Journal of Mechanics Engineering and Automation 6 (2016) 85-94
doi: 10.17265/2159-5275/2016.02.004

DAVID PUBLISHING

Influences on Generation of White Etching Crack Networks in Rolling Bearings

Joerg Loos[1], Toni Blass[2], Joerg Franke[1], Wolfram Kruhoeffer[1] and Iris Bergmann[1]

1. Schaeffler Technologies AG & Co. KG, Herzogenaurach 91074, Germany

2. Schaeffler Technologies AG & Co. KG, Schweinfurt, Germany

Abstract: In rare cases rolling bearings fail by WEC (white etching crack) damage before reaching their calculated rating life, if so called additional loads are applied on the bearing in addition to the normal Hertzian stress (p_{Hz}). A number of additional loads have been identified by means of tests with rolling bearings. These can be small direct currents as a result of electrostatic charge or large alternating currents from inverter-fed drives that unintentionally flow through the bearing. WEC damages can also be initiated by a pure mechanical additional load which is dependent on factors including the bearing kinematics but also on the dynamics of the drive train. The current state of knowledge on this subject is presented and taken as the basis for developing a hypothesis on the WEC damage mechanism. If load situations critical for WEC cannot be avoided, the risk of WEC can be considerably reduced by the selection of suitable materials and coatings as well as, in some cases, of suitable lubricants.

Key words: Rolling bearing, WEC (white etching crack), WSF (white structure flaking), hydrogen, fatigue.

1. Introduction

In some applications, there is an increased occurrence of premature rolling bearing failures at running times of 1-10% of the rating life L_{10} [1]. These failures are attributed to a specific fatigue mechanism that is known by the terms WEC (white etching crack), WSF (white structure flaking) or Brittle Flaking [2, 3]. WECs are networks of cracks at and in white etching phases (Fig. 1) which can emerge in both through hardened and case hardened rolling bearings. The white etching phases (White Etching Areas, shortened to WEA) comprise very fine-grained ferrite oversaturated with carbon or cubic martensite. They do not contain any carbides or carbides of a very small size [4]. The cracks occurring under rolling contact load between the white, very hard phases and the microstructure as well as in the white phases itself grow over time up towards the surface. This leads to axial cracks and pittings or bigger spallings [2, 4].

Corresponding author: Joerg Loos, Dr.-Ing., research fields: tribology, and rolling bearing fundamentals.

2. Service Strength Behaviour

The WEC rating life cannot be calculated using the classic theory of rolling bearing rating life. WECs can be found in all types of rolling bearings. In greased as well as in oil lubricated bearings and either in bearing rings or in rolling elements [5, 6]. The influence of load on WEC fatigue is significantly less than compared to calculation according ISO 281 [7], what can be seen from Fig. 2. i.e. an increase in running time achieved by load reduction while maintaining the identical additional load is significantly smaller than conventional theory would predict [5, 6, 8].

In addition to early failures at relatively low Hertzian pressures, WEC fatigue is also characterised by very small scatter. Even small ball bearings with only a small volume subjected to load show Weibull shape parameters ß greater than 3 (Fig. 3), while roller bearings in some cases have values greater than 10 [5].

Therefore, once the first WEC failures have occurred in the field a high likelihood for increased

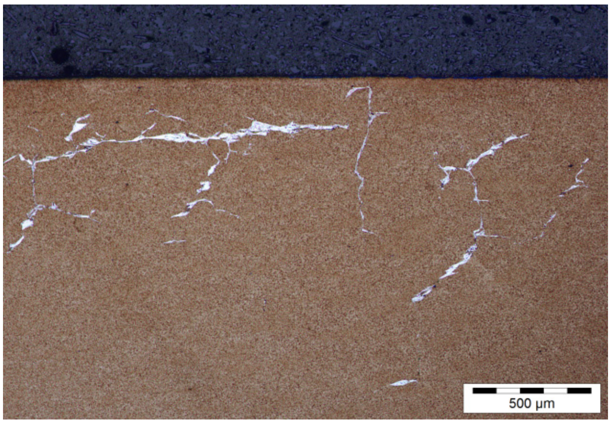

Fig. 1 WEC network below the racetrack.

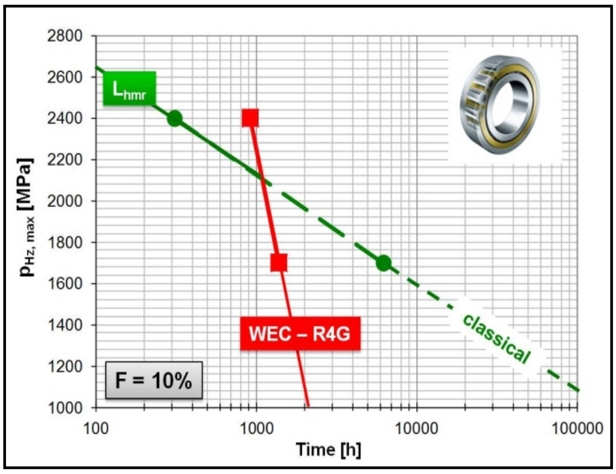

Fig. 2 Influence of Hertzian pressure on WEC damage, vs. rating life calculation in accordance to ISO 281 [7].

