STUDENT POSTER ABSTRACT

Investigations of White Etching Crack (WEC) Formation under Rolling Contact Fatigue

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INTRODUCTION

A premature failure mode in steel rolling element bearings called *white structure flaking* (WSF) occurs in wind turbine gearbox bearings. WSF can occur in as little as 6-24 months of operation. WSF is associated with microstructural alterations called *white etching area* (WEA) and *white etching cracks* (WECs) that form in the ~1 mm zone beneath the contact surface.

The tribological drivers for WSF are contested. Suggestions of drivers are hydrogen release and diffusion into bearing steel (sourced from the lubricating oil or water contamination) and transient operating conditions, e.g., load, vibrations and slip (see review paper [1] for details and references). Hydrogen has previously been found to diffuse into steel during RCF tests at concentrations between about 0.1-4.2 ppm.[1] For this reason, to replicate this diffusion of hydrogen into the steel during rolling contact fatigue (RCF), hydrogen charging on test specimens/bearings has been used in various WSF studies. Hydrogen entering steel during rolling contact has been suggested to occur by two mechanisms: (1.) through surface cracks where water contamination or lubricant enters surface cracks, allowing local release of hydrogen ions by tribochemical reactions at crack tip nascent surfaces. (2.) through wear induced nascent surfaces where hydrogen is generated by decomposition of lubricants through catalytic reactions and tribochemical reactions of water.[1]

The initiation and propagation mechanisms of WSF are contested. Surface initiation at cracks and subsurface initiation by inclusions or impact events have been suggested.[1] This group has applied serial sectioning to map subsurface wear volumes of bearings from service and large scale test rigs[2] and test specimens from laboratory,[3-5] which has allowed investigation of initiation/propagation mechanisms of WSF and thresholds of WSF formation. Extensive FIB/TEM studies to enhance understanding of butterfly crack and WEA formation mechanisms has also been conducted.[6]

MATERIALS, TECHNIQUES & EXPERIMENTAL METHODS

TE-74S Two-Roller RCF Testing

12 hydrogen-charged RCF tests has been conducted on a TE-74S two-roller RCF machine.[3,4] Two 100 Cr6 bearing steel rollers (26 mm vs. 52 mm diameter, see Figure 1) were used as test specimens with hardness ~62 HRC. The tests were

Snow is actually colorless upon formation but appears to be white due to light reflections. Snow

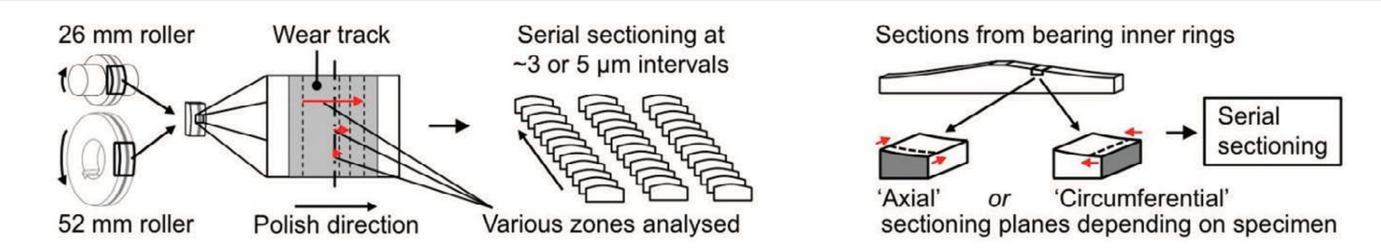

Figure 1 | **Process of serial sectioning in the TE-74S test rollers and bearing inner rings.**

