Optimization of the Gear Profile Grinding Process Utilizing an Analogy Process

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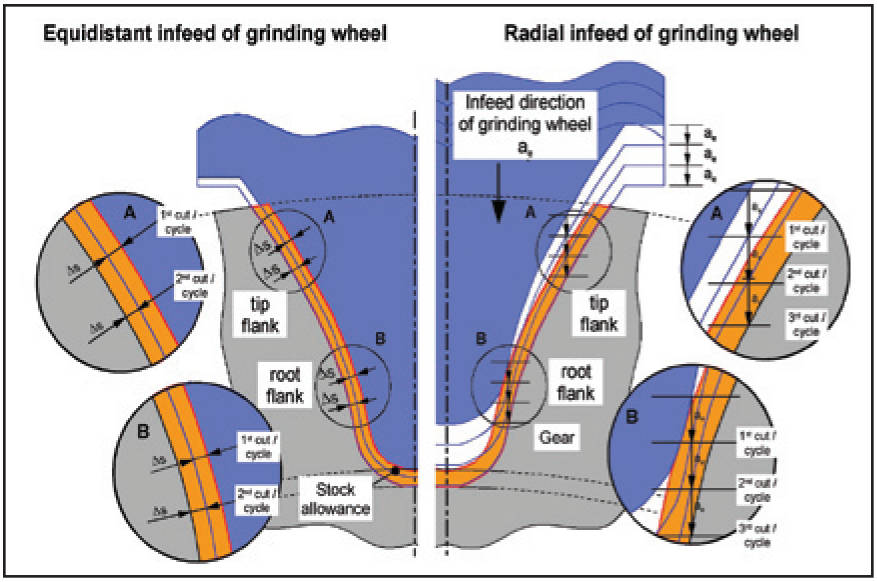

Figure 1—Local stock removal depending on the process strategy.

Management Summary

The requirements for transmission gears have continuously increased in past years, leading to the necessity for improvements in manufacturing processes. On the one hand, the material strength is increasing, while on the other there is a demand for higher manufacturing quality. For those reasons, increasing numbers of gears have to be hard-finished.

The appearance of grinding burn in gear profile grinding, especially when using dressable grinding wheels, seemed to increase over the past years. As we know, grinding burn reduces the load-carrying capacity of gears tremendously. Conversely, costs need to be cut in order to assure a company's competitive position in the global market. And yet, reducing the machining times in gear grinding still increases the risk of producing grinding burn (Ref. 1).

In order to grind gears burn-free and as productively as possible, a better understanding of the process is required. This is especially important for gear profile grinding, due to the complex contact conditions between workpiece and grinding wheel (Refs. 2–3). In this article, an analogy process and a process model will be presented in order to gain a closer look into the process. Finally, different process strategies will be analyzed using the presented process model in order to give examples for the use of the described calculations.

Introduction

Discontinuous gear profile grinding is commonly used in the manufacture of large-module gears. And because the batch sizes are typically small to medium, the process must be highly flexible. In order to achieve this flexibility, dressable—rather than CBN-plated—grinding wheels can be applied. But in using these tools, the process robustness can be compromised by local structural damage—such as grinding burn—to the external zone.

In tooth-flank profile grinding, due to the variation of contact conditions along the profile between grinding wheel and tooth flank, process optimization is difficult. And in comparison with other grinding processes, these conditions clearly lead to varying grinding conditions along the profile. Examination of the complex geometrical and contact conditions requires fundamental technological investigations in an analogy process. In this way, the relationship between various material removal conditions can be investigated as functions of the machining parameters and grinding wheel specifications.

The purpose of this article is to develop a better process understanding in order to use new potentials for process optimization. The knowledge gained in the analogy process is the basis for a new mathematical model, allowing that understanding to be transferred to the real process. Finally, a process optimization for gear profile grinding using this mathematical model will be presented.

Local Stock Removal and Grinding Burn in Gear Profile Grinding

Local grinding conditions along the profile in gear profile grinding. Basically, there are two process strategies that are commonly used for gear profile grinding in industrial practice. The left side of Figure 1 shows a grinding process with the removal of an equidistant stock along the profile. These are typical contact conditions occurring in single-flank grinding, with an infeed realized by a rotation of the workpiece (Refs. 2, 4).

The right side of Figure 1 shows the removal of a constant stock in the radial direction, realized by a radial infeed of the grinding wheel in multiple steps. This is the process strategy most commonly used in industrial practice. It is obvious that the initial stock removal is not constant along the profile. In the first cut, stock is removed in the area of the root flank only. With further infeed, the area of stock removal is increasing. The whole stock in the tooth root is removed in the last cut only.

Appearance of grinding burn in gear profile grinding. Typically, grinding burn appears only locally along the tooth profile in gear profile grinding. This is due to either the chosen process strategy or heat distortions and centering defaults. In this article, two examples of local grinding burn—dependent upon the process strategy—will be shown. For these trials, a typical truck gear from the case-hardened steel 20MnCr5E has been ground using a dressable, white corundum grinding wheel and using different process strategies. The tooth gaps have all been pre-ground in order to remove the influence of heat distortions and to ensure a constant stock removal in either infeed or equidistant direction.