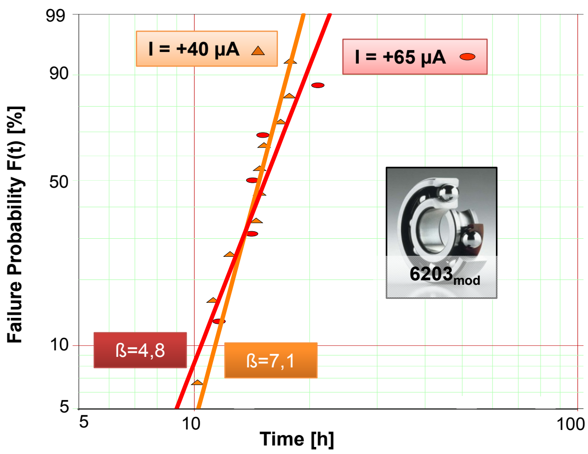

Fig. 3 Typical distribution of WEC failures [5].

failure propensity in such application exists. Furthermore, such a small scatter provides evidence that failure initiation sites, i.e. the potential weak points in the structure, have to be present at a very high density. This clearly supports the idea that the relative few inclusions distributed within the structure cannot constitute a decisive influence on the formation of WEC (Figs. 12 and 13).

3. WEC and Additional Loads

It is exceptionally difficult to reproduce WEC field failures on rolling bearing test rigs since the typical additional loads necessary for WEC damage, such as passage of electric current or high dynamic characteristics, are normally intentionally excluded in test rigs. In many cases, a reduction of testing time by increased high test loads or high electrical currents is not possible because this often leads to other failure mechanisms.

Up to now, four different operating states and additional loads critical for WEC have been identified in various applications and on Schaeffler test rigs, which can result in WEC damage (Fig. 4).

For example, small direct currents due to electrostatic charge can lead to WEC damage in bearing rings acting as the cathode. This was shown by tests on ball bearings with grease lubrication and roller bearings with oil lubrication. In such cases, the driving force seems to be the large electrical field occurring in the lubrication gap [5]. In contrast to this, tests with high electrical currents have been carried out on ball bearings with grease lubrication [9] and also roller bearings with oil lubrication [8] where the failure is not restricted to the cathode. Additionally, a correlation between the current strength and the WEC running time was found which is not present in the tests with small direct currents. Therefore, the interaction with high currents is different from those with low currents (electrostatics). Subsequently, two different damage hypotheses have been introduced: “Cathodic WEC fatigue” and “Energetic WEC fatigue” [5, 8].

WEC damage can also be produced as a result of a high frictional energy load on the rolling contact surfaces. Comparable to electrically induced damage, two different damage modes are present here, too.

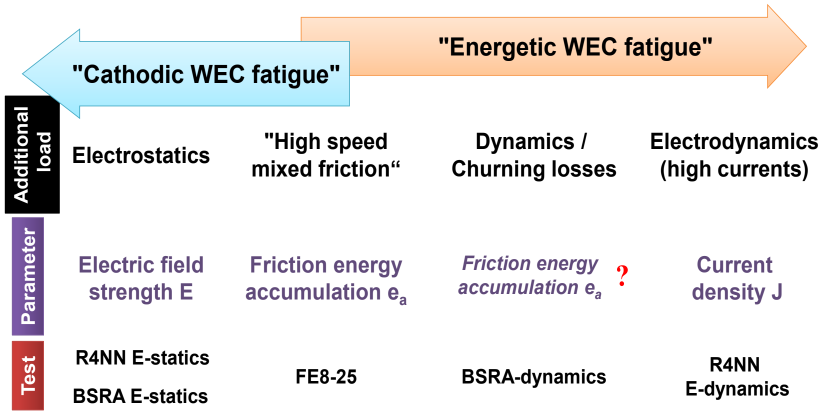

Fig. 4 Classification of operating conditions and additional loads critical for WEC [5, 6, 8].

When a rolling bearing is operating at a high sliding velocity under mixed friction conditions (FE8-25), WEC formation is heavily dependent on the lubricant formulation and presumably the electrical potential. In this case, the WEC tendency correlates with the frictional energy accumulation [6], which relates the surface-related frictional energy of an overrolled surface element to the time it has to recover from this process. However, WEC damage can also occur rarely under fluid friction at very high relative lubricant film thicknesses. Based on the current state of knowledge, WEC is initiated here by high drive train dynamics or high churning losses.

3.1 Additional Load “Dynamics”

There are many indications that torsional oscillations and vibrations, such as occurring in belt drives [10], CVT transmissions [11] or wind turbines [2], represent an additional load critical for WEC. For example, Tamada [10] was able to induce WECs in ball bearings by means of forced torsional dynamics. With the aid of Schaeffler’s tensioner and idler pulley test rig (BSRA-test, shown in Fig. 5) WECs could be induced in the outer rings of these bearing types as a result of high frequency vibrations (Fig. 6).

