GfT Gesellschaft für Tribologie e.V.

White Etching Cracks

Position Paper of the Gesellschaft für Tribologie e.V. (German Society for Tribology)

Damage patterns, origin hypotheses, influencing factors, risk assessment and recommended actions

Tribology in Germany

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Inhalt

1. Introduction

White etching cracks (WEC) are defined as damage patterns of metallic rolling element pairings observed in rolling bearings. White etching cracks are characterized by crack networks flanked by white etching areas visible in metallographic sections (Fig. 1.1). Under the light microscope, these areas appear white as they react only slightly to the etchant and reflect light.

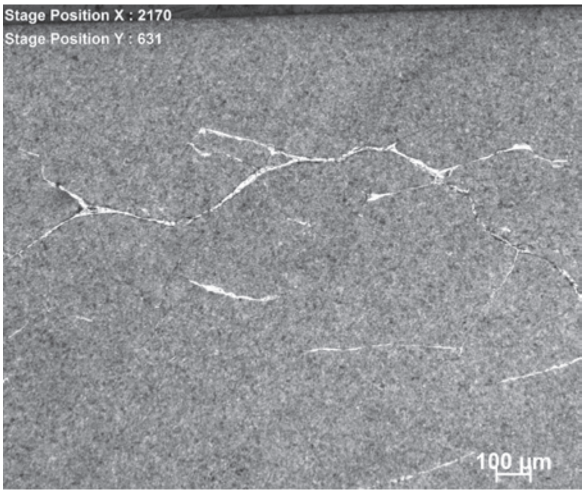

Fig. 1.1: Typical appearance of WECs occurring the cross-section of the inner ring of a rolling bearing (Stadler et al. 2018)

Fig. 1.2 depicts 3D-reconstructions of repeated sections of the same sample, displaying distinct three-dimensional structures.

Damage to rolling bearings associated with WECs may occur with all types and sizes of rolling bearings and in widely varying applications.

In addition to numerous research papers and publications on the subject, the necessity manifested to compile the present know-how and make it available to bearing manufacturers, users and research institutions. For this purpose, the Gesellschaft für Tribologie (GfT) established a task group to create this position paper on „White Etching Cracks".

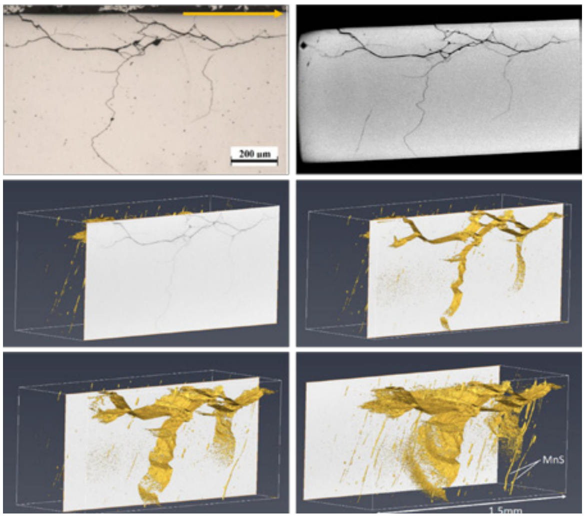

Fig. 1.2: 3-dimensional structure of WECs (Danielsen et al. 2019)

This position paper strives to establish the link between microscopic findings and actual conditions in the rolling bearing. It is the objective to deliver an unbiased and comprehensive overview over the safe state-of-the-science characteristics for WECs, and present influences inducing WECs but also provide the measures for mitigating or eliminating the risks of WECs. This document intends to present the different positions, and, by integrating all the involved stakeholders into the task group, tries to achieve maximum credibility, and ultimately aims to offer valuable impetus for further research approaches.

2. Damage patterns

Generally, rolling bearing damage caused by white etching cracks manifests in premature bearing failures occurring way before the calculated L10 (fatigue) life and at bearing loads distinctly below the fatigue limit load Pu (ISO 281 Annex B). Designs in accordance with ISO 281 and ISO/TS 16281 do not consider WEC as damage mechanism.

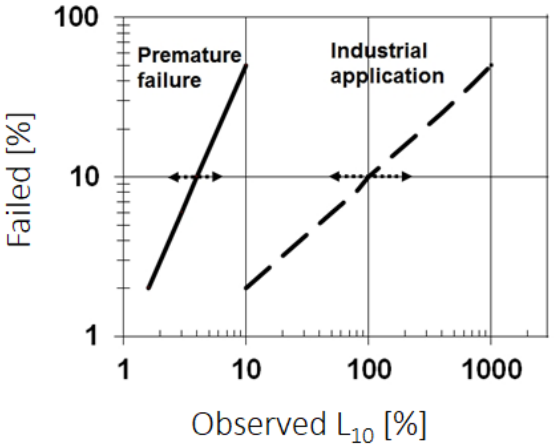

Fig. 2.1: Premature failures of rolling bearings due to WECs (Stadler et al. 2015b; Stadler et al. 2018)

Typical for WECs damage is an accumulation of damage with low variance (Fig. 2.1), as recognizable by the Weibull distribution.

