

Analysis of Micropitting on Prototype Surface Fatigue Test Gears

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American Gear Manufacturers Association



TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Early stages of micropitting were examined on experimental gears designed for surface fatigue studies by the AGMA Helical Gear Rating Committee. Optical profilometer, SEM and metallographic examinations were conducted on the first prototype gearset tested. The gearset was tested in an FZG test rig. To evaluate tooth bending fatigue strength, the gears were loaded to load stage 12. A tooth broke from bending fatigue in .88 hours (the expected time). This short run time allowed for the examination of micropitting at an early stage of development. The distribution and morphology of micropitting over the tooth face and associated relationships to surface micro and macro geometry features and traction are examined. Micropitting was primarily associated with finish geometry. A few pits were associated with sulfide inclusions and one pit was possibly initiated by a small non-metallic inclusion. Metallographic examinations revealed asperity related lines of dark etching alterations (DEA) caused by high asperity contact and traction stresses.

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ANALYSIS OF MICROPITTING ON PROTOTYPE SURFACE FATIGUE TEST GEARS

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Introduction :

The pinion and gearset studied and reported on in this paper was the first test of a group of prototype gears manufactured with a new design for surface fatigue life tests in FZG rigs. This work is being conducted under the auspices of the American Gear Manufacturers Association (AGMA) with the intent of developing a new surface fatigue life model that will include lubricant and additive effects. The gears are made of carburized 8620 steel. They have a 20:30 tooth ratio, tip relief and a 560-mm radius crown across the pinion tooth face. The crown serves to increase the contact stress and avoid high stresses at the sides of the tooth due to contact ellipse truncation. The gears were ground to a finish of 0.3 μm Ra. Surfaces were hardened to 62 Rc. The test program, gear design and initial test results were presented at the 1998 AGMA Fall Technical Meeting at Cincinnati, OH. The details of the gear design and test program can be obtained from the AGMA.

This paper covers the examination of gear and pinion surfaces to provide insight into the factors influencing the initiation and progression of surface fatigue and possibly help to direct future testing. This gearset was tested at a high load level (Load Stage 12 ~ 535 Nm pinion torque) as a test of tooth bending fatigue strength. The tooth contact stress was 2.6 GPa. Pinion shaft speed was 1500 rpm. Since this first test was primarily an evaluation of tooth bending fatigue strength, a high viscosity lubricant (M-460-EP) was used to minimize the probability of surface fatigue development. The test gearset lasted 0.88 hours, when a tooth broke due to bending fatigue at the root. This was the expected calculated life. The short duration of this first test allowed for the examination of the early stages of micropitting development. The heavy contact

stresses most likely resulted in an exaggeration of some phenomena, but this may have been beneficial in revealing various processes. The work reported in this paper involved teeth that were not affected by the broken tooth.

Surface Fatigue Damage Analysis and Observations :

Figure 1 shows macro photographs of a pinion and a gear tooth and also the pinion tooth 4% nital etched. The gear tooth shown in Figure 1(A) shows some scuffing (primarily near the tooth tip) and micropits scattered over the tooth face, often forming a horizontal band along the finish lay. A band of heavier micropitting is at the tooth addendum. The same can be seen in Figure 1(B) for the pinion with a heavy band of micropitting at the tooth dedendum and at the addendum where the tip relief begins. It can also be seen how the tooth crown and the tip relief combine and result in reducing the stress near the tooth tip to form a curved pattern of distress. Micropits can be seen over the entire face, including the pitch diameter at this early stage of surface fatigue development. The gears were nital etched to again check for grinding injury. During manufacture they were checked with the Barkhausen method. No grinding injury was seen on the non-contacting surfaces; however, the dark bands shown on the contacting surfaces indicate tempering temperatures (~ 370 °C) were reached during the test. Three temper bands are seen: heaviest at the bottom, lighter at the top and slightly noticeable at the middle. The top and bottom locations correspond to the heavier micropitting bands. When teeth first contact at the pinion dedendum, the lubricant film is in a transient stage of development and the slip is high, thus tooth contact is very harsh here. These temperatures were very superficial because subsequent examination of a

tooth cross section did not reveal tempering. These locations of high temperature would have strongly affected lubricant viscosity, EHL film thickness, coefficient of traction, stresses, scuffing, wear and fatigue development. Obviously the design and execution of the tip relief is crucial.

