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Characterisation of white etching crack damage in wind turbine gearbox bearings

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ABSTRACT

White etching cracks (WECs) have been identified as a main failure mode of wind turbine gearbox bearings (WTGBs). This study reports an investigation of the destructive sectioning of a failed low speed planetary stage WTGB and the damage found at manganese sulphide (MnS) inclusions. The bearing inner raceway was sectioned through its circumferential and axial directions in order to compare the damage around inclusions in different directions. 112 damage initiating inclusions were catalogued and their properties were investigated.

WECs were found attached to MnS inclusions of lengths 3–45 μm at depths of up to 630 μm from the bearing raceway surface and at a wide range of angles of orientation. Damage at MnS inclusions included internal cracking of the inclusions, separation from the surrounding steel matrix, crack initiation and WEC initiation. Evidence has been found to support the theory that WECs are subsurface-initiated by MnS inclusions, but that butterfly cracks with wings propagating at 30–50° from parallel to the raceway surface are not necessarily the same features as MnS inclusion-initiated WECs. Shorter inclusions were found to initiate longer WECs, as were the inclusions that were closer to parallel to the raceway surface in axially sectioned samples.

1. Introduction

The wind industry faces tough challenges to reduce the cost of wind energy; particularly its high operating cost. The European Wind Energy Agency has a planned target of 230 GW of installed wind power capacity by 2020, representing 20% of the total European Union (EU) electricity consumption [1]. This expansion is being limited by a number of maintenance issues, most critically concerning wind turbine gearboxes (WTGs) which are not reaching their anticipated lifespan of 20 years. It is estimated in the United Kingdom that operation and maintenance accounts for 20% of the cost of offshore wind energy [2].

A majority of WTG failures initiate in the wind turbine gearbox bearings (WTGBs) [3], and the exact modes of their failure have been intensively researched and widely investigated by industry. White etching cracks (WEC) have been found to lead to premature failure by white structure flaking (WSF) [4], or axial cracking [5]. Previous work has identified material defects, particularly manganese sulphide (MnS) inclusions as WEC initiators, in both actual WTGBs obtained from the field and WTGBs after rolling contact fatigue (RCF) testing on large scale test rigs [6–9]. This study will investigate damage initiation at manganese sulphide (MnS) inclusions, by destructively sectioning the inner raceway of a failed planetary stage WTGB. Damaged inclusions were catalogued and their properties were recorded. The objective was to investigate different types of damage caused at the inclusions and to find any links between their properties and possible connections to operating conditions.

1.1. MnS inclusions in bearing steel

MnS inclusions have been classified into three types since 1938 [10]. Type I inclusions are globular in shape and appear in steels with practically no aluminium content. Type II are dendritic chain formations on grain boundaries and appear with the first traces of aluminium (0.005 wt%). Type III are strings of broken silicates and initially appear alongside Type II at levels of 0.01–0.03 wt% aluminium. At levels greater than 0.04 wt%, Type III is the only MnS inclusion to appear [10]. Since typical bearing steel, such as 100Cr6 or 100CrMo7, has a very low aluminium content [11], globular Type I MnS inclusions are most commonly found. MnS inclusions in hot-rolled steels of irregular shape and which are elongated and flattened in the direction of plastic deformation [12] during the

Abbreviations: EU, European Union; SCADA, supervisory control and data acquisition; BCC, body-centred cubic; RCF, rolling contact fatigue; WTG, wind turbine gearbox; WTGB, wind turbine gearbox bearing; WEC, white etching crack; WEA, white etching area; WSF, white structure flaking; MnS, manganese sulphide

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metal forming process are randomly distributed. Therefore their orientation may vary from bearing to bearing due to differences in the metal forming process. Inclusions have been observed to have been elongated to different extents in bearing steel and can be defined by their aspect ratio (length/width) when viewed two-dimensionally. Those inclusions with an aspect ratio of less than three are described as globular and those with larger aspect ratios as long and thin [6].

1.2. White etching cracks

Currently, WTGB failure via white etching cracking is not fully understood, despite intense research effort [5,6,9,13–20]; therefore bearing life prediction models have yet to be developed to include this failure mode in the selection of bearings [4,5,16,19]. WECs are physical cracks in the material subsurface decorated by white etching areas (WEAs) and appear white after etching in nital (nitric acid/methanol) solution due to microstructural change that causes the material to be resistant to the etching process [6]. WEAs have been found to be areas of ultrafine nano-recrystallised carbide-free body-centred cubic (BCC) ferrite microstructure [4,18,21]; the WEA microstructure has no, or very few remaining carbides and is supersaturated with dissolved carbon, which makes the material brittle and harder (about 30–50%) than the steel matrix [4,18,22]. Cyclic Hertzian stresses caused by rolling contact at and close to the surface promote the ‘glide’ of subsurface dislocations, which repeatedly interact with retained temper carbides, leading to their dissolution [4,23]. One theory is that when the accumulation of dislocations reaches a critical density; a dislocation cell-like structure forms to release the strain energy [13], possibly explaining why obstacles to dislocation glide, such as inclusions, voids or large carbides have been found to be areas at which WEAs form [21]. This theory is contradicted by findings in [18,24], which suggest that WEAs are formed at “butterfly cracks” by an evolving microstructural change leading to the nanocrystalline structure by material transfer and “rubbing” between inclusions and the steel matrix.