The results for a radial infeed of the grinding wheel without grinding the tooth root are shown in Figure 2. In the trials, a variation of the specific stock removal rate Q'w has been realized by a variation of the axial feed speed f_a. The picture in the lower left shows the tooth flanks after nital etching. It is readily apparent that the grinding burn appears only in the area of the tip flank.

Additionally, technological trials have been conducted with a constant stock removal along the gear tooth profile (see results in Figure 3). The specific stock removal rate Q'w varies in this operation along the tooth profile. The values shown in the chart are calculated at the indexing diameter in order to be comparable to the previous results. The picture in the lower-left

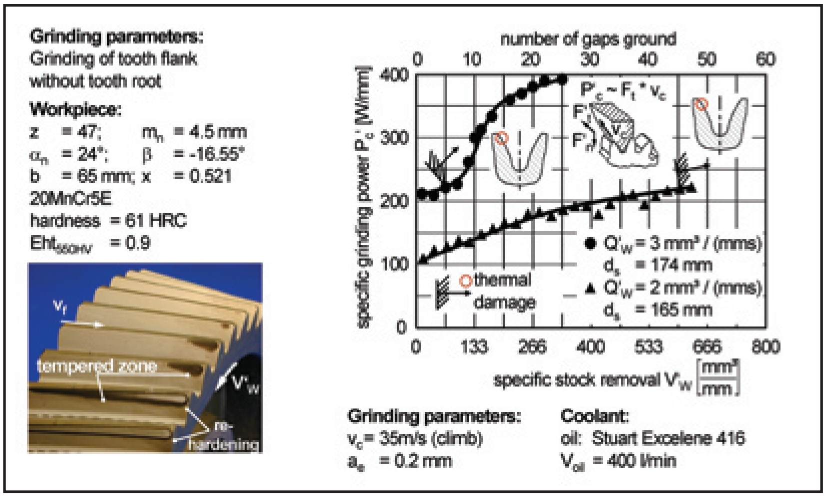

Figure 2—Typical grinding burn for radial infeed of the grinding wheel.

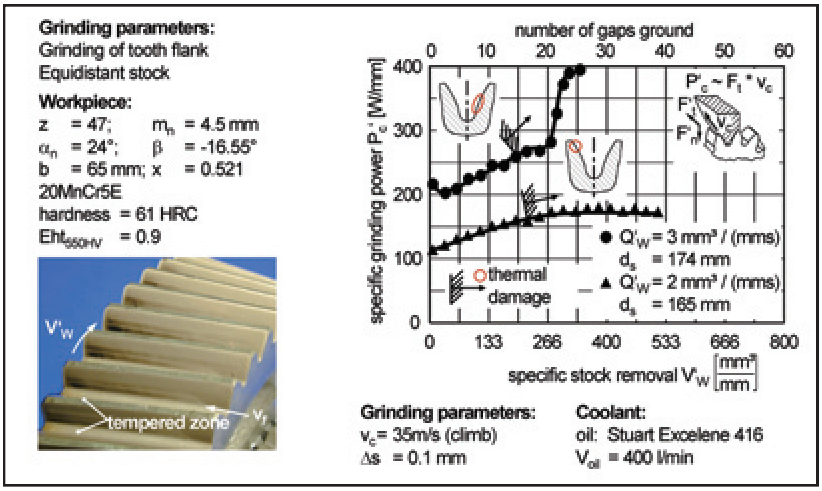

Figure 3—Typical grinding burn for equidistant infeed of the grinding wheel.

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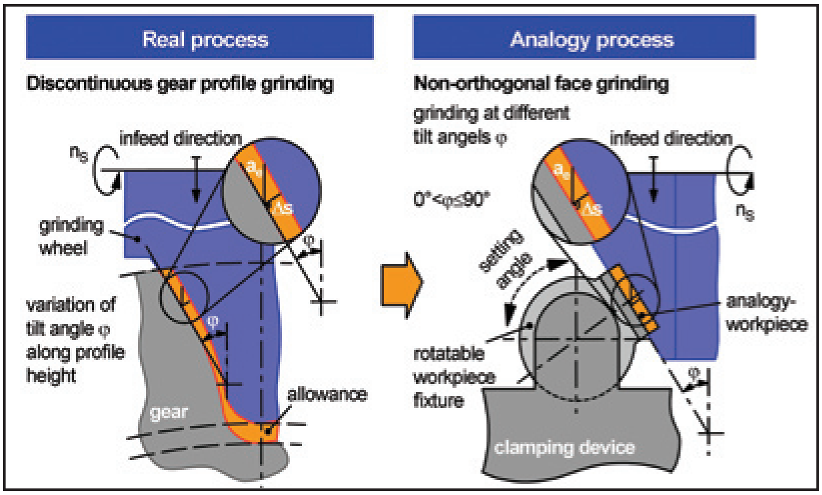

Figure 4—Analogy process for gear profile grinding.

