Flank Breakage on Gears for Energy Systems

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Management Summary

Gear flank breakage can be observed on edge zone-hardened gears. It occurs, for example, on bevel gears for water turbines, on spur gears for wind energy converters and on single- and double-helical gears for other industrial applications.

The nature of flank breakage is described in this paper. An ultrasonic inspection technique has been shown to be suitable for carrying out an inspection within the volume of case-hardened teeth. The nature of various ultrasonic indications could be identified by means of metallographic and fractographic investigations. Various phenomena such as white etching areas, nonmetallic inclusions and large cracks are involved. Recurring inspections have shown that indications associated with increases in reflectivity and in the lengthwise extent, or in individual indications growing together, have appeared. This confirms a cyclic crack growth under vacuum.

Over time, it can be noticed that the cylindrical form of gears has lost as much as several tenths of a millimeter. Measurements of retained austenite have shown that the content decreases in areas with visible high temperature and loading.

Within the framework of an earlier research project—Flank Breakage with Spur Gears—a calculation model was developed that shows good correlation with the investigated gears that have suffered flank breakage.

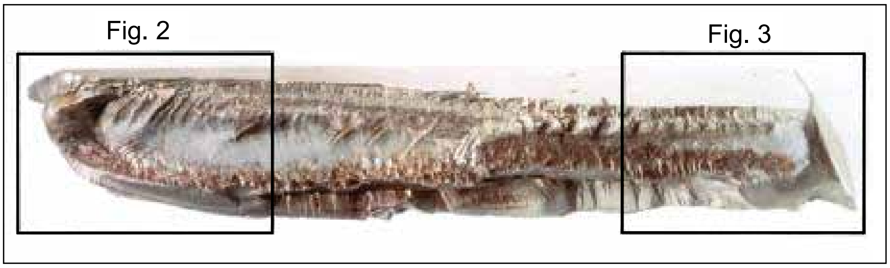

Figure 1—Fragment of a pinion tooth.

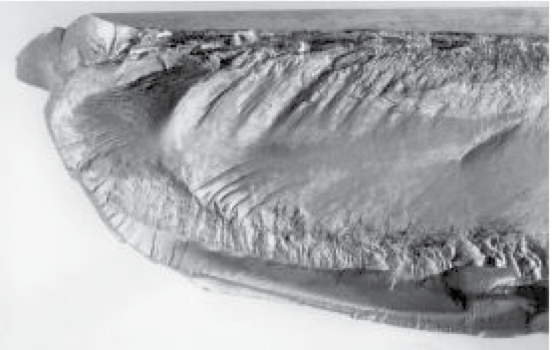

Figure 2—Section of Figure 1–left.

Introduction

In contrast to the known classical tooth damages shown in Reference 1—where the damage starts at the surface—in this presentation the flank breakage—i.e., the primary crack starter—is found in the volume of the tooth; it propagates as a fatigue crack in vacuum towards the surface of the load flank—as well as into the core of the material. The problem of flank breakage in high-performance gears was presented in 1997 (Ref. 2). What follows here are new findings.

The Nature of Flank Breakage

Flank breakage can occur at the pinion and gear wheel. Figure 1 shows a broken piece of a tooth from a case-hardened pinion (double-helical) that was found after several thousand operating hours at the bottom of the casing. The contact pattern indicates that high local loads are present on both tooth halves in the rear of the gap. The broken piece is situated at the turbine-side tooth half over about 30% of the tooth width.

In the middle of the fragment, the fracture surface is distinguished by a planed, finely structured surface. Towards the load flank and the lower boundary (Fig. 1), this surface is surrounded by a border comprised of fretting and fractured surface parts arranged in a terrace shape. At both ends of the fragment (Figs. 2–3), arrest lines can be detected with a local direction of crack propagation—to the left in Figure 2; to the right in Figure 3. Therefore, it can be concluded that the fatigue crack starts in an area between Figures 2 and 3 and propagates along the tooth width in both directions.

The area with the primary crack starter is shown in Figure 4; the crack initiates from the marked region. The investigations of the primary crack starter with the SEM (scanning electron microscope) provide, in general, no suitable information because the fracture surface is—as a secondary effect—strongly deformed. Therefore it is necessary to prepare a microsection through the crack starter.

The primary crack starter (*PR*) can be characterized as a local separation; around the local separation (approx. 20 µm) the structure is plastically deformed (Fig. 5). Starting from the local separation, one can see radial cracks. This implies that the local separation was filled with a globular, nonmetallic inclusion that has disappeared in the course of the metallurgical preparation.