Here, excitation is achieved by means of a toothed belt, whose backside is in contact with the belt tensioner and idler pulley. The test bearing used was a modified ball bearing of type 6203. The lubricant was a polyurea grease with a SHC/MIN base oil. In order to maximise comparability in the tests, all test pieces were taken from a single production batch.

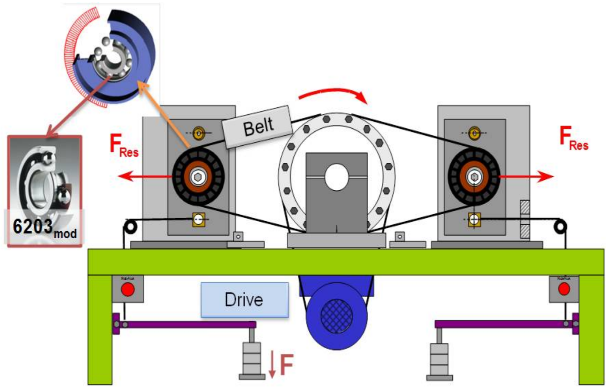

Fig. 5 Test principle of belt tensioner and idler pulley test rig (BSRA).

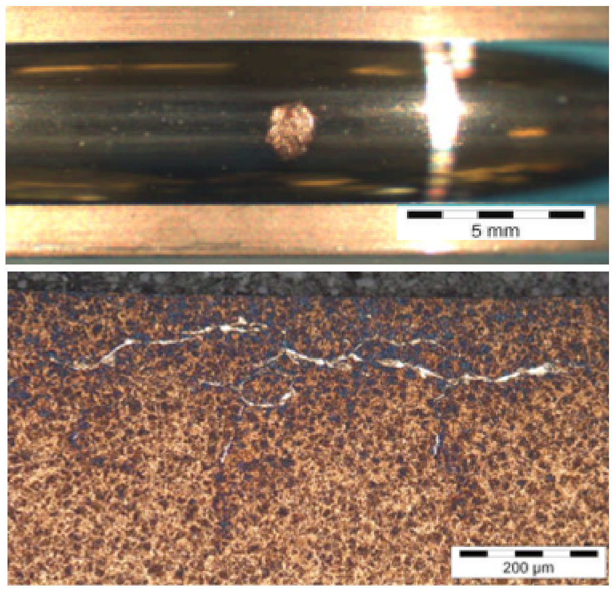

Fig. 6 Pitting in an outer ring of belt tensioner and idler pulley bearing caused by WEC formation (after test, using belt B).

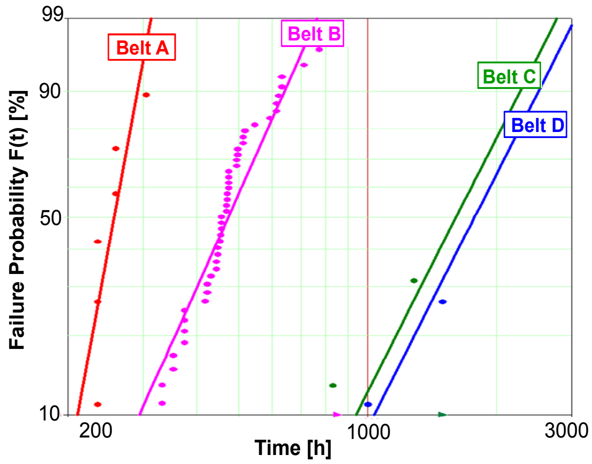

Fig. 7 Influence of toothed belt on WEC running time in the belt tensioner and idler pulley dynamic test (WEC damage in outer ring; $p_{Hz,max,OR}$ = 2,050 MPa).

As shown in Fig. 7, the WEC life is strongly dependent on the belt type being used. In the case of belt A, the mean time to failure was only 240 h, while utilizing the belt type D, a running time of 1,700 h could be achieved, increasing the lifetime of more than a factor of 5. Using the belts C and D, not all test pieces failed due to WEC damage and therefore a significant increase in the scatter of results could be seen.

In order to check the possible electrical influence on the WEC formation, tests were carried out using the same test-pieces and belt type B with current passing through the test pieces on a similar basis to [5]. Here, the current passage had no significant influence on the WEC lifetime. “Cathodic WEC fatigue” as a result of current passage due to electrostatic charge can thus be disregarded for this test [5]. As in the case of chains or gears the excitation of the toothed belt to vibration results from the fluctuations of the number of teeth or links in contact.

The WEC formation was also more pronounced at belts where the teeth are sharply “silhouetted” on the pulley. These belts with a less uniform force application then lead to significantly stronger vibrations. As shown in Fig. 8, the accelerations measured at the fixing screw of the tensioner and idler pulleys are significantly greater with belts A and B than with belts C and D, which are “less critical for WEC”.

