Wind Turbine Gearbox Bearing Material Analysis to Study Crack Nucleation, Propagation, and Damage Mechanisms

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INTRODUCTION

Low reliability of wind turbine gearbox bearings result from wide variety of challenging operating conditions which may push the bearings beyond their designed limits. The occurrence of premature bearing failures (20% < L_{10} life) are attributed to specific failure mechanism that is known as white etching cracks (WECs). WECs are parallel or randomly oriented cracks under the subsurface bearing raceway which appear white upon etching, indicating an altered microstructure. The altered microstructure consists of Nano-crystalline grains about 10nm in diameter. White Etch Cracks (WECs) have been observed in through hardened martensitic, bainitic and case hardened AISI 52100 steel, nevertheless some steels are considered more durable and immune to WECs [1, 2]. WECs can cause premature failures in rolling element bearings occurring as early as 1-20% of the calculated L_{10} life [3]. WECs have been discovered in many rolling element bearing applications (generators, mill drives, dryers, cranes, industrial gearboxes) that are operating in conditions that bare no common denominator. Several hypotheses have been proposed to explain the mechanism of WEC's. Some of the influencing factors leading to premature failures due to WEC formation are listed below.

1. Hydrogen penetration into steel from lubricant decomposition, water ingress, stray current
2. Adiabatic shear banding due to transient loads and torque reversals
3. Tensile stresses in the bearing raceway
4. Stress conc. factors such as non-metallic inclusions, voids etc.
5. Shaft displacement and misalignments causing bending stress and impact loading

In the present work, failed bearing from the 1.5 MW turbine gearbox are collected to analyze the microstructure alterations, understand the damage mechanism, and relate it to the existing hypothesis. Bearings from planet stage and high speed stage locations are examined using metallographic and microscopic techniques.

MATERIALS AND METHODS

Wind turbine gearbox bearings studied are sourced from 1.5 MW capacity onshore wind turbines. Several bearings from planet stage and high speed stage locations were sectioned and analyzed. All analyzed bearings were composed of through hardened martensitic bearing steel except one with bainitic microstructure and have a cylindrical roller bearing configuration. The chemical composition of the analyzed bearings remains within the range of martensitic AISI 52100 (100Cr6) steel.

Small 20 x 10 mm sections were cut from the bearing raceway using electric discharge machining (EDM) to examine surface and sub-surface material damage. Sectioned samples were mounted in a mounting compound and polished with diamond and silica suspensions. Each sample is then etched with 2% Nital (2ml HNO_3 + 98ml Ethanol) solution for imaging under optical microscope and scanning electron microscope (SEM).

The SEM investigation is performed using JOEL JSM 7000F field-emission gun scanning electron microscope equipped with EDAX system. Nano-hardness on the WEC is measured by nanoindentation using a Hysitron Triboindenter TI – 950 equipped with a Berkovich diamond probe and loads in the range of 0.5 mN to 12mN.

RESULTS

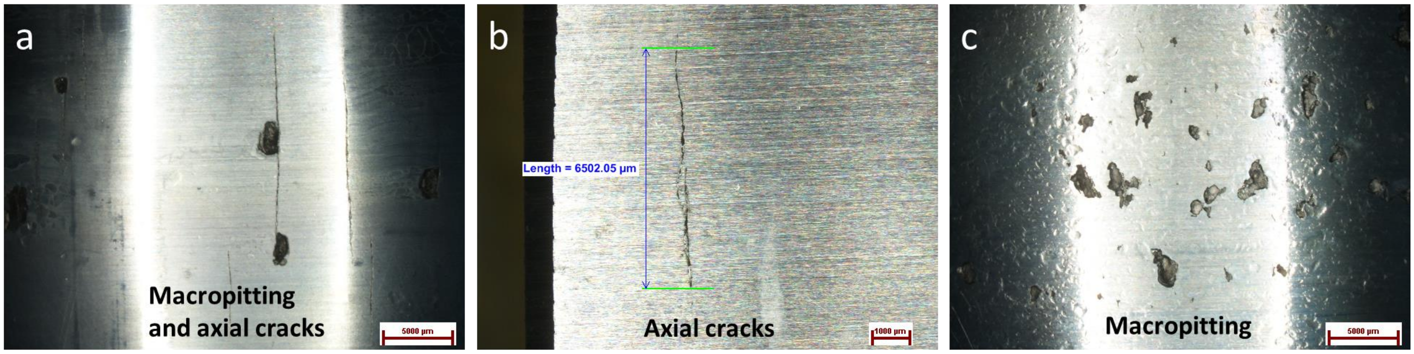

Figure 1 Macro-pitting and axial cracks on the inner raceway of through hardened martensitic steel bearings (a, b) and macropitting on bainitic bearing (c).

