressure angle on the process forces and the resulting geometry will be investigated.

First, for the sample gear the flank sequence is analyzed to choose the tool pressure angles. In fig. 11 the results of this analysis is shown for a changing tool pressure angle. For the tool pressure angle $\alpha_{an0} = 20^\circ = \alpha_n$, a flank sequence of 4-3-2-3-4 can be seen.

This flank sequence is not ideal because of the frequent changes between an uneven and an even number of contacts [10]. With a tool pressure angle of $\alpha_{an0} = 19,5^\circ$, a flank sequence can be achieved with only even number of contacts. The flank sequence changes between two and four contact points (4-2-4).

With a tool pressure angle of $\alpha_{an0} = 21,5^\circ$, a more homogeneous flank sequence can be adjusted. The flank sequence changes between four and three point of contact. The flank sequence is not ideal concerning the existing scientific thesis [9, 10]. The influence of the different flank sequences on the cutting forces have not been investigated yet. The analysis of the cutting forces in fig. 12 shows a significant influence of the tool pressure angle on the penetration volume between workpiece and grinding worm and the cutting forces.

The cutting forces in the $xy$-plane $F_{xy}$ decrease about 25 percent, if the flank sequence changes from 4-3-2-3-4 ($\alpha_{an0} = 20^\circ$) to 4-2-4 ($\alpha_{an0} = 19,5^\circ$) or 4-3-4 ($\alpha_{an0} = 21,5^\circ$). This effect can also be seen for the tangential force $F_t$ and the radial force $F_r$. That the average of the cutting forces with a flank sequence of 4-3-4 are the lowest contradicts existing theories in [10]. This shows the need for a better analysis of the cutting processes for example by a manufacturing simulation. The power $P_c$ changes proportionally with the cutting forces. In spite of that the profile form $f_{pp}$, the profile angle deviations $f_{\alpha_n}$ and the surface topography is not influenced significantly by the change of the tool pressure angle.

**VERIFICATION OF SIMULATION AND ANALOGY TRIALS**

In this last section a first verification of the introduced research methods will be made. Therefore, a comparison between simulation results and the results of the generating gear grinding trials as well as a comparison
between the analogy trials and the generating gear grinding trials will be made.

**Comparison Between Simulation and Grinding Results**

A comparison between the simulation and the generating gear grinding trial can be seen in fig. 13. It shows a comparison between the tool load and the profile deviations. The diagrams on both sides show a gradient in the accumulated chip volume between the tool tip and root. This means the tool root that grinds the gear tip has a higher tool load than the tool root. This leads to higher tool wear at the tool root. This effect can be detected by a profile measurement of the gear, which is shown in the middle of fig. 13. Two parts are ground at the same shifting position. The wear of the grinding worm leads to a high profile angle deviation because of the different tool load. This load distribution was predicted with the manufacturing simulation for the generating gear grinding. Therefore, the manufacturing simulation can be used to predict for example tool loads.

**Comparison of the Analogy and the Generating Gear Grinding Trials**

The force measurements in the analogy trials and the generating gear grinding trials have been compared in a few measurements. These first results show that the average force and the developing values are nearly the same. However the verification is not completed yet.

**SUMMARY AND OUTLOOK**

The variable contact conditions during generating gear grinding result in an exaggerated dynamic in the process. This is a challenge for the machine tool development, control engineering, and process design. On one hand the knowledge of the expected manufacturing forces and their time course can be used to describe the process dynamic. On the other hand they can be used to optimize the process design.

The first aim of this report was to introduce the research methods that can be used to analyze the generating gear grinding process in more detail. Therefore, a manufacturing simulation and an analogy trial have been introduced. The second aim of this report was the determination of cutting forces in generating gear grinding depending on the process parameters. By a dynamometer, which was integrated in the flux of forces, cutting forces in three directions of space are measured and analyzed. For the evaluation of the process result the workpiece geometry and the surface roughness were measured.

The analysis of the cutting force measurements showed that the cutting forces are mainly depending on the axial feed and the cutting speed. The surface roughness and the workpiece geometry are not significantly influenced by the process parameters. Furthermore, the results of the generating gear grinding trial were used to verify the introduced research methods. A first verification of the manufacturing simulation and the analogy trials was made. The results of this report were used to verify the analogy trial for the generating gear grinding in more detail in the future.

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