There is a clear relationship between the measured accelerations and the WEC lifetime. The greater the accelerations respectively the vibrations excited by the belt are, the earlier the pulleys will fail with WECs.

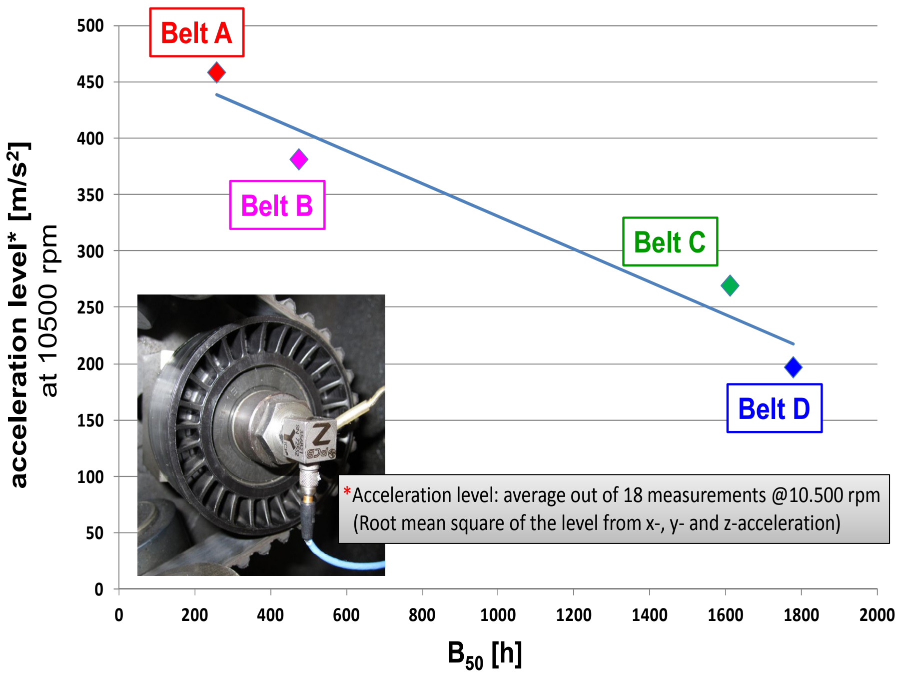

Fig. 8 Relationship between belt-dependent acceleration on fixing screw of tensioner and idler pulleys and WEC running time.

4. WEC Mechanism

So far, the mechanism responsible for WEC has not been conclusively identified. In addition to an increased uptake of hydrogen by the steel during rolling contact, which can lead to WEC formation [3, 5, 12], other WEC damage mechanisms such as stress corrosion cracking [13] or electromagnetism [14] are currently considered. Starting from the test results at Schaeffler and taking into account the current state of knowledge on the formation of WEC, the hypothesis shown in Fig. 9 on the WEC damage mechanism has been developed. If the “Cathodic WEC fatigue” occurs, chemical reactions cause formation of hydrogen cations (protons), which leads to adsorption of hydrogen on the steel surface at the cathode (Volmer reaction). A small part of this atomic hydrogen diffuses into the material [15]. High deposition rates only occur in the case of high ion mobility as the result of high electric field strength E (Nernst-Planck equation) [5] or a high reaction rate for boundary layer regeneration due to wear (high frictional energy accumulation) [6].

Within the mechanism “Energetic WEC fatigue”, atomic hydrogen can also form through thermal dissociation. The high temperatures required for this process, are generated for instance from electric discharge in the lubrication gap or during the acceleration of rolling elements on entry to the load zone in radial bearings. In this case, the flash temperatures are so high that in some occasions the individual events can also lead to surface damage such as fusing (current passage) or smearing. However, there is not necessarily any correlation with this damage, because WEC fatigue is determined more by the frequency of such events and less by their magnitude.

There are varying hypotheses on the influence of hydrogen on the structure. At present, the HELP mechanism (hydrogen enhanced localized plasticity) appears most suitable for explanation of the formation of WEAs and subsequently of WECs.

The HELP mechanism assumes that due to a high local concentration of hydrogen the yield stress is reduced. The locally inhomogeneous distribution of hydrogen leads to localised dislocation glide with high local dislocation density [16]. The rearrangement of the dislocation structures ultimately leads to formation of the nanocrystalline structure.