In Figure 6 a model is shown to explain the crack path. The crack starter is located in the region of the pitch diameter and can be found underneath the case-hardening depth (about 1.5 × CHD) where the stress is significantly lower than within the CHD (Fig. 7).

In general, the local separation is filled with a nonmetallic inclusion from the oxide type. It is known that at the boundary of the inclusion, tangential and radial stresses are induced (Fig. 8). The microcracks (Fig. 5) are

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Figure 3—Section of Figure 1–right.

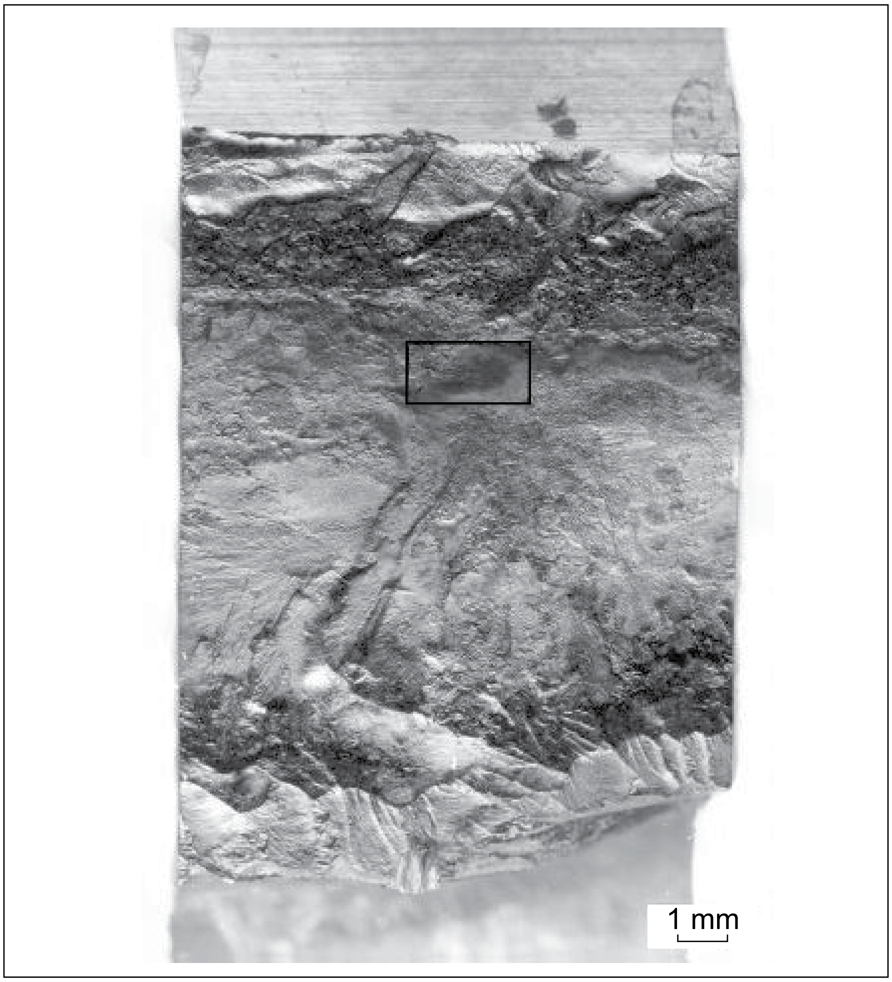

Figure 4—Position of the crack starter *PR*.

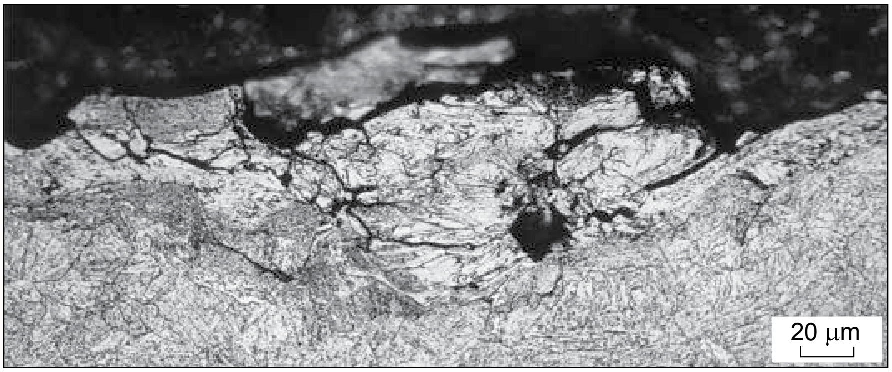

Figure 5—Local separation with radial cracks (Fig. 4).