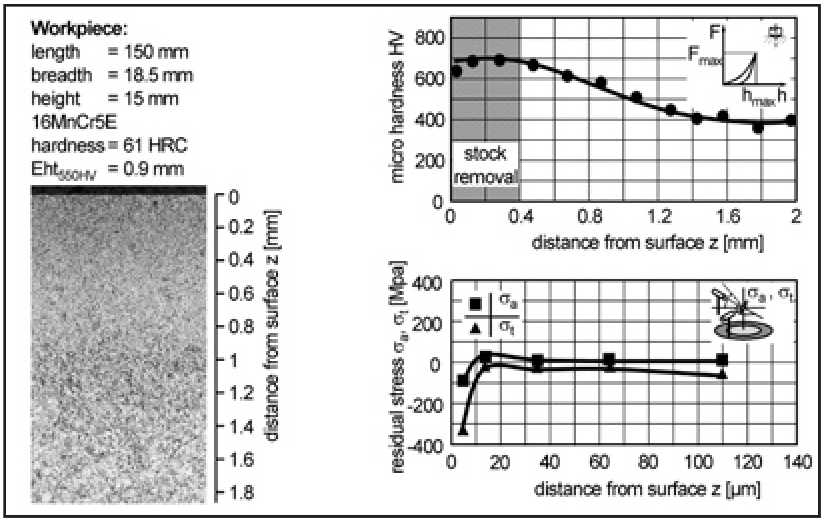

Figure 5—Workpiece data.

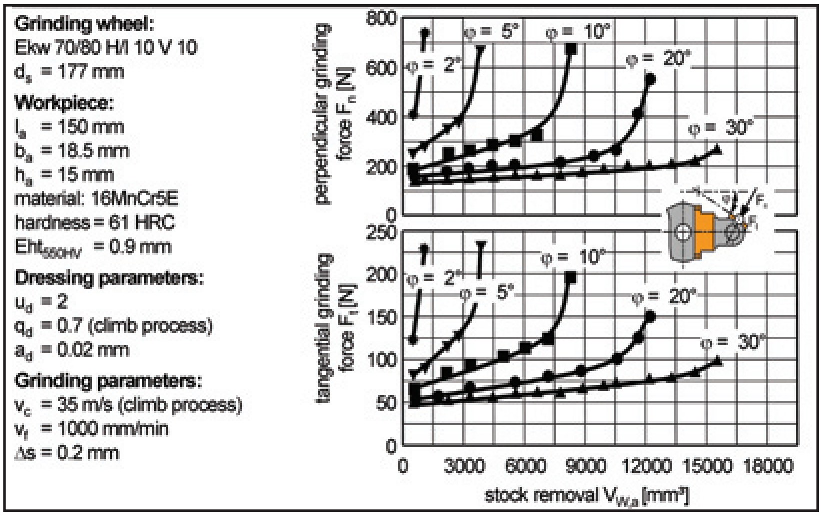

Figure 6—Grinding forces depending on the profile angle.

corner shows the gear after nital etching, and the tempered zone has moved from tip flank to root flank. Again, this is a typical phenomenon for this process strategy of removing a constant stock along the profile.

These results show that process strategy greatly influences local grinding conditions and, in turn, the area where grinding burn can appear. But why this area in particular shows thermal damage from grinding burn is not obvious. As the diagrams showing the specific spindle power P'c clearly reveal, the grinding burn nearly always appears before the spindle power shows a disproportionate increase.

Analogy Process for Gear Profile Grinding

The main difference between gear profile grinding and standard grinding is the varying profile angle φ along the tooth flank. Investigations of gear profile grinding can only show total effects over the whole profile height and varying grinding conditions. This is a major reason why it is difficult to find out what leads to grinding burn occurring only locally on the tooth flank.

In order to investigate the technological conditions separately along the tooth flank, an analogy process has been developed at the WZL laboratory at RWTH Aachen University. The basic setup of this analogy process is shown in Figure 4. The left picture shows the varying contact conditions along the tooth flank for a radial infeed of the grinding wheel into a pre-ground tooth gap. The radial infeed a_e is constant along the profile height, while the stock in normal directions varies with the local profile angle φ.

On the right side of Figure 4, the analogy process is shown. The local contact conditions, infeed a_e, stock Δs and profile angle φ of one position of the gear tooth profile are transferred to the grinding of a rectangular workpiece. In this way, all possible grinding conditions occurring along the profile can be examined separately.

The first trials using the analogy process have been carried out using a corundum-white grinding wheel, commonly used in industrial practice for gear profile grinding. The machining parameters have also been adjusted to those common in gear profile grinding. The trials were conducted on a Kapp VAS55P gear grinding machine in order to keep the pre-conditions in the analogy process as close to gear profile grinding as possible.

The workpieces are rectangular parts of the case-hardened steel 16MnCr5E, with a hardening depth of 0.9 mm. In the trials, a maximum total stock of Δs = 0.4 mm was removed in the grinding process. The hardness of 61 HRC was nearly constant from the surface to this depth. The workpieces were also ground before the trials in order to assure a constant surface quality and to remove the distortions from heat treatment. The material structure, the hardness and the residual stress profile are shown in Figure 5.

In Figure 6, the grinding forces in the normal direction (F_n) and in the tangential direction (F_t)—depending on the stock removal for different profile angles and a constant stock of Δs = 0.2 mm—are shown. It is obvious that, with a smaller profile angle, grinding forces increase and the possible stock removal is significantly lower. Especially in the steep areas, with a profile angle of $\varphi = 2°$, the initial grinding force is very high, and it increases rapidly, indicating that there is high wear of the grinding wheel.