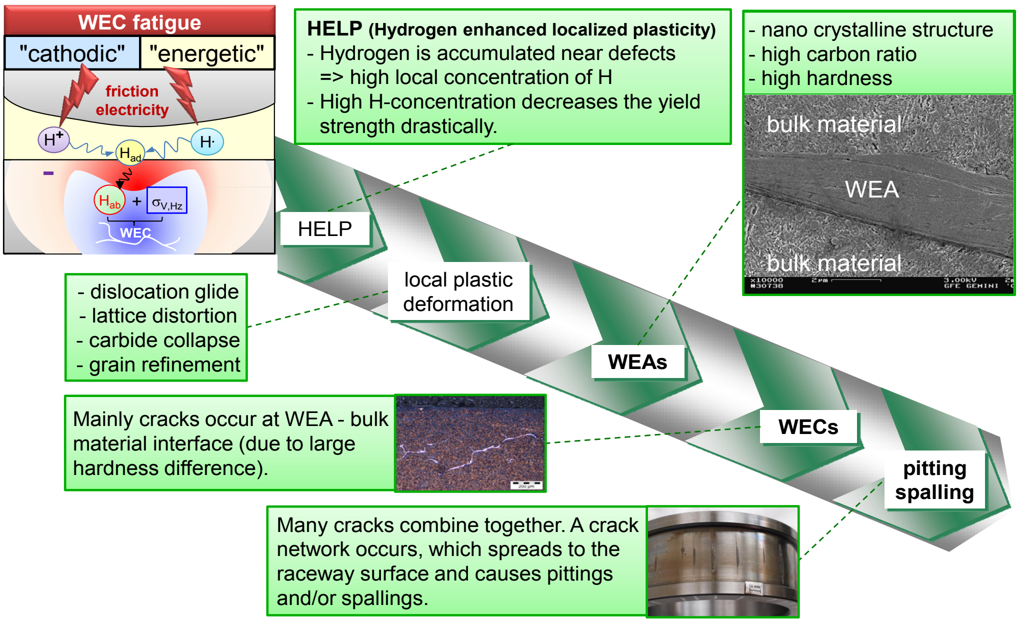

Fig. 9 Hypothesis on WEC damage mechanism.

It is extremely difficult to obtain evidence of the hydrogen formation in rolling bearings because, according to Evans [1], hydrogen concentrations of less than 1 ppm (averaged over the bearing life time) are sufficient for WEC formation, which are probably below the detection threshold of current measurement methods [17]. Furthermore, the hydrogen gradients in the material are very large in some cases. As shown in Fig. 10 using the example of a washer in a cylindrical roller thrust bearing, high hydrogen concentrations after typical test running time of 40 h can only be expected near the surface in the areas of hydrogen absorption (<0.8 mm deep within the pitch circle). The simulated mean hydrogen concentration is only approx. 40% of the maximum hydrogen concentration. Furthermore, the diffusible hydrogen evaporates rapidly after the run.

5. The Influence of Material

5.1 Base Material

The literature contains numerous pieces of evidence that both through hardened and case hardened materials are susceptible to WEC [18, 19].

As preventive measures against WECs numerous suggestions were made by Evans [2] which focus on both a change in the material alloy and its manufacturing technology. For the example of bearings in a wind power application Errichello [20] reported that a case hardening steel with a high residual austenite content in the surface zone could prevent WEC formation. This has been contradicted by our own investigations [21]. In FE8-25 test runs at Schaeffler with the additional load "High speed mixed friction" it was demonstrated that, when using the case hardening steel SAE4320, no increase in running time could be achieved in comparison with 100Cr6, either martensitic or bainitic hardened (Fig. 11). Comparable results were also obtained on belt tensioner and idler pulley test rigs (Fig. 5) with the additional load "Dynamics" where case hardened materials show the same susceptibility to WEC formation as through hardened bearings.

Only the pressurized electroslag remelted (PSER) steel Cronidur 30 shows excellent performance on all test levels and a general resistance to WEC. This is in good accordance with experiences gained in the field so far. There has never been a case of WEC failure for a bearing made from Cronidur 30.

In order to investigate the influence of material cleanliness on the formation of WECs more precisely, both the test level FE8-25 and the large size bearing test rig R4G were used. On those test rigs comparative investigations of WEC lifetime were utilized, testing standard grades of the rolling bearing steel 100Cr6 vs. very clean grades of 100Cr6 (VU = vacuum remelted and VIM + VAR = vacuum melted + vacuum arc remelted). From Figs. 12 and 13, it can be seen that no increase in running time to WEC failure can be achieved with very clean steel grades on both test levels.

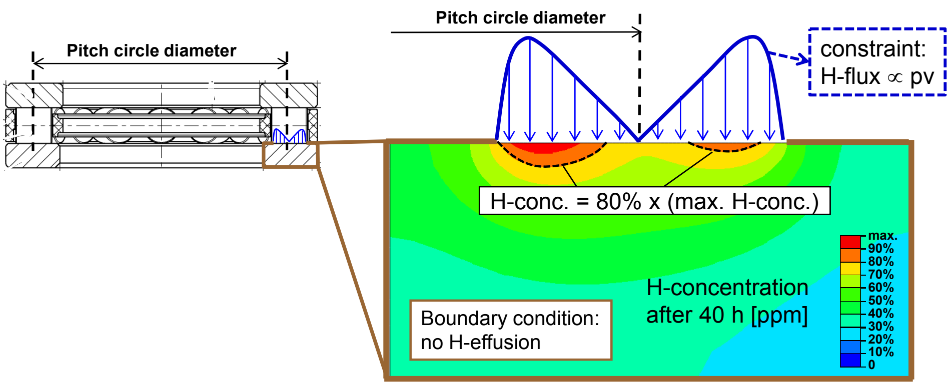

Fig. 10 Hydrogen concentration in the washer of a cylindrical roller thrust bearing 81212 after 40 h test (assumption for simulation: diffusion coefficient of H in steel 0.765 mm²/h at 100 °C).

