Potentials for Process Monitoring in Bevel Gear Grinding

Thomas Bergs, Christoph Löpenhaus and Mareike Solf

Manufacturing of Bevel Gears

Manufacturing of bevel gears commonly takes place in one of two possible process chains, as can be seen in Figure 1. In both process chains, the machining of the gear body follows the production of the blank. The soft machining of bevel gears can be carried out either in a discontinuous face milling or a continuous face hobbing process. After soft machining, the bevel gear is subjected to a heat treatment which is usually followed by hard finishing.

Since the macro geometry of bevel gears is directly dependent on the manufacturing process, there are limitations in the combination of pre-machining and hard finishing processes which are related to the geometry of the gaps (Ref. 9). For this reason, grinding is most commonly used for hard finishing of face milled bevel gears. For face hobbed bevel gears, lapping is the dominant hard finishing process.

In bevel gear grinding, machining is usually carried out using vitrified grinding wheels. The defined and correctable machining with the grinding wheel allows good gear quality and reproducibility to be achieved, enabling free pairing of the bevel gears (Ref. 13). In addition, the process provides more possibilities for tooth flank modifications and is less sensitive to deviations from pre-machining and heat treatment.

During a bevel gear lapping process, the pinion and ring gear are engaged under low load, so that the grains contained in the lapping compound remove material from the tooth flanks in the contact zone (Ref. 7). In one process setting, a complete gear set is machined simultaneously, but subsequently the gear and pinion cannot be separated from each other. Regarding the gear properties, the surface structure resulting from lapping and the less uniform pitch are often classified beneficial for the noise excitation behavior (Ref. 13).

Bevel gear grinding. Bevel gears are theoretically always produced by a generating motion between the workpiece and the virtual generating gear (Ref. 14). In the manufacturing process, the tool profile represents the geometry of the virtual generating gear. The most important parameters for generating bevel gear grinding are the cutting velocity v_c and the rolling velocity v_w as shown in Figure 2 (Refs. 7 and 17). The cutting velocity v_c results from the grinding wheel rotation around its center axis. The rolling velocity v_w indicates the speed at which the tool is guided around the cradle axis (Ref. 7). The rotation around this axis, which corresponds to the center axis of the virtual generating gear, results in the relative rolling motion between the tool and the tooth gap.

For transmission ratios larger than 2.5, the rolling motion is often left out when machining the ring gear in order to achieve

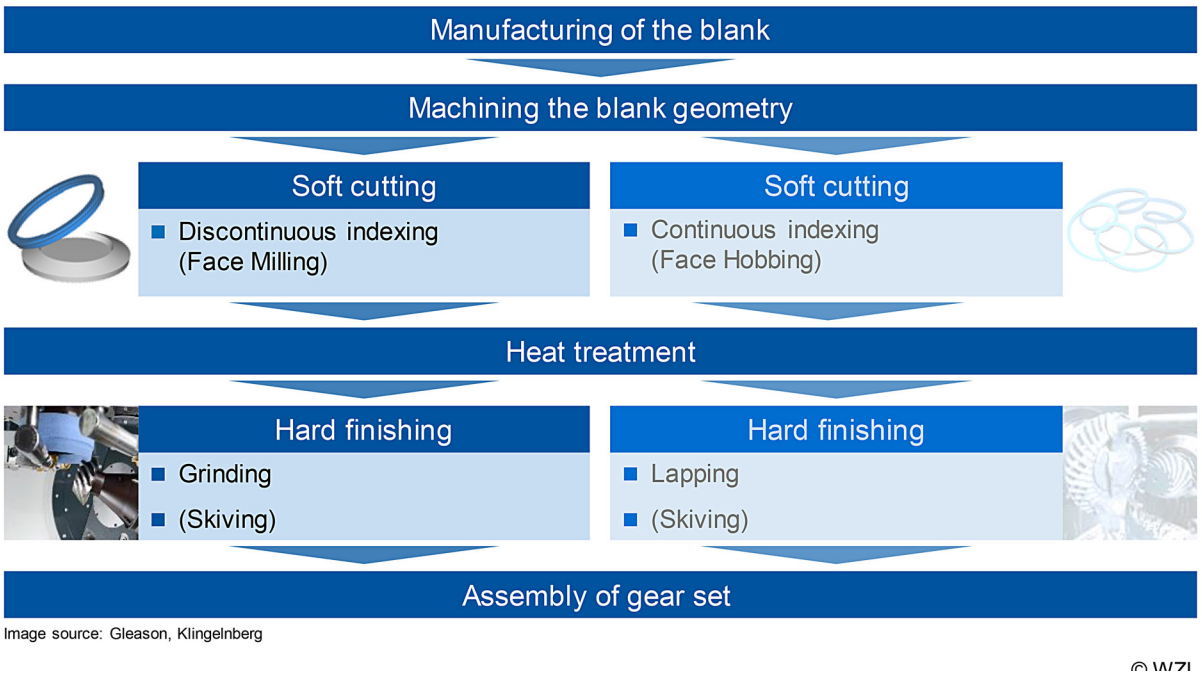

Figure 1 Process chain of bevel gear manufacturing.

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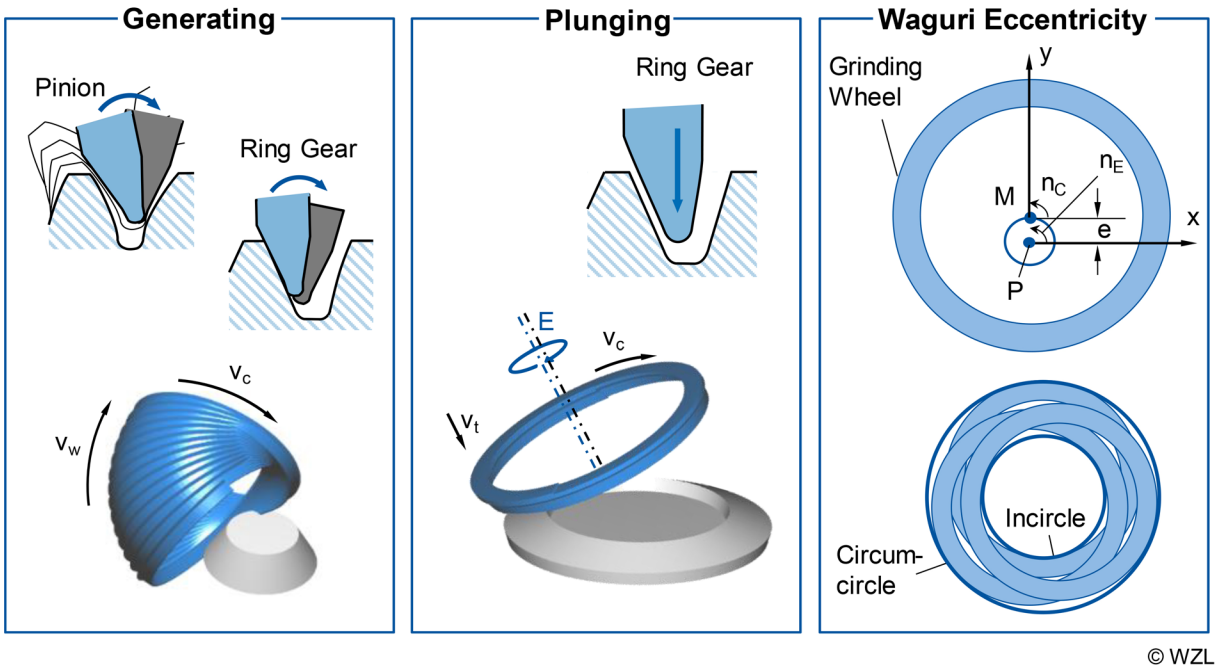

Figure 2 Bevel gear grinding.

shorter machining times (Ref. 7). In this simplified process, also referred to as plunging, the tool infeed takes place along a straight line vector. The target geometry of the resulting ring gear is therefore determined directly by the profile of the tool (Fig. 2). Except for tooth flank modifications such as crownings, plunged ring gears have straight flanks in tooth height direction. The most important process parameters for plunging bevel gear grinding are the cutting velocity v_c and the plunging feed rate v_t (Refs. 7 and 17.)The cutting velocity v_c results from the rotation of the grinding wheel. The plunging feed rate v_t indicates the speed at which the grinding wheel is plunged into the gap.

