Surface Damage Caused by Gear Profile Grinding and Its Effects on Flank Load Carrying Capacity

Prof. Dr.-Ing. Fritz Klocke and
Dr.-Ing. Heiko Schlattmeier

Management Summary

Instances of damage to discontinuous form ground and surface-hardened gears, especially of large scale, have recently increased. This may be attributed partly to a faulty grinding process with negative effects on the surface zones and the surface properties.

The studies reported in this article are intended to contribute to the knowledge of the interrelationships between surface zone damage and the effects on flank load-carrying capacity for the case of profile grinding.

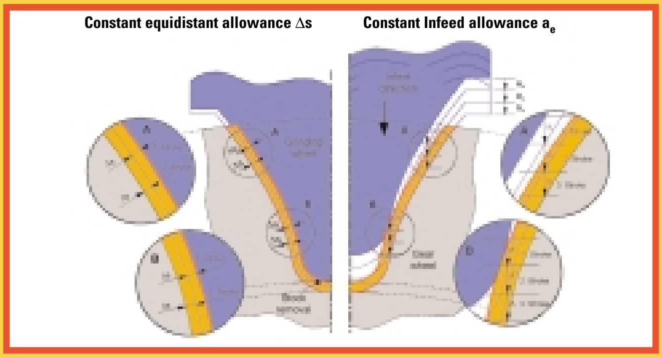

Figure 1—Stock allowance at tooth flank profile grinding.

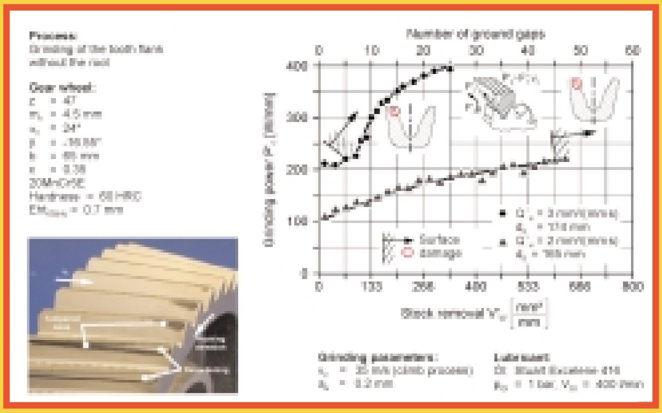

Figure 2—Grinding power and surface zone, depending on constant infeed allowance (without tooth root).

Introduction

In addition to its high accuracy, discontinuous form grinding is characterized by high material removal rates because of the line contact between grinding wheel and tooth flank. The efficiency and reliability of the process are affected not only by the use of optimized grinding wheel specifications and machining parameters, but also by the risk of local surface zone damage in the form of grinding burn on the tooth flank.

The location and onset of local grinding burn damage have seemed for a long time to be random and unpredictable, for which reason the feed rates and material removal rates have been increased only incrementally in procedures used in industrial practice.

Grinding tests have been conducted in order to investigate more closely the occurrence of surface properties in the form of grinding burn as a function of grinding parameters. Further studies of the flank load carrying capacity of case hardened gears subjected to different surface properties are intended to provide a more detailed analysis of the interrelationship between gear geometry and different surface properties during the grinding process.

Research of Grinding Burn at Tooth Flank Profile Grinding

Nital etching is used in a lot of industrial applications to review a ground gear regarding structural damage caused by grinding burn (Refs. 6, 8). This method shows a positive result if the surface zone of the ground gear shows light and dark differences. Although different grinding processes cause different distributions and intensities of structural damage, those distributions are not taken into account for the estimation of the load carrying capacity.

The target of a first step is to examine the area where the thermal damage occurs at the flank by systematic tooth profile grinding. In addition to grinding the tooth flanks of the gear wheel, grinding the tooth root will also be considered. The grinding tests may give further information, regarding which areas of the tooth flank and the root are susceptible to thermal damage by grinding burn.

Geometrical Research of Stock Allowance

At the precutting of spur gears, different standard tool profiles can be used, depending on the chosen machining process (Ref. 10). In the case of gears to be hard finished, there remains extra stock after precutting at the tooth flank. This stock can be described as a constant equidistant allowance Δs.

Fig. 1 gives an overview of the shape of stock allowance along the profile geometry depending on the form grinding process and the number of strokes. Also, it is necessary to distinguish between form grinding with constant equidistant allowance Δs and with constant infeed allowance a_e.

When grinding smaller spur gears, the stock can be removed in only one stroke of the grinding wheel. But when grinding bigger gears, a lot of grinding strokes may be required to finish the gear wheel, because of high deviations after premachining and carburizing. The number of grinding strokes and the geometry of the grinding wheel will determine the shape of stock along the ground tooth gap for each stroke. Additionally, the contact conditions between the grinding wheel and the tooth gap depend on the local contact conditions. These parameters should be considered when analyzing grinding trials and developing the tooth form grinding. In the case of profile grinding, including the tooth root and removing a constant equidistant allowance Δs along the whole profile geometry, the small figures on the left side show in detail that the stock in infeed direction a_e increases from the tip of the tooth nearly to the area of the root at the flank. Removing the stock this way is possible when using different grinding wheels with electroplated CBN or changing the wheel geometry by dressing. That is why a higher amount of material will be removed from the tooth flank near the tooth root (Ref. 11).

The removal of a constant stock in infeed direction occurs when grinding with a constant wheel geometry in more than one stroke (Fig. 1, right). This process is used in most industrial applications when grinding high module gears. The details from the tip and the root area of the flank show that the stock in equidistant direction decreases along the flank geometry. In contrast to grinding with a constant equidistant allowance, the maximum stock will be removed in the area of the tip in the last stroke.

