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Laboratory Simulation of Rolling Contact Fatigue Cracks in Wind Turbine Bearings Using Hydrogen Infused 100Cr6 Bearing Steel

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Abstract

Premature fatigue failure is observed in rolling element bearings used in wind turbine components. It is believed that decomposed hydrogen from the lubricant diffuses into the surface of the bearing inner ring making it susceptible to failure. An attempt is made to simulate the formation of these cracks by accelerated laboratory tests. Hydrogen is artificially infused into the surface of ring specimens and the rings are then press fit onto shafts. This introduces a tensile Hoop Stress in the rings. The rings are then run against each other until fracture of one of the rings is observed. Preliminary test results show a failure characteristics similar to those observed in the inner rings of rolling element bearings used in service.

Keywords: Rolling Contact Fatigue, bearing failure, hydrogen charging, white etching areas, 100Cr6 steel.

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1. INTRODUCTION

Rolling element bearings used in wind turbine drive shafts experience premature rolling contact fatigue failure (RCF). These bearings are usually press-fit onto the shaft. This gives rise to a compressive radial stress and a tensile Hoop stress on the inner ring of the bearing. It is believed that diffusion of hydrogen from the lubricant plays a crucial role in their failure. Kohara et al., [1] conducted tests to conclude that the decomposition of the lubricant causes hydrogen to infuse into the fresh steel surface. Clark [2] states that the time for crack initiation decreases with the addition of a tensile Hoop Stress. Clark predicts that at a max. Hertzian radial stress of about 2GPa and a tensile Hoop stress of about 350GPa, the endurance life of the bearing is decreased by 88% compared to a bearing not under the influence of a Hoop Stress. Clark expects the crack initiation to occur in Mode I near the surface and change to Mode II as the circumferential stress decays. Czyzewski [3] modeled the effect of an applied Hoop Stress due to an interference fit. He estimated a maximum reduction in fatigue life of 98 %. White Etching Areas or Cracks (WEA/WEC) are a characteristic feature of failed bearings in wind turbines. Uyama [4] et al. conducted RCF tests on hydrogen infused bearing steel samples and observed that the fatigue life of these samples was shorter than the life of the uncharged samples. They also supposed that the basic role of hydrogen in these RCF tests is to localize plasticity. Evans [5] et al. conducted similar tests to study the white etching areas (WEA) formed subsurface in the test samples. They concluded that the WEA were initiated at inclusions. Evans also concluded that a certain threshold quantity of hydrogen, coupled with a maximum Hertzian stress value and number of cycles was necessary for the formation of WEA. Neither Uyama nor Evans applied any tensile Hoop Stress to their test specimens during the course of the experiments. Neither Czyzewski nor Clark studied the effects of the addition of hydrogen to the 100Cr6 bearing steels.

2. EXPERIMENTAL SET-UP

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. The rings have a conical bore, fitting on a corresponding conical shape on the shafts. 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 0-50Hz. 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.

An inlet resting above the contact between the two rings allows for the lubricant to flow into the contact. A torque transducer is attached to drive shaft 2, so the interfacial torque generated between the two surfaces during slip can be measured.

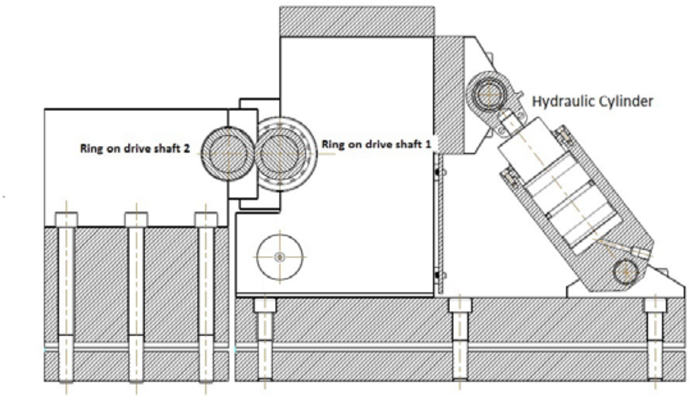

Figure 1: *Schematic of the Test Rig.*

The rings have an outer diameter of 70mm. One of the rings has a chamfered surface with an axial width of 7 mm. The angle of chamfer is 10 degrees. The opposing ring is unchamfered and has an axial width of 10mm.

The rings are through hardened, martensitic 100Cr6 bearing steel.