In non-optimized plunging bevel gear grinding, there is permanent, full-surface contact between the grinding wheel and the tooth flanks. Due to the continuous contact between the grinding wheel and the workpiece, thermal energy is continuously introduced into the entire surface zone. In addition, the supply of cooling lubricant is almost completely eliminated (Ref. 9). This results in a high risk of grinding burn.

As shown in the right of Figure 2, an eccentric motion is superimposed on the grinding wheel rotation to reduce the risk of thermal damage (Ref. 7). This eccentric motion, also known as WAGURI motion after its inventor, leads to a displacement of the grinding wheel perpendicular to its central axis. Depending on the machine tool manufacturer and grinding machine type, the eccentricity e varies from several hundredths of a millimeter to a few tenths of a millimeter and is usually not adjustable by the user (Ref. 17).

The grinding wheel geometry must be adapted so that the same tooth gap geometry is produced despite the superimposed eccentric motion. Compared to the theoretical grinding wheel geometry, whose profile corresponds exactly to the gap geometry, the inner diameter of the eccentric grinding wheel is increased by twice the eccentricity e whereas the outer diameter of the eccentric grinding wheel is reduced by twice the eccentricity e. In this way, the eccentrically moved grinding wheel forms the contour of the theoretical grinding wheel and thus the curvature of the tooth flanks.

Motivation and Objective

Due to increasing requirements concerning efficiency and noise excitation of gear drives, the hard fine machining of gears has become a necessary process step for many applications. The hard fine machining by grinding is an established manufacturing process for wide variety of applications, as good geometric and surface quality can be achieved (Ref. 1). Grinding of bevel gears is used especially for the machining of gears with high requirements concerning the gear quality, such as for automotive transmissions (Ref. 13). In industrial environments, bevel gear grinding processes are usually designed based on experience (Ref. 17). Suitable process parameters are determined for each workpiece geometry and grinding wheel specification in time and cost-intensive empirical investigations. In addition, it is not known whether the derived process parameters are within the range of the productivity maximum.

Knowledge of the cutting force is necessary for predicting both the thermal influence on the near surface zone and the load and thus the wear of the grinding tools (Ref. 15). In addition, the cutting force is of high relevance for the misalignment behavior of the tool in the process and is thus required for determining the process-machine interaction, as shown in Figure 3. Knowing the cutting force therefore plays a decisive role in knowledge-based process design and process optimization.

The process force can be determined by means of force modelling or measurements in the grinding process. Monitoring of the cutting force in the process can help to identify and eliminate critical process conditions. Therefore, this work shall introduce and analyze potentials for the application of process monitoring in plunging and generating bevel gear grinding.

Testing Procedure and Conditions

Due to the complex component geometry, process kinematics and clamping devices, measurement of the cutting force in the bevel gear grinding process is not yet easily possible. In order to still be able to determine the cutting force, an adapted test setup was designed for plunging bevel gear grinding, see Figure 4 on the left. A 9129AA force measuring platform from Kistler

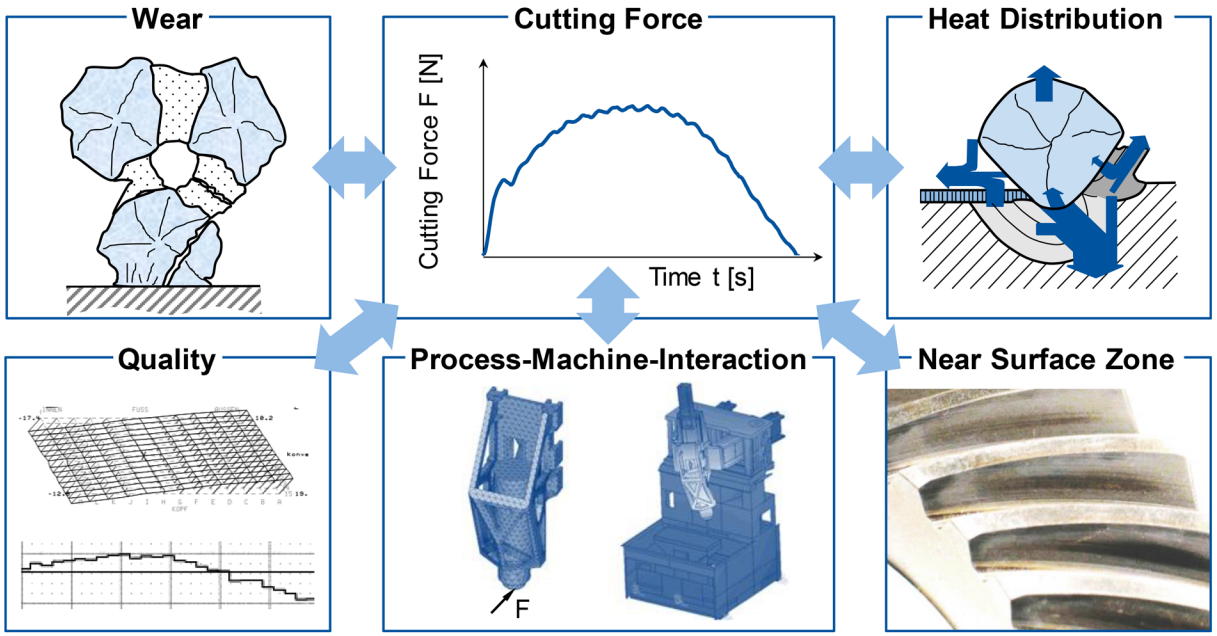

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Figure 3 Influence of the cutting force in grinding processes.

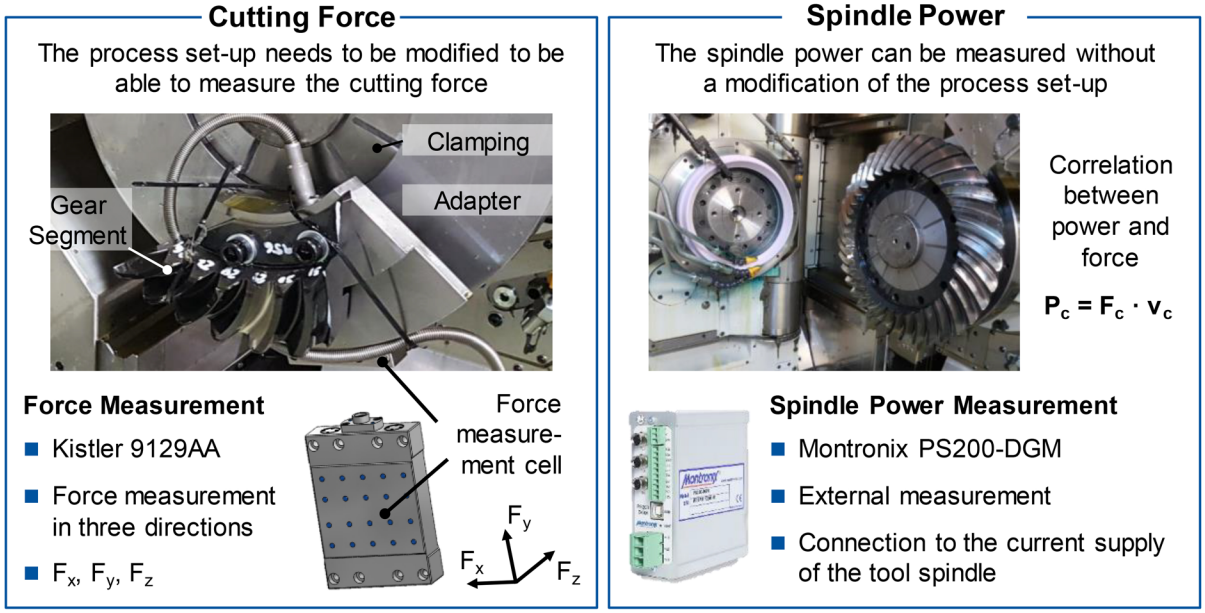

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Figure 4 Measurement of the cutting force and the tool spindle power.