However, for a large profile angle of $\varphi = 30°$, there is hardly any increase of the grinding forces with the stock removal. Thus, hardly any wear of the grinding wheel occurs. It can therefore be stated that the larger the local profile angle, the more material can be removed before a dressing operation of the grinding wheel is needed.

A reason for the tendency of the grinding wheel to wear earlier with a smaller profile angle can be attributed to the increasing contact length caused by a decreasing profile angle. The dependency of the grinding forces on the removed stock Δs is shown in Figure 7. The grinding forces in the tangential direction (F_t) and the direction normal to the surface (F_n) are displayed, depending on the stock removal for different Δs and a profile angle of $\varphi = 10°$. The grinding forces increase with the stock Δs, especially the maximum stock removal, until the super-proportional increase of grinding forces begins lowering significantly.

The results in the analogy process provide a better understanding of the effects occurring in gear profile grinding. It has been shown that gear geometries with a rather small profile angle lead to high grinding forces and to increased wear of the grinding wheel. And yet, it is rather difficult to transfer the results to the gear profile grinding process directly. At this point, one must analyze the local grinding conditions along the profile and attempt to find similar conditions in the analogy process. In order to more easily compare the profile grinding process to the analogy process, developing a process model is required. The model that has been developed is explained below.

Transfer of the Analogy Results to the Real Process of Gear Profile Grinding

Development of an empirical process model. As a first approach to the technological description of profile grinding processes, an empirical process model was developed to allow application of the results from the analogy process to profile grinding. In the analogy process, a large number of trials with profile angles varying from $\varphi = 2°$ to $\varphi = 90°$, and a stock varying from Δs = 0.05 mm to Δs = 0.4 mm, were conducted. A function shown in Figure 8 was chosen as an approach in order to calculate the grinding forces in profile grinding, based on the results of the analogy process. The coefficients were determined using the least-squares method. Grinding forces for conditions within the parameters tested in the analogy process are calculated using linear interpolation.

The graphs in Figure 8 show the correlation between the measured value and the calculated value for all three grinding forces in the different coordinate directions. A perfect result would be gained if all points were on the 45° line, meaning that the measured values are exactly the same as the calculated values. In this case, the graph shows quite clearly that the points are very

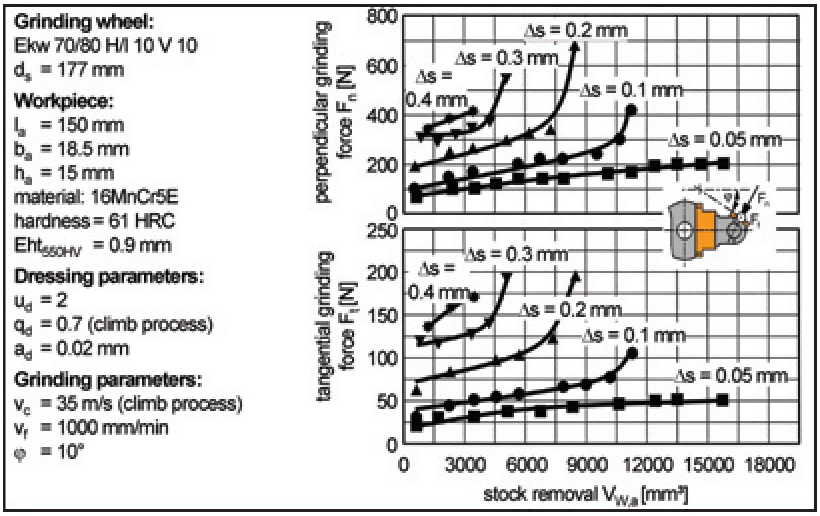

Figure 7—Grinding forces depending on the stock Δs.

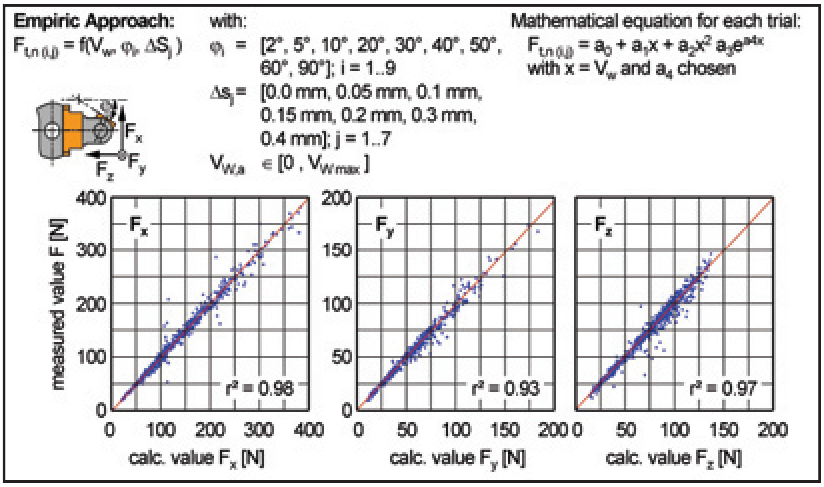

Figure 8—Development of an empirical process model.

