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FORMATION OF WHITE ETCHING CRACKS (WEC) UNDER ROLLING LOADING IN A TWO-DISC TEST RIG AND A KINEMATIC STUDY ON A FULL-SCALE BEARING

Rolling Element Bearings II, May 21, 2018

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INTRODUCTION

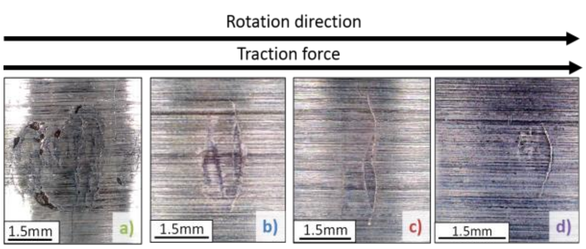
A common challenge in multiple fields of the mechanical driveline technology consist of premature rolling bearing failures caused by white etching cracks (WEC). This failure mode can lead to bearing failure at 5-20 % of the nominal life [1]. This damage pattern is characterized by sub-surface crack networks within regions of altered microstructure, which ultimately lead to axial cracking or spalling of the bearing's raceway. These altered regions are resistant to etching and are called white etching areas (WEA) due to their white appearance under reflected light. Although the WEA had been well characterized by different microscopy techniques [2,3], the relevant drivers and formation mechanisms are still under debate. Some authors propose that the cracks are the precursor of the WEA [4,5], while other authors have suggested that the crack initiation and propagations is a consequence of the formation of WEA [6,7]. Besides a local hydrogen ingress [1] other WEC influence factors such as lubricant composition [1,8], sliding conditions [1,9,10], tensile stresses [1,5] and electrical effects [11] had been proposed. In a previous study, WEC tests were carried out using cylindrical roller thrust bearings. Through ultrasonic analysis on the bearing´s washers, it was shown that the WEC are mainly located in the region under negative slip [12]. However, through testing on a component level, it is not possible to decouple and assess the influence of single contact parameters, such as the slide roll ratio (SRR). Therefore, the main tribological conditions had been transferred on a two-disc test rig using inner rings from radial cylinder roller bearings made of martensitic hardened 100Cr6 (1.3505 / SAE 52100) steel. This has allowed to recreate WEC on a two-disc test rig under rolling contact loading without additional loading such as hydrogen pre-charging or passage of electrical current. This abstract summarizes the state of the investigations regarding the influence of the lubrication regime and slip on the WEC formation on the two-disc test rig. The tests have confirmed that a WEC failure is promoted under boundary lubrication conditions. Furthermore, the tests have shown that the WEC formation is influenced not only by the slide roll ratio (SRR), but also by the type of slip (+/-). Moreover, in order to verify if high sliding conditions may occur in loaded radial roller bearings, which can be found in wind turbine gearboxes, large size roller bearing tests were conducted under transient conditions. The determined cage and roller slip provide an insight into operating conditions, which can promote the WEC formation and could be found in wind turbine gearboxes.

TECHNIQUES AND EXPERIMENTAL METHODS

The rolling contact tests were performed on a two-disc test rig, which resembles a disc-disc tribometer. Two inner rings from radial cylinder roller bearings of type NU208-TVP2 and NU2208-TVP2 are used as test specimens. The bearings rings are made from martensitic hardened 100Cr6 steel and are powered by independent servomotors. Testing is carried out until either a predefined number of contact load cycles is reached or a vibration level, normally caused by spalling, surpasses a set threshold. In this study a mineral oil with a viscosity grade of ISO VG 100 ($\vartheta_{40°C}$ = 103.78 mm²/s) was used. This lubricant has led in previous studies to WEC formation in a reproducible manner [12,13]. In the framework of this study, twelve tests were carried out in order to investigate the influence of the lubrication regime and SRR on the WEC formation. Two different test series were defined on the basis of previous investigations on two- and four-disc test rigs [12,13]. Whereas for the first test series λ-values > 3 were chosen, the second test series was conducted under boundary lubrication (λ<1). The selection of five different SRRs (0, 8.3, 12.7, 15.0 and 21.0-23.5 %) is based on previously published work [12,13]. Alongside these influence factors, the kinematics of the two-disc test rig allow the assessment of the influence of the slip type on each test simultaneously. While the bearing ring NU208 runs under negative slip (follower), the bearing ring NU2208 runs under positive slip (driver). Furthermore, in order to address the question whether similar conditions can occur in cylindrical roller bearings and consequently in wind turbine gearbox bearings, where WEA/WEC formation had been observed, the effects of transient operating conditions in the kinematic behaviour of a bearing of type NU2330-E-M1/C3 were investigated. The study confirms that transient conditions, e.g. speed and load ramps, can lead to cage and roller slip in loaded radial bearings.