was used for the measurement. To ensure that the cutting force can be correctly measured by the force measuring platform, the entire cutting force must pass through the force measuring platform and a force shunt must be prevented. For this reason, grinding was performed on a segment of a ring gear. Using an adapter, the ring gear segment was attached to the force measurement platform. This assembly was bolted to another annular adapter, which had the same internal diameter as the ring gear. The measuring setup was clamped in the machine using the standard clamping device via the inner diameter of the annular adapter, see Figure 4, left. With this setup, it was possible to measure the cutting force in a process comparable to the conventional plunging bevel gear grinding process.

The measurement setup presented here cannot be used with a complete ring gear, as otherwise a force shunt would occur. For this reason, it is currently not possible to measure the cutting force in series production without implementing sensors in the clamping device. Alternatively, process monitoring can also be performed by a measurement of the tool spindle power (Ref. 3). Monitoring of the tool spindle power is possible without a complicated adaption of the process. The total tool spindle power P is the sum of the cutting power P_c and the idle power *Pi*. The idle power is assumed to be constant at constant process parameters and corresponds to the power before the grinding wheel comes into contact. Therefore, the increase in power from the initial point of contact is interpreted as an increase in cutting power. According to the equation on the right side of Figure 4, the cutting power P_c is commonly assumed to be proportional to the cutting force component *Fc* (Ref. 8). Due to the alignment of the cutting velocity vector tangential to the flank surface, the cutting force component *Fc* corresponds to the tangential force F_t in plunging bevel gear grinding.

The load on the main spindle of machine tools can be determined via the machine control or via external measuring devices. Depending on the type of machine control, the spindle load is sometimes only output in relation to the currently possible maximum load and is therefore dependent on the characteristic curve of the machine drive. Because the determination of the physical spindle power from the machine control can therefore be difficult, an external measuring device of type PS200-DGM from Montronix was connected to the main power supply of the tool spindle as part of the investigations presented. The measuring setup shown in Figure 4 and the Montronix power meter were used to measure the cutting force and spindle power in plunging bevel gear grinding. The test results presented in the following chapter were used to validate the relationship between cutting force and spindle power for bevel gear grinding. In this way, it will be verified whether process monitoring can be performed by means of a measurement of the spindle power.

The investigations presented in this report were carried out at Scania CV AB in Södertälje, Sweden. All tests were performed in the series production on a Gleason PHOENIXII 600G bevel gear grinding machine. The workpieces were the ring gear and the pinion of a bevel gear set with a module of $mnm = 9$ mm from a Scania axle gearbox as can be seen in Figure 5. Existing clamping devices, coolant nozzles and dressing tools from series production were used for machining. Analogous to series production, grinding of the ring gear was carried out with a vector feed and a superimposed eccentric movement according to WAGURI. The pinions were ground in a generating process. For the tests, Saint-Gobain grinding wheels were used that consisted partly or completely of rod-shaped sintered corundum (Altos grain) in a vitrified bond.

In this work, the tests and measurements performed for plunging and generating grinding are shown. The correlation between the monitored signals and potentials for process monitoring for bevel gear grinding will be introduced.

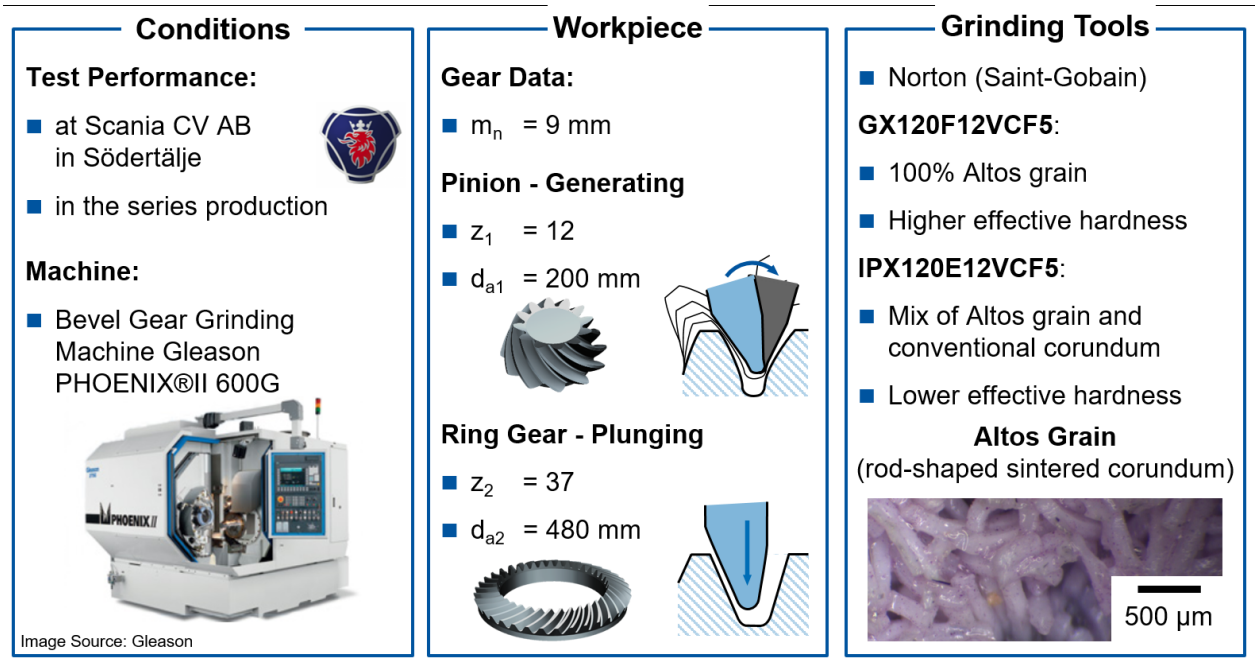

Figure 5 Testing conditions.

Plunging Bevel Gear Grinding

In the field of bevel gear production, the research environment has mainly focused on the milling process in recent years. For plunging bevel gear grinding, an empirical model was developed for predicting the risk of grinding burn as a function of the process parameters (Ref. 17). However, no modelling was carried out and the results are only valid for a very limited range of components and grinding wheels. Investigations on the measurement or prediction of the cutting force in bevel gear grinding do not exist so far.

Cutting Force and Spindle Power in Plunging Bevel Gear Grinding. A model that is frequently used in grinding processes is the force model according to (Ref. 16). Originally, this model was developed for surface grinding processes. For gear grinding, the calculation approach has already been adapted (Ref. 5). In the calculation according to (Ref. 16), the specific normal grinding force F'_n is calculated according to equation 1 (Ref. 16).

$$F'_n = \int_0^{l_g} k \cdot A_{cu}(l)^n N_{kim}(l)\,dl \qquad (1)$$

F'_n	[N/mm]	Specific normal grinding force
l_g	[mm]	Contact length
k	[N/mm²]	Specific cutting energy
A_{cu}	[mm²]	Chip cross section
N_{kin}	[l/mm²]	Kinematic number of cutting edges
n	[-]	Exponential coefficient

In the investigations carried out, it was examined whether the Werner model could be used for bevel gear grinding processes (Ref. 11). In order to transfer the force model from Werner to bevel gear grinding, the contact conditions of plunging bevel gear grinding were analyzed. The cutting rate and the chip cross section over time were calculated using the example of a heavy automotive ring gear. For the finishing process, an almost constant average material removal rate over time was determined. On the basis of the contact conditions, the cutting force model according to Werner was applied for plunging bevel gear grinding (Refs. 16 and 11). With the aid of the transferred model and the contact conditions determined, the expected force curve for plunging bevel gear grinding was derived, as shown on the left side of Figure 6. The expected force curve according to Werner was qualitatively compared to the measured tool spindle power. The investigation of the measured spindle power signal revealed a strong increase in power during the process despite theoretically approximately constant geometric and kinematic contact conditions, see Figure 6 (Ref. 11). This increase is most likely caused by an increase in cutting force, as the cutting force is commonly assumed to be directly proportional to the tool spindle power.