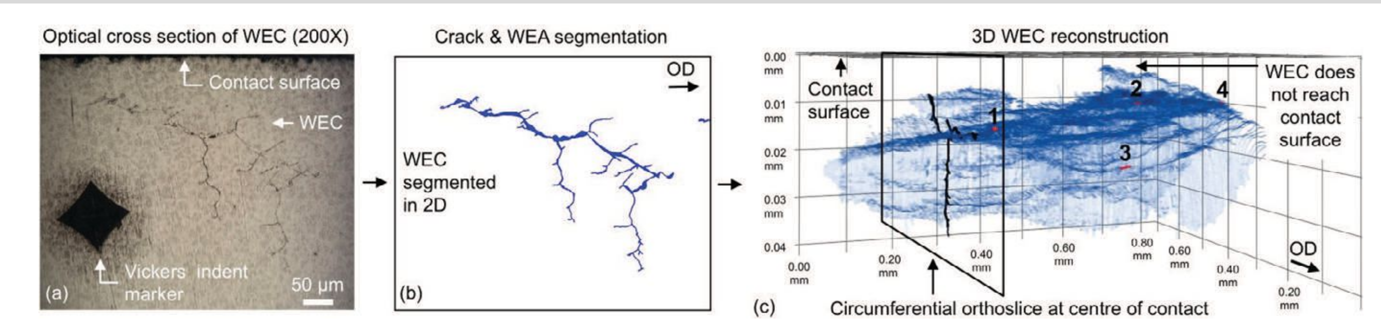

Figure 2 | **Images showing process of 3D WEC reconstruction. (a) Optical image of WEC at miscellaneous slice in the circumferential plane. (b) 2D crack + WEA segmentation at slice in (a). (c) 3D WEC model of all slices in WEC model (~160 slices). No's 1-4 highlights inclusion-WEC interactions. See [4] for images and 3D crack reconstruction videos.**

conducted under constant conditions with P_{max} 1.2-2 GPa. PAO-4 base oil was delivered on the entrainment side of the contact and load was applied pneumatically. Oil inlet temperature was 67°C and mixed/EHD lubrication regimes prevailed. Rolling cycles numbers ranged from ~0.5 x 10^6-100 x 10^6 depending on the test. Thermal desorption analysis (TDA) quantified the different concentrations of diffusible hydrogen under different charge conditions in the test rollers.[3] Details of steel cleanliness can be found in [3-5].

Wind Turbine Transient Gearbox Bearing Testing and Planet Bearing Operating Conditions

(i) A large-scale transient test rig designed to simulate conditions to wind turbine gearbox bearing operation was used to test four high-speed wind turbine gearbox spherical roller bearings (inner bore diameter 150 mm).[2] Mechanical spindles statically radially loaded each bearing continuously. Transient speed operation with load dynamics was used throughout 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. The test cycle was designed with transients so that the bearings ran at base-speed for 5 minutes, followed by a transient drop to low-speed for 1 minute. The base-speed rpm replicated typical upper high-speed gearbox bearing operation of ~1500 rpm, and the low-speed rpm was ~20X lower than the base-speed. The time of the transients to ramp the bearing speed up and down was 20 seconds in each case. The oil used was a commercially available ISO VG 320 water-soluble PAG fully formulated wind turbine gearbox oil and the kappa value ranged between ~1-10 during the test under a P_{max} of 2.15 GPa. The bearings experienced ~1400 x 10^6 stress cycles. The bearing temperature measured at the outer ring was about 85-90°C during the test.

(ii) For the planet bearing from service, this failed from WSF during operation in the wind turbine gearbox. The planet bearing was of double-row spherical roller bearing type with inner bore diameter of 300 mm and inner ring stationary.

Both the tested and ex-service bearing inner rings were bainitically through hardened (100Cr6 steel variants) with hardness ~60 HRC. Details of steel cleanliness can be found in [2].

Serial Sectioning, FIB Tomography and 3D Crack Reconstruction

Serial sectioning has been conducted to map WECs in 3D for the first time. The process involves fine grinding and polishing of cross-sections of the test rollers and bearing inner rings at ~3-5 µm material removal intervals typically over 100's of slices (Figure 1). Cross-sections are polished and etched with Nital 2% before being examined with optical mi-