In comparing the different forms of stock at the root of the tooth gap, the figures show that a higher stock removal happens in case of grinding with a constant infeed allowance compared to grinding with a constant equidistant allowance.

The geometrical results explain that the local stock removal varies along the profile of the tooth gap and the local strain of the flank also depends on the local stock removal and the wheel geometry. It can be expected that the area of grinding burn depends on the local stock removal and the local contact conditions between the grinding wheel and the tooth gap when grinding with different process strategies.

Grinding Research of Stock Allowance

For the investigations, a helical gear with a number of teeth of z = 47, a module of m_n= 4.5 mm and a helix angle of β = –16.55° was used. The pressure angle has a value of α_n = 24°. The material of the workpiece consists of a carburized steel 20MnCr5E, with a surface hardness of 60 HRC and a case hardening depth of Eht_{550HV} = 0.7 mm. The profile and the lead are not modified.

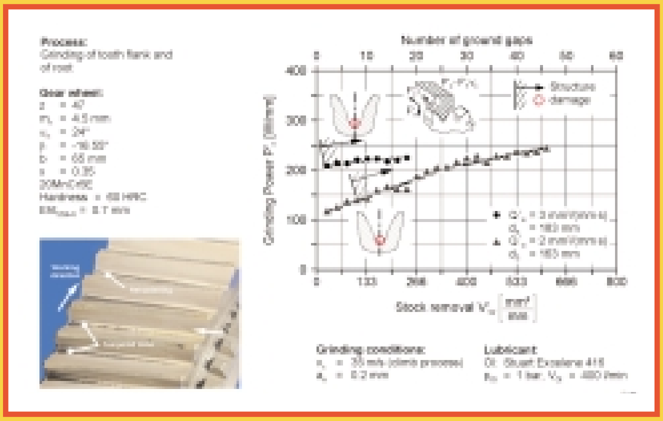

Figure 3—Grinding power, depending on infeed allowances (including tooth root).

For the grinding trials, a grinding wheel with a specification of 53A60 K5V made of conventional corundum is used. A wheel with a high bonding hardness and a cohesive structure was used. Such a grinding wheel is very likely to cause structural damages of the surface structure even with just a low amount of stock removal. The trials will be conducted on a modern gear grinding machine. To guarantee the same grinding conditions, all helical gears are pre-ground with the same dressing and grinding conditions before the trials are made.

Before the grinding test is conducted, the grinding wheel is always dressed with the same dressing conditions. According to a finishing process, the following data will be chosen—a dressing infeed of a_d = 0.01 mm, a contact ratio of u_d = 8.0 and a speed ratio in counter direction of q_d = –0.8. In the grinding tests, the tooth space allowance is removed consistently in one cut, at a speed ratio of v_c = 35 m/s in the same direction. The cooling lubricant is supplied by two jet nozzles, which are arranged tangentially to the grinding wheel diameter.

Constant Infeed Allowance

In a first step, the occurrence of a structural change on the tooth flanks should be examined. The structural change is caused by grinding with constant infeed allowance of a_e = 0.2 mm, without additional machining of the tooth root for a different material removal rate. According to the usual definition of the relative material removal rate, $Q'_w = a_e \cdot v_f$, a feed speed of v_f = 600 mm/min is calculated for a relative material removal rate of Q'_w = 2 mm^3/(mm · s) and for a relative material removal rate of Q'_w = 3 mm^3/(mm · s), a feed speed of v_f = 900 mm/min. is calculated.

Prof. Dr.-Ing. Fritz Klocke

is head of the Chair of Manufacturing Technology and a member of the directory board of the Laboratory for Machine Tools and Production Engineering (WZL), a department of the Aachen University of Technology in Germany. Also, he is head of the Fraunhofer Institute for Production Technology in Aachen, Germany.

Dr.-Ing. Heiko Schlattmeier

is the chief engineer of the WZL Gear Research Department of Aachen University of Technology. For the past five years, he has been working on hard gear finishing and gear form grinding.

For the evaluation of the grinding process, the relative grinding power P'_c is evaluated over the relative equidistant allowance V'_w in Fig. 2.

The relative grinding power increases during the operating time, independently of the chosen stock removal rate. This can be attributed to the fact that, with increasing operating time, the grinding wheel topography is being changed by wear.

For instance, grain flattening causes an increase of friction in the machining process, which again causes an increase of the grinding power and a higher heat contribution to the tooth flank surface. The consequence of inserting a higher heat amount is a structural change at the tooth surface (Refs. 12, 13).

A comparison of the trials with different relative stock removal rates shows that the relative grinding power is on a lower level if a lower relative stock removal rate of $Q'_W = 2$ mm^3/(mm · s) is chosen. This can be attributed to a lower stock removal per time unit. Beginning at a stock removal rate of $V'_W \approx 550$ mm^3, which corresponds to a machining of 45 tooth spaces, an impact on the structure of the flank appears. In a trial with a higher relative stock removal rate of $Q'_W = 3$ mm^3/(mm · s), an impact of the structure occurs already from an equidistant allowance of $V'_W \approx 60$ mm^3 on, and the grinding power increases in a disproportionate manner.

In both trials, the structural damage occurs near the tooth tip, as it can be seen on the etching image of the tooth flanks with the orientated stock removal rate of $Q'_W = 3$ mm^3/(mm·s). The structural damage begins on the running out of the grinding wheel from the gearing on one side of the tooth flank and increases with every additional machined tooth space.