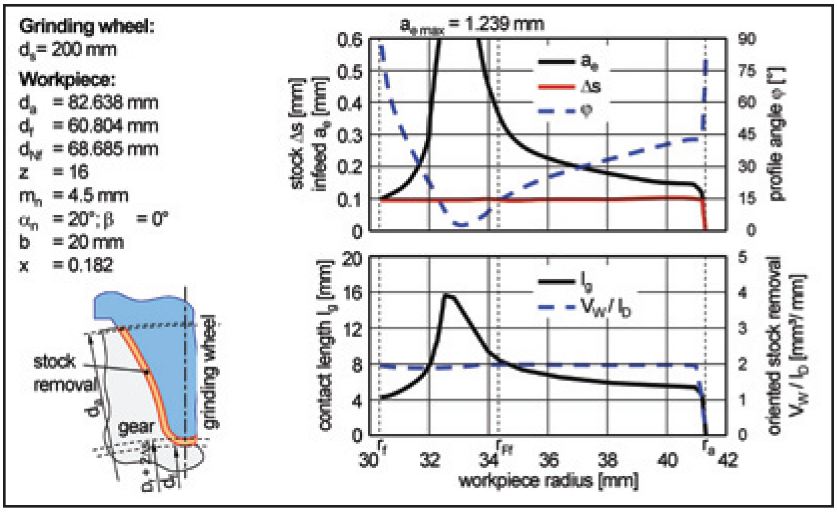

Figure 9—Local contact conditions in gear profile grinding with a constant stock Δs along the profile.

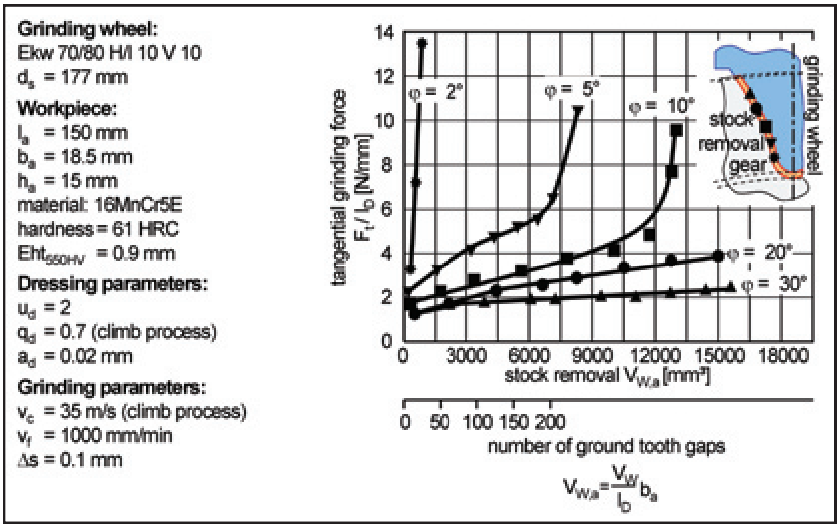

Figure 10—Transference of the analogy results to gear profile grinding.

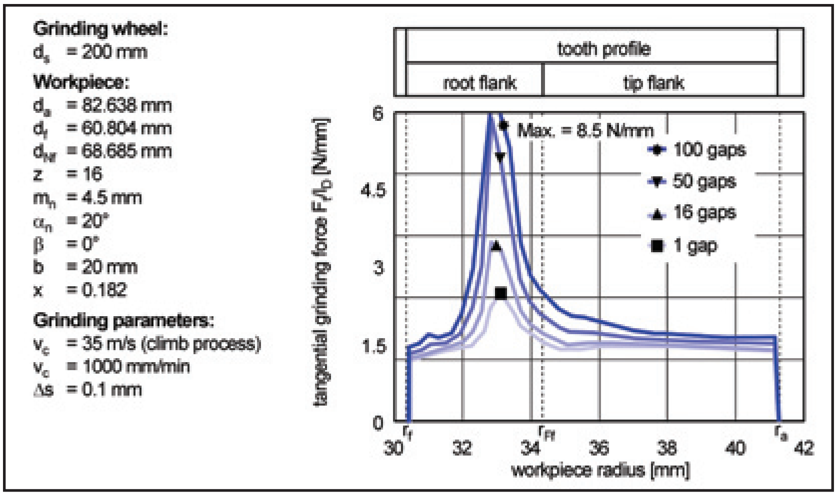

Figure 11—Local grinding forces when removing a constant stock Δs along the profile.

close to this line, and that there is a very good correlation between the measured and calculated values. Additionally, the stability index amounts to values between $r^2 = 0.93$ for the tangential grinding force, and $r^2 = 0.98$ for the grinding force in the direction of the x-axis—a good result in this case.

Calculation of local grinding forces in gear profile grinding. For the transfer of these results to the profile grinding process, a typical spur pinion with a gear geometry of the FZG-C gear was chosen. It has z = 16 teeth; a module of $m_n = 4.5$ mm; a pressure angle of $\alpha_n = 20°$; and an outside diameter of $d_a = 82.638$ mm. The grinding wheel diameter used to calculate the geometrical contact length l_g is $d_s = 200$ mm.