Figures 2 and 3 show SEM photographs of micropits from the pinion tooth surface. Figures 2(A) and 2(B) are from the upper portion of a pinion tooth where the traction force is directed toward the tooth tip (toward the top of the photographs). Figures 2(C) and 2(D) are from the lower portion of the tooth, where the traction force is directed toward the tooth dedendum (toward the bottom of the photographs). The wear and plastic deformation indicate asperity contact and most likely boundary lubrication. It is seen that cracks grow in the direction opposite to the traction force and are associated with the raised portion of the finish texture, as previously observed [Webster and Norbart (1995); Berthe et al. (1980); Olver (1995)]. Apparently micro-Hertzian stress fields developing below contacting asperities are the primary stresses initiating the micropitting. Micropitting in Figures 2(A), 2(B) and 2(D) is located on asperity tops with the crack intersecting the asperity surfaces off center in the direction of the traction force. A significant amount of plastic flow is seen on the asperity top in Figure 2(B). Whether this affected crack initiation in some manner other than geometric stress effects is not known. The asperity tops in Figures 2(A) and 2(D) have worn to a very smooth surface, perhaps due to chemical wear. The wear may have removed micro features, which affected fatigue development. Optical profilometer measurements indicate that most micropits were from 0.25 to 2.50 μm deep. Figure 2(C) shows a multitude of micropits forming near one another on the tooth where the teeth first come into contact. It is quite likely that micropit development changes after the initial pits are formed. The changing surface texture and stress fields cause damage which is self propagating and slowly degrades tooth profile, thus eventually leading to more severe modes of macro fatigue [Errichello and Muller (1994), AGMA (1995)].

Figures 3(A) and 3(B) show additional interesting and possibly less common features. Based on the beach marks present, the micropit in photograph Figure 3(A) may have initiated at a very small non-metallic inclusion. Both Figures 3(A) and 3(B) show the surface metal, undermined by a crack, being pulled downward and sloughed off by the traction force. Figures 3(C) and 3(D) show two micropits associated with sulfide inclusions. These were the

only two sulfide related micropits found. The two pits in Figure 3(D) are apparently connected by the same sulfide thread. These sulfides were very close to or even on the surface. There are no apparent cracks associated with these pits. Micrographs will be shown later with sulfides in the micro-Hertzian region of an asperity which did not initiate cracks. Sulfide micropits are curved relative to the finish texture unlike the rest of the observed micropitting.

It appears that the higher elevation features of the finish are carrying load (mixed or boundary lubrication). The asperity normal load and associated traction force are initiating the fatigue as opposed to micro EHL stress raising effects. If micro EHL effects were at play, the cracks would develop in the direction opposite to that observed (in the direction of the relative slip) and would initiate at the side of the groove or depression toward which the slip is directed [Xu (1996)]. Figures 4(A) and 4(B) show the expected crack development above and below the pitch diameter respectively if there were sufficient lubricant film thickness for micro EHL effects to develop. Figure 4(C) shows the micro-EHL crack development positioned on the tooth profile in comparison to the micropit cracks actually observed. The hydraulic pressure propagation concept would also direct the crack toward the tooth tip above the pitch diameter, opposite of what really occurs. A possible mechanism for crack development and orientation will be discussed later.

Metallographic Examination :

Figure 5 shows the location of several micrographs shown in Figure 6. The numbers on the micrographs correspond to the distances from the tooth tip measured down along the centerline of the tooth profile, as shown in Figure 5. These photomicrographs show regions of dark etching alterations (DEA) just below the contacting surface of the pinion. The lines of DEA are likely related to plastic deformation and dislocation accumulation rather than microstructure transformation. The areas of DEA were primarily found above and below the pitch diameter. Very little DEA material was found near the pitch diameter where sliding does not occur

These lightly nital etched micrographs shown in Figure 6 (1000x) are on a pinion tooth sectioned half way across the tooth flank on a plane perpendicular to the axis of the pinion. What is seen is the edge view of the tooth profile surface half way across the tooth width where the contact stresses are highest. To minimize edge rounding during polishing, the surface was nickel plated before mounting and polishing. In the lower photographs, the plating

pulled away. Lines drawn at the edges of the photographs indicate the true surface. The photographs are ordered from tooth addendum to dedendum. Dark circular dots are the end view of sulfide inclusions that were drawn out in the direction of the centerline of the gear during steel processing.