According to the machining of a tooth gap using a climb process, the beginning structural damage in the running-out of the grinding wheel can contribute to a declined coolant supply into the gap. It is furthermore visible that the extent of the flank damage is increasing up to the formation of a new hardening area, yet the location of the structural damage over the profile does not change. This phenomenon is caused by a local overload of the grinding wheel.

In the following, the grinding of the tooth root will be examined. Therefore, the tooth surfaces of the workpieces are already machined in the rough grinding process in order to guarantee constant trial conditions. Like in previous examinations, the machining is done in one cut with a constant infeed allowance of the grinding wheel of $a_e = 0.2$ mm.

Fig. 3 shows the orientated grinding power over the relative removal for different orientated material removal rates.

The orientated grinding power increases during the cumulative operating time, independent of the feed speed, which is caused by the wear of the grinding wheel topography. If an orientated stock removal rate of $Q'_W = 2$ mm^3/(mm·s) is chosen, the orientated grinding power is on a lower level compared to the trial with an orientated stock removal rate of $Q'_W = 3$ mm^3/(mm · s). Compared to the examinations in which the tooth root was not machined, an impact of the structure of the ground tooth profile occurs definitely earlier, not near the tooth tip but in the tooth root.

Pictures of the etching of the experimental gears show that the structural damage in this case also begins on the running out of the grinding wheel of the tooth space, and the damage also rapidly increases to form a new hardening area in the tooth root. In this trial, a structural damage on a tooth flank does not occur.

Geometrical considerations of a constant stock infeed allowance of the grinding wheel should help to find the reason for the structural damage on the tooth tip and root (Fig. 4).

The diagram shows, by means of the chosen gear geometry, the equidistant and the infeed allowance of a grinding wheel in a normal section. The calculations are done by means of the constant infeed allowance of $a_e = 0.2$ mm, which was chosen in the previous trial. The allowances are determined for every single point of the gear profile between the tip circle radius and the root circle radius and then removed. The diagram shows how the allowances change over the profile height.

It is furthermore visible that the equidistant allowance in the area of the tooth flank is definitely lower than the infeed allowance. Beginning from the tooth tip radius, it decreases first over the profile height in the direction of the tooth root and reaches its minimum near the tooth root form radius, where the tooth flank develops to the root surface. The equidistant allowance increases rapidly in the direction of the tooth root. On the root circle radius, it corresponds to the value of the infeed allowance.

In the trials in which the tooth root was not machined, an impact of the material structure occurs in the area of the tip flank (Fig. 3). The structural damage in this area contributes to the fact that the tip flank has more material volume which has to be removed than the root flank.

In the trials in which the root was machined as well, a grinding burn occured in the tooth root after machining only a few tooth spaces. This can also be explained with the fact that the local material volume that has to be removed by the grinding wheel is higher than the one in the tooth flank. The results show that, in the grinding process with constant infeed allowances, the area near the tooth tip is imperiled with regard to grinding burn. If the tooth root is ground too, it can be assumed that a structural damage caused by grinding will first occur in the tooth root.

Constant Equidistant Allowance

Based on the examinations on the constant infeed allowance, examinations on equidistant stock allowance will be done. Since the removal of an equidistant allowance is only possible by means of a change in gear profile, the tooth flanks are preground with a higher addendum modification factor and root circle diameter.

Previous to test grinding, the grinding wheel is profiled on the final shape again and dressed with the same parameters. The grinding process is performed with a cutting speed of $v_c = 35$ m/s using a climb process. The average infeed allowance of the grinding wheel approximately amounts to $a_e \approx 0.2$ mm for this gear geometry with an equidistant allowance of $\Delta s = 0.1$ mm.

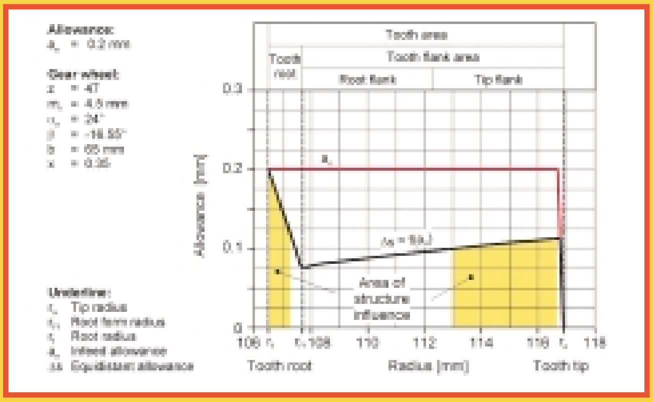

Figure 4—Equidistant allowance, depending on infeed allowances.

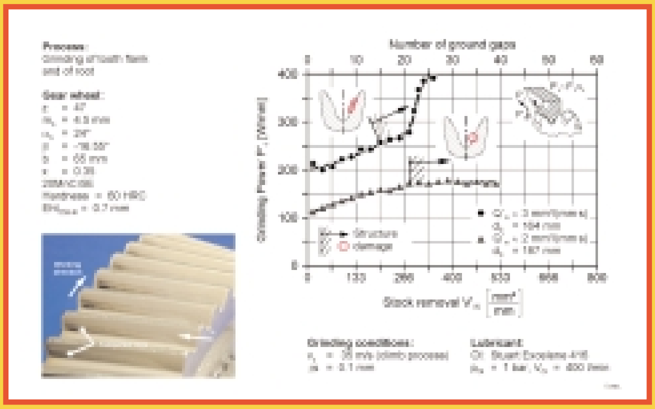

Figure 5—Grinding power, depending on equidistant allowance.