As a good first example, a grinding process with a constant stock Δs along the profile was chosen. This is a typical process occurring in single-flank grinding with an in-feed realized by the rotation of the workpiece. The stock amounts to Δs = 0.1 mm constantly along the profile geometry. The radial infeed a_e differs along the tooth flank due to the changing profile angle φ. It amounts to a maximum of $a_{e\,max} = 1.239$ mm in the area of the minimum profile angle $\varphi_{min} \approx 3°$ on the root flank. The distribution of the stock and the profile angle versus the local radius is shown in the upper diagram of Figure 9.

The lower diagram shows the calculated geometrical contact length along the profile, which varies from $l_g = 4$ mm in the tooth root, $l_{g\,max} = 16$ mm on the root flank, and $l_g = 5$ mm in the tip flank area. The stock removal related to the length of the considered contour element amounts to a constant value of $V_w/l_d = 2$ mm³/mm along the profile. So it can be concluded that, using this process strategy, the extreme values for the infeed a_e, as well as for the contact length l_g, can be found in the area of the root flank below the root form radius.

The grinding forces have been calculated for grinding 1, 16, 50 and 100 gaps. Even though the workpiece does not have more than 16 gaps, these calculations make sense in order to show the behavior of the grinding forces after a high stock removal, which can occur when grinding a similar gear with a much larger face width.

By knowing the local contact conditions, it is now possible to apply the results gained from the analogy trials to the gear profile grinding process. The first step is to transfer the analogy trials' contact conditions to each point of the gear profile. These calculated contact conditions are shown in Figure 10.

The different curves showing the tangential grinding forces versus the stock removal are representative of contact conditions occurring in the gear profile grinding process. The x-axis has a second label indicating the number of gaps being ground after removing a certain amount of stock. This method is rather time consuming, and it is only possible to determine the grinding forces in areas of the profile, i.e., where the contact conditions (stock Δs and profile angle φ) are known from the analogy process. Therefore, the calculations of the local contact conditions are used in order to calculate local grinding forces, as opposed to using the process model. The results of the calculations of the tangential grinding forces related to the contour length of l_d = 1 mm versus the workpiece radius are shown in Figure 11.

Those results show that the lowest grinding forces of $F_{t\,min}/l_d = 1.2$ N/mm can be found in the area of the largest profile angle, which is the tooth root. Along the profile geometry, the grinding forces are increasing up to a maximum of $F_{t\,max}/l_d = 2.3$ N/mm in the area of the root flank just below the root form radius, where the minimum profile angle φ_{min} is found. The grinding forces are then observed decreasing again, to $F_t/l_d = 1.5$ N/mm in the area of the tip flank with a rather high profile angle. Furthermore, these calculations show that the grinding forces are increasing most when machining multiple gaps in the area with the maximum grinding forces. In this area, initial grinding burn can be expected for this process strategy. This has already been shown by Schlattmeier (Ref. 2).

The most common process strategy in industrial practice is the radial infeed of the grinding wheel. In this case, the local stock Δs varies along the profile geometry. For typical trials, as well as for these calculations, a pre-ground gap is used in order to make sure that infeed a_e is constant along the profile. The important geometric values for a radial in-feed of $a_e = 0.235$ mm versus the workpiece radius are shown in Figure 12.

The local stock shows a maximum of $\Delta s_{max} = 0.235\text{ mm} = a_e$ in the area of the tooth root, and lowers to a minimum short below the root form diameter of $\Delta s_{min} = 0.02$ mm. Towards the tip flank, it increases again—to a local maximum of $\Delta s = 0.2$ mm. The contact length l_g is constant along the profile, but the oriented stock removal shows an absolute maximum in the tooth root, a minimum short below the root form radius, and a local maximum in the area of the tip flank.

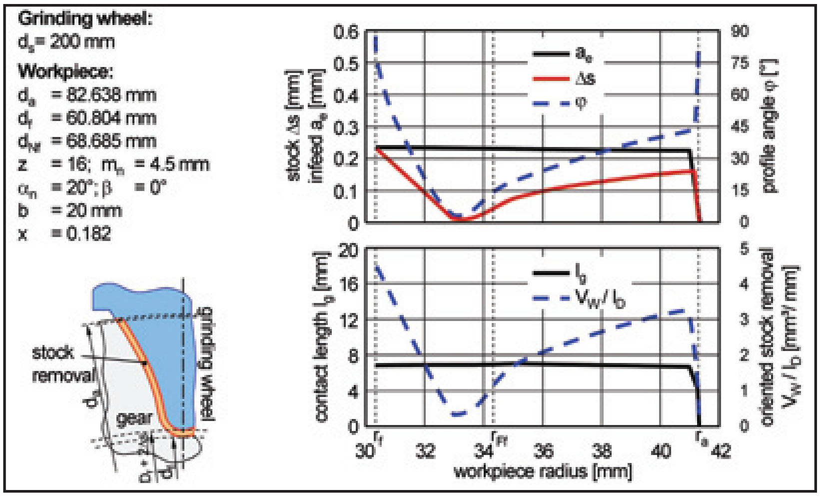

Figure 12—Local grinding conditions for a radial infeed of the grinding wheel.