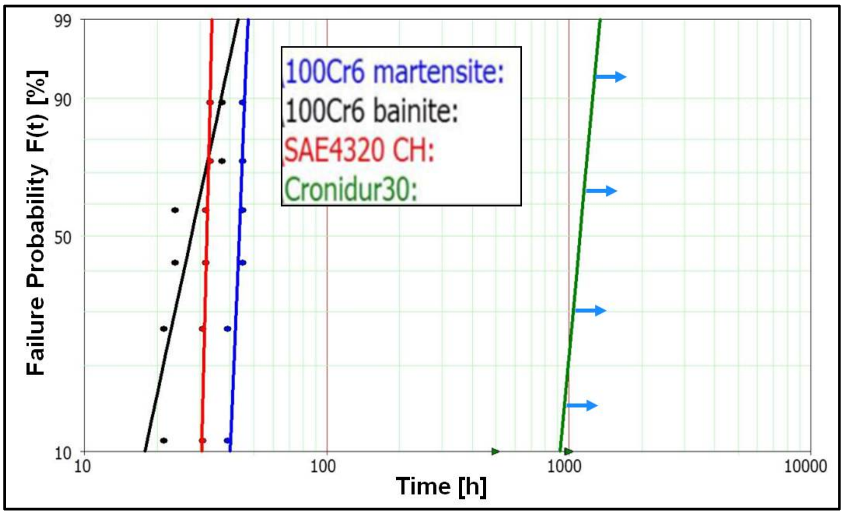

Fig. 11 **Influence of material on WEC formation in the FE8-25 test [21].**

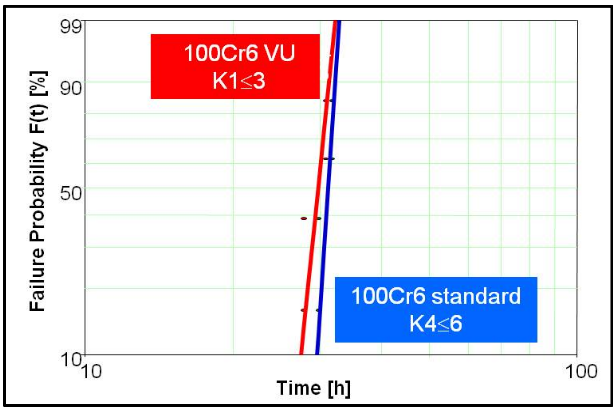

Fig. 11 **FE8-25 tests of martensitically variants of 100Cr6 with different microscopic cleanliness.**

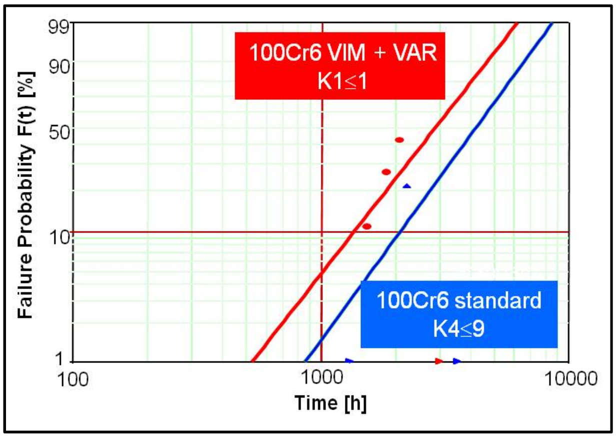

Fig. 12 **R4G tests of martensitically hardened variants of 100Cr6 with different microscopic cleanliness.**

5.2 Coatings

According to Evans [2], it is possible to use coating systems that have the effect of reducing friction, causing passivation or inhibiting hydrogen permeation for preventing WEC. These include the coating system Durotect®B, a systematic further development of conventional black oxide coatings, which increases the robustness of resistance to WECs [4]. This has been demonstrated at Schaeffler in numerous rig tests on different bearing types and additional loads. As an example, Fig. 14 shows the test results obtained on the belt tensioner and idler pulley test rig under dynamic conditions (Fig. 5). The coating of martensitically through hardened 100Cr6 with Durotect®B leads to an increase in running time by a factor of more than 20. Positive experience in the field with a very low failure rate underlines the high suitability of the Durotect®B coating.