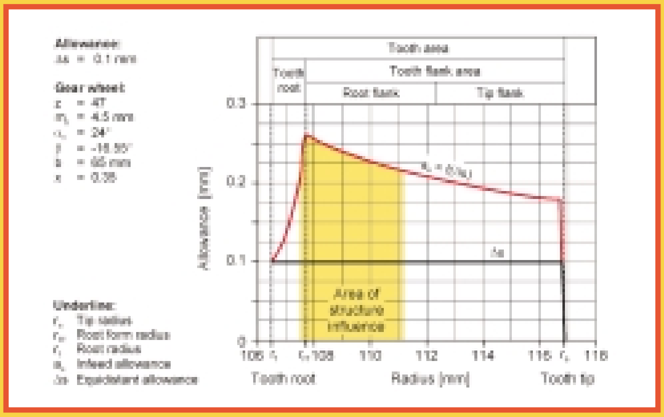

Figure 6—Infeed allowance, depending on equidistant allowances.

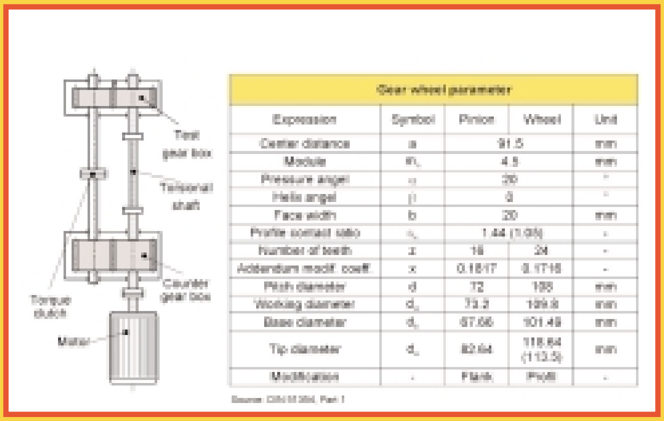

Figure 7—Gear test rig and gear geometry.

If axial advance speeds of v_f = 600 and 900 mm/min are chosen, orientated stock removal rates of $Q'_W \approx$ 2 mm³/(mm · s) and $Q'_W \approx$ 3 mm³/(mm · s) can be calculated. The tooth root is machined as well in these examinations.

To examine the operational behavior, the orientated grinding power is applied over the orientated stock removal for different stock removal rates in Fig. 5.

For both chosen stock removal rates, the orientated grinding power increases with a constant equidistant allowance during the cumulative operating time in the grinding process due to the wear. Therefore, the grinding power in the experiment with the lower orientated stock removal rate of $Q'_W \approx$ 2 mm³/(mm · s) is running on a lower level and the structural damage on the tooth flank occurs from an orientated stock removal rate of $V'_W \approx$ 300 mm³/mm (22 spaces) on. In the experiment with a higher orientated stock removal rate of $Q'_W \approx$ 3 mm³/(mm · s), the stock removal is $V'_W \approx$ 200 mm³/mm (15 spaces) before the grinding burn occurs.

In both cases, the impact on the structure occurs at first in the area of the tooth root flank. The structure impact gets stronger for every single tooth space in the feed direction of the grinding wheel. This could also be attributed to a worsening cooling lubricant insert in the running out area of the grinding heel. Contrary to the examinations with the constant infeed allowance a_e, the surface of the tooth root is not thermally affected by the machining.

In order to interpret the location of the structural damage over the tooth profile, new geometrical considerations will be made. Therefore, the infeed allowance a_e will be calculated over the gear profile for a constant equidistant allowance of Δs = 0.1 mm in the normal section of the gap (Fig. 6).

The diagram shows that the infeed allowance is higher than the equidistant allowance Δs and that it increases beginning from the tip circle radius in the direction of the tooth root. In the area of the root form circle, the infeed allowances reach a maximum. In the tooth circle radius direction, the infeed allowance decreases. After reaching the root circle radius, it equals the equidistant allowance of Δs = 0.1 mm.

Exactly like in previous geometrical considerations, the reason for a beginning of the structural damage in the area of the tooth flank can be seen in the removal of a high local material volume in the area of the root form circle radius. Due to the low local material volume in the tooth root, there are no thermal structural damages occurring in the examinations in this area. The examinations show that, in the grinding process with a constant equidistant allowance, it has to be anticipated that thermal structural damage can occur in the area of the root flank. It is not assumed that premature structural damage can occur in the tooth root.

Research of Flank Load Carrying Capacity Caused by Case Hardened and Tooth Flank Profile Ground Gears

The focus of this research is to show the difference between the structural damage caused on the tooth flank by grinding burns and the damage caused by the tooth flank loading. Therefore, the flank loads for different torques are examined in the first step. In a second step, the flank load over the profile height should be varied through a change of the profile contact ratio.

Testing Preparation

The research of the flank load carrying capacity of case hardened gears is conducted on a standard gear test rig according to DIN 51354 with a center distance of a = 91.5 mm (Ref. 14). The torque is mechanically arranged using a torque clutch, and a capacity loop is built up over a torsion axle, a gear train and a test gearbox. In the execution of the test, the test gear wheel is actuated with a speed of n_1= 3,000 min^{-1} . The lubricant supply is realized using a jet lubrication with an oil temperature of 90°C. Tribol 1100/220 oil is chosen as lubricant because it has a high viscosity, which guarantees a high safety with regard to gray discoloration on the tooth flank.

