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Serial sectioning investigation of butterfly and white etching crack (WEC) formation in wind turbine gearbox bearings

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ABSTRACT

Premature wind turbine gearbox bearing failures in the form of white structure flaking (WSF) can occur in as little as 6–24 months of operation. WSF is not fully understood but is thought to be due to hydrogen release and diffusion into the bearing steel and/or transient operating conditions not fully understood. The initiation mechanisms of white etching cracks (WECs) are contested, where amongst others mechanisms, subsurface initiation at non-metallic inclusions (perhaps associated with extension of butterfly cracks) and surface crack initiation are cited. For the first time this study applies serial sectioning to map WEC networks in wind turbine gearbox bearings to elucidate WEC initiation mechanisms. A comparison is made between WEC data for inner rings of an industrial transient test gearbox bearing and a planet bearing that spalled in service. It is proposed that one mechanism of WEC formation in wind turbine gearbox bearings is due to subsurface WEC initiation from inclusions, either in a butterfly manner or non-butterfly manner; where these small WECs link together to form larger WEC networks, these eventually propagating to the surface resulting in WSF. Small size/length inclusions were found to be likely WEC initiators, therefore the data suggests that steel cleanliness standards analysing inclusion density (as opposed to maximum inclusion lengths) are more relevant in understanding butterfly/WEC initiation in wind turbine gearbox bearings. However standards used should be able to differentiate pure sulfides from sulfides+oxide encapsulations and record inclusions that are only a couple of mircometer's in length/diameter.

1. Introduction

Wind turbine gearboxes often fail at a number of critical bearing locations, where micropitting, smearing and white structure flaking (WSF) are the predominant failure modes [1]. The rolling contact fatigue (RCF) life of a bearing for a given operating condition can be characterised by the *'L_{10} life'* at which statistically 90% of bearings survive. Normal RCF failures by spalling tend to occur well beyond the L_{10} life, however WSF differs from the conventional subsurface material decay caused by RCF. As a result, WSF can occur extremely prematurely in as little as 1–20% of the L_{10} life [1–3] and 6–24 months operation in wind turbine gearbox bearings [4].

The formation of *white etching cracks* (WECs), and also perhaps *butterflies*, in the 1 mm zone beneath the contact surface are associated with WSF. Butterflies are cracks with microstructural changes induced around stress raisers (typically non-metallic inclusions) under highly localised subsurface shear stresses forming a butterfly shape. WECs are metallographically similar to butterflies but are distributed in irregular shaped branching networks [3].

White structure or white etching area (WEA) refers to the appearance of the cracks associated altered microstructure when cross sections are polished and etched with nital and examined under reflected light, due to the etching resistance of the microstructural change. WEA is nano-crystalline in nature (grains varying in size from ~10 to 300 nm). Formation mechanisms of WEA are discussed in [3].

WSF is thought to be driven by hydrogen release and diffusion into bearing steel (sourced from the lubricating oil or water contamination) [2,3] and/or transient operating conditions that are not fully understood [1,3]. Varying methods have been used to enable the creation of WECs in tests, which has been reviewed in [3]. These include use of special oils in RCF tests that promote hydrogen release and diffusion into steel, use of water additions in the lubricant, use of electrical currents across contacting surfaces to release hydrogen, hydrogen charging steel prior to testing, running RCF tests in hydrogen gas atmospheres, use of test rigs that enable rapid acceleration–deceleration transients to force slip in bearings, use of spin slip between contacts and causing vibrations in bearings by inducing resonances in belt drives. The maximum contact pressures used in the majority of WEC

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studies has been high at 3–5.6 GPa [2,5–14], however the mechanisms of damage at these high contact pressures are likely to be different than for service realistic contact pressures of ~1–2 GPa.

Hydrogen has been shown to diffuse into the steel during RCF [2,12,13,15,16] to bulk concentrations between about 0.1–4 ppm [2,12,16], however to what level is likely in actual wind turbine gearbox bearings is currently unknown due to practicality of removing bearings from service and quickly freezing the samples for thermal desorption analysis needed to measure bulk concentrations of diffusible hydrogen. Two mechanisms for hydrogen entry into bearings during operation are cited; (1) bulk diffusion continuously during operation from tribochemical reactions at nascent surfaces created by severe events, (2) surface cracking begins and subsequently the lubricant or water contamination inside the cracks release hydrogen locally due to intense crack rubbing and nascent surfaces at the crack tip to diffuse into the surrounding vicinity [17].

The possible hydrogen entry routes links to the initiation mechanisms of WECs, which are still contested. Both surface initiation at surface flaws/cracks, initiation at microstructural discontinuities from high impact events and subsurface initiation at non-metallic inclusions (perhaps associated with extension of butterfly cracks [18,30]) are cited [3]. To effectively design solutions against WSF, it is important to understand the initiation process of WECs since surface crack initiation or impact initiation links to surface engineering and tribological operating conditions, and subsurface initiation links to steel cleanliness (e.g., non-metallic inclusions).