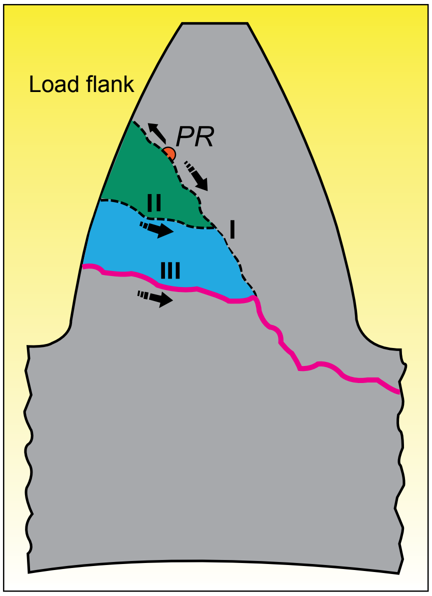

Figure 6—Path of crack.

positioned perpendicular to the direction of the tangential stress. It cannot be excluded that the microcracks are generated during or shortly after the last heat treatment process. Only those microcracks in line with the direction of the main shear stress can propagate towards the load flank and the core (Fig. 6).

With the calculation of load capacity according to DIN 3990/ISO 6336 (e.g., surface durability), it is not possible to estimate the exposure of flank breakage. (In Ref. 2) it is therefore suggested to:

- Develop an inspection method for detecting internal faults within the volume of the teeth
- Develop a calculation model capable of predicting whether an actual gearbox can fail due to flank breakage

Ultrasonic Inspection Technique

The object of ultrasonic inspection is to detect internal discontinuities at the earliest possible date and to check alterations of inner faults during further operation by repeated inspection. All demonstrated results included in this paper were obtained from gearboxes with a module of 10 mm. For better comparison between the inspection findings determined on different gearboxes, a registration limit of 6 dB above the reflectivity from a 1mm circular disk reflector was generally specified. Further details related to inspection technique, adjustment, size assessment and determining the lengthwise extent are described in Reference 3.

To justify the inspection technique, it was necessary to conduct laboratory investigations on single indications (inner faults). Initial tests were done on a tooth segment of a pinion after it had been removed. The number of indications found in this segment was astonishing; some of the findings are shown in Table 1.

The indications are located at depths of between 1.1 mm and 3 mm below the load flank. The maximum indication length is 35 mm in the case of tooth No. 3. The maximum reflectivity is also present here at a level of 11 dB above that from a 1-mm disk shape reflector; the indication was not completely continuous and showed small interruptions.

A metallographic specimen was taken through the area with indications of tooth No. 3 (Fig. 9). Several indications are present within the case-hardening zone (CHD ~ 1.8 mm) and below; they are lying parallel to the surface in the area of the pitch diameter.

In Figure 10 it is shown that the indications consist of White Etching Areas (WEAs).

After further preparation, one of the WEAs was broken up in the laboratory (Fig. 11).

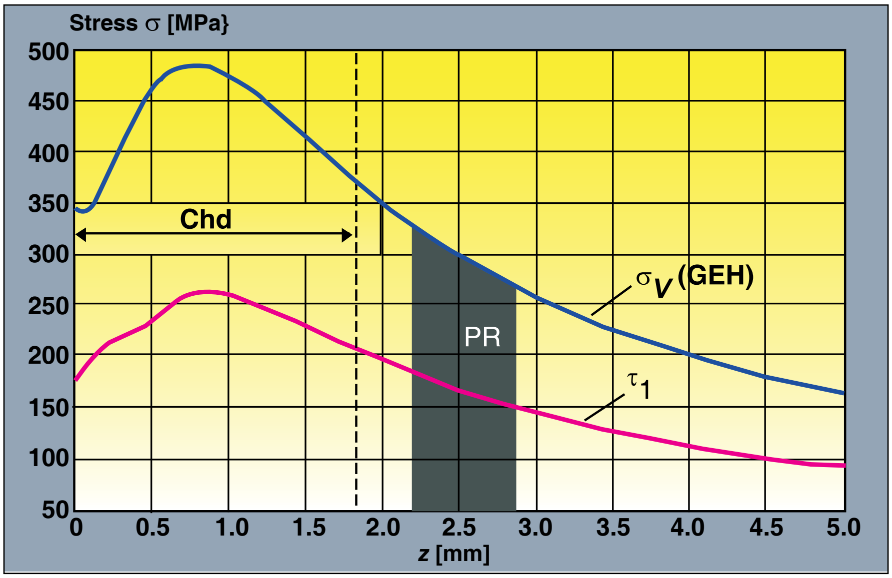

Figure 7—Distribution of equivalent stress and main shear stress over the depth.