Beside the principle test rig arrangement, the chosen gear geometry is shown in Fig. 7.

Since the flank damages of case hardened gears should be examined in their dependency of the workpiece surface changes which are caused by grinding, all used gears must have preferably consistent gearing qualities and surface roughness.

Therefore, a grinding wheel of the specification 53A120 J6V is used in the hard finishing process, because it has a small grain size, a high bond hardness and a closed structure, which all lead to structure changes on the tooth flank even if a low relative stock removal rate is being used. Furthermore, the use of this grinding wheel guarantees that the surface roughness will not be explicitly changed even if the feed speed is increased. The allowance characteristic corresponds to a constant infeed allowance, so that the structural damage occurs on the tooth flank tip. The tooth root surface is not machined. The analysis of the changes in the workpiece surface structure is conducted after the etching process (Ref. 8). The question of whether a beginning structural damage on gears leads to a reduction of the flank load carrying capacity is especially interesting in this case. Therefore gears with a low grinding burn on the tooth flanks are used in this research. For the analysis of the load carrying capacities, some additional test gear wheels are used. Some are without grinding burn and some have higher damage up to the formation of a new hardening area.

Independent of the chosen stock removal rate, comparable roughness on the tooth flank can be achieved. The values of the average roughness depth lies between R_z = 3 and 4.3 µm and the values of the arithmetic average roughness about R_a = 0.6 µm. The surface roughnesses are alike so that this does not influence the results. Residual stress measurements on the flank surface should confirm the different workpiece surface characteristics over the profile height, which were previously assumed by means of etching. The residual stresses, which are measured on the tip flank in the area of the grinding burns and on the root flank, are displayed in tangential and axial direction in Fig. 8.

Independent of the measuring point, compressive residual stresses are realized on the test gear wheel without a structural

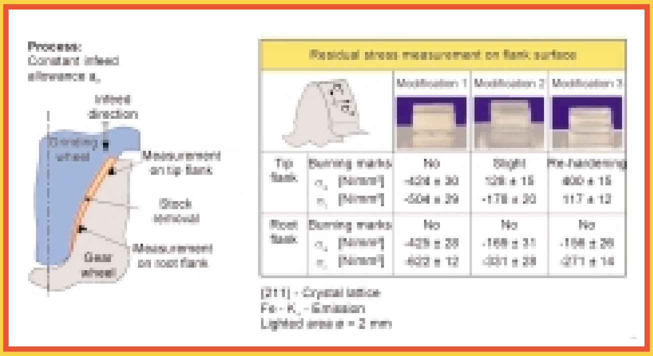

Figure 8—Residual stress, depending on tooth flank profile grinding.

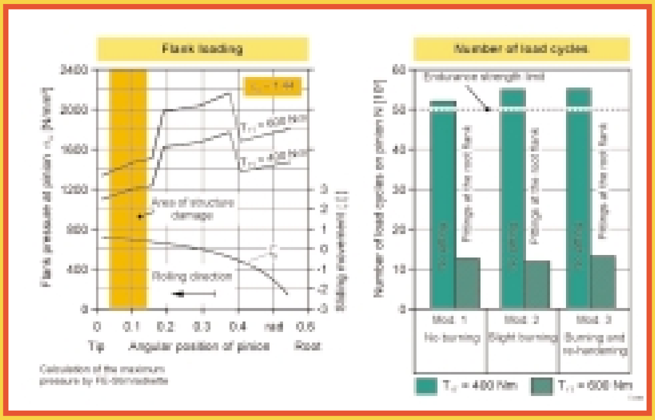

Figure 9—Flank pressure and load reversal, depending on different torques.

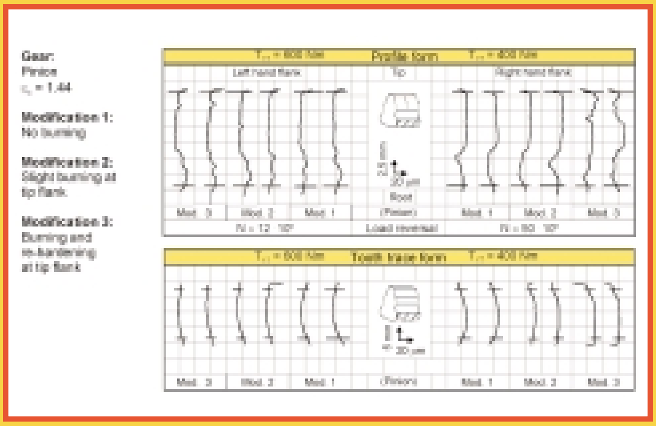

Figure 10—Test gear wheels after use, depending on different torques.

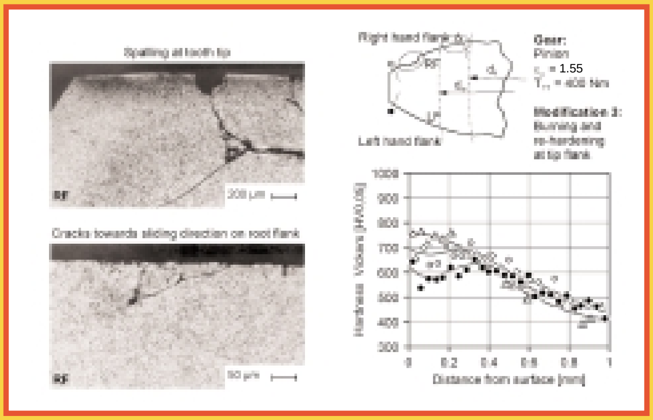

Figure 11—Structure and hardness measurements after use.

change in axial and tangential direction in a height of σ_a = –425 N/mm^2 and σ_t = –504 to –622 N/mm^2. Due to the increase of the feed speed, it comes to a change of machining conditions and of the heat, which is induced into the gear surface. The compressive residual stresses are reduced on the tip flank as well as on the root flank.

