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Multiscale characterization of White Etching Cracks (WEC) in a 100Cr6 bearing from a thrust bearing test rig

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ABSTRACT

A common cause for premature bearing failures in wind turbine gearboxes are the so-called White Etching Cracks (WEC). These undirected, three-dimensional cracks are bordered by regions of altered microstructure and ultimately lead to a cracking or spalling of the raceway. An accelerated WEC test was carried out on a FE8 test rig using cylindrical roller thrust bearings made of martensitic 100Cr6 steel. The resulting WECs were investigated with several characterisation techniques. Ultrasonic measurements showed the WEC were mainly located in the region of the overrolled surface in which negative slip occurs, which agrees with hypotheses based on an energetic approach for a prognosis. SEM orientation contrast imaging of the area around WEC revealed an inhomogeneous structure with varied grain sizes and a large amount of defects. Microstructure characterization around the WEA using EBSD showed significant grain refinement. Atom probe tomography showed the microstructure in the undamaged zone has a plate-like martensitic structure with carbides, while no carbides were detected in the WEA where the microstructure consisted of equiaxed 10 nm grains. A three dimensional characterisation of WEC network was successfully demonstrated with X-ray computerized tomography, showing crack interaction with unidentified inclusion-like particles.

1. Introduction

White Etching Cracks (WEC) is a particularly aggressive, unpredictable and wide spread bearing failure mode that is common for large multi-megawatt wind turbines at the main shaft, gearbox and generator. It causes premature breakdowns typically after 5–10% of the rated lifetime [1]. The nano-crystalline area bordering the cracks is called White Etching Areas (WEA) as it appears white in optical microscopes due to the resistance to etching, not to be confused with the cracks themselves that are named after this feature (White Etching Cracks). WEC can appear on different locations (raceways, rollers), in different bearing designs, with different lubricants and in different steel grades [2]. While WEC is known to appear in many different bearing applications [3], the frequency is considered to be highest for wind turbine applications [4] and has become even more prominent with the introduction of large megawatt sized turbines [5].

While being one of the most pronounced bearing failure modes, WEC is poorly understood and is difficult to reproduce at laboratory scale. Several hypotheses have been established on the cause of WEC, including [4]: Hydrogen from lubricant composition, stray currents or water contaminations; frictional surface cleavage cracking followed by corrosion fatigue crack growth. The cause of WEC seen in industrial applications could very well consist of a combination of these effects. There is a severe lack of consensus regarding even the basic initiation mechanism of these failure modes [1,4]. For example it is still discussed if WEA initiate the cracks [6,7] or the cracks are causing the WEA [8,9]. Smaller WEC, so-called butterflies, are frequently found around stress raising inclusions within 1mm of surface, which has led to the debate on whether these link up and form WEC networks that

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originate below the surface [10] or WEC networks originate at the surface and then grow inwards [2,11].

For this paper, WEC were provoked using a rolling bearing test rig. With the aim of giving an insight in the initiation progress, samples of one test specimen were distributed to several research facilities for investigations using highly specialized characterization techniques such as EBSD, atom probe tomography and X-ray tomography. This paper gives an overall view from macro to nano scale of the WEC characteristics of one specimen.

2. Experimental details

2.1. Test conditions

The test was performed on a FE8 rolling bearing test rig produced by FAG, standardized in accordance with DIN 51819 [12]. Fig. 1a shows the sectional representation of the test rig. Two type 81212 cylindrical roller thrust bearings are loaded by a plate spring package. A closed lubrication circuit carries out the lubrication of the test rig. It supplies each of the test bearings separately with a defined oil volume flow rate and at the desired temperature. The mass temperature of the non-rotating washer of each bearing is controlled by a heating jacket. The frictional torque is continuously measured via a sheave.