WECs have been observed to form (not necessarily exclusively) from “butterfly cracks”, named such due to their two-dimensional appearance. Despite considerable evidence [6,7,9,15,18,23–26], there has been, as yet, no method devised to prove absolutely that butterflies are indeed the point of damage initiation. Butterflies have been reported to initiate most commonly at inclusions [7,27], but voids and carbides may also be candidates for butterfly initiation [4,5] while other studies have found that voids are most likely to initiate butterflies [28,29]. Impurities may be initiation points due to local Hertzian stress concentration, residual stress from heat treatment, the creation of free surfaces during quenching, and/or dislocation accumulation [7]. WEAs form adjacent to microcracks, or possibly form first and promote microcrack growth. WEAs initiate and propagate between 30–50° and 130–150° from the over-rolling direction, giving the appearance of “butterfly wings”, which may be due to the position of maximum Hertzian unidirectional shear stress [4]. Similar cracks may form in the direction opposite to over-rolling if the rolling direction is reversed [30], or sometimes without this reversal (although the symmetric cracks are smaller than the two formed in the over-rolling direction) [7].

WECs may form irregular crack networks that possibly follow pre-austenite grain boundaries, or may propagate radially from straight-growing cracks [5]. It is claimed by Errichello et al. that through-hardened bearings fail by the axial crack method, whereas carburised bearings with less than 20% retained austenite fail by WSF, based on a comparative metallurgical study of both bearing types [5]. If a network of WECs beneath the contact surface weakens the near-surface material sufficiently, WSF may occur causing material to flake away from the surface, leading to eventual failure possibly within 1–20% of the L_{10} design life [31–34] predicted by current bearing design standards [35].

1.3. Hertzian stress in RCF line contacts

Using Hertzian line contact theory, it is possible to calculate the approximate depth of maximum unidirectional shear stress τ_{max}, orthogonal shear stress $\tau_{0,max}$, and equivalent (von Mises) stress σ_V. Although this method must be used with some caution, since the contact between rolling element and raceway is neither static nor smooth and is separated by a lubricant film, it is common practise to approximate contact pressures in rolling element bearings using the Hertzian theory [36]. Since in most bearings, both the roller and inner raceway are made from the same material, the standard equation used to calculate the Hertzian contact pressure can be simplified to

$$P_0 = 0.418\sqrt{\frac{WE}{RL}} \tag{1}$$

where

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} \tag{2}$$

r_1 and r_2 are the radii of the contacting inner raceway and rolling element respectively, W is the contact load (N), L is the width of the raceway, υ and E are Poisson's ratio (0.3) and Young's modulus (210 GPa) of the steel respectively [7]. The width of the contact rectangle, $2b$, is calculated from the contact half-width b, using Eq. (3).

$$b^2 = \frac{4WR}{\pi LE} \tag{3}$$

The position of τ_{max} for line contacts is at $0.78b$, $\tau_{0,max}$, at $0.5b$ and for σ_V, at around $0.7b$. For elliptical contacts between a spherical roller and cylindrical raceway, shear stress maximum depths are as follows: τ_{max} at $0.48a$, $\tau_{0,max}$ at $0.25a$, where a is the radius of the semimajor axis [7,9,37–39].

Grabulov used a RCF loading test rig to apply a contact pressure of 2.6 GPa for 13×10^6 cycles to test specimens with artificial aluminate (Al_2O_3) inclusions, finding that there were three distinct butterfly development zones dependant on depth from the contact surface. At depths of up to 150 µm, fully developed butterflies were found, between 150 and 800 µm, early stages of the butterfly development process had taken place, and at depths deeper than 800 µm, no butterflies were found. For the tested conditions, $\tau_{0,max}$ occurred at a depth of 63 µm and τ_{max} occurred at ~120 µm (approximate value calculated from position of $\tau_{0,max}$) [39], both values were well within the zone of fully developed butterfly formation. τ_{max}, $\tau_{0,max}$ or a combination of both, may be critical in the formation of WECs.

1.4. MnS inclusions as crack initiation sites

All inclusions may act as crack initiation sites under high enough contact stress [7], however MnS inclusions have been found to be the most likely to interact with WECs in WTGB steel [6,8,25–27]. Shorter inclusions have been found to be more likely to initiate damage than longer inclusions, with the ideal length for crack propagation found to be smaller than 20 µm [6,25]. During quenching, the larger thermal contraction rates of the MnS inclusion than the bulk material, may lead to the detachment of the inclusion from the surrounding bulk material, thereby creating a free surface at the subsurface inclusion [7]. The weak bond between MnS inclusions and the matrix may contribute to the