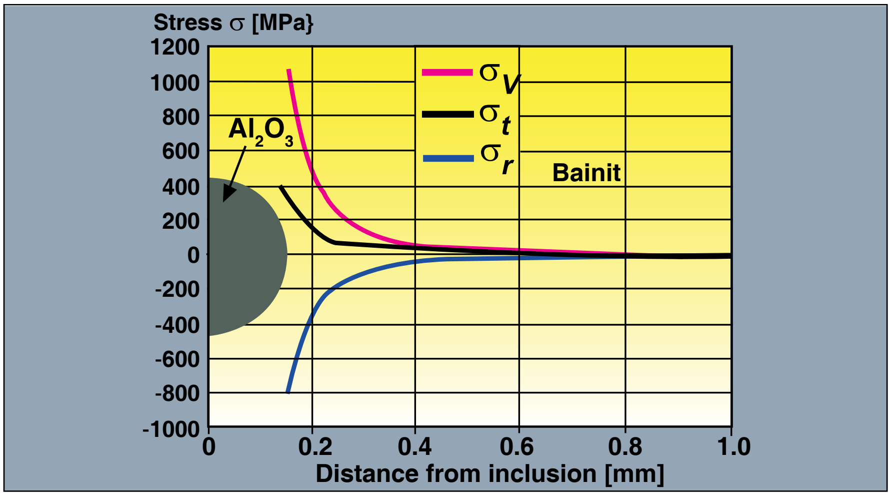

Figure 8—Internal cooling stress at the boundary of a non-metallic inclusion (Al_2O_3).

The structure of the WEA shows the effect of an intense plastic deformation caused by hydrostatic pressure with superimposed shear load (Fig. 12). This structure is quite different from the dimple fracture (D, Fig. 12) produced in the laboratory. The boundary surface between WEAs and surrounding microstructure is sharply lined so that WEAs can be easily detected by ultrasonic inspection.

During a UT (ultrasonic testing) inspection on a gearbox after 44,000 operating hours, indications providing evidence of a large internal discontinuity were found on one tooth of the wheel. An indication with a length of 243 mm is present in tooth No. 4. When scanned from the rear flank, it reflects up to an axial extent of 243 mm from the central recess (gap) and, when scanned from the load flank, between 5 and 212 mm. A maximum reflectivity of more than 20 dB above that from the 1mm disk shape reflector is located at the axial position (153 mm). At one position of the indication, a metallographic specimen was taken (Fig. 13). Within the tooth, a crack with a length of 6 mm is visible in the normal section; the progress corresponds to the known pattern in that it is located with an inclination of approximately 45° to the load flank.

After numerous UT inspections on more than 30 investigated gearboxes, the following changes can be observed:

- Appearance of new indications
- Increase in the lengthwise extent of individual indications
- Individual indications are growing together
- Increase in the reflectivity

Development of a Calculation Model

The previously cited research project (Ref. 4) was started in 2000 at the TU München and was supported by the Bavarian Research Foundation, concluding in 2003.

The fundamental idea for the calculation model is the comparison between the local-occurring equivalent stress and the local strength over the depth—thus determining the risk of flank breakage of an actual gearbox. The Hertzian contact stress, along with shear stress caused by the tangential force and residual stress, are basic data to determine the stress condition. The influence of a nonmetallic inclusion on the local stress is also considered. The strength profile is mainly based on the hardness profile. The investigations show that the main shear stress is responsible for the crack propagation. The calculation of the local stress is based on the equivalent stress according to the shear stress intensity hypothesis (SIH). The ratio between the local equivalent shear stress τ_f and the local

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Table 1—Indications at several positions along the tooth width

Tooth No.	Length of indication [mm]	Sound Path [mm]	Position axial [mm]	Position radial [mm]	Reflectivity
1	10	1.7	150-160	13	+2 dB
2	15	1.7 - 3.0	215-230	11-15	+10 dB
3	35	1.1 - 2.5	85-120	8-18	+11 dB (max. at 105 mm)