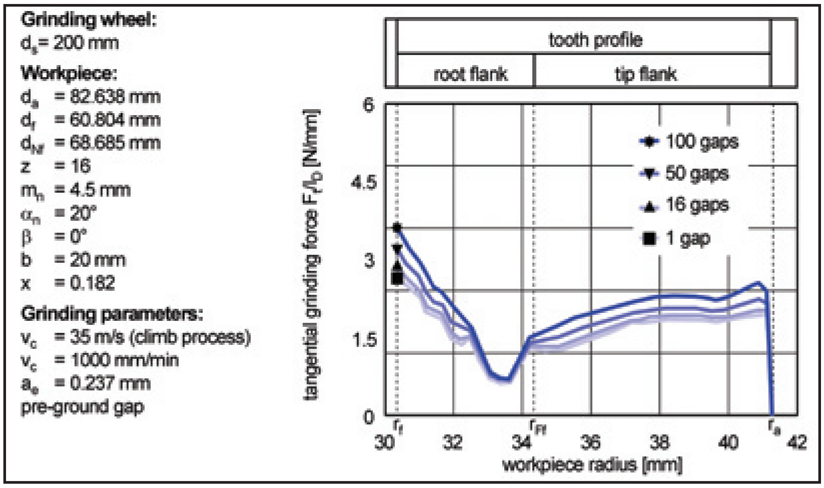

Figure 13—Tangential grinding forces for a radial infeed of the grinding wheel.

With this data, it is now possible to calculate the local grinding forces along the gear profile geometry. The calculations of the tangential grinding forces F_t versus the workpiece radius are shown in Figure 13.

The grinding force F_t shows a maximum in the tooth root and a minimum in the area of the root flank, just below the root form radius. Another local maximum can be observed in the area of the tip flank. After grinding multiple gaps in the area of the minimum forces, there is hardly any increase. But in the areas of the tooth root and the tip flank, grinding forces are increasing with the number of ground gaps. Increased grinding wheel wear can be expected, and grinding burn is most likely to occur in these areas.

With these calculations, it is known that in the areas found to be critical, grinding burn occurs when using a radial infeed strategy in gear profile grinding (Ref. 2). When grinding the gear with a radial infeed including the tooth root, a grinding burn occurs mostly at the tooth root. When grinding the gear with a radial infeed

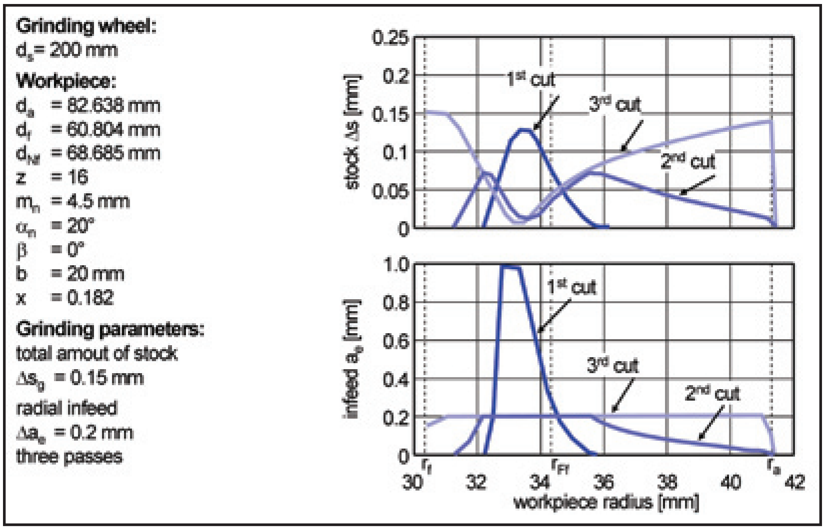

Figure 14—Local stock removal in infeed direction a_e and normal to the profile Δs.

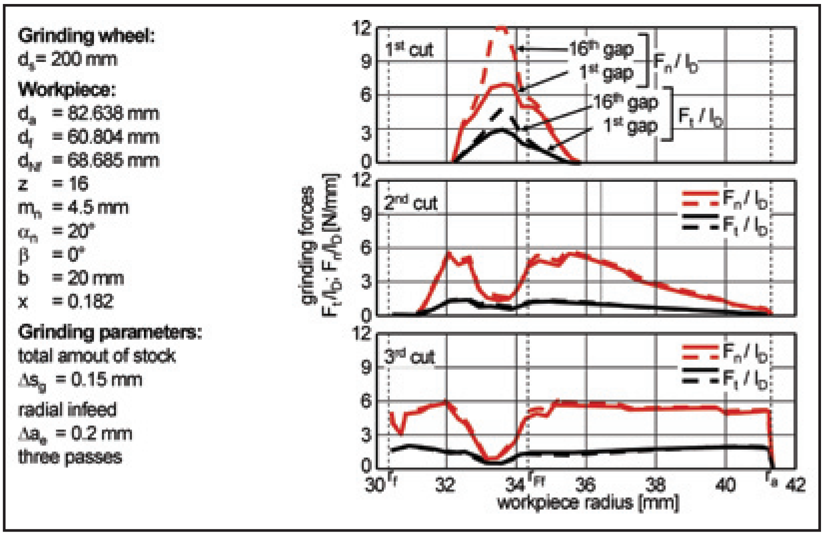

Figure 15—Tangential grinding forces for a radial infeed of the grinding wheel.

without the tooth root, the grinding burn is most likely to occur at the tip flank. These are the areas where, based on these calculations, the maximum grinding forces can be found.

