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Observations of the effect of varying Hoop stress on fatigue failure and the formation of white etching areas in hydrogen infused 100Cr6 steel rings

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ABSTRACT

White etching cracks (WECs) in wind turbine gearbox bearings have been studied previously. Rolling contact fatigue (RCF) tests are conducted on 100Cr6 bearing steel rings, in this study, to generate WECs like those found in wind turbine bearings. This research studies the effect of two different levels of tensile Hoop stresses on the failure life and formation of WECs in the rings. The rings are pre-charged with hydrogen before RCF tests are conducted. It is found that these rings experience incremental fatigue failure, followed by a sudden rapid failure. The fractography, Reflecting Light Microscopy (RLM) and Scanning Electron Microscopy (SEM) results are presented in this paper.

1. Introduction

Rolling element bearings experience premature rolling contact fatigue (RCF) failure in engine auxiliary devices and wind turbine drive trains [1–5,9–11,38,44]. Their fatigue failure is characterized by the formation of regions of microstructural changes along cracks called white etching areas (WEAs) [5,8,12–14]. WEAs appear white when the sectioned and polished cross-sections of the bearing sample are etched in nital and viewed with the Reflecting Light Microscope (RLM). The cracks bordering or passing through WEAs are termed white etching cracks (WECs). Ref. [15] showed that the WEA is a region of ultra fine grained material formed by cyclic plasticity. The grains vary in size from 10 nm to 300 nm [2,30,31,46,52,54,57,58]. WEAs are thought to be caused by 2 main factors, viz. transient operating conditions like sliding, vibrations, etc. Refs. [8,20] and diffusion of hydrogen into the surface of the bearing steels [5,8,12–14,21].

According to [8], WECs likely initiate subsurface. However a complete three-dimensional view of the crack network could indicate surface interaction. Hence it is important not to make final judgements based on viewing a single cross-section, which represents a two-dimensional view of a three-dimensional crack network. Ref. [38] showed that WECs can be surface initiated. Ref. [55] suggested subsurface initiation at inclusions. Ref. [19] conducted extensive work to conform that subsurface initiation at non-metallic inclusions was one mechanism of WEC formation. Serial sectioning of failed bearings from service [56] and test specimens from experiments [16,18] provided significant metallographic analysis that proved that WEC formation could be subsurface. Further research needs to be conducted to obtain a clearer understanding of WEC formation mechanisms.

Hydrogen embrittlement has been studied extensively [22–26,28,29]. Yet these studies do not fully explain the role of hydrogen in the failure of bearing steels. Refs. [21,27] supposed that the effect of hydrogen is to localize plasticity and cause microstructural changes. Hydrogen weakens the bearing steel by decreasing mode I and mode II failure stress limits [32,33].

Hydrogen has been found to diffuse into the surface of steels during rolling contact tests [5,12,14,42]. Ref. [41] observed the diffusion of hydrogen into the steel surface while conducting ball on disk sliding tests. Hydrogen diffused into the surface of the bearing steel resides either in diffusible form or non-mobile form [34–37]. Hydrogen is believed to enter into the surface of steels by tribochemical reactions occurring at surface cracks [38] or fresh steel surfaces formed by wearing of the surface [41].

Measuring the concentration of hydrogen in bearing steels is an onerous task. Hydrogen diffuses out of the steel at room temperature. This study does not measure the hydrogen concentration during testing. However other studies have measured the concentration of hydrogen in their samples [5,12,16,21,43–45]. Given the uncertainties associated with the testing conditions, the measured

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concentrations vary significantly and no comparison can be made between them. However, despite the difficulties with measurement and interpretation, what could be gleaned from these previous studies is that perhaps only a small concentration (less than 1 ppm) of mobile hydrogen is required to promote the formation of premature RCF damage.

The hydrogen charging conditions for the two Hoop stress levels in this study are kept the same. During the charging process, no stress is applied to the ring. Hence it is assumed that the concentration of hydrogen diffused into each ring does not vary because the charging conditions are exactly replicated. The concentration of hydrogen diffused into the bearing surface in offshore wind turbines is hard to measure. Given the delay in time to extract the bearing from the gearbox to the actual measurement of hydrogen in the lab, most of the diffused hydrogen escapes the bearing.

The maximum Hertzian contact pressures applied in this study are similar in magnitude to the pressures experienced in wind turbine gearboxes (less than 2 GPa [16]). WECs have been generated by other researchers at much higher pressures (greater than 3 GPa) [5,9,12,14,21,43,44,46–48]. The test rig used in this study to conduct RCF tests is unique because the shafts allow for a conical fit of the rings, thus enabling the application of a simultaneous static tensile Hoop stress and compressive radial stress. So a study is done to observe the differences in WEA formation at two different tensile Hoop stress levels and their Weibull curves are plotted.