3. EXPERIMENTAL METHOD

Two rings are immersed in a 20% by weight aqueous solution of Ammonium Thiocyanate for 48 hours at 50º C. This process diffuses hydrogen into the rings. The quantity of hydrogen in the rings is not measured in this paper. Since Evans [5] observes that an increased quantity of hydrogen causes the WEA to be formed closer to the rolling surface, it is believed that the quantity of hydrogen beyond a certain threshold ppm value, does not change the mode of failure, but only changes the depth at which the WEA are formed.

The rings are removed from the solution after 48 hours, cleaned using ethanol and water and then slightly buffed to remove any oxidation layer on the surface.

Each ring is then press-fit mounted on a shaft and the process is completed when the outer diameter of each ring measures a certain pre-determined value that corresponds to a tensile Hoop Stress of 350MPa in the inner diameter and a compressive radial stress of 110 MPa. Once the rings are mounted on the shaft, the shafts are aligned as shown in **(Fig. 1),** so as to develop a line contact between the two rings.

The lubricant inlet is turned on and the shafts are then run at a frequency corresponding to the required inlet lubricant velocity. No load is applied at this time. A normal load is then gradually applied through the hydraulic cylinder. The loading is stopped when the required loading condition has been reached. The two shafts are run at a frequency very close to each other, so as to achieve conditions as close as possible to pure rolling. These test conditions are kept constant until the conclusion of the test.

The test is stopped when one of the rings develops a surface crack. Since there was no access to instruments that could check for in situ crack formations, the tests are run until visible surface cracks were generated. When the surface of either ring cracked, both the rings are dismounted from the shaft. The cracked ring is then sectioned to be observed under a microscope.

The fracture surfaces and the axial cross sections of the through cracked rings are observed by Reflecting Light Microscopy (RLM) microscope and Scanning Electron Microscopy (SEM). Three axial cross sections are prepared by making cuts parallel to the over-rolling direction from each ring around the area of the crack (**Fig. 2**).

The cross sections are studied to understand the failure mechanism.

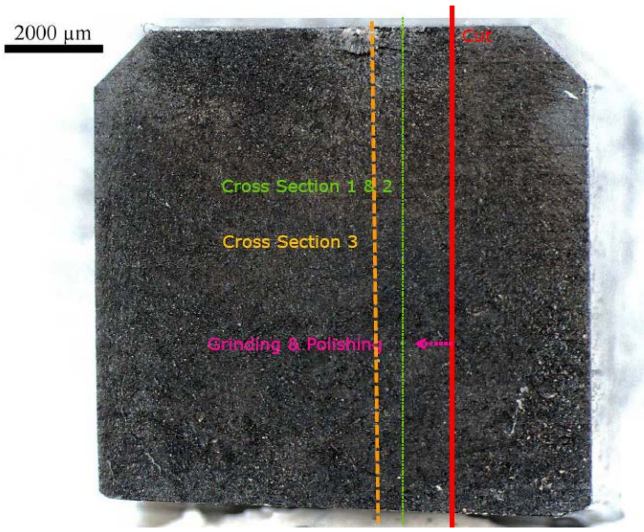

Figure 2 : Stereomicroscope image of the fracture surface of ring B1

A cut is made along the red line in (**Fig. 2**) and the sample is mounted. The specimen is then ground and polished, with material removed in the axial direction, until faces close to the crack are reached. White Etching Areas are usually observed in these axial cross sections. However, there may be some cross sections where the white areas might not be found as the total number of WEA can be small. Thus, the probability of finding a White Etching Area close to a crack increases with increasing number of axial cross sections studied.

4. RESULTS & DISCUSSION

Table 1: *Number of cycles to failure for each ring pair.*

Ring Pair	Cycles to Failure (million)
A1 – B1	13
A2 – B2	11
A3 – B3	26
A4 – B4	11.5

The number of cycles to failure for each ring pair are shown in **Table 1**.

Of each ring pair that is tested, the test is stopped as soon as one of the rings fractured. The ring that is not fractured is not tested further to develop any surface cracks.