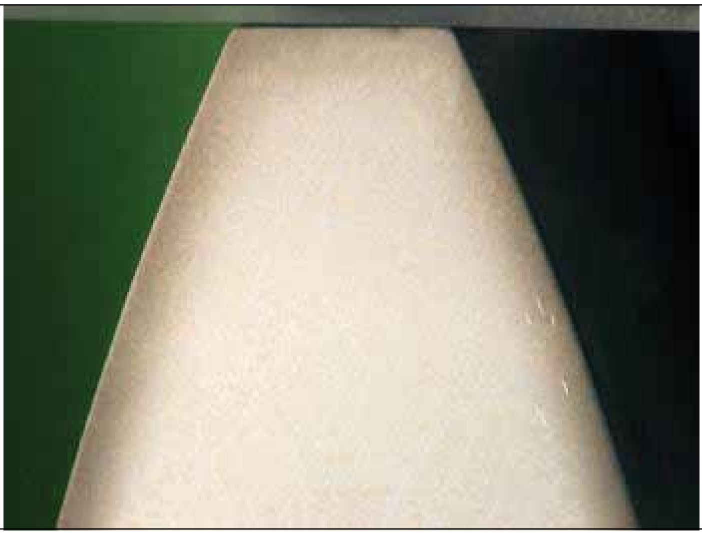

Figure 9—Indications beneath the surface of the load flank.

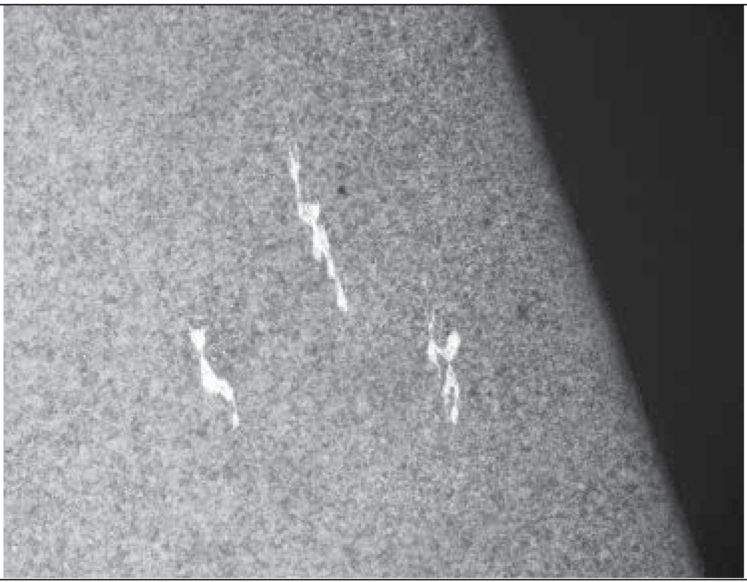

Figure 10—White etching areas (WEAs).

material resistance is defined as the local strain and yields information about the risk concerning flank breakage. According to the experience of FZG, it has to be stated that above a strain value of 0.8, the risk concerning flank breakage increases.

Within the research project some gearboxes that failed because of flank breakage were recalculated with the abovementioned calculation model. From the damaged parts, the actual hardness profile is known. In all cases the maximum of the calculated risk is in a great depth below the flank surface—well underneath the case-hardening depth; the local strain is clearly higher than 0.8.

The calculation model shows good correlation with the investigated pinion and wheels that have suffered flank breakage; it is therefore now possible to:

- Estimate the risk in the stage of construction
- Recalculate the risk of gearboxes in operation
- Use it for failure analysis

An example is provided in Figure 14.

One important point of interest could not be solved within the framework of the research project—i.e., the estimation of the remaining lifetime of teeth with inner cracks of a certain length, as detected by the UT inspection.

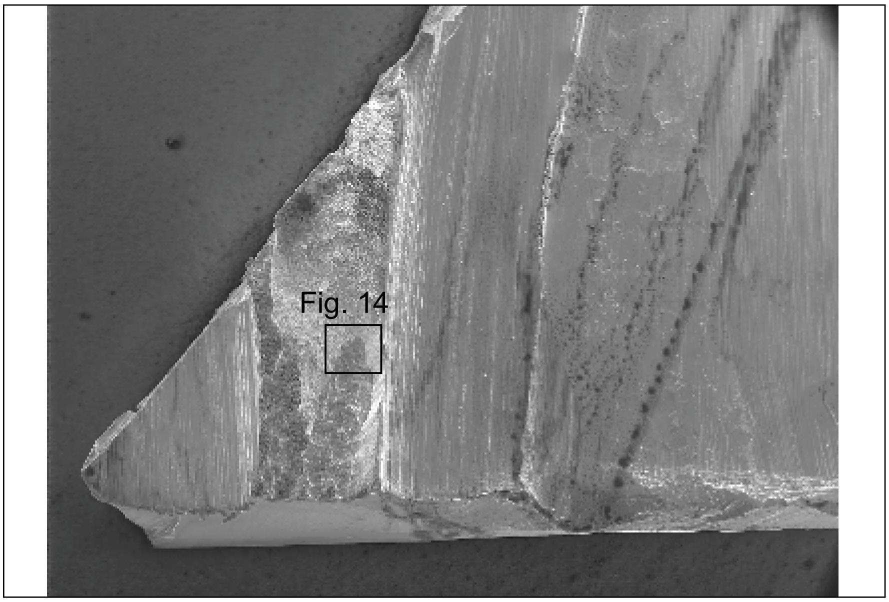

Figure 11—WEA broken up in the laboratory.