A section of new surface from the unused side of the tooth is shown at the bottom of Figure 6. The new surface micrograph is shown to allow an estimate of the wear and change in the surface that occurs during running. Obviously the surface does smooth up considerably due to wear and plastic deformation; however, subsurface damage may be accumulating in the process. Some of the new surface asperity slopes are very steep and would lead to high initial stresses and plastic flow. These high stresses could lead to immediate cracking or very early subsurface fatigue cracks below asperities and provide the mechanism for some micropits to form immediately anywhere on the surface.

The DEA lines shown below high spots (asperity tops) are of primary interest. This suggests a phenomenon similar to that reported by Maeda (1990) where hydrogen related black needlelike structure was found in the macro-Hertz stress fields of carburized rolling bearings. The areas of DEA shown in this paper were found in the micro-Hertzian high stress regions below asperities, almost exclusively away from the pitch diameter at locations where slip is present. DEA areas are also found in the more heavily micropitted regions at the tooth dedendum and addendum.

The heavily micropitted areas are shown in the 1.205 mm and 5.654 mm locations. The 1.205 mm photograph is in the heavily micropitted region near the tooth tip in Figure 1(B). The DEA are quite dense here. At the 5.654 mm location, dark etching microcracks are even more dense and wide spread. This location is the heavily micropitted region at the tooth dedendum shown in Figure 1(B).

At locations with apparently less wear (1.628 mm and 1.709 mm photographs), it can be seen that the lines of DEA occur in what appears to be the highest stressed region of the asperity's subsurface micro-Hertzian stress field. The DEA regions do not extend to the surface because the maximum stresses decrease in magnitude toward the surface.

A few sulfide inclusions (dark circular dots), which are very close to the surface, are pointed out in the 1.628 mm and 1.709 mm photographs. They do not appear to initiate cracking. The sulfide inclusion in

the 1.709 mm photograph is located in the dark etching region and still did not initiate a micropit.

There is a directionality shown by the DEA lines. This can be seen more clearly in the 1.628 mm through 4.898 mm photographs. At both addendum and dedendum, the DEA lines slope downward, but in opposite directions toward the pitch line. This is consistent with the SEM surface crack observations. In the 2.256 mm photograph, a micropit crack is seen which appears to have been initiated in a region of DEA and then propagated in a direction generally parallel to the DEA lines. Of course, both initiation and propagation phenomena are controlled by the stress field, which is in turn a function of the local geometry (finish) and traction (lubrication). In this case, it could be that a small micropit first formed from cracking in the DEA region and crack propagation developed from the right side of the original micropit (opposite in direction to micro-EHL and hydraulic pressure propagation concepts). It is not evident in Figures 2 and 3 that this possible sequence of events occurs at other micropit locations.

The changing direction of the traction force above and below the pitch diameter would provide a mechanism to help explain the observed crack development. The traction force is reorienting the stress field on and below the asperity tips thus affecting crack development and orientation. Actually, the changing shear stress direction has the same effect on the macro-Hertzian stress field. Lubrication conditions and additives would affect the magnitude of the traction force and amount of stress field rotation. If conditions were more favorable for full EHL film separation, high asperity loads, corresponding traction forces, high flash temperatures and possibly micropitting would be reduced or eliminated.

To further explore what might be learned from these experimental observations, order of magnitude contact stresses were calculated for asperity's distant from the pitch diameter where sliding exists. The radii of curvature and depth to maximum shear stress of asperities A1 and A2 in Figure 6 were measured. The depth to maximum shear stress was assumed to be at the center of the DEA area. The radius of A1 is 38.1 μm and the maximum shear stress depth is 1.25 μm . The radius of A2 is 68.6 μm and the maximum shear stress depth is 8.5 μm . Because the DEA areas are fairly centrally located below the asperities, the coefficient of traction must be relatively low. Although the tooth face is crowned, the very narrow width of an asperity contact relative to its length allows use of the relatively simple line contact