The same could be realized in the examinations of other grinding processes (Refs. 7, 15, 16). In the area of the tempered zone in the tooth tip, the tensile stresses have to be measured in tangential direction with a value of σ_t = 128 N/mm^2. The measurements on the tip flank show that tensile stresses increase if a new hardening area occurs. Compared to this, tensile stresses in the root flank still cannot be measured.

Research Depending on Different Torques

To analyze the damage that occurs on the tooth flanks in the running tests depending on different structural damages, the flank load is displayed in Figure 9 over the angular position of the pinion in a profile contact ratio of ε_α= 1.44. Furthermore, the figure shows the number of load cycles on the pinion that are bearable for the different used control variants. Different load levels result, depending on the chosen torque.

Single areas on the tooth flanks are differentially charged depending on their generating position during the process of generating the test gearing (Refs. 4, 5, 17). If a torque amounts to T_{1T} = 400 Nm at the contact beginning, a flank pressure of σ_H = 1,500 N/mm^2 is calculated. A double tooth contact occurs in this area, due to a profile contact ratio of ε_α= 1.44. The maximum flank pressure increases at first in the area of the double teeth contact, from the root into the direction of the tip of the pinion, until the maximum flank pressure jumps up to almost σ_h = 1,800 N/mm^2 in the inner single tooth contact point.

In the following generating process of the gear, the flank pressure is reduced in the direction of the tooth tip in the single tooth contact area as well as in the double teeth contact area. This can be explained through a reduced flank curvature and a higher sustained effect on the pinion. The overlap of the normal stress and the sliding movement has an essential influence on the load bearing capacity of gears (Ref. 17). The specific sliding is therefore shown for different angular positions on the pinion. The area of the negative slippage at the involute is always situated between the tooth root of the impulsive gear and the generating point. The generating speed and the sliding speed are arranged contrary to one another in this area. Extensive research of the flank load carrying capacity shows that the pitting damage occurs mostly in the area of the negative slippage (Refs. 17, 18, 19, 20).

The diagram additionally shows the location where the structure area, which is damaged by the grinding process, is generated on the pinion. The area of the structural damage is loaded with a low flank pressure and lies in the area of the positive slippage. On the right side of Fig. 9, the number of load cycles of the pinion is applied for the different test variants depending on the torque. A pitting size of 6 mm^2 on a flank of the pinion is defined as the damage criterion. The examination shows that there is no difference with regard to the bearable load reversal at a torque of T_{1T} = 400 Nm, independent of a structural impact on the tip of the pinion. The experiments were aborted after a running time of 300 hours. Contrary to that, the test torque collapses early at a torque of T_{1T} = 600 Nm, because of pitting damages which occur closely underneath the generating circle. Yet here is still no visible difference between the single variants with regard to the load carrying capacity.

Measurements of the profile form and the tooth trace form of the used pinion on the teeth without pitting damages show locations in which the tooth flank is mostly impacted during the operation (Fig. 10).

Independent of the test variant and the chosen torque, there are visible deviations of approximately 10 µm in the lower area of the root flank. The deviating point is a plastic deformation of the material during the running or at fatigue phenomena of tooth flanks (wear). The pitting in this area in experiments with a torque of T_{1T} = 600 Nm can contribute to the high local flank pressure and the negative slippage (Ref. 17).

On the pinion with a new hardening area, profile form deviations occur independently of the load level at the tip flank, as it can be clearly seen on the right tooth flank after a number of load cycles of $N \approx 50 \cdot 10^6$ at a torque of T_{1T} = 400 Nm. The local generating load of the material in the area of the flank tip is lower because of the lower flank pressure and the positive slippage. The deviations therefore point at the fact, that the load carrying capacity of the material is strongly reduced in the fringe structure, which is damaged in the grinding process.

The lead trace, measured on the pitch diameter, shows no reinforced deviations compared to the gears which were not used. The convexity is still existent, so that a curtailing of the experiments through the gearing deviants in the running-in or the running-out area of the grinding wheel can be excluded.

The destructive pitting at a torque of T_{1T} = 600 Nm is clearly visible in the area of the tooth flank underneath the pitch circle d_w, as other investigations show. If a torque of 400 Nm is chosen, a destructive pitting does not occur. In this case, only initial pitting or gray discoloration occur closely underneath the pitch circle.

Smaller material break-outs can be found on the tip flank of the gearing beside rills in the lead direction. Since the rills could also have been partially caused by the grinding process, the chipping could also be seen as initial pitting and attributed to the material fatigue, which is caused by the generating load. Since the little material break-outs can be found on both test gears, the damage cannot be attributed to the slight impact of the structure, which is caused by grinding.

Compared to this, in the examinations in which a torque of T_{1T} = 400 Nm was chosen, the damages occur in the tip flank too. Yet, there are no damages in the area of the grinding burn, which could have led to a breakdown of the gearing within 300 hours.