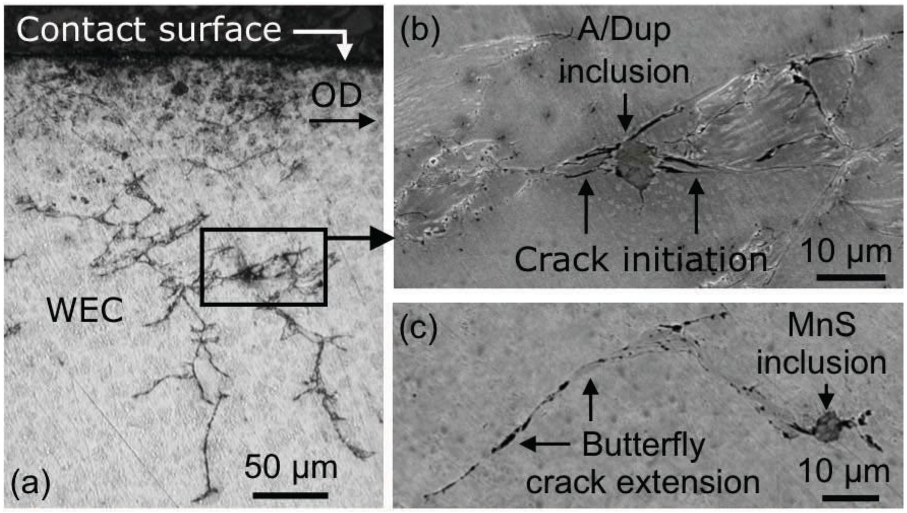

Figure 3 | Examples of inclusion-WEC interactions found in hydrogen-charged test rollers. (a) Optical image. (b) SEM image of detail in (a) showing inclusion-WEC interaction. (c) Evidence showing apparent butterfly crack propagation to WEC. Circumferential sections with over-rolling direction marked 'OD'. Images from [4].

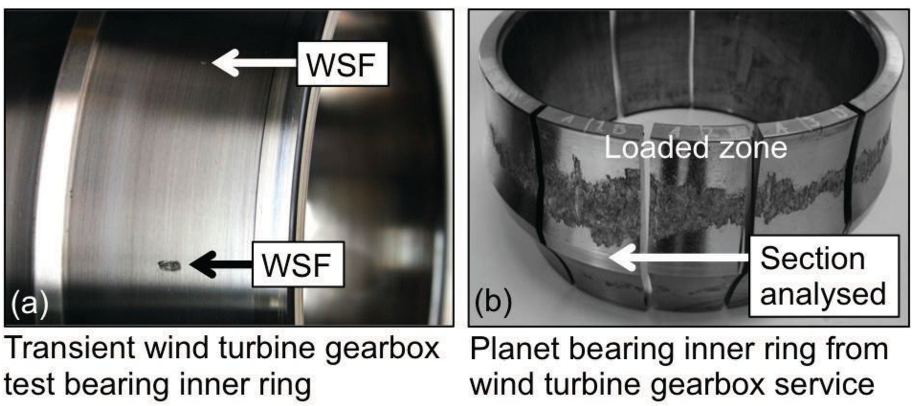

Figure 4 | Bearing inner rings analyzed by serial sectioning. (a) Two small flaking areas on inner ring raceway are apparent, where serial sectioning was conducted in their close vicinity. (b) Extensive spalling on the inner ring raceway where the serial sectioning locations were chosen at non-damaged raceway locations adjacent to the spalling. Images from [2].

croscopy and select features by SEM/EDX. FIB tomography was used to analyse crack initiation mechanisms. 3D crack models of WECs (Figure 2) and inclusion-WEC interactions were constructed (see [4] for 3D crack reconstruction videos).

RESULTS & DISCUSSION

WEC Formation Overview

WEC/WSF was successfully reproduced in hydrogen-charged rollers at low loads (P_{max} 1.5-2 GPa) and low/moderate concentrations of diffusible hydrogen (~0.8-1.9 ppm).[3-5] Figures 2-3 shows examples of WECs formed. In the transient gearbox test, WSF was reproduced under controlled conditions in actual wind turbine gearbox bearings for the first time (see raceway in Figure 4(a)).[2] WECs were found extensively in the inner ring of the planet bearing which spalled in service (see Figure 4(b)).[2]

Standard cross-sections and the 3D modelling of WECs showed that the sectioning direction is influential on the shape of WECs. In the circumferential plane, WECs tend to appear highly vertically branched, whereas in the axial plane WECs tend to appear more parallel with less vertical crack branching.

