INTRODUCTION

Formation of the subsurface White Etching Crack (WEC) has been identified as a cause of detrimental failures in SAE 52100 and SAE 4320 bearing steels that appears to be different from the classic Rolling Contact Fatigue (RCF) in a wide range of rolling contact applications. Typically, RCF failures are due to medium to high contact pressure and high rolling cycles, where a sequence of microstructural transformations takes place, starting from Dark Etching Regions (DER) then Low- and High- Angle Bands (LAB/HAB) and leading to long but finite life of bearings. Little detailed research has been conducted in recent years to investigate the differences between RCF and WEC.

This study, for the first time, has analysed the microstructure changes in DER, HAB and LAB using a combination of advanced microstructure characterisation techniques, including Electron Channelling Contrast (ECCI), Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD) in combination with Energy Dispersive X-ray spectroscopy (EDX), to reveal differences and relationships between RCF and WECs.

MATERIALS AND EXPERIMENTAL METHODOLOGY

DER, LABs, HABs and WECs being investigated in this study were from standard AISI 52100 (100Cr6) through-hardened martensitic steel bearings subjected to RCF testing stopped at different stages when the relevant microstructural transformation occurred.
Cross-sectioned bearing specimens with DER, LABs, HABs and WECs were mechanically polished. Colloidal silica suspension (OP-S) was also used to achieve the necessary deformation-free surface for ECCI, EBSD and EDX analyses. After ECCI, EBSD and EDX analyses, the specimens were slightly re-polished to remove contamination layer and etched with 1% Nital solution for imaging with Light Optical Microscopy (LOM) (Olympus BX51) and Secondary Electrons (SE) in SEM (JEOL JSM 7000F).

RESULTS AND DISCUSSIONS
The results are presented in three sections including observations on the DERs, HABs/LABs and WECs. Due to the length of this extended abstract, limited amount of results and images can be presented. Full details and discussions can be found in a journal publication by the authors.

**DER**: A DER in the subsurface of a bearing ball rolling element is clearly shown in an LOM image in Fig. 1a (marked between the two white lines). From an SE-SEM image of the highlighted area, newly formed elongated-grain groups and small globular grains indexed as ferrite (α-Fe) are observed (see Fig. 1b). The primary spherical iron-chromium carbides (Fe₃C) are seen to be unaltered (see Fig. 1c) and are correlated with the carbon (Fig. 1d) and chromium (not shown in this paper) distributions in this area. The formation of elongated and globular grains is suggested to be the initial stage that results the formation of further microstructure alterations, such as those observed in LABs, HABs and WEC. Elongated grains may appear to be deep grooves under Nital etched condition due to the chemical composition and grain size. The bigger grain sizes and the fact that ferrite has lower carbon solubility have led to the heavier attack by etchant, leaving a rougher topography of deep grooves, whereas unchanged martensite remain unaffected by etchant [1].

**LABs & HABs**: Fig. 2a shows an LOM image of a bearing inner ring cross-section containing both LABs and HABs in its subsurface. Elongated grains and globular grains similar to those in DER are found (see the highlighted regions in SE-SEM images in Figs. 2d&e). The elongated grains are seen to be aligned in same directions towards the surface, suggesting a strong relation to the external loading
conditions. Different from the DER, no retained austenite ($\gamma$-Fe) and significant reduction of primary spherical iron-chromium carbides (Fe$_3$C) are observed in altered area (Fig. 2c). Carbon and chromium redistributions are detected and carbon-rich areas are found around the HAB (Fig. 2b). It is thus suggested that the alteration of spherical iron-chromium carbides has led to a chemical elements redistribution that results in the formation of LABs and HABs.

**Figure 2**: Micrographs of LABs and HABs using different techniques: (a) LOM; (b) EDX Carbon map; (c) EBSD phase map; (d) SE-SEM in Nital etched condition; (e) ECCI OP-S polished.

**WECs**: An LOM image of a networked WEC in the subsurface of a bearing inner ring is shown in Fig. 3a. From an EBSD phase map of the highlighted area, it can be see that no retained austenite ($\gamma$-Fe) and primary spherical iron-chromium carbides (Fe$_3$C) were seen in the WEAs (Fig. 3c). The carbon distributed inhomogeneously in the WEAs (Fig. 3b) while the chromium distributed homogeneously (not shown here), similar to that in the LABs and HABs. Also, it can be seen that carbon has largely depleted in the WEAs while small regions with very high carbon concentrations are observed (Fig. 3b). Elongated grains are also observed inside of the WEA typically close to the cracks, however regular growth direction of these grains is not observed (Figs. 3d&e).

**Figure 3**: Micrographs of WECs using different techniques: (a) LOM; (b) EDX Carbon map; (c) EBSD phase map; (d) SE-SEM in Nital etched condition; (e) ECCI OP-S polished.
CONCLUSIONS

Using a combination of SEM, ECCI, EBSD and EDX techniques, this study has provided qualitative analysis of the microstructure alterations that is important for the clarification of complex steel microstructure changes such as DER, HABs/LABs and WECs. ECCI reveals complex microstructure of elongated grains that had previously been mis-regarded as defect/grooves/micro-cracks under SEM of Nital etched samples. The main conclusions from this study are:

- the formation of altered microstructures in the classic RCF and in WEC accompanies similar primary spherical carbides dissolving processes;
- carbon and chromium elements dissolved from the disintegrated primary spherical carbides are scattered inhomogeneous and homogeneous respectively in the altered microstructures of LABs, HABs and WEC, thus the formation of such altered microstructure may be controlled by the diffusion of these chemical elements;
- the formation of globular ferrite, elongated grains and carbon-enriched areas are observed in both classic RCF and WEC specimens. However the elongated grains in WEC do not grow in defined directions and are locally varying but often occurring from the cracks;
- the distinct directional characteristics observed in the altered microstructures due to RCF is suggested to be related to the external loading conditions. However WECs appear geometrically irregular thus suggests that the external rolling conditions are not dominating their formation.

Future work is planned to further investigate these findings using Transmission Electron Microscopy (TEM), Atom Probe Tomography (APT) and nano-indentation techniques.

ACKNOWLEDGMENTS

The authors thank EPSRC and Armourers & Brasiers for financial support. We would like to extend our sincere gratitude to colleagues from Schaeffler, Germany, for providing the specimens as well for funding this study.

This research was carried out under EPSRC project number EP/M50662X/1.

REFERENCES


KEYWORDS: Materials: Ferrous Alloys, Steel, Rolling Bearings: Rolling Element Bearings, General, Wear: Fatigue, White Etching Cracks, White Etching Area, Rolling Contact Fatigue