The realized flank damages should be analyzed more exactly by means of structure research (Fig. 11). The structure images show, by the means of a dark tempered zone and a thin new hardening area, the gear damage caused by the grinding process. By means of the material structure, it becomes obvious that the structural damage is strongly shaped in the area of the tip flank. Compared to the damage on the root flank, the tip flank has some deep cracks, which are processed normally to the flank surface and deeply into the surface. In a depth of approximately 6 mm, the cracks process parallel to the flank surface. The course of the cracks indicates that, during the further use of the test pinion, a massive damage in the form of a large surface of material break-outs of the tooth flank, or a break of the tooth in the tip area, could have occurred.

This realized damage could have been caused by the high measured tensile stresses in the structural damaged zone by grinding burns, which leads to an exceeding of the material stability (Refs. 7, 17).

In the area of the structural damage, the hardness on the tooth flank surface is reduced for at least 100 HV0.05, beginning from 750 HV0.05, measured on the undamaged structure in the area of the flank root. Since the stability of metallic materials depends on the material hardness (Ref. 21), the strong decrease of the hardness in the area of grinding burns indicates a reduced load carrying capacity of the surface.

Contrary to this, the area underneath the pitch circle shows only a low cleft formation in the fringe area. The cracks are running contrary to the sliding direction and are typical for gears under generating load (Ref. 17).

Metallographical examinations additionally show that a strong damaging of the fringe through the grinding process can also be recognized on used gears and that evidence is derivable on turned-out gears.

Research Depending on Profile Contact Ratio

In this section, the influence of an increasing flank loading, in the area of the damaged workpiece material, on the number of tolerable alternations will be shown. The area where pitting occurs does not change through an increasing torque. Therefore the test gearing needs to be modified. For that reason the contact ratio is reduced from ε_α = 1.44 to ε_α = 1.05 by reducing the tip diameter of the mating gear. Fig. 12 shows the resulting flank pressure versus the angular position of the pinion for a torque of T_{1T} = 400 Nm.

A comparison of the distribution of the flank pressure for equal torque shows that the contact distance has decreased. The pinion's tooth root comes into contact with the tip of the mating gear at a later point in time. This reduces the area with double tooth contact significantly so that the flank pressure escalates in the area of single tooth contact. The calculations show that, in the running-in area, the maximum pressure is equal for both contact ratios. For the gear with the contact ratio of ε_α = 1.05, the gradient of the flank pressure is relatively constant for all angular positions and just decreases in the tip area of the pinion. The gradient of the flank pressure indicates that in the area of structural damage, the loading of the flank is sig-

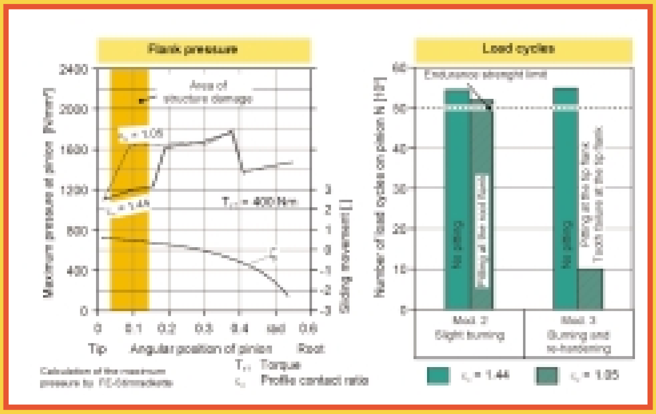

Figure 12—Flank pressure and load reversal, depending on profile contact ratio.

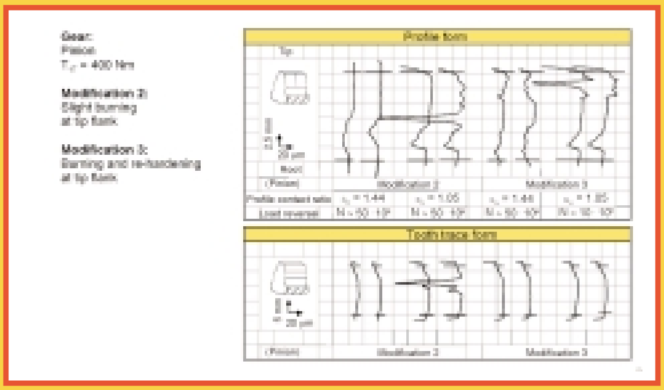

Figure 13—Test gear wheel after use, depending on profile contact ratio.

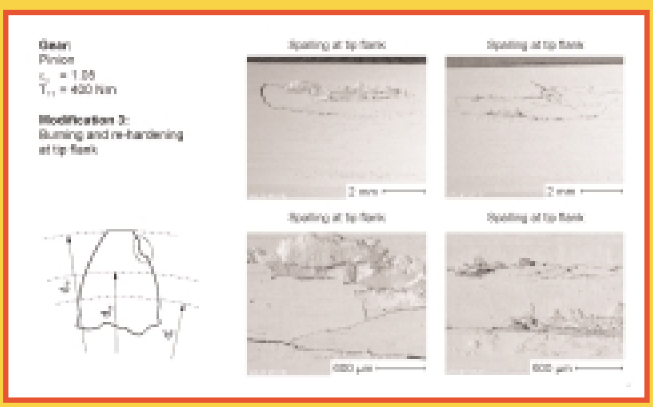

Figure 14—Damage on the tooth flank after use.