WEC Initiation and Propagation

(i) Hydrogen-charged RCF test rollers: In one study,[4] a WEC was tracked and mapped in its entirety during the serial sectioning process and subsequently modelled in 3D for the first time (see Figure 2). It can be seen that the WEC does not interact with the contact surface and that inclusion-WEC interactions were found (labeled 1-4 in Figure 2c)). In the serial sectioning process, 15 WECs were mapped in their entirety over ~300 slices and only 2 WECs had a surface connection. Therefore, most WECs initiated in the subsurface. 67 non-metallic inclusions were found to interact with the 15 WECs mapped and 57 of these inclusions were ranked with a high likelihood for crack initiation. Similar evidence in another study[3] was found for testing over a range of diffusible hydrogen concentrations. Serial sectioning and FIB tomography provided evidence that butterflies can initiate WECs[3,4] (see Figure 3).

(ii) Wind turbine transient test gearbox bearing and planet bearing from service: Two WECs in both types of bearing were chosen for mapping with serial sectioning. In the 125 slices conducted it was observed that inclusions interacted with the WECs (see Figure 5). 76 inclusions were found to inter-

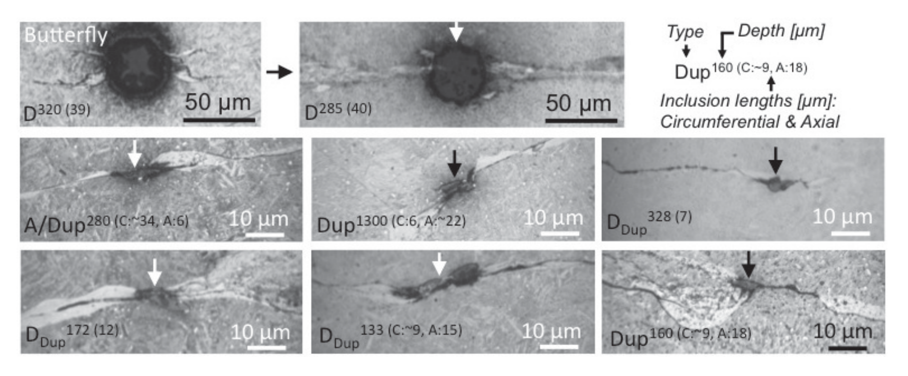

Figure 5 | **Examples of inclusion-WEC interactions from the transient test gearbox bearing tests (non-hydrogen charged) and bearing from wind turbine gearbox service. Inclusion types: A (sulfide), Dup (sulfide + oxide), D (globular oxide or sulfide), D_{Dup} (globular oxide + sulfide). Images from [2].**

act with the four independent WECs and 51 of these inclusions were ranked with a high likelihood for crack initiation. It is not possible to confirm whether subsurface or surface initiation occurred, as some of the WECs were located below flaking areas or made connection to the contact surface and only portions of the WECs in the bearings were analyzed.

In general, small length/diameter (~3-20 µm) sulfide (type A & type D_{sulf}), sulfide + oxide (type Dup & D_{Dup}) and oxide inclusions (type D) were found to predominate as crack initiators. This suggests that for WSF more emphasis should be put on steel cleanliness standards that assess the density of small inclusions rather than those that measure and predict maximum inclusion lengths.

WEC Formation Thresholds

Thresholds of load (P_{max} between 1.2-1.5 GPa), number of rolling cycles (~10 x 10^6) and concentration of diffusible hydrogen (~1 ppm) was observed for WEC formation in the hydrogen-charged two-roller tests.[3] This was quantitatively confirmed by the serial sectioning technique.

SUMMARY

The formation of WEA/WECs that were created in wind turbine gearbox bearings from service, large scale transient gearbox test bearings (non-hydrogen charged) and hydrogen-charged lab scale test rollers were investigated by a serial sectioning process to map their features and elucidate initiation/propagation mechanisms. FIB was also used to confirm initiation mechanisms.

- Strong evidence was found that WECs initiate subsurface at inclusions. Crack initiation predominated at small length/diameter inclusions (~3-20 µm).
- It is proposed that *one* mechanism of WEC formation is due to multiple linking of small WECs to form larger WEC networks that eventually propagate to the surface resulting in WSF.
- In the hydrogen-charged lab scale tests, WEC formation was found to be highly sensitive to the concentration of diffusible hydrogen. Thresholds for WEC for load and rolling cycle number were also observed.
- The sectioning direction (axial or circumferential) is influential on the shape of WECs.

ACKNOWLEDMENTS

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