ISO 15243 compiles and documents common cases of rolling bearing damage in detail, however, the standard has not yet incorporated specific WEC damage. The macroscopic image of WECs can be very diverse. Material breakouts or axial cracks occur in many places, starting from separate locations. With advanced damage, allocation as WECs becomes increasingly demanding. Fig. 2.2 shows macroscopic damage patterns as they are recorded during visual inspection. The right-hand side of the figure („axial cracks“) shows a damage pattern with the corresponding micrograph depicting damage related to WEC. Spalls found in the image center can originate from WECs, but may also be generated by other causes. The micrograph below shows clear indication of WECs. The cause for the flaking („spalls“) on the left-hand side of the image cannot be clearly determined. Only a metallographic examination can clarify whether the damage was caused by WECs.

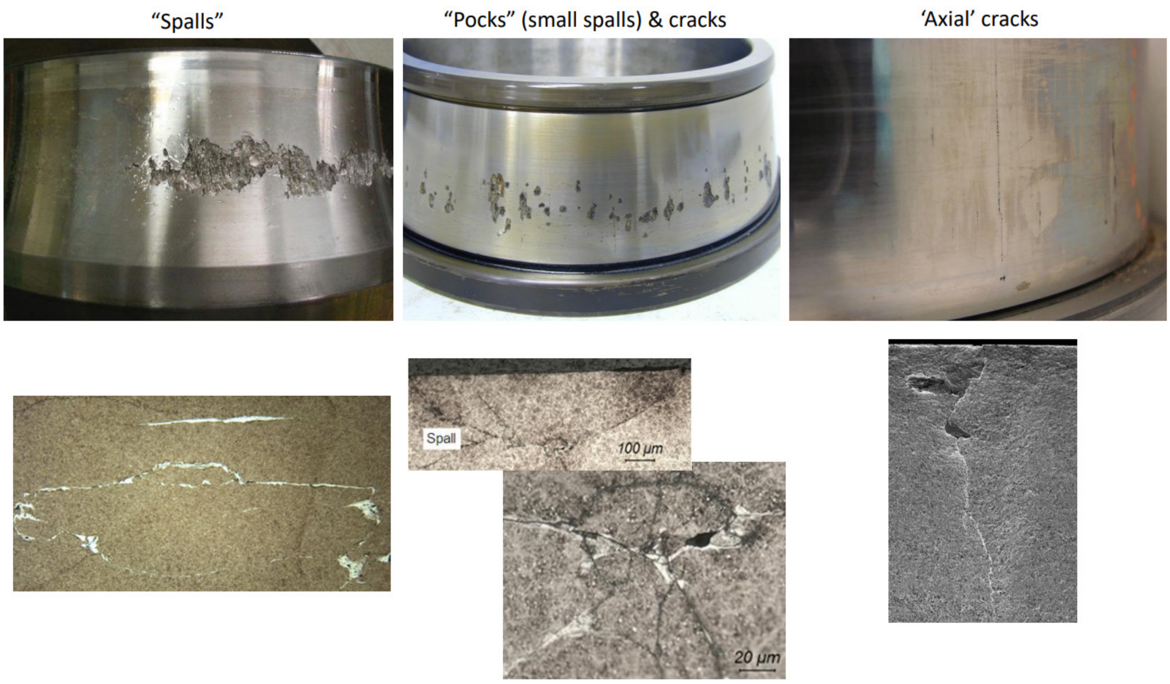

Fig. 2.2: Bearing damage related to WECs (Source: SKF)

When conducting a structured damage analysis after visual inspection, usually sections are cut through the component. In order to prevent secondary damage concealing primary damage, areas without major macrostructural damage are selected and cut immediately upstream and downstream of the damage. If WECs are suspected, sections are cut in circumferential direction first and subsequently in axial direction (Fig. 2.3, Fig. 2.4). In order to visualize the affected area, the cutting surface is polished first and subsequently etched with nital or pikral. A first analysis step provides an overview of a large, stressed area. Subsequently, a targeted search shall identify white etched areas with adjacent crack networks. Those usually lie within in the range of maximum Hertzian equivalent stress.