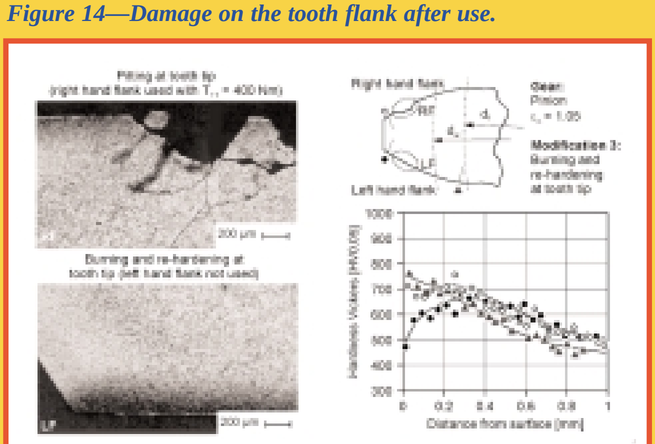

Figure 15—Structure and hardness measurement after use.

nificantly higher compared to the gearing with a contact ratio of ε_α = 1.44. The sliding movement does not change through the modification of the gear in the tip area.

The results of the gear tests with a contact ratio of ε_α = 1.05 are compared to the results with a contact ratio of ε_α = 1.44. The pinion with the slight grinding burn (variant 2) does not show any significant influence of an increased flank pressure on the number of tolerable alternations. From those results, it can be concluded that the damage of the surface layer is so low that it does not reduce the bearing capacity. An enormous structural damage of the surface layer, which is shown by variant 3, reduces the number of tolerable alternations. After only a few hours of testing, there is a strong pitting at the tip flank in the area of the grinding burn. In this case, the trial was stopped due to a tooth break in the tip area.

The measurements of the tooth profile and lead show more wear on the tip flank above the pitch circle especially for the significantly damaged pinion, variant 3 (Fig. 13).

The large differences from the profile form in the tip area indicate large breakouts. The cracks must be far below the tooth surface because they do not directly show on the flank surface, as the profile trace of variant 3 shows. The pinion with the slight grinding burn (variant 2) has significantly smaller deviations of the profile form in the tooth tip area. Increasing deviations in the area of the lead trace (pinion diameter) cannot be concluded except for the deviations caused by pittings.

Figure 14 shows the damages on the tooth flanks of the pinion with a strong grinding burn. The large surface with material breakouts in the tip area and the overhanging material on the tooth flank are clearly visible. In Figure 14, a more detailed picture of a crack in the lead direction is shown.

The material structure is shown in Figure 15. The intense structural damage of the martensite surface layer and the re-hardened zone in the tip area is clearly visible. In the gear with a contact ratio of ε_α = 1.44, the cracks in the pitting area were orientated opposite of the sliding direction. In contrast, the cracks in this case are significantly longer and run deep into the basic structure. The large surface areas with material breakouts indicate a change of the surface layer properties due to grinding burns. In this case, the measurement of residual stresses could help in order to find the cause of damage.

The measurement of the hardness of the unused flank shows a decreasing hardness of nearly 300 HV0.05 in the surface layer. The zone of the influence structure is about 0.25 mm deep. The utilized tooth flank shows in the tip area, compared to the un-used flank, only a small decrease of the hardness in the area of about 50 HV0.05. This indicates a strengthening of the surface of the workpiece material during operation.

The form of the flank damage of the test gear pinion with the structural damage at the tip seems to be independent of the gear geometry. The investigations show that cracks running deep inside the part occur in the damaged zone for the gears with a contact ratio of ε_α = 1.05 as well as ε_α = 1.44. Besides the results show a significant difference in the number of sustainable alternations. The investigations about the load carrying capacity of case hardened gears show that a slight structural damage of the tooth flank surface layer caused by the grinding process does not necessarily lead to an early gear failure. In order to estimate the load carrying capacity, the local burden caused by flank pressure, slip and tooth flank bending have to be taken into account.

If the stresses exceed the load carrying capacity of a gear with a damaged surface zone, high wear after just a short inset can be expected.

Conclusions

The requirements for modern automobile transmissions are increasing as well as for industrial gearings. In order to fulfill those requirements, a gear design that is beneficial for noise and load carrying capacities is gaining more importance. Recently, the number of failures has increased. This applies especially to case hardened and large module gears. The damages can partially be related to the grinding process that causes a negative influence on the material structure in the surface area of the parts. This report has shown the connection between the area of the structural damage, the kind of the flank loading and its influence on the load carrying capacity.

In tooth profile grinding, the stock removal depends on the chosen process strategy. If the tooth is ground with an equidistant stock, the structural damage is likely to occur on the tooth root. This kind of stock allowance can occur with the grinding of gears after hobbing or by using two grinding wheels with different geometries for a roughing and a finishing process. The reason for the local thermal damage is a high local stock removal, which leads to a local overloading of the grinding wheel.

Due to deviations from the desired tooth form caused by the initial gearing process and the heat treatment, gears with a larger module are usually ground in several steps with the same grinding wheel profile. This leads to constant stock removal in infeed direction because the grinding wheel geometry for roughing and finishing is the same. Because of the locally higher removed material volume, thermal damage has to be expected at the tip.

Because damages have occurred mainly in large gears, the pinions were manufactured with an equidistant stock on the flanks, according to the commonly used process strategy in the industry. Therefore, different structural damages occurred in the tip area. During the use of the pinions, a conclusion between the area and the seriousness of the thermal damage depending on the local flank loading could be found.

The investigations have shown that a slight structural damage of the tooth flank surface layer caused by the grinding process does not necessarily lead to an early gear failure. In order to estimate the load carrying capacity, the local burden caused by flank pressure, slip and tooth flank bending have to be taken into account. If the stresses exceed the load carrying capacity of a gear with a damaged surface zone, high wear after just a short inset can be expected.

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