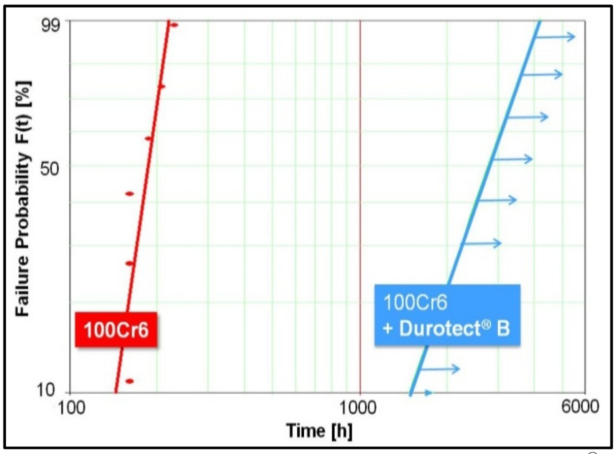

Fig. 13 **Increase in running time by applying Durotect®B on the rings (test setup: BSRA-dynamics, Fig. 5).**

6. The Influence of Lubricant

In accordance with the different “WEC additional loads”, the influence of lubricant ranges from promoting damage in the case of “Cathodic WEC fatigue” to preventing damage in the case of “Energetic WEC fatigue”. Since the type of additional load cannot always be predicted, the objective in the selection of lubricant must always be avoiding “damage-promoting” formulations as far as possible.

There are now tests for automotive transmissions (e.g., ZF pitting test, VW pitting test, Schaeffler FE8-25 test), where the influence of the lubricant on the formation of WEC can be assessed. By these tests, it is possible to identify additives that have the effect of promoting WEC damage [22]. Due to the various tribological contacts within a modern gearbox or assembly, an application of unadditivated lubricants is virtually impossible. With respect to wear and friction, the use of fully formulated lubricants is absolutely essential. In relation to WEC life, the positive effect of passivating additive layers in the presence of hydrogen has also been demonstrated [23]. In selection of the correct lubricant, it is therefore important to achieve a reasonable balance between additive load and the intended effect [24]. The mantra here can only be “only as much additive function as necessary, not as much as possible”. The detection of possible WEC risks through appropriate analyses and tests is an essential factor in achieving holistic lubricant selection.

The selection of anti-corrosion protection [25] and the presence of water [26] can also have a decisive influence on the tendency towards WEC.

7. Conclusions

The current state of knowledge on WEC fatigue damage which occurs in certain applications or under specific operating conditions is presented. It is a discrete fatigue mechanism that cannot be calculated using the classic theory of rolling bearing rating life. The bearing life time is significantly less dependent on the external load and scatters considerably less in case of WEC damage than in the classical case. Moreover, the WEC formation seems to be not significantly influenced by steel purity according to the bearing tests.

Four operating conditions have been identified to be critical for WEC (electrostatics, high speed mixed friction, dynamics, electrodynamics) and have been reproduced on test rigs. Reproduction of dynamics as a critical additional load was carried out using a belt tensioner and idler pulley test rig on which excitation was induced by means of a toothed belt. The WEC running time of the rolling bearing in this case was decisively dependent on the system dynamics of the belt drive. Measurements of vibrations on the inner ring show a relationship between acceleration and the tendency towards WEC formation.

Starting from tests carried out at Schaeffler and taking into account the current state of knowledge on the formation of WEC, a hypothesis on this failure mechanism has been developed and presented. If the “Cathodic WEC fatigue” occurs, the formation of hydrogen cations (protons) is caused by chemical reactions which are initiated by strong electrical fields or ongoing wear/replacement of the boundary layer. In case of “Energetic WEC fatigue”, atomic hydrogen is formed by thermal dissociation as a result of high flash temperatures. A small fraction of this atomic hydrogen is adsorbed by the steel surface and diffuses into the material. According to simulations, high hydrogen concentrations only occur near the surface and only in a small volume close to the raceway. A further accumulation of hydrogen then occurs in the structure, predominantly at defect locations. At or above a critical concentration of hydrogen, the strength of the material is then reduced drastically at localized areas (HELP mechanism). Hence, even after a relatively small number of load cycles and at low Hertzian pressures, plastic deformations can occur and fatigue processes proceed that lead to the formation of new phases (WEAs) and cracks in and on these phases

(WECs).

The tendency towards WEC is not only influenced by the additional load but also by the lubricant including the anti-corrosion protection and the material used. While conventional low-alloyed materials are capable of developing WEC, irrespective of the type of heat treatment, the formation of WEC is prevented completely by special steels, such as Cronidur 30. However, by applying appropriate coatings on conventional low-alloyed materials the resistance against WECs can be increased significantly. In this respect, the Durotect®B coating has become established as a potent countermeasure.

References

[1] Evans, M. H., Richardson, A. D., Wang, L., and Wood, R. J. K. 2013. "Effect of Hydrogen on Butterfly and White Etching Crack (WEC) Formation under Rolling Contact Fatigue (RCF)." *Wear* 306 (1-2): 226-41.

[2] Evans, M. H. 2012. "White Structure Flaking (WSF) in Wind Turbine Gearbox Bearings: Effects of 'Butterflies' and White Etching Cracks (WECs)." *Material Science and Technology* 28 (1): 3-22.

[3] Ruellan, A., Ville, F., Kleber, X., Arnaudon, A., and Liatard, B. 2013. "Understanding White Etching Cracks (WEC) in Rolling Element Bearings: The Effect of Hydrogen Charging." Presented at the 40th Leeds-Lyon Symposium on Tribology & Tribochemistry Forum, Lyon, France.