This increase of the cutting force cannot be predicted directly by the Werner model, which mainly takes into account geometrical and kinematic conditions and no material changes and elastic effects in the contact zone (Ref. 16). The increase of the cutting force despite theoretically almost constant geometric and kinematic contact conditions could also be determined for gear honing (Ref. 6). The main difference between the grinding processes in which the Werner model could be applied for the entire process duration and plunging bevel grinding as well as gear honing is the main direction of feed. In profile grinding and generating grinding, the main feed component points in the direction of the tooth width and the infeed into the material takes place in discrete passes outside the tooth gap. In plunging bevel gear grinding and gear honing, the feed is continuous in the direction of the tooth height into the material, resulting in an infeed of only a few micrometers per tool pass.

Due to the continuous feed into the material, the same areas of the tooth flank are repeatedly machined with increasing plunging depth. If the workpiece-tool-machine system deforms elastically during grinding, not the entire infed stock is machined (Ref. 2). If the theoretical stock is insufficiently machined, an increase in the volume to be machined at the next

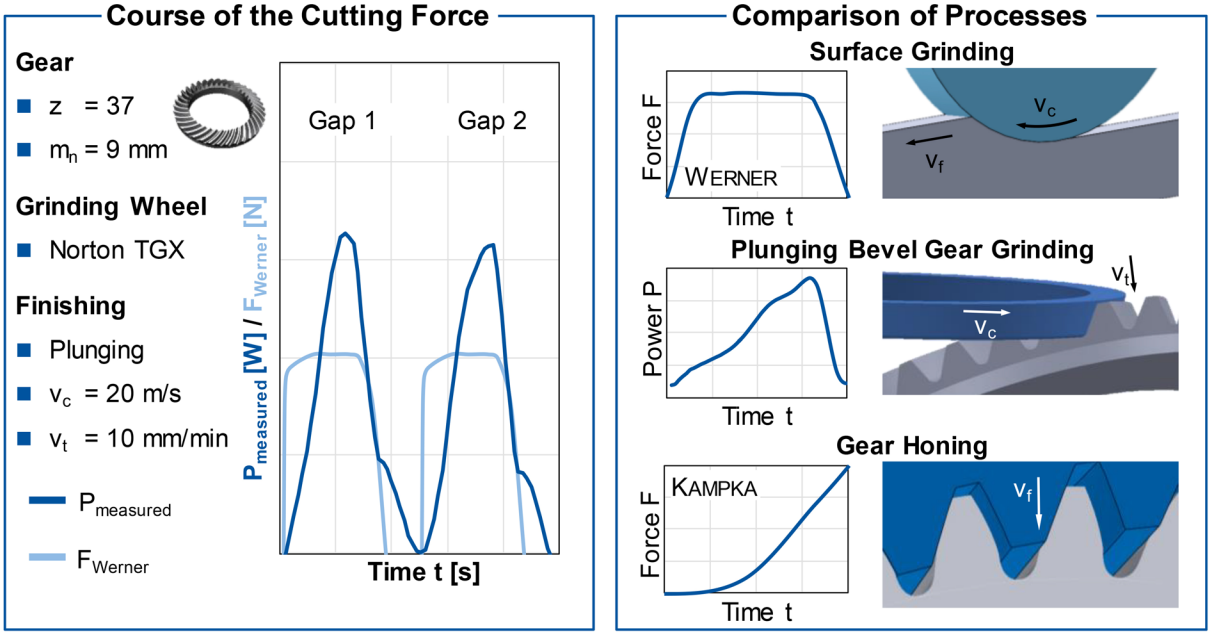

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Figure 6 Investigations on the cutting force in plunging bevel gear grinding (Ref. 11).

grinding wheel pass can occur, leading to an increase of the cutting force required for machining.

In order to validate the correlation between the tool spindle power and the cutting force and to further examine the division of the force components, the cutting force in plunging bevel gear grinding was measured in a single flank grinding process with the setup shown in Figure 4.

With the aid of a coordinate transformation, the measured force signals were transferred to the tooth flanks. The components were divided into a tangential force F_t component parallel to the flank and the tool rotation and a normal force F_n component perpendicular to the flank. For the grinding of the convex flank, the cutting force components tangential force Ft, normal force F_n and the simultaneously measured power are shown in Figure 7.

It can be seen from the diagrams that the normal force F_n accounts for the largest share of the cutting force. This is in accordance with the state of the art for surface grinding (Ref. 8) and profile gear grinding (Ref. 4). The course of the force components initially shows an increase that reaches its maximum value at the same time. The measured spindle power increases in a comparable manner. The start of the rise and the maximum value of the power are reached with a slight delay compared to the force. The almost identical increase in cutting force components and spindle power confirms the previously determined increase in spindle power for plunging bevel gear grinding, see Fig. 1. This confirms the assumption that the cutting force for plunging bevel gear grinding increases over the process duration, although the penetrated material removal rate remains almost constant (Ref. 11).

All force curves show an oscillation with the frequency $f = 1{,}500\ \text{min}^{-1}$ corresponding to the frequency of the eccentric movement. For single-flank grinding, it can be seen that the cutting force components vary between a maximum value and zero at the beginning of machining with every rotation of the eccentric axis. Therefore, it is assumed that the eccentric movement leads to the grinding wheel losing the contact completely in every rotation during single-flank grinding. The measured signals also show that the force level does not return to zero after a process time of t = 1.7 seconds. Since the kinematics remain unchanged, this is an indicator for elastic deformation, which was already assumed in earlier investigations (Ref. 11).

Elastic deformation in the contact zone due to the flexibility of the workpiece-tool-machine system means that the infed stock is not entirely machined. This can result in the grinding wheel no longer leaving the engagement completely, despite the superimposed eccentric movement. Another indication of elastic deformation is that the cutting force does not drop to zero immediately after reaching the final depth. Due to the elastic deformation of the system, not all of the theoretically penetrated material is cut immediately and the grinding wheel must remain in the tooth gap at the end of the plunging bevel gear grinding process. During this dwell time, the remaining stock is machined at a constant infeed depth, with the force decreasing approximately linearly.

Concluding, the presented measurement of the forces confirms the existence of significant elastic deformation in bevel gear grinding. Furthermore, the proportionality between the tool spindle power and the tangential force could be validated for a bevel gear grinding process. Therefore, the tool spindle power can be used for a simplified process monitoring in further investigations. In the following, an investigation on the influence of elasticity in plunging bevel gear grinding and whether a stationary process can be achieved will be carried out.

