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THE EVOLUTION OF DARK ETCHING REGIONS AND WHITE ETCHING BANDS IN BEARING STEEL DUE TO ROLLING CONTACT FATIGUE

CATEGORY

Rolling Element Bearing

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INTRODUCTION

Rolling element bearings experience cyclic loading throughout operation which can result in the formation of irreversible microstructural alteration in the steel bearing subsurface known as dark etching regions (DER) and white etching bands (WEBs) due to rolling contact fatigue (RCF). These features have been believed to develop in the region of maximum shear stress in bearing subsurface under medium to high stress cycles [1-3]. The terminology DER is deduced from the dark appearance of the feature when etched with Nital whereas WEBs from the white appearance when observed under light optical microscopy (LOM). DER is believed to be randomly scattered patches of ferrite [1]. WEBs are parallel three-dimensional ferrite discs which initially form at an inclination angle to the surface in the rolling direction of 20-35° known as low angle bands (LABs) followed by much thicker and longer bands known as high angle bands (HABs) which are inclined at 65-85° to the surface [1-3]. All three microstructural features are found to be ferritic in nature and form in bearings in an orderly sequence. DERs typically initiate from 5 million stress cycles, followed by low angle bands from 100 million cycles and high angle bands from 500 million cycles [2]. While the first publication on these microstructural alterations was 7 decades ago, many findings and hypotheses have been published on the formation conditions, their characteristics and models for their formation. A recent investigation using high resolution imaging methods has revealed that DER and WEB features all consist of globular and elongated ferrite grains. It also showed, while the elongated grains in DER are oriented at random directions due to martensite decay, in WEBs the sizes of both globular and elongated grains are much larger and unlike the DER, have a distinctive orientation at roughly 30° in LABs and 80° in HABs to the surface. Furthermore, carbon rich areas, which are believed to be carbides, have been observed adjacent to these ferrite grains. However, many questions still remain unanswered. A demonstrated formation mechanism of DER and WEBs, their evolution processes as well as how DER/WEB leads to final spalling on bearing surface remain to be hypotheses due to lack of detailed experimental evidences shown in literature.

This paper presents results from a systematic study of DERs and WEBs formed in the inner ring of an angular contact ball bearing (ACBB) in two cleanliness grades of SAE 52100 steels under two different contact pressures over a wide range of stress cycles. Detailed quantification of these features has been carried out on all test bearings and a 3D model of multiple HABs has been established based on serial sectioning methods.

METHODLOLGY

RCF testing was conducted on axially loaded ACBBs of the type 7205B at Schaeffler Technologies L-17 test rig to create DER, LABs and HABs at different stages of the bearing life. Details of the test conditions are shown in Table 1. It should be noted no surface damages were observed on all the bearings analysed. The inner rings are cut in both axial and circumferential directions (Figure 1) and standard metallographic procedure [1] has been carried out on the cross sectioned specimens which were etched with 2% Nital to distinguish the DER/WEB regions. The density of the WEBs was investigated using ImageJ where an appropriate threshold was established and applied to the LOM images to determine the percentage area covered by the LABs and HABs. A 3D model of the HABs is obtained by serial sectioning at 5 µm intervals on a sample with fully grown HABs.

Table 1) *Overview of test conditions of the ACBB samples investigated. Operating temperature was 80°C and speed was at 12,000 RPM*

Cleanliness Grade of SAE 52100	Total K3 value (O+S Inclusions)	Number of Samples Investigated	Range of Stress Cycles (Millions)	Maximum Contact Pressure (GPa)
High (H)	3.4	5	151 - 885	3.5
High (H)	3.4	5	591 - 3016	2.9
Very High (VH)	0.1	6	8 - 4141	2.9