The housing and shaft washer raceway, as well as the 15 rolling elements, are made of martensitic hardened 100Cr6 steel. The brass cage (Ms60), which is normally used as described in [12], was substituted by a polyamide cage (PA 66) in order to avoid a chemical influence. The tested lubricant was a mineral oil based oil, considered to enhance the formation of WEC, with a viscosity grade of ISO VG 100. An analysis of the elemental composition showed that Phosphor, Sulphur and Zinc have been added to the oil. This specific oil is a commercial product, therefore its chemical components are unknown. The test conditions are listed in Table 1 [13]. Termination criterion of a test is a predefined number of load cycles (revolutions of drive shaft) or an exceedance of a vibration level which surpassed the set threshold, normally caused by pitting or spalling. The arithmetic mean surface roughness R_a of the bearing washers and rollers was measured before the test run and lies in a range from 0.44 to 0.49 μm for the washers and 0.66 to 0.72 μm for the rollers. Using the lubricant properties and measured surface roughness, the specific lubrication film thickness λ was determined, using the Dowson and Higginson [14] equation for the lubrication film thickness. The initial λ-values for the tests at 100 °C lie in a range from 0.57 to 0.62. Based on the calculated values, it is evident that the test was running within the mixed friction regime. The test shut off after 200 hours due to the vibration threshold being surpassed. Four large spallation areas were found, see Fig. 2. The test exceeded the calculated value for the nominal bearing lifetime L_{nm} of 57 h.

2.2. Ultrasonic measurements

Ultrasonic measurements were done using a pulse-echo water-based HFUS 2000 with a 50 MHz transducer. The measurements of the bearing washers were done on the opposite side of the raceway so that the back-echo from the raceway surface was investigated. The surfaces which were investigated had no surface defects, thus the anomalies detected were cracks. This was verified by removing 50 μm of the surface and polishing it, which gave the same results.

2.3. SEM

Sample cross sections were cut transverse to the over-rolling direction from the received ring segments. After cutting, the samples were hot mounted in Bakelite. Samples were ground and polished until a finishing step of 1 μm diamonds followed by polishing in colloidal silica on a Struers Rotopol 22. After the final polishing step, the samples were removed from the resin and glued to a pre-tilt sample holder using silver paint for electron microscopy investigations.

Scanning electron microscopy on cross sections was performed using an FEI Helios Nanolab 600™. Cross sections were studied using backscattered electron (BSE) imaging mode. Orientation contrast was used to reveal the structure and orientation differences both inside WEA and in the martensitic matrix.

Table 1
Test conditions.

Axial load (Max. contact pressure)	Oil flow rate	Bearing mass temperature	Rotational shaft speed	Averaged Specific film thickness λ
80 kN (2282 N/mm²)	0.25 l/min	100 °C	300 rpm	0.59 (Automotive motor/gear oil, fully formulated)

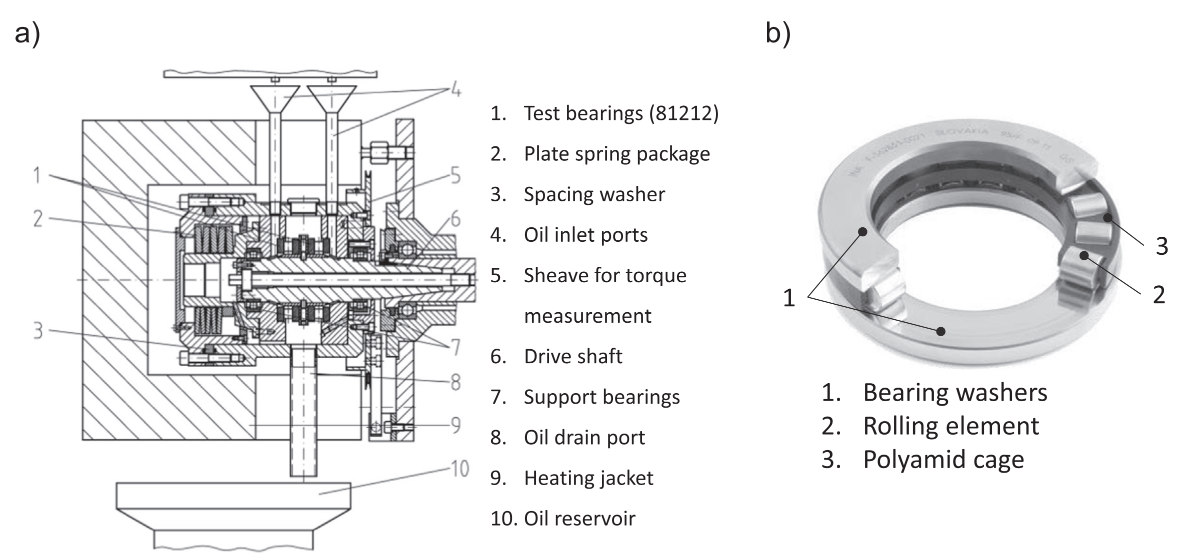

Fig. 1. Test rig: A) FE8 test rig with test bearings of type 81212 according to[12]. B) cylinder roller thrust bearing 81212.