Influence of elasticity on the course of the cutting force. In plunging bevel gear grinding, no stationary condition was determined in the previous tests. For this reason, the following section will examine whether a stationary state can be achieved

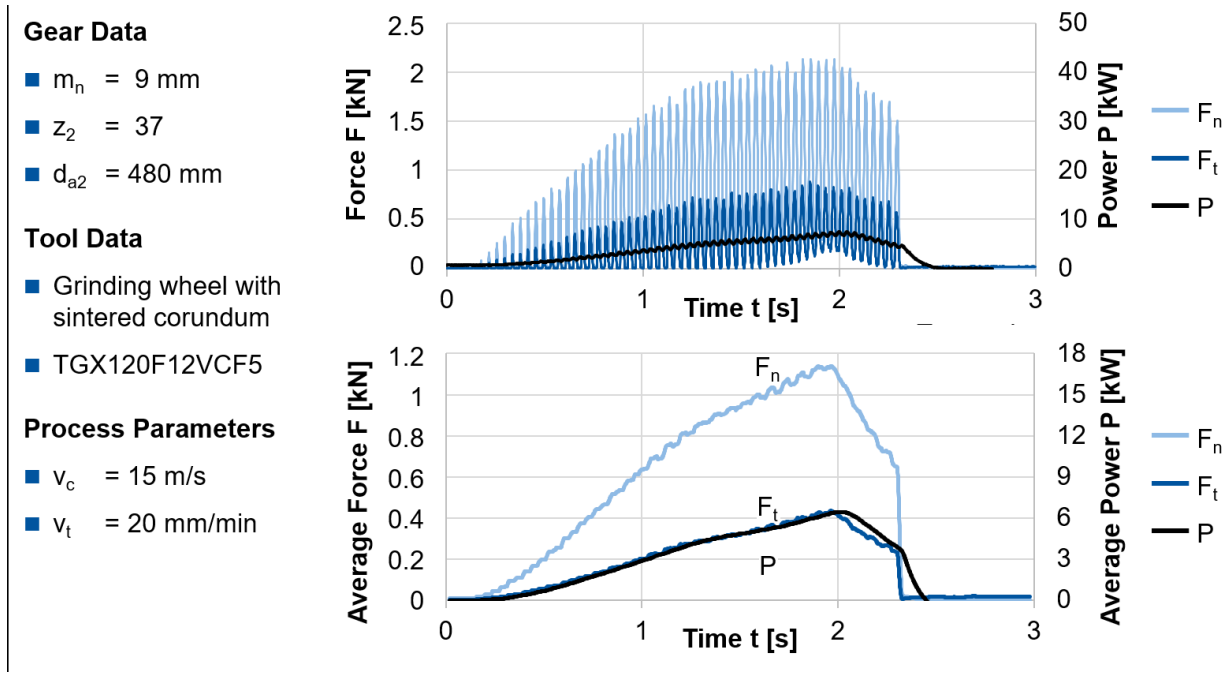

Figure 7 Investigations on the cutting force in plunging bevel gear grinding.

with increased cutting force. With increased force, there is the possibility that elastic effects can be overcome and thus a complete machining of the infed material can be achieved. The increase of the cutting force should be achieved by successively increasing the maximum plunging depth. The aim was to determine the relationship between the machined stock and the cutting force as well as the characteristic course of the cutting force over the infeed in plunging bevel gear grinding.

For each plunging depth tested, one gear was pre-ground and subsequently finished to the desired plunging depth while measuring the tool spindle power. The infeed per flank Δs can be calculated out of the plunging depth d according to eq. 2:

$$\Delta s = d \sin(\alpha) \tag{2}$$

Δs	[µm]	Infeed per flank
α	[°]	Angle between flanks and feed vector
d	[µm]	Plunging Depth

For the investigation, the maximum tool position was increased in steps of d = 50 µm plunging depth. According to equation 2, steps of $\Delta s = 17$ µm infeed were obtained. The total infeed per tooth flank was successively increased by $\Delta s_{tot} = 17–137$ µm. In comparison, the maximum total infeed in the reference process is $\Delta s_{tot} = 50$ µm. By increasing the total infeed, it should be determined whether a stationary process and thus a stationary cutting force level can be achieved in this way. The grinding wheel tip was shortened to avoid machining the tooth root despite the increased plunging depth. Finishing was carried out at a cutting velocity of $v_c = 15$ m/s and a plunging feed rate of $v_t = 30$ mm/min. The course of the spindle power during the machining of one tooth gap each over the process time for the various total infeeds Δs_{tot} is shown in Figure 8.

The Figure shows that an increase in the maximum total infeed is accompanied by an increase in the maximum spindle power. In addition, three phases are visible in the power curve. In the first phase, there is a roughly linear increase in spindle power for all variants regardless of the maximum total feed Δs_{tot}. As this phase takes place before the initial contact between grinding wheel and flank it is attributed to oil friction in the gap (Ref. 12).

The first phase of increase is followed by a faster linear increase in the second phase for all variants which is caused by the material removal. For the spindle power curves, both the points in time and the gradients are comparable.

The first phase of increase is followed by a faster linear increase in the second phase for all variants which is caused by the material removal. For the spindle power curves, both the points in time and the gradients are comparable. For the variants with maximum total infeed $\Delta s_{tot} \leq 67$ µm, the rapid increase in spindle power after reaching the maximum value is followed by a rapid decrease in spindle power to the initial level. For the variants with maximum total infeed $\Delta s_{tot} \geq 85$ µm, the second phase of the rapid increase in spindle power is followed by a third phase with approximately constant spindle power before the spindle power drops. From this it can be seen that with an increase in infeed and thus of the machined material, a stationary tool spindle power level can be achieved in plunging bevel gear grinding. Based on the previously determined proportional relationship between tangential force and spindle power, this means that the tangential force also reaches a stationary level in

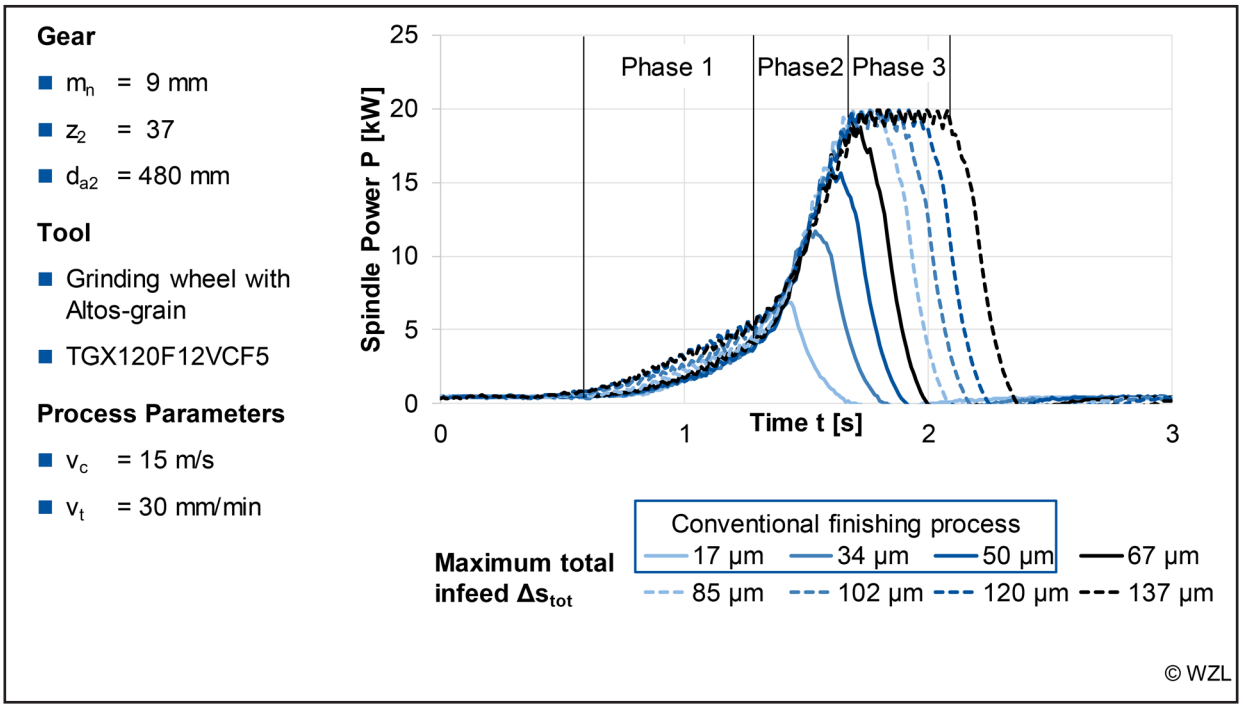

Figure 8 Influence of the infeed on the tool spindle power.

this state. This is due to the fact that machining conditions have been achieved under which the entire stock can be machined.