2. Test-rig

The test rig consists primarily of two drive shafts and a hydraulic cylinder (Fig. 1). One test ring is mounted on each shaft respectively. The two ring surfaces are brought into contact against each other by applying a normal load, using a hydraulic cylinder. Each ring has a conical bore, fitted onto a corresponding cone on the shaft. The contact pressure between the ring and shaft is controlled by the axial positioning of the ring on the shaft. Each drive shaft is capable of rotating at frequencies between 0 and 50 Hz. There is a provision for relative slip between the two rings when the two shafts rotate at different frequencies respectively. Hence it is possible to create conditions of rolling and sliding. Drive shaft 2 is connected to the master motor and drive shaft 1 is connected to the slave motor. In the current study there is no application of slip in the RCF tests.

An inlet resting above the contact between the two rings allows for the lubricant to flow into the contact. The lubricant used is Mobil Delvac synthetic gear oil 75W-140, which is a fully synthetic, heavy duty drivetrain lubricant. This lubricant has a viscosity 182*cSt* at 40 °C and 25*cSt* at 100 °C. The lubrication is not pressurised and the lubricant is allowed to fall freely, from a distance of approximately 2 cm, into the conjunction between the two rings.

A torque transducer is attached to drive shaft 2, so the interfacial torque generated between the two surfaces during slip can be measured. When one of the rings fails, the torque readings fluctuate wildly, setting off an internal alarm and automatically shutting down the test rig.

Each ring has an outer diameter of 70 mm. One ring has a chamfered surface with an axial width of 4 mm or 7 mm. The angle of chamfer is 10 degrees and 45 degrees respectively. The ring opposing the chamfered ring is unchamfered and has an axial width of 10 mm. Even though the axial widths of the chamfered rings may vary from test to test, the load is adjusted so that the maximum Hertzian pressure at the conjunction is kept the same. The maximum Hertzian pressure is 1.65 GPa. The contact half width is 0.55 mm. Based on the analytical formula for the minimum film thickness provided by [60], the value of the minimum film thickness in the conjunction is 1.8 μm. The lambda value for this conjunction, given the surface roughness $R_a = 0.15$ μm, is 12. This value of lambda points to a full film lubrication in the conjunction. The inner diameter of each ring is tapered at (2.86°) so as to enable a conical fit on the shaft. The Hoop stress is calculated analytically using Eq. 1.

$$\sigma_{\theta\theta(r=r_f)} = \frac{E \cdot d}{2} \frac{r_b^2 + r_f^2}{2 \cdot r_b \cdot r_f^2} \quad (1)$$

where

E is the effective Elastic Modulus, r_f is the fit radius, r_b is the outer radius of the hub, d is the increase in outer diameter of the ring.

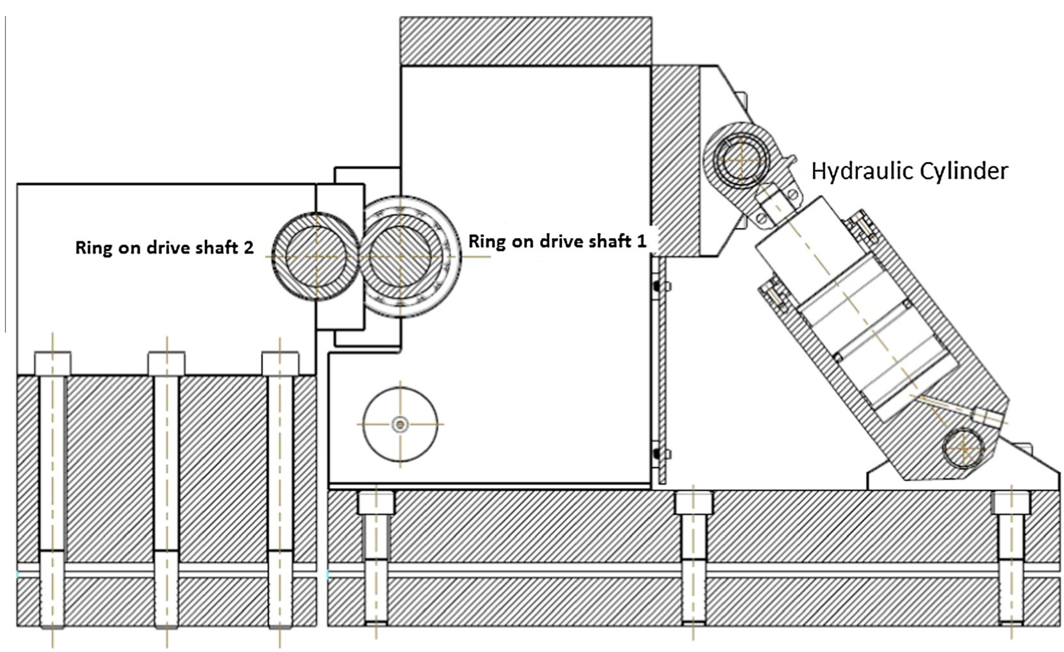

Fig. 1. Schematic of the rolling contact test rig.