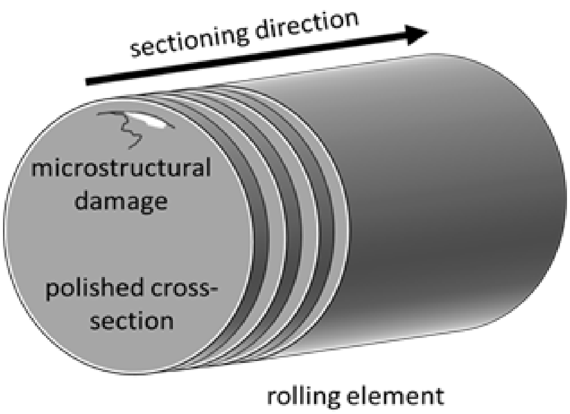

Fig. 2.3: Sketch of the sectioning direction using the example of a cylindrical roller

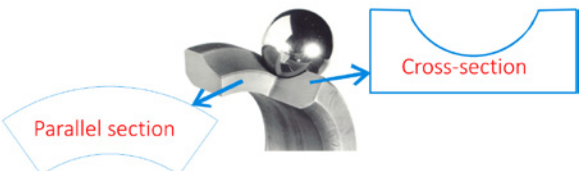

Fig. 2.4: Cut sections on the bearing inner ring in circumferential direction (cross-section) and axial direction (parallel-section)

Fig. 2.5 compares different damage patterns with cracks and white etchings. Classic fatigue would reveal cracks without white etching areas (Fig. 2.5: 1, 8). White etching areas (WEA) manifest in various characteristics (Fig. 2.5: 1, 8). Regularly arranged white bands with flat (low angle bands - LAB) or steep (high angle bands - HAB) angles (Fig. 2.5: 2, 3) are not considered typical for WECs; they will occur when exposed to high pressures at the end of an extended service life (Voskamp 1997). So-called „butterflies“ (Fig. 2.5: 4) whose typical shape forms symmetrically on micro-inclusions even at moderate pressures of around 1.3 GPa also do not fall under WECs. In cross-sectional view, they appear two-dimensional with a size of maximum of 250 µm from tip to tip. Fig. 2.5 (6 and 11) show large butterfly-shaped structures with dimensions of well over 250 µm, identified here as WECs. Crack networks flanked by white etching areas are characteristic for WECs (Fig. 2.5: 5, 6, 7, 9, 10, 11). Cracks expand three-dimensionally (see Fig. 1.2) with lengths ranging from approx. 10 µm to several millimeters. They occur primarily below the surface in areas of maximum Hertzian equivalent stress (0.6∗contact width of the small semi-axis) and often in significantly deeper areas.

Networks of widely branched, irregular cracks consist of ultra-fine, nanocrystalline and carbide-free ferrite or of ferrite with a very fine distribution of carbide particles. The white etching areas are located along the crack flanks and in immediate vicinity of the cracks. Such areas appear white because they react only slightly to the etchant and reflect light. Compared to the undamaged microstructure, the hardness is approximately 10 % to 50 % higher.

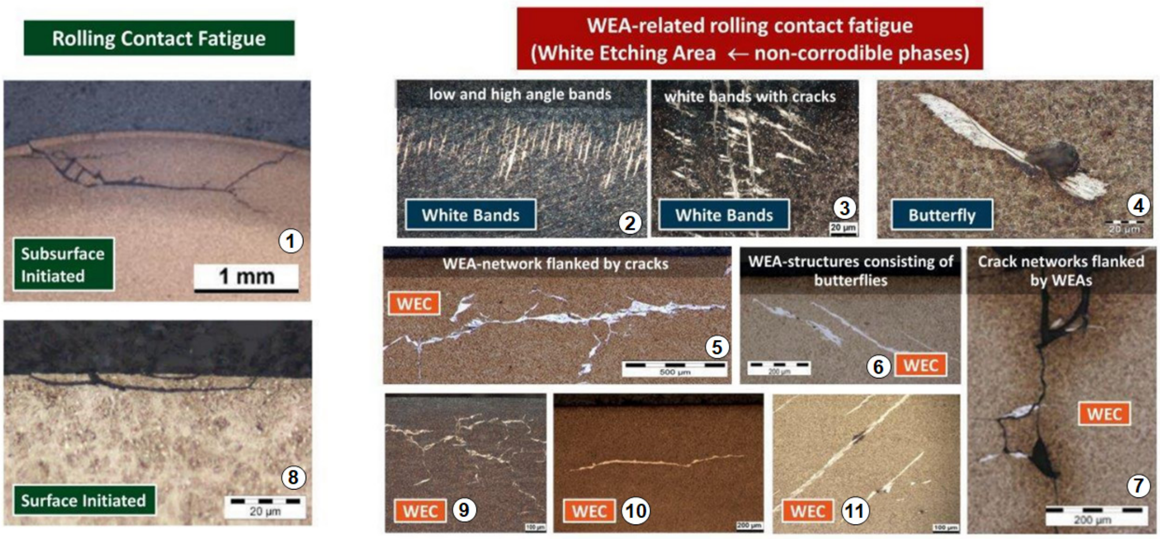

Fig. 2.5: Comparison of damage to the microstructure (Loos et al. 2019a)