In the following, the elastic deformation in plunging bevel gear grinding is determined with the help of the gears from the previously performed tests with variable infeed Δs_{tot}. In order to be able to determine the actually machined volume as a function of the maximum total infeed, no dwell time after reaching the maximum plunging depth was set for finishing. After machining, the tooth thickness for all gears was determined and compared with the theoretical tooth thickness as a function of the maximum total infeed. In this way, the remaining stock Δs_R per tooth flank could be determined, see Figure 9.

The light colored points and the regression line represent the course of the remaining stock Δs_R per flank depending on the maximum total infeed Δs_{tot}. It can be seen that the remaining stock initially increases with the infeed and then reaches a near stationary level. If the maximum total infeed is set to $\Delta s_{tot} = 137\,\mu m$, the remaining stock of $\Delta s_R = 16\,\mu m$ per tooth flank occurs. It can be assumed that the remaining stock is composed of a deformation of the tool, workpiece and machine tool. In the future, this should be further investigated by individual displacement measurements. The dark points in the diagram represent the maximum spindle power P over the maximum total infeed Δs_{tot} for all test points. The comparison shows that the remaining stock Δs_R and the maximum spindle power P increase proportionally. The last three test points with the highest total infeed have an approximately constant remaining stock and an approximately constant maximum spindle power.

If the maximum spindle power P is plotted over the remaining stock Δs_R, an approximately linear relationship becomes apparent, see bottom of Figure 9.

The spindle power P is proportional to the tangential force F_t and approximately proportional to the normal force F_n. This correlation corresponds to the theory according to (Ref. 10) that the overall system behaves like a spring with the stiffness k_e (Ref. 10). Accordingly, the relationship between the normal force F_n and the deflection and thus the resulting remaining stock Δs_R can be described using the usual approximation for springs, see equation 3

$$F_n = k_e \cdot \Delta s_R \tag{3}$$

F_n	[N]	Normal force
Δs_R	[µm]	Remaining stock
k_e	[N/µm]	Total spring stiffness

Based on the stiffness, the system deformation and thus the remaining stock Δs_R can be predicted for the considered test setup with the aid of the monitored spindle power. In this way, for example, the required dwell time can be set. In order to be able to transfer the relationships determined to other process configurations, the composition of the spring stiffness must be determined more precisely in the future. In addition, the validity of the relationship between the spindle power and the normal force for must be checked for different gear geometries.

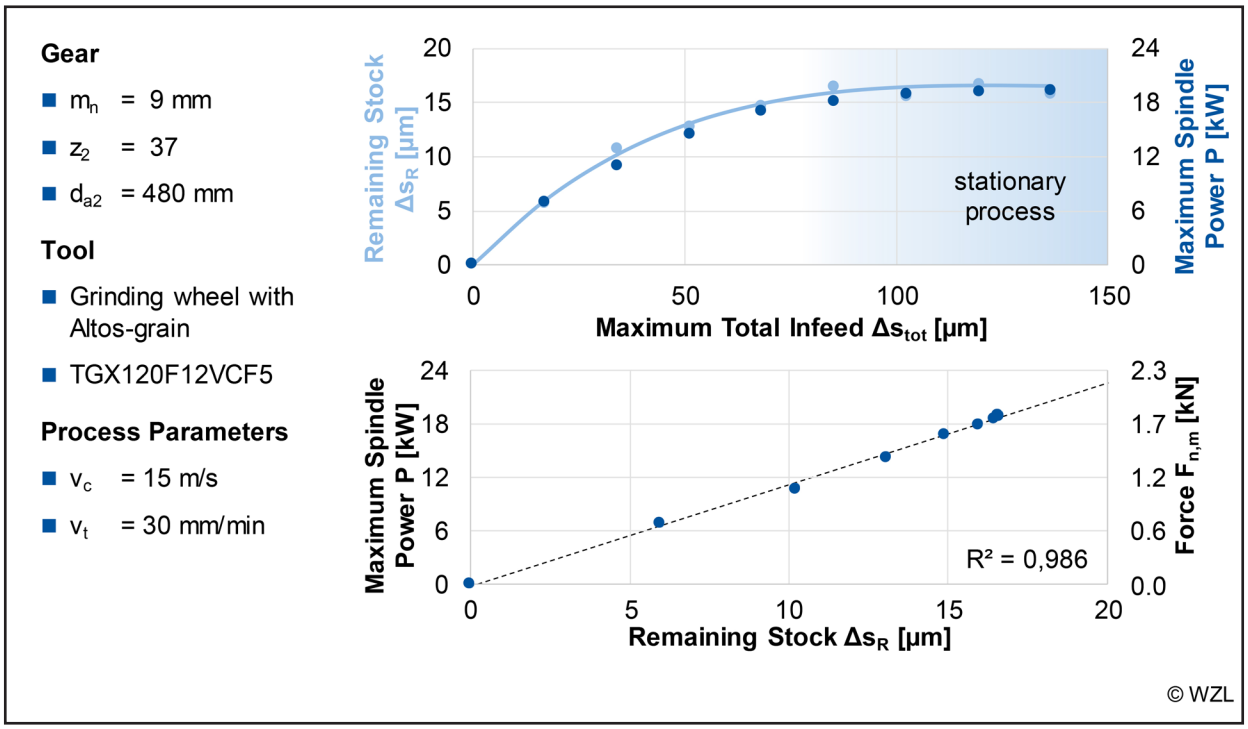

Figure 9 Correlation between the remaining stock and the tool spindle power.

Generating Bevel Gear Grinding

In addition to the tests performed for plunging bevel gear grinding, tests for process monitoring were also performed for generating grinding of bevel pinions. In these tests it was evaluated, how the tool spindle power signal can be used to detect critical process conditions. By this means, process monitoring should be made applicable to find a suitable process design. It was tested if the rolling velocity v_w in the series production could be increased in order to optimize the process productivity. The monitored tool spindle power for three levels of rolling velocity are shown in the top of Figure 10.

The test results showed, that the tool spindle power is directly influenced by the rolling velocity of the process. An increase of the rolling velocity led to an increase of the tool spindle power. In the examinations, an increase of the rolling velocity by 25% compared to the reference process was tested. After the grinding process, the geometry of all ground pinions was measured. The pinions ground with a significantly increased rolling velocity showed remaining stock on the tip area of the heel. The amount of remaining stock increased with the number of flanks ground before. An analysis of the grinding wheel showed, that whole areas of grains and bonding had broken off the tool.