The wind turbine gearbox martensitic bearings failed either with macropitting or with both axial cracks and macropitting (Figure 1 a,b) whereas bainitic bearing failed with macropitting only (Figure 1 c) in agreement with the literature [2]. The sub-surface microstructure of the characterized bearings revealed altered microstructure(WECs). The measured Nano-hardness on the altered microstructure was about 27% higher than that of surrounding matrix which is consistent with the literature [3, 4]. The variation in the hardness values within the altered microstructure is most likely from the variable grain size and carbon composition in the localized areas [5].

Table 1 Nano-hardness values of WEC and the surrounding steel matrix

Location	Nano-hardness, GPa
WEC	13.4 ± 0.8
Matrix	10.6 ± 0.4

Butterfly wing formations were observed in planet stage bearings, while both butterflies and Ir-WECs were observed in high speed intermediate stage bearings. Butterfly wing formations in planet bearings were initiated at non-metallic inclusions in maximum shear stress sub-surface regions. Butterflies are developed by crack initiation at non-metallic inclusions that caused microstructural alteration by low temperature dynamic recrystallization of the highly strained regions in agreement with the literature [6, 7]. Butterfly formations are detected mainly in MnS and dual phase oxide inclusions. Only one Titanium Nitride (TiN) inclusion is identified with microstructural alteration. This relates well with the literature as TIN inclusions generally do not participate in butterfly formations [8]. Analysis shows higher likelihood of WECs formation around oxide and dual phase inclusion within the maximum shear stress zone than the MnS inclusion, which could be due to low deformability index and brittle character of oxide inclusions which makes them more detrimental than the sulfide inclusions [9].

Figure 2 Butterfly wing formation around non-metallic inclusions observed in planet stage and low speed intermediate bearings

The mean depth of butterfly generated inclusions are found close to the depth of maximum orthogonal shear stress in agreement with the literature [7, 10]. However, butterfly generated inclusions are also found near unidirectional maximum shear stress by other researchers [11, 12]. There is no consensus in the literature whether maximum shear stress or maximum orthogonal shear stress is more detrimental to the development of damage. However, whichever shear stress is more detrimental, fractured and butterfly generated inclusions are located sub-surface at depth of both maximum unidirectional shear stress and orthogonal maximum shear stress

Ir-WECs observed in high speed stage bearings have optical appearance like butterflies with no preferred orientation as shown in Figure 3. Ir-WECs are connected through randomly oriented micro-cracks with and without white etched areas. Similar Ir-WECs have been observed earlier, which are proposed to be originated and propagated from the non-metallic inclusions [11, 13, 14]. However, butterflies can propagate as a single crack without forming multiple crack networks, which makes this hypothesis debatable.

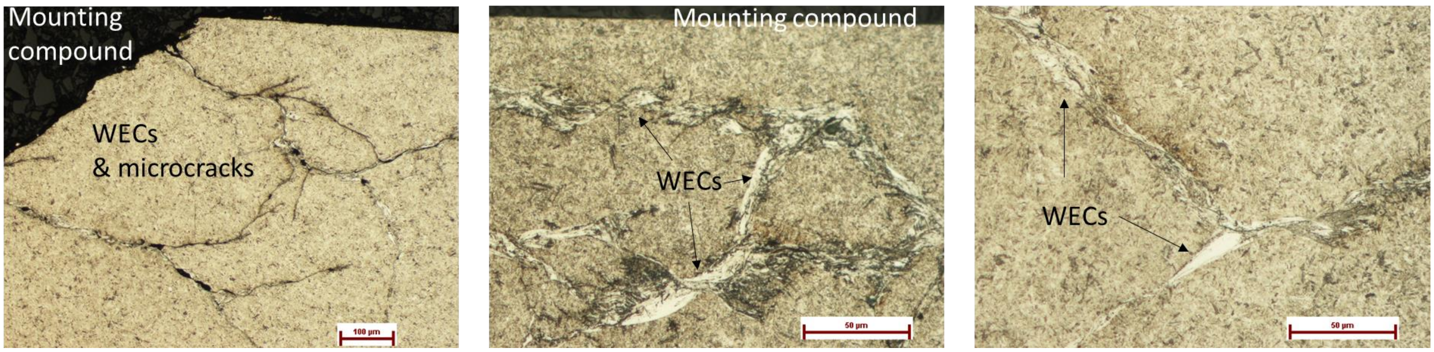

Figure 3 Optical images of circumferential cross-section showing randomly oriented cracks and white etched areas close to the contact surface

The variation in circumferential spacing of the axial cracks observed on the high-speed intermediate stage bearings raceway suggests repeated loading conditions under which cracks are initiated and then allowed to propagate. High speed stage bearings experience large torque reversals at the time of generator-grid engagement and high torque peaks during sudden brakes that can induce excessive stresses than the designed loads. It is possible that excessive loads from transient events combined with tensile stresses initiated cracks [15]. Cracks once initiated either due to single or combination of factors can lead to the formation of WECs depending upon the cumulative number of cycles.

