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Effect of lubricants on bearing damage in rolling-sliding conditions: Evolution of white etching cracks

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ABSTRACT

To understand the role of lubricants in generating white etching cracks (WECs), cylindrical roller thrust bearings were life-tested in different oils in rolling-sliding conditions. The bearings were damaged prematurely when the tests were performed in an oil with additives (so-called "WEC critical oil"). Bearing life in the WEC critical oil was less than 5% of that of the mineral oil without additives. In the bearings tested in the WEC critical oil, post-test investigations revealed a non-uniform ~ 100 nm thick tribo-film and micro-scale line cracks parallel to the contact line in the slide zones of the tribo-surface. In contrast, typical "point surface origin" (PSO)-type damages were observed when the bearings were tested in the mineral oil.

Electron microscopy investigations showed that the line cracks in the case of the WEC critical oil tests propagated deeper into the subsurface. Only in the negative slide zone, the cracks then became WECs. The PSO damages generated in the mineral oil testing did not show subsurface cracking or white etching features. The results support the conclusion that, in the case of the WEC critical oil, a tribo-film formed and caused an increase in surface shear forces, which consequently resulted in the line cracks on tribo-surface that subsequently propagated deep into the subsurface.

1. Introduction

Key mechanical engineering components are tested rigorously in application-relevant tests to ensure high reliability of the components in the actual application and to avoid damage in severe conditions. Roller bearings are key components in rotating machinery, and avoiding premature bearing damage is essential for uninterrupted operation of the machinery and for minimal maintenance costs. Due to the existing dynamic loading and severe operating conditions in wind turbines, wind turbine gear box bearings have been reported to become prematurely damaged [1]. But replacing them with new bearings at top of the wind tower adds to the maintenance cost immensely. Investigations of prematurely damaged wind turbine bearings have shown cracks in the bearing steel. So, in addition to choosing the right bearing design, a suitable steel grade, an appropriate heat-treating condition and high steel cleanness must be present to minimize the cracks generation in the bearings. For example, in wind turbine gear boxes, bearings face non-RCF (rolling contact fatigue) loads from the shaft; these loads include installation stresses (hoop stresses) and bending stresses. Under these stresses, it is reported that through-hardened bearings develop axial cracks and damage prematurely [2]. Owing to their tough core, case-hardened bearings can accommodate these loads and hence minimize the chances of axial cracking.

In addition, the microstructure should be designed to resist fatigue damage from dynamic loading in wind turbines. In fact, investigations of the field-returned bearings suggest that case-carburized bearings with more than 20% retained austenite in the case-microstructure can achieve very long lives in the wind turbine environment [3]. However, evidencing these insights in a laboratory test is a challenge because of the unavailability of a laboratory-scale test method that can represent the environmental and mechanical loading conditions of wind turbines. Developing such a test method is still a challenge to date. Deeper optical metallographic study of the prematurely failed turbine bearings has revealed white etching matter (WEM) along the cracks in the steel, as well [3]. The white appearance comes from the nanograined ferrite material present along the crack faces. This nanograined material doesn't get etched or etched uniformly during the etching step of the metallographic sample preparation. Therefore, it doesn't produce a local contrast by diffracting the optical light, and consequently appears as white in optical metallography observations. Since WEM was found along the cracks, it was initially assumed that WEM is a cause of bearing damage [4,5].

When WEM is found along a crack, the crack is often called a "white etching crack" (WEC). Several investigators have reported different

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ways of producing WECs in laboratory-scale bearing and RCF tests and have discussed underlying mechanisms. The following test parameters are proven to reproduce WECs: i) using low-reference lubricant oil in rolling-sliding conditions [6–11]; and ii) using test components with material and surface finish defects (e.g., inclusions, cracks, intergranular embrittlement and rough surfaces) [12–14]. Recent reports published on the topic suggest that WECs are not a root cause of bearing damage after all; instead, WEM along a crack is a consequence of the crack faces rubbing [2,12,13]. In other words, the cracks form first, and when the crack faces rub each other, WEM forms along the cracks. However, in contrast to these insights, there are other published reports that suggest WECs are a type of failure mode and cause premature bearing failures [15–17]. More study is required to elucidate the mechanisms associated with WEC formation and to evaluate the relationship between WEC formation and bearing life.

In fact, the method of testing the bearings in low reference oil under rolling-sliding conditions is used to compare lives of Cylindrical Roller Thrust Bearings (CRTBs) made with different materials and heat treatment conditions [16]; the used test apparatus is called FE-8 test rig. This test rig is a commercially available and is recommended for lubricant evaluation by the DIN 51819 standard [18]. Using this test rig and a low reference oil, several published reports suggest that WECs form consistently in the bearings and cause premature bearing damage [8–11,15,16,19,20]. More detailed studies are needed relating to influence of lubricants on bearings' damage and respective damage mechanisms. To address this, we performed life tests on CRTBs in the FE-8 test rig in different lubricant oils. The tested bearings were investigated in detail by optical and electron microscopy, and accounted the associated damage mechanisms with respect to the used lubricant oils.