[4] Holweger, W., and Loos, J. 2011. Beeinflussung der Wälzlagerlebensdauer durch neue Werkstoffphänomene in speziellen Anwendungen, Antriebstechnisches Kolloquium ATK 2011, ISBN 978-3-940565-83-9.

[5] Loos, J., Goss, M., and Bergmann, I. 2015. Einfluss von Lagerströmen aus elektrostatischen Aufladungen auf die WEC-Bildung in Wälzlagern, Tribologie und Schmierungstechnik, 62. Jahrgang, 1/2015, 41-51.

[6] Loos, J., and Kruhoeffer, W. 2015. Einfluss der Reibbeanspruchung auf die WEC-Bildung in Wälz-lagern, Tribologie und Schmierungstechnik, 62.Jahrgang, 4/2015, 33-43.

[7] N. N. ISO 281: 2007. Rolling Bearings—Dynamic Load Ratings and Rating Life.

[8] Loos, J., and Goss, M. 2015. Einfluss hoher elektrischer Ströme auf die WEC-Bildung in Wälzlagern, Antriebstechnisches Kolloquium ATK 2015.

[9] Kawamura, T., and Mikami, H. 2007. Development of NA103A Long-Life Grease for Automotive Components. NTN Technical Review No. 75.

[10] Tamada, K., and Tanaka, H. 1996. "Occurrence of Brittle Flaking on Bearings Used for Automotive Electrical Instruments and Auxiliary Devices." *Wear* 199: 245-52.

[11] Tanaka, S. 2006. Pulley Support Bearing for Push-Belt CVTs, Motion & Control No. 19, NSK.

[12] Vegter, R. H., and Slycke, J. T. 2009. "The Role of Hydrogen on Rolling Contact Fatigue Response of Rolling Element Bearings." *Journal of ASTM International* 7 (2): 1-12.

[13] Gegner, J., and Nierlich, W. 2011. "The Bearing Axial Cracks Root Cause Hypothesis of Frictional Surface Crack Initiation and Corrosion Fatigue Driven Crack Growth." Presented at the Wind Turbine Tribology Seminar, USA.

[14] Kaldre, I., Ščepanskis, M., Jakovičs, A., Maniks, J., Nacke, B., and Holweger, W. 2014. "Influence of an EM Field on Changes in Microstructure of Bearing Steel." Presented at the International Scientific Colloquium Modelling of Electromagnetic Processing, Hannover, Germany.

[15] Juilfs, G. G. 2000. Das Diffusionsverhalten von Wasserstoff in einem niedriglegierten Stahl unter Berücksichtigung des Verformungsgrades und der Deckschichtbildung in alkalischen Medien, Dissertation Hamburg-Harburg.

[16] Hoelzel, M. 2003. Struktur und Gitterdynamik wasserstoffbeladener austenitischer Edelstähle, Dissertation an der Technischen Universität Darm-stadt.

[17] Suter, T. et al. 2009. Lokale Wasserstoffbestimmung auf (hochfesten) Stahl, Institut für Werkstofftechnologie, Wallisellen.

[18] Holweger, W., Wolf, M., Merk, D., Blass, T., Goss, M., Loos, J., Barteldes, S., and Jakovics, A. 2015. "White Etching Crack Root Cause Investigations." *Tribology Transactions* 58: 59-69.

[19] Stadler, K. 2014. "Premature Wind Gearbox Bearing Failures & White Etching Cracks ("WEC")." Presented at the NREL 2014, Golden, Colorado, USA.

[20] Errichello, R., Budny, R., and Eckert, R. 2013. "Investigations of Bearing Failures Associated with White Etching Areas (WEAs) in Wind Turbine Gearboxes." *Tribology Transactions* 56: 1069-76.

[21] Blass, T., Trojahn, W., and Holweger, W. 2015. WEC Formation in through Hardened and Case Hardened Bearings—Influence of Retained Austenite, CWD Aachen.

[22] Surborg, H. 2014. Einfluss von Grundölen und Additiven auf die Bildung von WEC in Wälzlagern, Dissertation Universität Magdeburg.

[23] Endo, T., Dong, D., Imai, Y., and Yamamoto, Y. 2005. "Study on Rolling Contact Fatigue in Hydrogen Atmosphere—Improvement of Rolling Contact Fatigue

Life by Formation of Surface Film." *Tribology and Interface Engineering Series* 48: 343-50.

[24] Nixxon, et al. 1995. Lubricant Additives, Friend or Foe, LUBRICATION ENGINEERING, October.

[25] Franke, J. et al. 2015. Einfluss des Tribolayers auf Wälzermüdung mit WEC auf dem FE8-Prüfstand, Antriebstechnisches Kolloquium ATK.

[26] Iso, K., Yokouchi, A., and Takemura, H. 2006. "Research Work of Clarifying the Mechanism of White Structure Flaking an Extending the Life of Bearings." SAE Technical Paper 2005-01-1868. doi:10.4271/2005-01-1868.