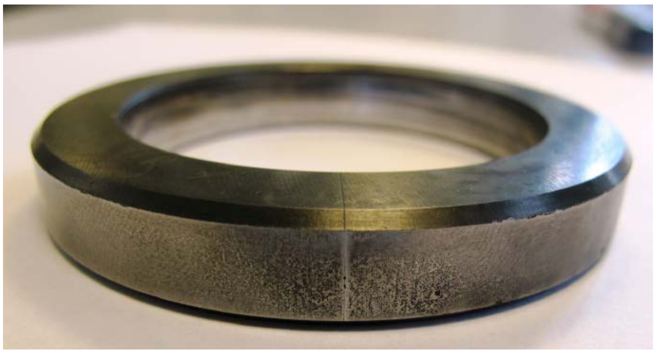

Figure 3 *: Axial crack on ring B1.*

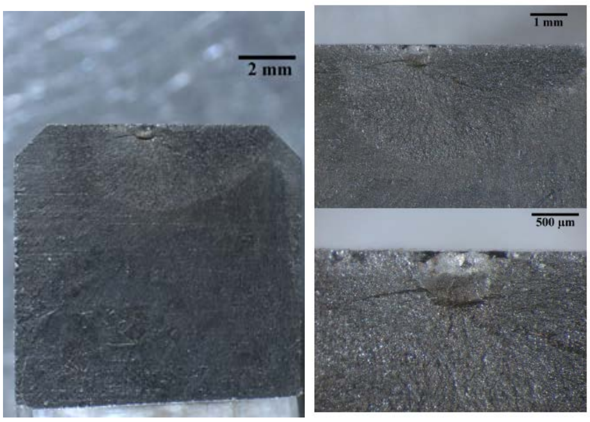

Figure 4: *Stereomicroscope images of the fracture surface of ring B1*

(Fig. 3) and **(Fig. 4)** show the fracture surfaces of the ring B1 that fractured after 11 million cycles. A cross section is defined as circumferential if the normal to that cross-sectional plane is pointed in the circumferential direction.

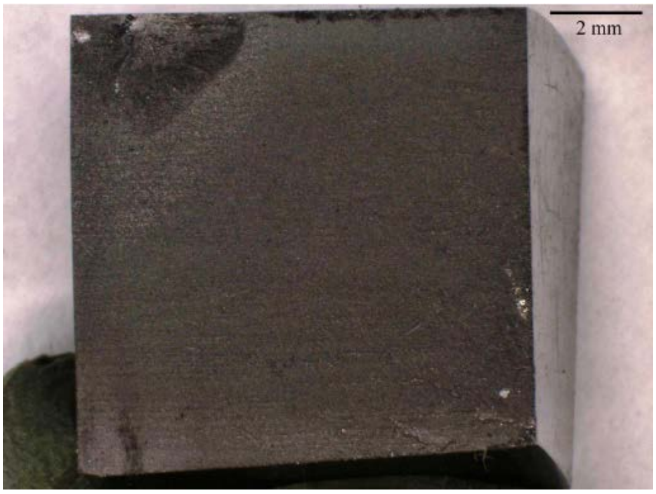

Figure 5: *Stereomicroscope image of the fracture surface of the ring A2*

(Fig. 4) and **(Fig. 5)** shows a resemblance to the fractured sample in the ball bearing fatigue test conducted by Clark [2]. The fracture surface shows a difference in texture between the top and bottom of the specimen. The rough, rounded portion close to rolling surface appears to have fractured by fatigue while the smooth lower portion appears to have fractured in a brittle manner.

Figure 6: *Axial crack on the inner ring of a bearing from service*

(Fig. 6) shows multiple axial cracks on the inner ring of a tapered roller bearing from service. The bearing was positioned on the shaft at the intermediate stage inside the gearbox of a wind turbine. The gearbox belonged to a 2.3 MW turbine. The material is a through-hardened martensitic bearing steel. This material is similar to the material of the test ring specimens used for testing. These cracks look similar to the axial crack on the surface of the ring B1 (**Fig. 3**). The failed bearing inner ring from service are sectioned, polished, etched and viewed under a microscope. Their failure characteristics are then compared to the failure characteristics in the laboratory simulated RCF rings.

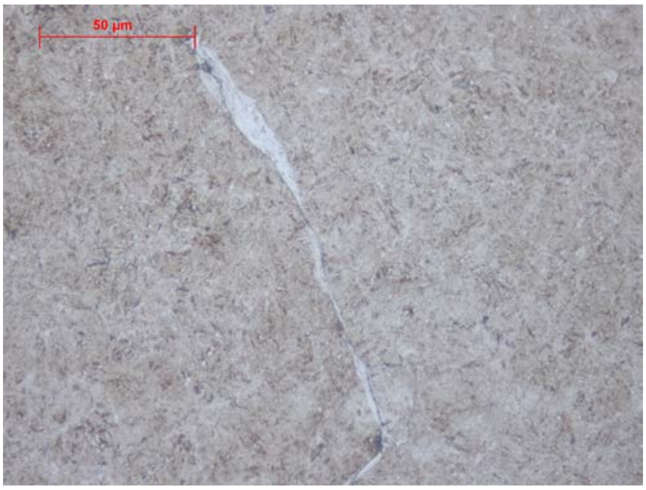

Figure 7: *RLM image* of a nital etched axial cross section (cut parallel to the over-rolling direction) showing a White Etching Area(WEA) around a crack in the inner ring of the bearing.