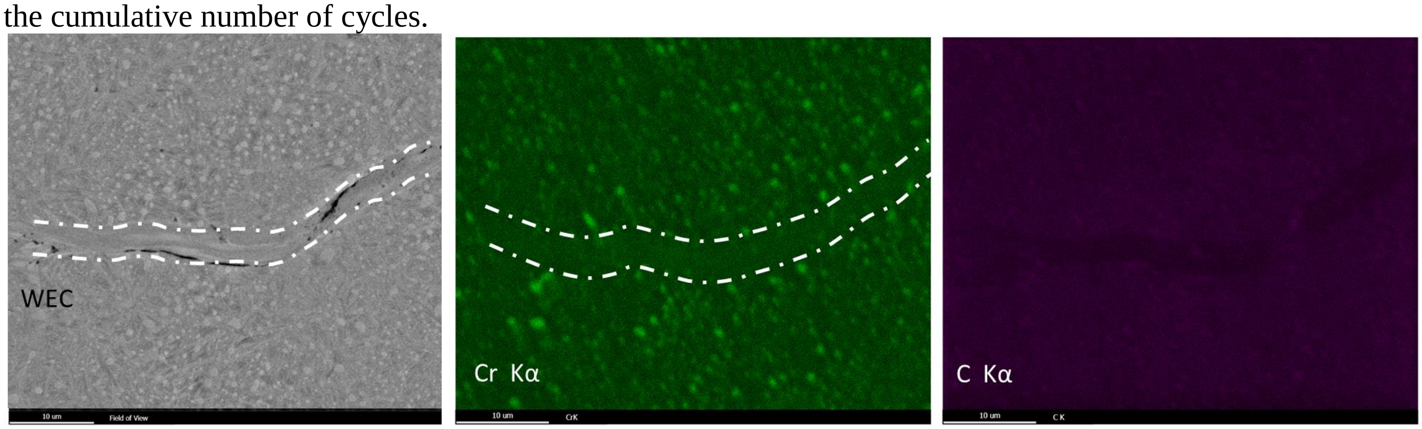

Figure 4 EDX maps of the WEA (a) SEM image (b) chromium map Cr-Kα and (c) carbon map C-Kα

EDX mapping was used to reveal the distribution of Cr and C concentration in the WEC. The chromium and the carbon map distribution measured using EDX in the energy range of Cr-Kα and C-Kα are shown in Figure 4. Primary carbides are seen uniformly distributed in the unaltered matrix. In the altered matrix (WEA), no high intensity spots are visible. The EDX maps shows that Cr is depleted or homogenously distributed in the WEA region.

FINAL REMARKS

In this study, wind turbine gearbox bearings are characterized to conduct qualitative analysis of butterfly wings and Ir-WECs formation. The understanding of these damage mechanisms will assist in developing materials-based prognostic life prediction models that could be useful to qualify the bearings at the design stage and reduce O&M costs. Surface topography of the bearings showed axial cracking and macropitting on the raceway surface. Microstructural alterations are observed in bearings with different crack morphologies.

- Oxide and Dual phase inclusion are detected to be more detrimental compared to manganese sulfide inclusions.
- Butterfly wing formations are detected initiated preferentially at MnS and Oxide inclusions and rarely at TiN inclusions. The mean depth of butterfly wing formations corresponds to the depth of maximum orthogonal shear stress. Wing span of observed oxide inclusions are short and wider compared to the butterflies around MnS inclusions.
- Characteristics of non-metallic inclusions found at sub-surface in the max shear stress zone includes; internal cracking, extended cracks to the surrounding matrix with and without butterflies, and butterflies without internal cracking and extended cracks.
- Ir-WEC with multiple cracks in randomly oriented directions and Nano-crystalline areas with variable grain size are present in the altered microstructure.

The above observations indicate that multiple factors either individually or in combination contribute to the formation of white etched cracks. The WECs on surface and sub-surface are driven by different mechanisms comprising material, mechanical, thermal and chemical phenomenon.

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KEYWORDS

Wind Turbine Bearings, 100Cr6 Steel, White Etching Cracks (WECs)