Evaluation of Process Strategies Using the Process Model

Following is an example for the evaluation of process strategies, using the empirical process model to calculate local grinding forces. Grinding forces are calculated not only for one grinding step, but also for an infeed strategy using multiple steps, including deviations from the desired shape that can be due, for example, to centering deviations. It is only necessary to be able to calculate the local stock removed in the evaluated cut, as well as in the local profile angle. An example of this using the grinding of a test gear will be simulated with three radial infeed steps of 0.2 mm each. This means that the first cut takes place at a center distance between grinding wheel and gear which is increased by 0.4 mm, compared to the final center distance creating the final contour.

In Figure 14, the local stock in the direction normal to the tooth flank Δs and the stock in infeed direction a_e are shown. In the first grinding step, material is removed from the gear flank only in the area of the root flank. In the infeed direction, the infeed into the material is up to a_e = 1.0 mm, which means that a stock in normal direction of Δs = 0.13 mm is removed. The result is that, in the area of the root flank, nearly all the stock is removed by completion of the first step. In the last step, material is removed along the whole profile, and the radial infeed amounts to a_e = 0.2 mm.

This is because the whole profile height has been ground in the second step. In the area of the root flank, only a very small amount of stock is removed in the normal direction. While in the area of the root and tip flanks, nearly all stock is removed in the last cut.

The resulting grinding forces for these contact conditions are shown in Figure 15. The upper diagram shows the grinding forces in cutting and normal direction for the first cut. The drawn-through lines show the grinding forces when grinding the first gap with a newly-dressed grinding wheel. The broken lines show the grinding forces for grinding the sixteenth and last gap in order to gain an impression of the development of the grinding forces with the set-in time of the grinding wheel.

In the area of the root flank, very high local grinding forces can be seen, and those forces are increasing quite a lot with an increasing stock removal. This means that this area is susceptible to grinding burn in the first grinding step. To reduce that burn risk, the center distance between the grinding wheel and the workpiece must be increased. However, this will require more cuts and thus increase the manufacturing time on the machine tremendously.

In the last grinding step, the grinding forces are smaller than in the first. There is also a smaller increase of those forces, with an observed increase of material removal. It is nevertheless apparent that the grinding forces are increasing towards the tip flank and the tooth root. This means that these areas are very sensitive to grinding burn when using an infeed strategy for a radial infeed of the grinding wheel. These areas are known to be most critical towards grinding burn, which can be seen in the grinding forces (Ref. 2).

It can thus be concluded that the areas most critical to grinding burn can be evaluated by a calculation of the local grinding forces. While the area of the root flank is most susceptible to grinding burn occurring in the first grinding step, the areas of the tooth root and the tip flank are most susceptible for burn in the last grinding step. Using this calculation of the grinding forces, it can be evaluated qualitatively how critical a gear geometry is in relation to grinding burn towards another, and if the chosen infeed strategy is critical as well.

Summary and Outlook

Gear profile grinding, especially using dressable grinding wheels, is a process rather sensitive to grinding burn. It therefore is important to understand the process well in order to either prevent grinding burn or, at minimum, if a grinding burn appears, to be able to change the process in a way that prevents it. This is especially important since grinding burn reduces the hardness of the external layer, and leads to tensile stresses which reduce the load-carrying capacity of the gear, thereby making gear failures more likely.

The main consideration when trying to better understand the process of gear profile grinding is the constantly changing contact conditions along the profile. In real process trials, only effects resulting from all those contact conditions along the profile can be observed. And since grinding burn, in most cases, occurs only locally, the effect on values like grinding power or grinding forces often cannot be seen initially.

In order to attain better knowledge of the effect of local grinding conditions on the process behavior, an analogy process was established to analyze them.

Rectangular workpieces were ground in a clamping fixture that can be turned in order to set the different profile angles occurring on a tooth flank. Particularly in this analogy process, grinding forces have been measured. The results reveal that grinding steep profile angles leads to a high risk of grinding burn, which can be due to the increasing contact length, and, in turn, can lead to a higher amount of energy conducted into the workpiece. The main goal of these tests is to facilitate an understanding of the real-time process.

Since the amount of heat conducted into the material is proportional to the cutting force, a process model has in fact been developed for calculation of local grinding forces. This model enables calculation of local grinding forces, provided local contact conditions and the set-in time of the grinding wheel are known.

With the aid of this process model and CASTOR software (with the ability to simulate different gear finishing processes), various process strategies in gear profile grinding can be considered and analyzed. Calculations show that in a radial infeed strategy of the grinding wheel in the first cut, maximum forces are calculated in the root flank area. In the last cut, the maximum is calculated in the tooth root and the tip flank—areas known to be most exposed to grinding burn. With these calculations, the reasons for this exposure can be demonstrated. They also demonstrate that for the removal of an equidistant stock along the profile, the maximum forces can be observed in the area of the root flank. This is also the area known from the real process of gear profile grinding to be most sensitive to grinding burn.

In order to evaluate the risk of grinding burn, both qualitatively and quantitatively, future research must focus on developing a specific value. Since the level of grinding forces observed depends very much on the ground profile angle, the goal in developing a specific value is finding a limit where, if the value exceeds the limit, grinding burn can be observed independent of the contact conditions.

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