(**Fig. 7**) shows a characteristic WEA around a crack in an axial cross section of the bearing inner ring surface. It has been suggested by Kino et al., [6] that hydrogen plays a role in the formation of these WEA. Uyama [6] studied these WEA using a Transmission Electron Microscope (TEM) and observed that the white structure consisted of an ultra fine grained structure. He further suggested that the localized microstructural changes are caused by the hydrogen and hence supposed that the basic role of hydrogen is to localize plasticity.

(**Fig. 8**) shows a WEA found in an axial cross section near a crack formed subsurface. This crack is less than 20 microns from the rolling surface. This is believed to be because raised levels of hydrogen closer to the rolling surface, weaken the material and make it more susceptible to crack initiation. Evans [5] showed that decreasing the levels of hydrogen artificially infused in the surface of the ring causes these cracks to be formed much further away below the rolling surface.

(**Fig. 8**) shows a highly magnified SEM image of the WEA. The light triangular shaped region within the red dotted circle is suspected to be a deformity like an inclusion or a void formed at the location of a former inclusion, just like Evans [5] had predicted, although not yet confirmed by performing EDAX studies. The shape of the crack also seems to resemble the butterfly cracks described by Evans in the same paper.

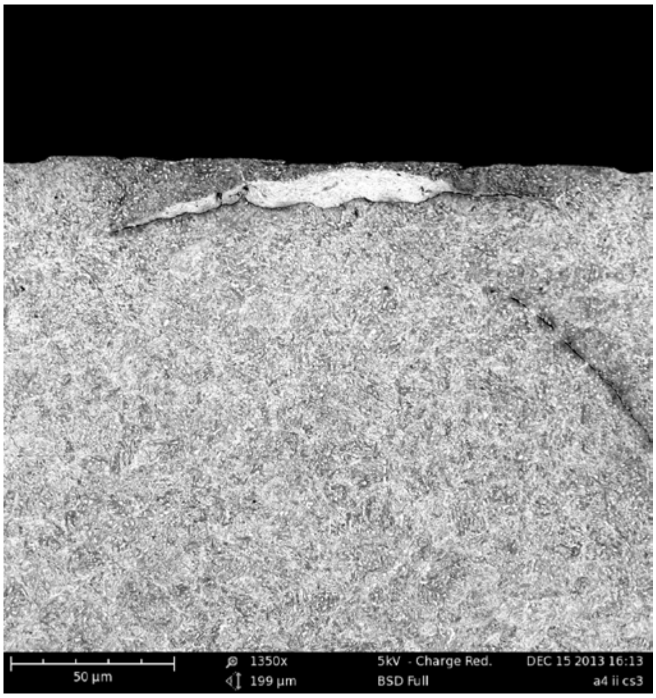

Figure 8: *WEA found near a crack on the failed lab specimen B2*

***Figure 9*:** SEM image of the WEA around the crack

(**Fig. 3**) and (**Fig. 8**) also show pitting on the surface of the test specimen. Pitting could occur due to the presence of small solid contaminants in the lubricant, or due to a subsurface cracks growing to the surface.

The surfaces of the test specimens are also not highly polished mirror surfaces. The Ra for these test rings is approximately 0.15 microns. This could lead to a mixed lubrication regime in certain phases of the tests, leading to metal on metal contact and hence removal of surface material. The primary reason for pitting in these set of fatigue tests in not known and needs to be studies further.

The microscopic studies however do not conclusively prove as to whether the cracks are surface initiated cracks or if the cracks are initiated subsurface.

5. CONCLUSIONS

The preliminary microscopy studies have shown encouraging results with regards to simulating the cracks found in wind turbine bearing, in the lab by conducting RCF tests . Axial cracks are formed on the test specimen, leading to failure. These are similar to cracks found on the inner ring of the bearing from service. Light Optical Microscopy and SEM studies have shown the presence of the characteristic WEA in the test rings. These WEA are similar to the WEA observed in the axial cross sections of the inner ring of the bearing from service. The presence of a WEA close to the rolling surface (< 25 microns) indicates a high quantity of hydrogen supplied to the test specimen during the hydrogen charging process. It is still not confirmed whether the cracks initiate subsurface or at pitting sites on the rolling surface. Further samples need to be sectioned and studied to understand if the cracks initiate subsurface.

The test rig has shown the capability to simulate characteristic failure features observed in cracked bearing specimens, through accelerated RCF tests.

6. REFERENCES

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