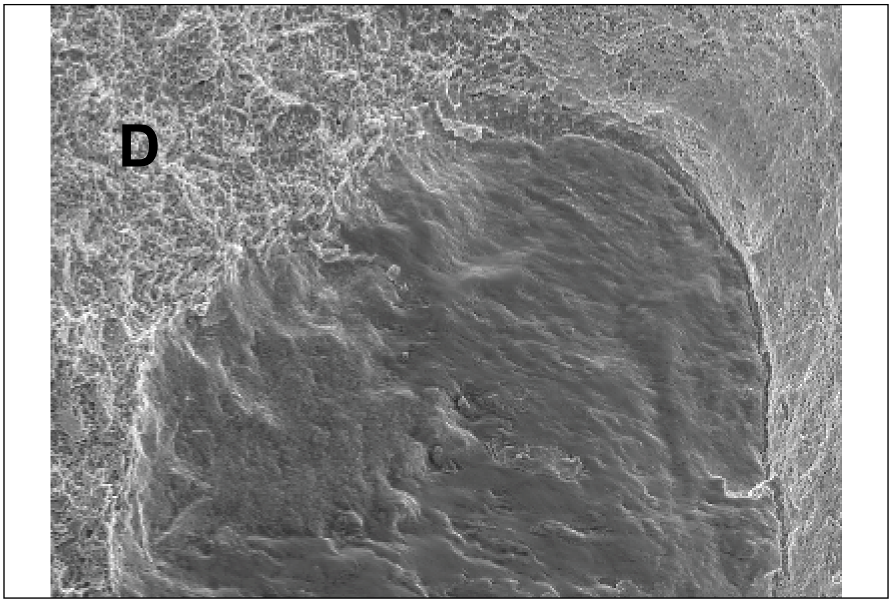

Figure 12—Intense plastic deformation within WEA.

The first cracks have a length of only a few micrometers (microcracks). For these microcracks the definite correlation between the stress intensity factor ΔK and the crack growth da/dN does not exist as with "long" cracks. The basis for the prediction of the behavior of microcracks is the knowledge of the fatigue crack growth curve for long cracks.

From the investigations it is known that the inner crack propagates along the mean shear stress under vacuum. Due to an absence of atmospheric oxygen, the absorption of oxygen at the crack tip is prevented. Therefore the crack growth under vacuum is about three to four times slower than under atmospheric conditions. To bridge the gap, it would be helpful to carry out crack propagation tests under vacuum and under Mode II conditions (sliding).

Form Stability of Pinion and Gear

By means of numerous gearbox inspections done by AZT Risk & Technology GmbH, it is noted that the teeth show unevenly distributed discolorations and deposits over the tooth width. The deposits consist mainly of sulfur and phosphor that have been formed by higher temperatures. The measurement of the cylindrical form of pinion and gear shows deviations of several tenths of a millimeter, which in general increase with extended use; these deviations are greater at the gear as compared to the pinion. As a consequence, the contact pattern is changing, resulting in high local loads. Typically, most indications in the volume of the teeth occur in the areas of the UT-inspection. The cause for the missing form stability can be attributed to a microstructural change of retained austenite.

The distribution of the measured content of retained austenite of a pinion is shown in Figure 15. At one tooth a flank breakage was detected at a certain distance from the NDE side. In this range with brown-colored teeth, an accumulation of indications was found by UT inspection. It is significant that in this area the content of retained austenite decreases from 16% to 8%.

Summary

Investigations at AZT Risk & Technology GmbH have shown that below the flank surface, underneath the case-hardening zone, a fatigue crack is starting; it propagates in the normal section in both directions towards the surface of the load flank, rear flank, and into both directions along the tooth width. The primary fracture surface is inclined at approximately 45° to 50° to the load flank (direction of the main shear stress). This failure type is called flank breakage.