2. Materials and methods

2.1. Bearing test rig and test rig parameters

An FE-8 test rig was used to test the bearings in different oils. The test rig is made by Schaeffler Technologies, Schweinfurt, Germany. Cylindrical roller thrust bearings (CRTBs) were used in this study. Fig. 1a shows an example of the CRTB; the rollers between the two raceways (washers) are held in place by a brass cage (a photograph of a roller assembly is shown in Fig. S3 of the Supplementary material). During bearing operation, load was applied normally on the bearing while the rollers and one of the raceways (washers) are under rotation. Because of the difference in local circumference and the resulting rotation speed differences along the "line of contact" between the rollers and the raceways, about 11% sliding is generated at the ends of the contact line, as shown in the bottom sketch of Fig. 1a [13,20]. Negative sliding generates toward the inner radius of the raceway because the velocity of the rollers' surface is higher than that of the raceway's surface. Toward the outer radius, positive slide generates on the raceway because the velocity of the rollers' surface is lower than that of the raceway's surface. Two CRTBs were assembled into the test rig as shown in the schematic in Fig. 1b (cross section of the test rig). The four washers of CRTBs are depicted in blue and the roller assemblies are shown in red. During the bearings operation, the washers placed at extreme ends are stationary and the other two inner washers are under rotation. The sliding applies to the stationary washers as well because of the difference in the local circumference along the contact line. The rollers also experience the sliding, except the sign of sliding is opposite to that of the washers.

Thrust load was applied on the bearings by compressing the springs to the required level. In this study, a load of 60 kN was applied (~ 1.9 GPa of contact pressure), the drive shaft was rotated at a speed of 750 rpm, and the temperature of the bearings was set at 100 °C. These test conditions are proven to produce WECs repeatedly. As shown in the schematic (Fig. 1b), oil was supplied to each bearing; the used oil flow to each bearing was 0.2 L/min. An oil tank was connected to the test rig from which the oil was circulated to each bearing and collected back into the tank. During the bearing test, damage to the bearings was detected by attaching a vibration sensor (accelerometer) to the bearing assembly. As can be seen in Fig. 1c, the vibration sensor is attached to the top of the bearing assembly. During each test, as the bearing damage begins to occur, the vibration signal increases. The tests can be setup to terminate at certain level of vibration increase. In these life-test experiments, to investigate initial stages of the damage to the bearings, tests were terminated at early stages of vibration signal increase by adjusting the respective sensor levels. The stop criterion of the test was set at 100% vibration increase compared to vibration at the start of test.

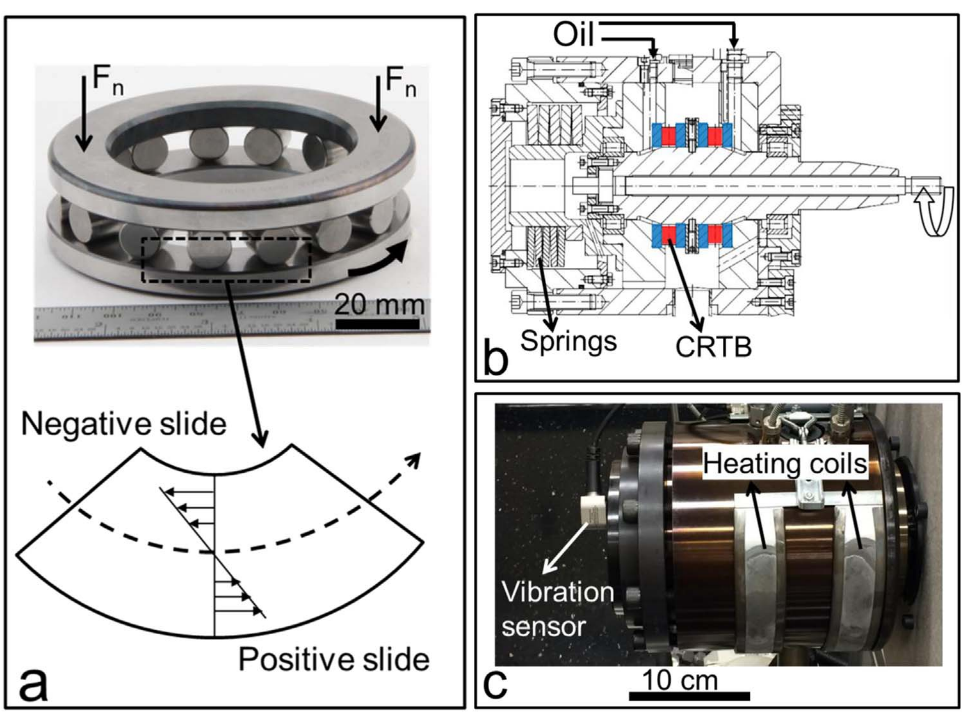

Fig. 1. (a) A photograph showing an example of a cylindrical roller thrust bearing (CRTB). The schematic diagram in the bottom shows sliding along the line of contact. (b) A schematic cross section of the bearing assembly in the test rig. (c) Photograph of the test rig with vibration sensor on top of the test head. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)