RESULTS

The four tests running under full fluid lubrication were stopped after $40 \cdot 10^6$ cycles and showed no macroscopic signs of surface damage. Metallographic inspections on selected rings showed no WEC. The results of the second test series are shown in **Figure 1**. Aside from test 5, which was stopped after $12 \cdot 10^6$, all tests where concluded when a spall failure occurred. Within these tests, five followers (color-coded blue) and three drivers (green) showed spalling. The development of surface spalling can be observed exemplary in Figure 1: Images of the follower surfaces from test 6 (a), 7 (b), 8 (c) and 9 (d). As RCF proceeds, a cluster of micro-cracks is formed, which ultimately leads to spalling of material. In contrast, the driver from test 6 showed axial cracks.



Test #	p_{Hertz} [GPa]	ϑ_{Oil} [°C]	SRR [%]	λ [-]	LC – Follower/Driver [Mio.]
5	1.4	70	12.8	0.78	10.5 / 12.0
6		100	23.5	0.24	**28.5** / 36.1
7			21.0	0.72	**48.6** / 60.0
8			15.0	0.71	**38.5** / 44.7
9			21.0	0.49	**29.8 / 36.8**
10			8.70	0.50	**34.7** / 37.9
11			21.0	1.0	36.3 / **44.9**
12			21.0	1.0	52.5 / **64.9**

Figure 1: Images of the follower surfaces from test 6 (a), 7 (b), 8 (c) and 9 (d) and results of the second test series

Investigation of the microstructure was carried out through electron backscatter diffraction (EBSD) to determine the origin of the damage. It is not fully understood yet, when WEA exactly form and whether they form before or after cracking of the material. EBSD provides crystallographic information for each measured point to gain knowledge about processes in the microstructure after the failure happened. **Figure 2** shows a crack alongside a big WEA from test 10. It is clearly seen that the tip of the crack is located in the region of maximal von Mises stress. The Image Quality (IQ) shows the altered microstructure next to the crack. It is well seen that the former martensitic structure was changed into a nanocrystalline ferrite microstructure. The Kernel Average Misorientation (KAM)-Map shows a big area of low misorientation. This indicates a recrystallization ocurred in this region. Dislocations accumulate at grain boundaries or defects in the microstructure. As soon as enough energy is stored, microstructure change can occur through transformation of the structure in the form of recrystallization. The new ferrite grains grow equiaxed and thus have a low misorientation, appearing blue in the KAM-Map. Because of Hall-Petch hardening, the WEA is much harder than the surrounding martensitic structure. A possible result are WEC alongside the WEA. The findings in this study may support the thesis, that energy is stored through movement of dislocations in the depth of maximal von Mises stress, resulting in a microstructure transformation before a crack is formed.

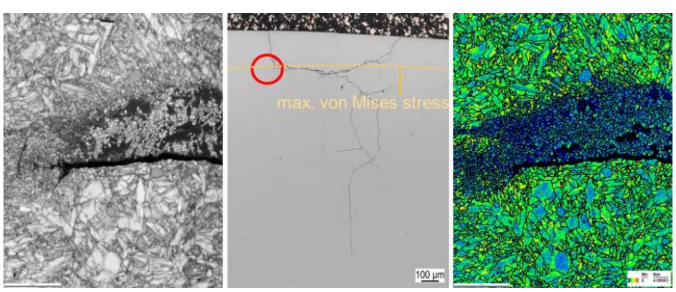


Figure 2: 1) IQ-Map 2) Light optical Image 3) KAM Map of test 10

On another hand, **Figure 3** shows the kinematic response of the bearing NU2330-E-M1/C3 to a speed ramp under constant load. It becomes evident that high cage and roller slip occur during and after the speed ramp. This high-slip phase – caused by the rapid acceleration – appears in spite of the prevailing radial load of 50 kN (850 MPa). The slip state diminishes over time is, however, observable for over 10 seconds (approximately 250 shaft rotations). For the purpose of comparing the kinematic response of the roller over time, two time intervals (of one second each) of this test are plotted as a function of the angular position of the roller relative to the shaft axis (**Figure 3-right**). The first interval (green) is set about one second after the speed ramp is concluded. At this point, the roller slip varies between 50 % (86 % SRR) and 85% (157 % SRR) – within and beyond the load zone respectively – while the cage slip has a mean value of about 50%. The second time interval (orange) starts seven seconds after the speed ramp is concluded. It can be seen that the roller slip has decreased up to 25 - 70 % (38 - 120 % SRR) – within and beyond the load zone respectively. From this measurements, it can be concluded that the speed ramp under constant load can lead to high-sliding conditions under moderate loading.