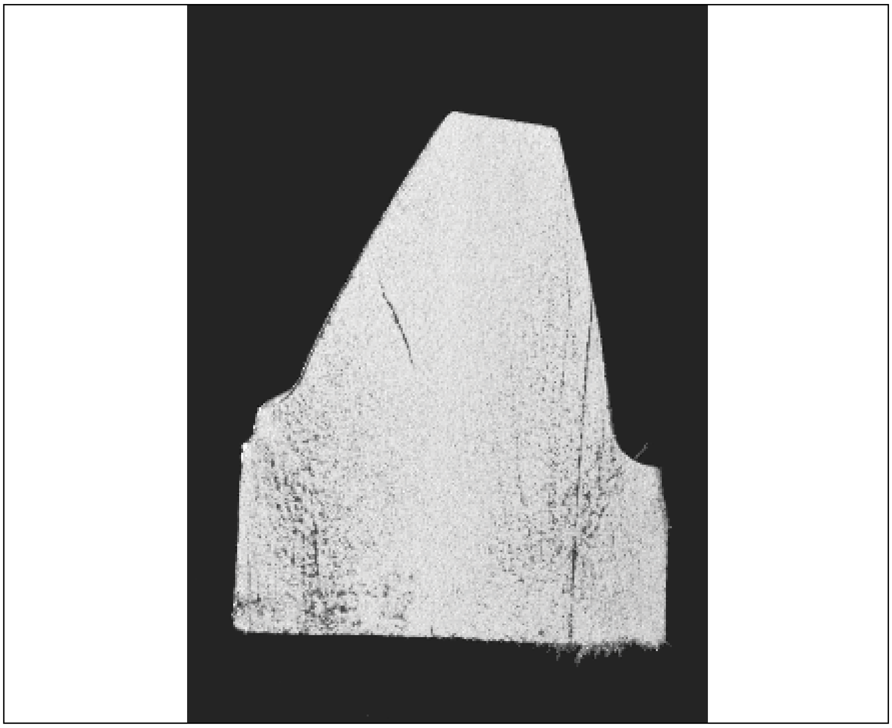

Figure 13—Crack within the volume of the tooth.

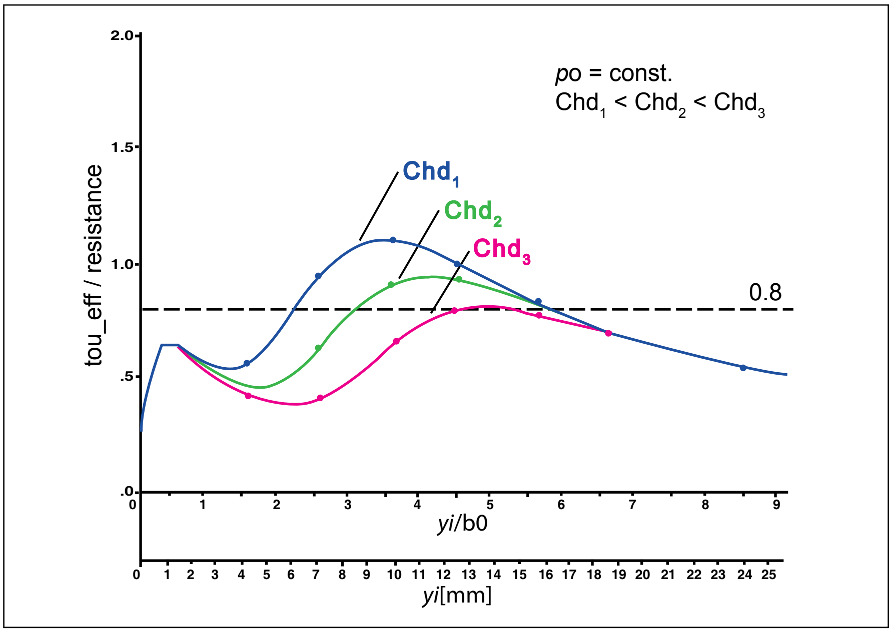

Figure 14—Depth gradient of strain by constant load *p*0 (MPa) and variable case-hardening depth (mm).

In the majority of cases the crack starter is formed from a small, nonmetallic inclusion of the oxide type, with a diameter of approximately 10 to 20 µm. From this type of inclusion, it is known that during hardening, internal cooling stresses are induced. The radial stress has a negative and the tangential stress a positive algebraic sign. Occasionally, the nonmetallic inclusion disappears during metallurgical preparation so that only a local separation can be seen in the microsection. Around the local separation, the structure is plastically deformed, and radial cracks are spreading out from the local separation over a length of about 20–40 µm; these microcracks lay perpendicular to the positive tangential stress. The local separation and the radial cracks are too small to be detected by ultrasonic inspection. In our opinion these microcracks are generated during or shortly after the last heat treatment process (case-hardening). The investigations also show that only cracks in line with the direction of the main shear stress are able to propagate; the crack propagation occurs under vacuum. Due to the absence of atmospheric oxygen, sliding is reversible so that the crack growth is about three to four times slower than under atmospheric conditions. At this time, we don't yet know the behavior of microcracks and the fatigue crack growth curve for long cracks under vacuum and for Mode II–III conditions. Therefore no statement about the remaining lifetime of a tooth with an inner crack can be made.