This failure of the tool is directly correlated to a continuous overload. Most likely, the combination of stock, rolling velocity

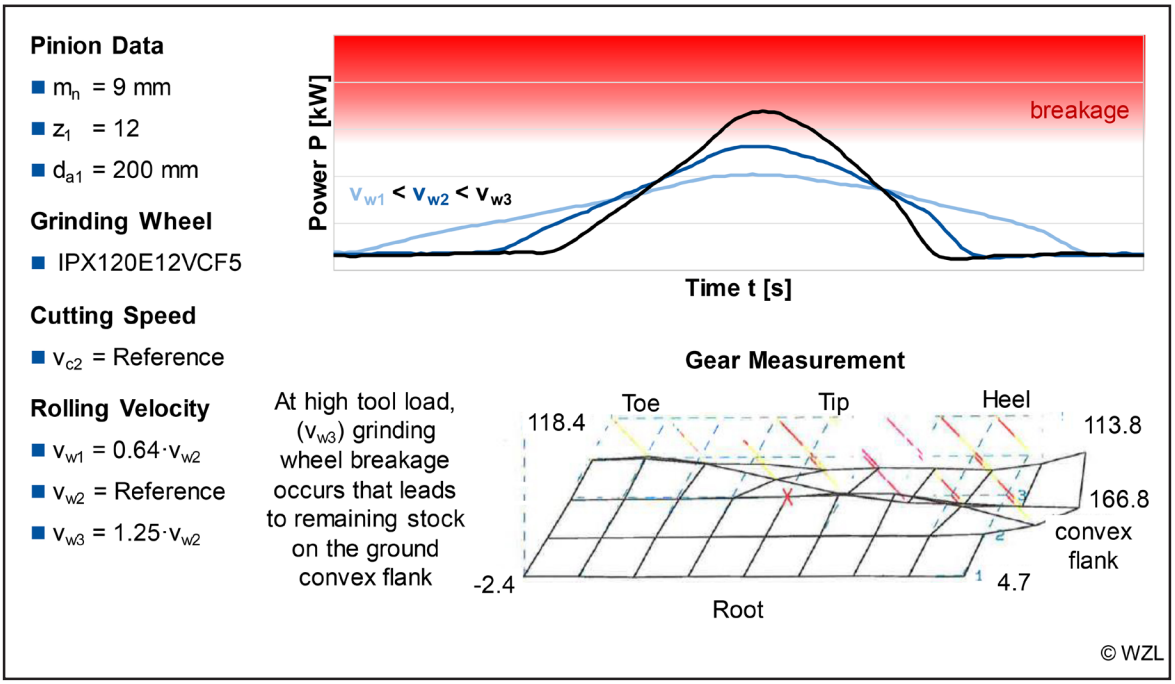

Figure 10 Influence of an increased rolling velocity in generating bevel gear grinding.

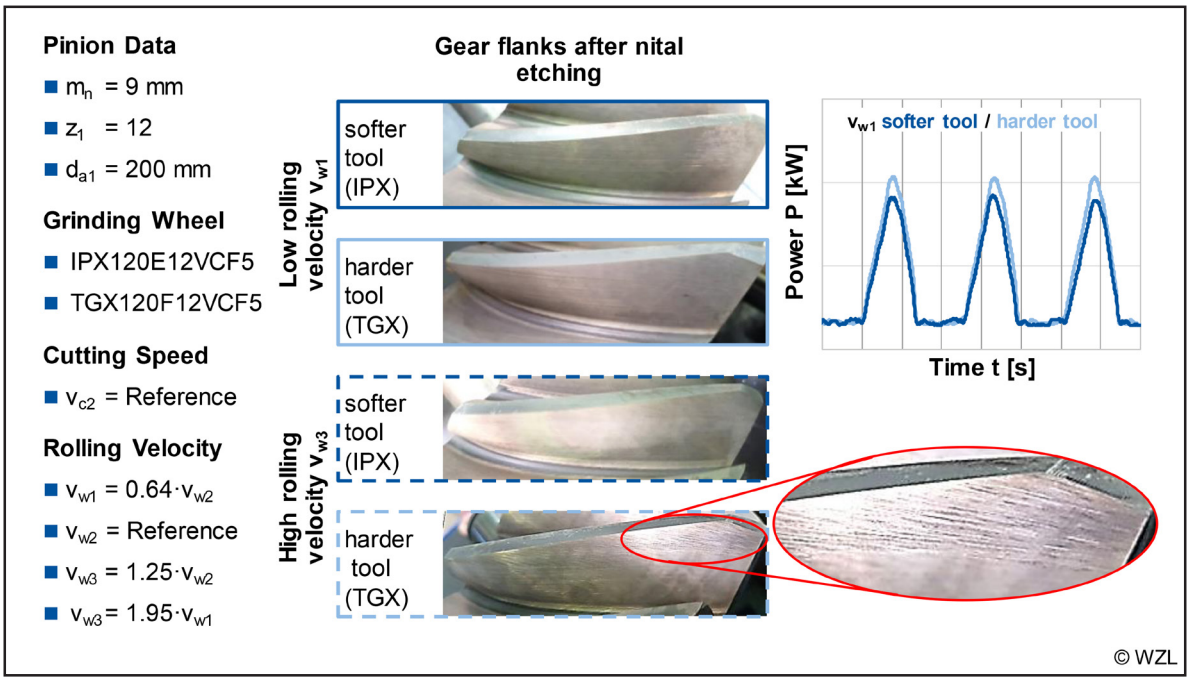

Figure 11 Influence of the grinding wheel specification in generating bevel gear grinding.

and cutting velocity have caused a critical load on the grains. By means of a monitoring of the tool spindle power, this type of overload can be avoided. From the tool spindle power, the tangential force in the contact zone can be calculated. From the tangential force, the load per grain can be estimated. Depending on the type of grinding wheel used, a maximum tolerable load level can be determined. By this means, a tool breakage can be prevented in advance and suitable process parameters can be determined.

In addition to the variation of the rolling velocity, the grinding wheel specification was varied in the tests performed. In the previously described tests, an IPX grinding wheel with a mix of Saint-Gobain Altos grain and conventional corundum was used. For grinding of the ring gears, a TGX grinding wheel with 100% Altos grain was applied. In further tests, the applicability of the TGX tool specification also for pinion grinding was investigated. The test results can be seen in Figure 11.

In case of a successful test, the number of different tool specifications for bevel gear grinding could have been halved. This would have been beneficial for purchase and storage capacities. Furthermore, the harder TGX grinding specification showed the tendency to be more stable in previous tests. The results from the generating pinion grinding confirmed these test results.

While the softer IPX grinding wheel broke at the increased rolling velocity v_w, the gears machined with the harder TGX wheel did not show any geometric deviations caused by tool failure. During the tests, it could already be seen that the tool spindle power consumption is increased for the harder TGX grinding wheel compared to the softer IPX grinding wheel, see top right of Figure 11. A higher tool spindle power can be an indicator of a higher energy input into the contact zone. Nital etching after the grinding process showed a slight change of color for the gears that were machined with the harder grinding wheel and increased rolling velocity v_w. Especially the area of the heel close to the tip turned out darker after nital etching. This was also the area, where the geometric deviations occurred due to a breakage of the softer grinding wheel. These results suggest that the load on the grinding wheel and the flank is maximum in this area. A measurement of the Barkhausen signal could also confirm the increased thermal influence on the pinion flanks for the combination of higher rolling feed and harder grinding wheel. It can be seen that the more stable harder grinding wheel can induce a higher risk of thermal damage.

The presented results for generating bevel pinion grinding showed possibilities to indicate critical process conditions by means of process monitoring. Both an overload of the tool as well as a higher energy input due to an increased tool hardness could be detected by means of the tool spindle power. When a process is well known, these signals can be applied for process monitoring and to successfully adapt or design a bevel gear grinding process.

Potentials for Process Monitoring in Bevel Gear Grinding

In the previously presented work, different potentials for process monitoring in bevel gear grinding were shown. An increased energy input into the workpiece caused by a critical feed rate can be detected by means of the tool spindle power. The tool spindle power is directly influenced by the process parameters, the grinding wheel and the lubrication. In order to be able to interpret the signal, the process has to be well known.

In addition to the influence on the workpiece, the influence on the tool can be determined by means of process monitoring. In order to determine the load on the tool, the cutting velocity needs to be taken into account. The ratio between the tool spindle power and the cutting velocity is proportional to the cutting force components. When the force and therefore the local load on the grinding wheel is too high, a high risk of breakage occurs. Too small loads on the grinding wheel can also cause difficulties, when the load is not sufficient for the tool to self-sharpen, as can be seen in Figure 12.