Steel cleanliness is an important aspect regarding subsurface initiation, as this affects the likelihood of crack initiation at non-metallic inclusions. The maximum lengths, density and types of inclusion are all important parameters [19]. Cleanliness can be determined by steel cleanliness analysis methods that quantify density of inclusions and maximum inclusion lengths by statistical methods.

Differences in coefficient of thermal expansion (CTE), elastic modulus, shape, size, adhesion property and coherence between inclusions and the steel matrix are considered to be the controlling parameters for crack initiation [20–29]. Compressive and tensile stresses are induced surrounding soft (sulfide) and hard (oxide) inclusions, respectively, due to the differences in coefficients of thermal expansion (CTE) [28]. The oxide part of a duplicate sulfide+oxide type of inclusion therefore also has locally surrounding tensile residual stresses [18,28]. Crack initiation and short crack growth at inclusions is governed by Mode I loading from a fracture mechanics approach [18]. Inclusions must have a locally surrounding residual tensile stress for positive stress intensity factors to prevail at the crack tips. Hence as the residual tensile stress field around an inclusion diminishes moving away from the inclusion, the mode I crack would eventually arrest at a crack size determined by the mode I threshold stress intensity factor [18]. Therefore in general, type D (oxide) and type A (with oxide parts) inclusions are those most likely to initiate cracks [3,30]. Further growth of the cracks would then be governed by Mode II/III shear loading from the high cyclic shear stress field induced during rolling contact if the Mode II/III threshold stress intensity factor were exceeded [18].

This study aims to reveal information about WEC initiators (non-metallic inclusions and/or butterfly interactions) by the application of serial sectioning to map WEC networks in wind turbine gearbox bearings for the first time. The serial sectioning process has been conducted on two different wind turbine gearbox bearing inner rings; (1) a bearing used on an industrial transient test rig, and (2) a planet bearing from a 3 MW wind turbine that spalled in service.

2. Techniques and experimental methods

2.1. Industrial transient test gearbox bearing rig operating conditions

A large-scale industrial transient test rig designed to simulate conditions to wind turbine gearbox bearing service was used to test wind turbine gearbox bearings. Four double-row spherical roller bearings with 150 mm inner bore diameter were tested simultaneously. Mechanical spindles statically loaded each bearing continuously during the test. A run-in period of roughly 2 h was conducted, with the inner ring of the bearings experiencing a peak maximum contact pressure in the centre of the contact of 1.5 GPa.

After the run-in period, transient speed operation with load dynamics was used throughout the remainder of the test. The set of four bearings were driven by a static shaft and also a dynamic shaft (a resonance being induced in this shaft from the dynamic motor). Torsional dynamics (speed dynamics) was achieved by inducing a resonance in the dynamic shaft at a high frequency, where load dynamics was achieved by a second independent resonance system generating a high frequency dynamic radial loading. Overlaid frequencies are sine shaped in both cases. Information on the frequencies used is not revealed due to proprietary sensitivity. The four bearings are aligned side-by-side in a row of four, resulting in one bearing being located adjacent to the static shaft, one bearing adjacent to the dynamic shaft and two bearings being located between these two end bearings. The loads experienced in the inner ring during operation were: mean contact pressure: 1.9 GPa and maximum contact pressure: 2.15 GPa. The test cycle was designed with transients so that the bearings ran at base-speed for about 5 min, followed by a transient drop to low-speed for about 1 min. The base-speed rpm replicated typical upper high-speed gearbox bearing operation of ~1500 rpm, and the low-speed rpm was ~20× lower than the base-speed. When operating at the low-speed portions, in combination with the speed dynamics, standstill is almost reached. The time of the transients to ramp the bearing speed up and down was about 20 s in each case.

The bearings experienced 130% of their basic rating life (L_{10} life), this equating to about 1400×10^6 stress cycles (over-rollings at any one point on the inner ring raceway) before the test was manually stopped. Each bearing was supplied independently with lubrication during testing. The oil used was a commercially available ISO VG 320 water-soluble PAG fully formulated wind turbine gearbox oil. The bearing temperature measured at the outer ring was about 85–90 °C during the test. The kappa value (Eq. (1)) is the ratio of the actual viscosity of the oil under operating conditions (pressure and temperature) to the minimum calculated viscosity required for adequate lubrication (i.e., EHL).

$$k = v/v_1 \tag{1}$$

where,

k = viscosity ratio (kappa value)
v = operating viscosity of the lubricant [mm^2/s]
v_1 = rated viscosity depending on the bearing mean diameter and rotational speed [mm^2/s]

Kappa values in the range of about 2 to 4 are required for optimum bearing life, where a kappa value in excess of about 4 equates to full-film operation. The predicted kappa values during the following operating conditions are as follows; base-speed (5 min portion): ~10, and low-speed (1 min portion): <1.

As the bearings are of spherical roller type, a phenomena called Heathcote slip would occur during periods of operation,