In addition, with the calculation of load capacity according to DIN 3990/ ISO 6336, it is not possible to estimate whether flank breakage occurs because these calculations describe the situation at and near the surface—but not in such a depth where the primary crack starter is located. During the AZT Expert Days (a biannual meeting in Germany hosted by AZT Risk & Technology GmbH to promote the exchange of ideas among experts in manufacturing and science, among other disciplines), it was suggested to develop an inspection method for detecting indications within the volume of the teeth and to develop a cal-

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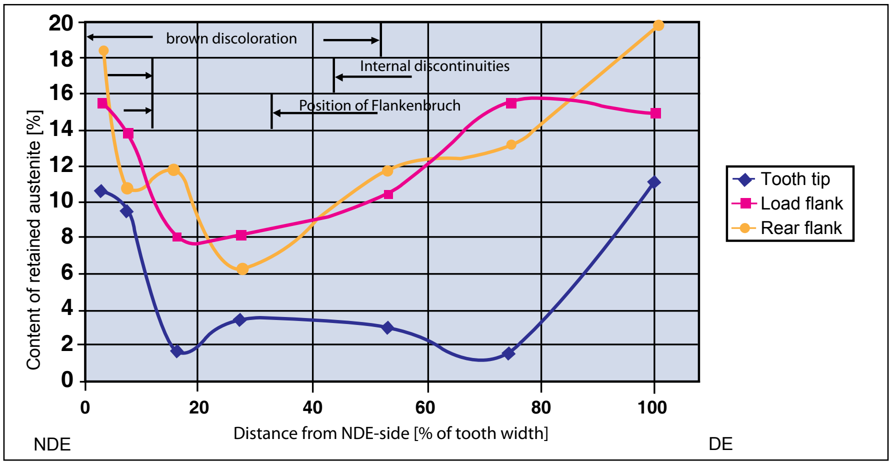

Figure 15—Distribution of retained austenite over tooth width/discoloration, internal discontinuities, position of flank breakage.

culation model to predict the risk of flank breakage. This work was done within the framework of the research project Flank Breakage with Spur Gears, which was supported by the Bavarian Research Foundation; it was managed by the Research Center for Gear Wheels and Gear Construction. An ultrasonic inspection technique has been shown to be suitable for detecting discontinuities within the volume of the teeth. The nature of various ultrasonic indications could be identified by means of fractographic and metallographic investigations. Various phenomena such as white etching areas, nonmetallic inclusions and large cracks are involved. Repeated inspections reveal that in changes of indications associated with an increase in reflectivity, an increase in the lengthwise extent has appeared; this confirms a cyclic crack growth under vacuum. The calculation model developed by FZG gives a second maximum of the strain in such a depth, where the primary crack starter is located. It shows good correlation with investigated pinions and wheels that have suffered flank breakage. It is therefore now possible to estimate the risk of flank breakage in the stage of construction and recalculate the risk of gearboxes in operation.

In some gearboxes the pinion and gearwheel have lost their cylindrical form; deviations of several tenths of a millimeter can be measured at the outside diameter. This irreversible deformation is mainly noticed in gearboxes with a high temperature level and where the teeth show unevenly distributed discolorations and debris. As a consequence, the contact pattern is changing and leads to areas with the highest local loads; i.e., where the flank breakage basically occurs. It cannot be ruled out that the irreversible deformation is caused by a microstructural change of the retained austenite (RA). Flank breakage was detected on a pinion of about 20% of the tooth width. In the same region the teeth are brown-colored and an accumulation of indications was found by UT inspection. In the same range the content of retained austenite has dropped from 16% to 8%.

References

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4. Research Project Final Report: Flank Breakage with Spur Gears, Bayerische Forschungsstiftung, Garching, 2003.

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Arne Böhl *apprenticed as a mechanic, mechanical technician (junior engineer) and welding technologist, acquiring hands-on experience in metallography and quality assurance. He joined the Allianz Group's Center for Technology in 1994 where—via ultrasonic testing—he currently is responsible for the development, planning and performance of non-destructive testing for gear teeth.*