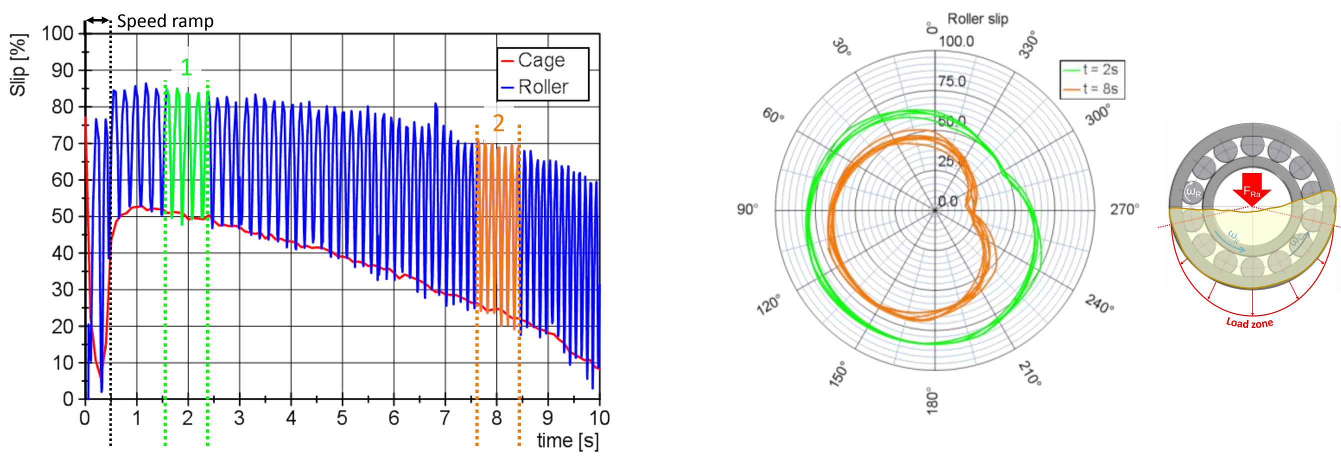


Figure 3: Measured cage and roller slip during and after a speed ramp

CONCLUSIONS

- The prevailing lubrication conditions have a dominant influence on the formation of WEC under rolling contact. Tests under full fluid lubrication (λ>3) did not show any material damage (after the pre-defined running times), whereas WEC formation occur on tests running under boundary lubrication conditions (λ < 1)
- Maintaining a roughly constant SRR while increasing the λ-value from 0.2 to 0.5 and 0.7 leads to an increase of the running time by 5 % and 63 % respectively
- A counter tendency was observed by varying the SRR and maintaining a constant λ-value. While an increase in the SRR from 15 % to 21 % (λ=0.7) lead to an increase in the running time of 20 %, the increase of the SRR from to 8.7 % to 21 % (λ=0.5) lead to a decrease in the running time of 14 %. Therefore, further testing is needed
- The slip type influences the extent of the WEA/WEC damage. Whereas the test rings running at λ < 1 that experienced negative slip showed large WEA/WEC networks – RCF crack propagation – the rings running positive slip showed considerably less WEA/WEC. Furthermore, a counter tendency was observed at λ=1 and SRR = 21 %. In this case the rings which experienced positive slip were prone to fail

Furthermore, the observations from this work confirms that transient operating conditions can lead to sliding conditions within the load zone of large size cylindrical radial roller bearing. During the bearing tests, high values of cage and roller slip (up to 50 % - 85 % respectively) were achieved in the loaded bearing (850 MPa) by applying a speed ramp (314 rad·s^{-2}). The amount of cage and roller slip diminishes over time can be, however, observed over several seconds. Although the results are yet to be confirmed statistically and further studies are needed to validate these initial observations, this work provides an insight into different WEA/WEC drivers and whether these conditions can be observed in large size cylindrical roller bearings and consequently in wind turbine gearboxes.

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KEYWORDS

Roller Bearing – Rolling Contact Fatigue – White Etching Areas and Cracks