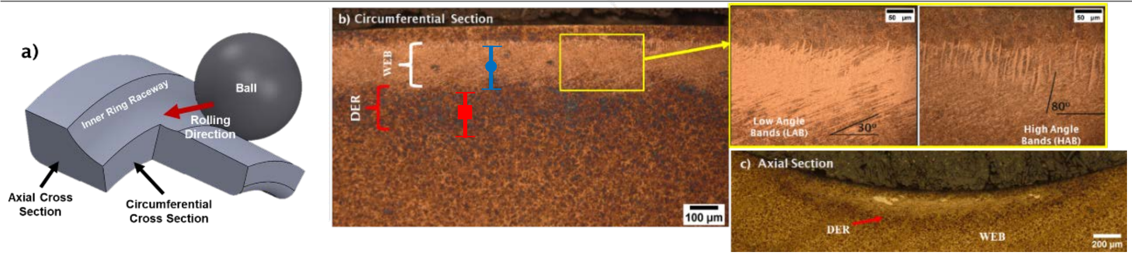

Figure 1. *a) Cut directions of bearing inner ring to observe DER and WEB (HAB and LAB) features in b) circumferential section and c) axial section of inner ring. Measurements taken for the depth of the upper/lower boundaries and centre of DER/WEBs are shown as red/blue lines respectively in b).*

RESULTS AND DISCUSSION

To confirm the uniformity of the features around the circumference of the ring, multiple cuts were taken from different regions around the inner ring circumference from the bearing tested for 3016 (H) and 4141 (VH) million cycles. The results have shown that the differences in the density of LABs is less than 9% while HABs show a difference of up to 30%. For this investigation, two random locations in the bearing inner ring circumference at point of contact were then chosen and their analysis results were averaged to represent the relevant bearing test condition. The spread (upper and lower boundaries) and the centre depths of the DERs and WEBs formed in the bearing subsurface is presented in Figure 2 under the two contact pressures. As it can be seen, the maximum von Mises stress appears to coincide with the regions of WEBs under both contact pressures whereas the DERs are much deeper from the very initial stages. Both DER and WEBs increase in depth slightly as the stress cycle increases, which is likely due to strain accumulation in the altered region resulting from the cyclic loading on the microstructure. An increase in contact pressure produces a widening of the spread and an increase in mean depth of the features which is more significant on the DER than on the WEBs, which suggests that the driver for DER and WEBs formation might be different. Nonetheless, as shown in Figure 2b, the upper boundary of the WEBs reached a saturate depth after approximately 1700 million cycles. Given the non-symmetrical distribution of von Mises stress in the subsurface, i.e. the reduction of stress is slower below the maximum stress depth comparing with that of the above, it might explain why DER/WEBs grow more rapidly in the lower boundary compared to the upper boundary causing the features appear deeper in the microstructure.

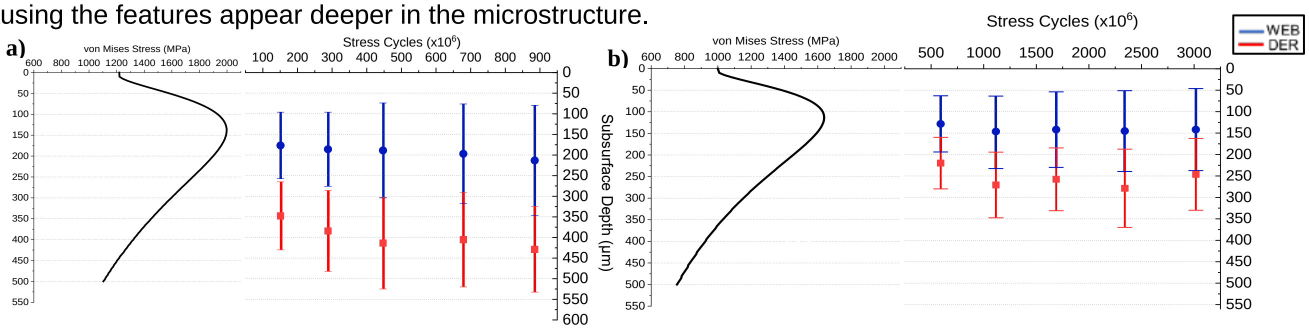

Figure 2. *Upper, lower boundaries and centre of DER and WEB subsurface depth in the high cleanliness steel bearing inner ring for different cycles based on defined positions in Figure 1 at a) 3.5GPa b) 2.9GPa compared the von Misses stress distribution*