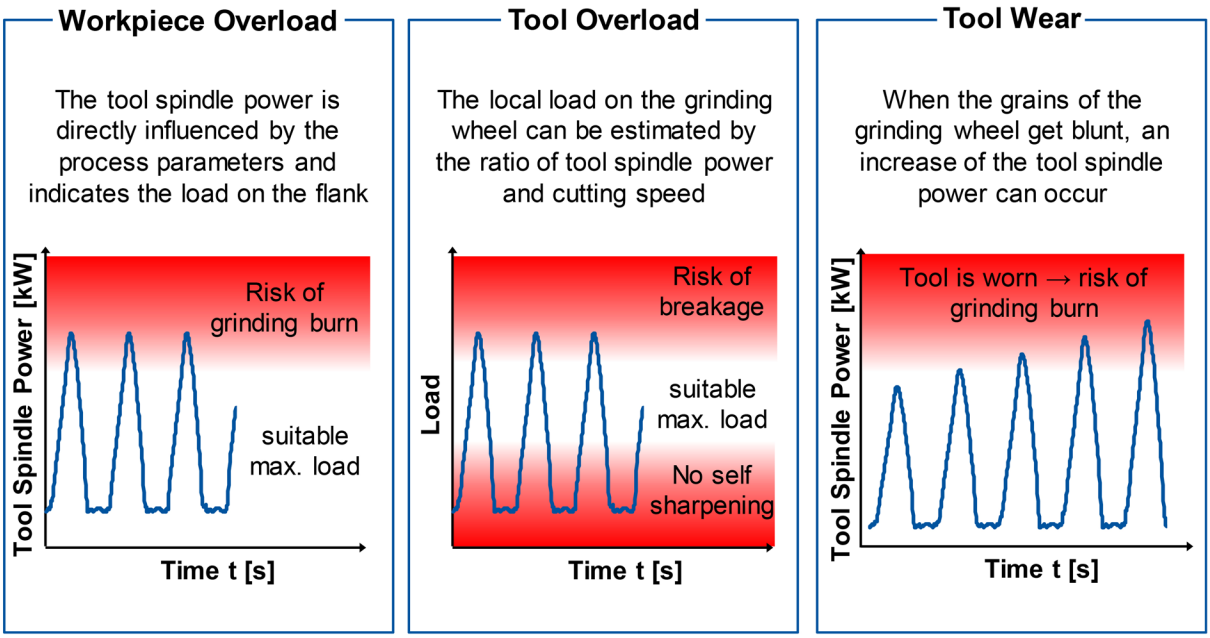

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Figure 12 Potentials for process monitoring in bevel gear grinding.

When the grinding wheel gets blunt due to wear or a lack of self-sharpening, an increased amount of rubbing and therefore increased friction in the contact zone can occur. This increased friction can lead to a rising spindle power and a higher energy input into the workpiece. Therefore, in case of a significantly increasing tool spindle power over time, a dressing process or a replacement of the grinding wheel should be taken into consideration. If the tool wear leads to a breakage of a large amount of grains, tool wear can also cause a drop in the spindle power. Each change of the signal should therefore carefully be examined and the process needs to be well known to interpret the signals.

For tool condition monitoring, a measurement of the dressing spindle power can also be useful. The course of the measurement can show if the dressing wheel is in contact from the first pass on. This can be an indication of the occurring amount of tool wear in a grinding process. By monitoring the dressing process, a sufficient dressing of the grinding tool can be assured and the number of dressing passes can be optimized. In addition, wear of the dressing tool can lead to a change of the dressing spindle power. The work presented shows that the tool and dressing spindle power of the machine tool is a relatively simple accessible signal which can give essential process information. To be able to use the spindle power signals for reliable process monitoring, the process needs to be well known and a reference process measurement is required for comparison purposes.

Summary and Outlook

In previous scientific research in grinding processes, the relevance of the knowledge of the cutting force for the prediction of the thermomechanical influence on the workpiece and the load on the grinding wheel have been shown. Therefore, for plunging bevel gear grinding an approach to model the cutting force was analyzed. As the cutting force measurement in bevel gear grinding processes is very complicated, the correlation between the cutting force and the tool spindle power was examined. It could be validated that the tool spindle power is directly proportional to the tangential force in plunging bevel gear grinding. In the tests performed, a strong increase of the cutting force was determined. This increase was most likely correlated with elastic effects in the process. These elastic effects could be described and directly correlated to the measured tool spindle power. Therefore, for plunging bevel gear grinding it could be shown that the measurement of the tool spindle power can be used to determine the cutting force and to estimate the elastic deformation in the process.

For generating grinding of bevel pinions, measurements of the tool spindle power have been applied to detect critical process conditions. A direct correlation between the tool spindle power and the load on the grinding wheel as well as the workpiece could be determined. It was shown that process monitoring can be used to design the bevel gear grinding process, to avoid tool failure, to detect grinding burn and to determine dressing cycles.

The test results showed that a lot of essential information can be obtained from the measurement of the machine spindle power signals. Furthermore, it could be seen that a detailed knowledge of the process is required in order to interpret the signals correctly. Therefore, in the future, further analysis on the interpretation of the process signals should be performed. This analysis could support the successful application of process monitoring for bevel gear grinding processes.

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For the main part of his academic qualification. **Thomas Bergs** studied design engineering at the Rheinisch-Westfälische Technical University, Aachen. He graduated in 1995 having written his diploma thesis at the Engineering Research Center for Net Shape Manufacturing in Columbus, Ohio. In 2001 he went on to earn a doctorate in engineering at the RWTH Aachen University for which he was awarded the Borchers Plaque. He also graduated as an Executive Master of Business Administration in 2011. Thomas Bergs was a research associate in the Process Technology Section at the Fraunhofer Institute for Production Technology IPT in Aachen from 1995 to 2000. In the year 2000, he was appointed Manager of the Laser Engineering Group and of the Business Unit »Aachener Werkzeug- und Formenbau«(Aachen Tool and Die Making). Since 2001 he has also held the position of Managing Director under Professor Fritz Klocke as institute head. Thomas Bergs has additionally founded the company Aixtooling in 2005, where he became Managing Director until 2018. Core area of the expertise at Aixtooling was tool making for precision glass molding as well as advanced glass optics manufacturing, In 2018 Thomas Bergs was appointed as Professor at the Chair of Manufacturing Technology at the Laboratory for Machine Tools and Production Engineering WZL of the RWTH Aachen University and as Director of the Process Technology Division at the Fraunhofer Institute for Production Technology IPT. As the successor to Professor Fritz Klocke, he is also a member of the Board of Directors of both production engineering institutes. The main focus of his ongoing research activities comply the digital transformation of manufacturing technologies—so called networked adaptive production.

Dr. -Ing. Dipl. -Wirt. -Ing. Christoph Löpenhaus is since 2021 working with Flender GmbH as head of production for the part manufacturing plants in Bocholt and Voerde, Germany, Flender is a worldwide leading provider of drive systems especially for wind turbine and industry applications. From 2019–2021 he was Business Development Manager Geared Bearings at Cerobear GmbH, a leading manufacturer of hybrid bearings especially in the aerospace, space and industry segment. From 2014–2019 he held the position as Chief Engineer of the Department of Gear Technology of WZL, RWTH Aachen with research focus on gear manufacturing, design and testing. He previously worked with WZL as Team Leader and Research Assistant. His educational background is in the field of Industrial Engineering with a diploma in 2009 and a Ph.D. in mechanical engineering in the field of gear technology in 2015. For his scientific achievements he was awarded the Springorum Commemorative Coin in 2010 and the Borchers Badge in 2016.

Mareike Solf M.Sc. studied mechanical engineering with a focus on production technology at RWTH Aachen University. After working as a student research assistant in the department of gear technology of the Laboratory for Machine Tools (WZL) for more than three years, she became a research assistant in 2016. Her research focus is gear manufacturing, especially grinding of bevel and cylindrical gears. Since 2019 she has been the leader of the research group of gear hard machining and is in charge of the department's industrial cooperation in the field of gear manufacturing.