The density of the LABs and HABs has been analysed to observe the growth of LABs and HABs over stress cycles. As the plots in Figure 3a show, for LABs in the high cleanliness steel bearings under 2.9 GPa, a steady growth from the beginning followed by a saturation trend is seen in all three cases; for HABs however no features were observed until after 500 million cycles, then a low level of HABs maintained constant till around 1700 million cycles when HABs started to grow rapidly, which happens to be when the maximum LAB density was achieved. HABs are typically found at the upper boundary of the LABs which is similar to the position of the maximum von Mises stress shown. It is interesting to see that the 1700 million cycles, when LABs density reaches its maximum in Figure 3a and the HAB density start growing rapidly, also corresponds with the saturation of the upper boundary of the WEBs shown in Figure 2b. This suggests that the development of the HABs is related to the density of LABs already formed, which agrees with theories stated in literature [2,3]. For the other two cases, due to lack of data points, the discussed trends are partially found. However, it is apparent that higher pressure causes the LAB/HAB to develop earlier while the cleaner steel grade shows a slightly less dense LAB/HAB network at similar cycles.

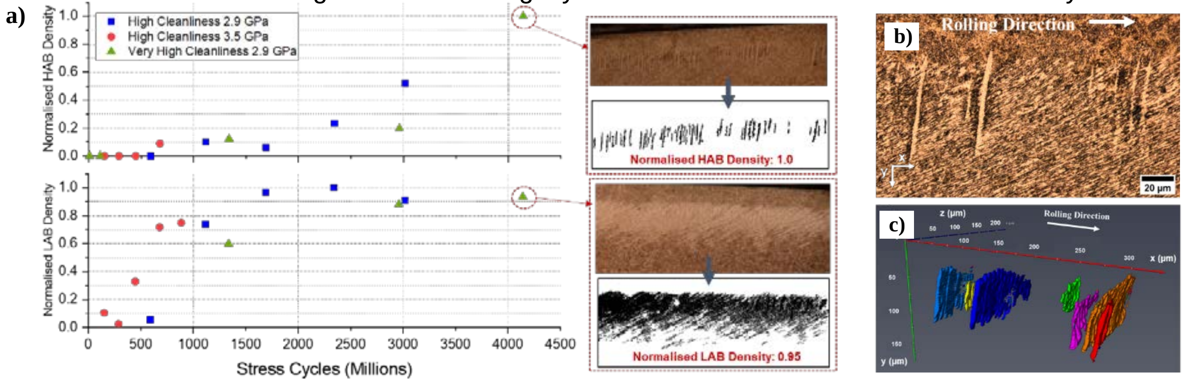

Figure 3. a) Normalised density of LABs and HABs vs. stress cycles for the two steels under two contact pressures. An example of the applied threshold to the optical images of HABs and LABs is shown for each plot. b) An optical image of the HABs in the bearing of very high cleanliness under 2.9 GPa over 4141 million cycles. c) A 3D model of HABs shown in b) obtained from serial section 5 µm intervals.

To investigate the 3D nature of the HABs, a serial sectioning process has been conducted on the 4141 million cycles very high cleanliness bearing sample, which contains well-formed HABs. Figure 3b shows a LOM image of the first slice of the 3D model of the HABs shown in Figure 3c. Within a span of 0.175 mm of serial sectioning depth across the wear track, a total of 7 HABs have been identified. The HABs appears to be in varied sizes in all three dimensions but have a common feature of being flat discs parallel to each other. The HABs are believed to be formed from LABs as they appear to be consumed in their formation based on the serial sectioning images.

CONCLUSIONS

This paper presents the results from a detailed study of DERs, LABs and HABs formed in ACBBs to provide quantitative evidence on how they evolve throughout bearing life. The main conclusions for this study are:

- The thickness of the region with DER/WEBs formed in the inner ring of the ACBBs increases with the contact pressure and stress cycles while the lower boundary grows at a faster rate compared to the upper boundary of the features.
- While higher contact pressure accelerates the formation of WEBs, cleaner steel grade impedes the growth of the features.
- The growth of LABs saturates after 1700 million cycles for the high cleanliness steel bearings under 2.9 GPa when the growth rate of HABs starts to rapidly increase. Further data points are required to valid the other two cases.
- For the first time, a 3D model of the HABs established through serial sectioning has demonstrated HABs to be parallel plates with a depth greater than 100 µm which overlap the pre-existing LABs.

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KEYWORDS

Wear: Rolling-Contact Fatigue, Rolling Bearings: Ball Bearings, Materials: Ferrous Alloys, Steel, Dark Etching Regions, White Etching Bands.