3. Formation White Etching Cracks (WEC)

Significantly differing scenarios inducing the formation of WECs in bearings under certain conditions have been determined in field tests. The multitude of influencing factors proves that the damage process leading to formation and propagation of WEC is rather a system response than a singular damage event which can be traced back to one individual root cause. Nevertheless, this chapter attempts to summarize the hypotheses for the formation of WECs proposed by the literature. However, it must be considered that the phenomenon of WEC formation is subject of ongoing national and international research projects. The following chapter bundles and presents the state of knowledge for stresses relevant to WEC formation and subsequently discusses the corresponding stress resistance. Chapter 3.3. will discuss the contribution of hydrogen. Finally, various approaches to the formation of WECs are presented.

3.1. Stress

Generally, WECs occur below the surface in rolling bearings made of steel. Typically, the origin of the observed cracks coincides with the maximum stress according to the Hertz theory. This area is also a location of potentially high hydrogen concentration (see Fig. 3.1) (compare to Chapter 3.3).

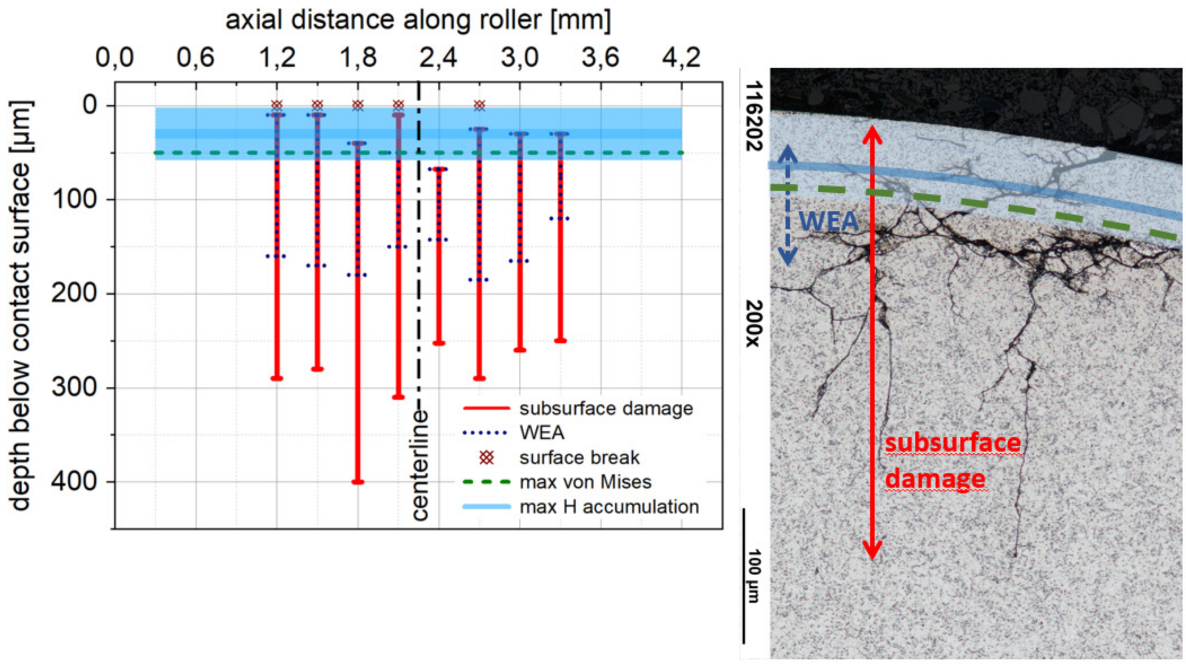

Fig. 3.1: Left: Distribution of WEC-induced subsurface damage in axial direction (Khader et al. 2019) (subsurface damage: crack lengths; WEA: area with white crack etching; surface break: surface damage; max von Mises: area of maximum equivalent tensile stress; max hydrogen accumulation: area of maximum hydrogen accumulation) RH: Section micrograph of a cylindrical roller (see Fig. 2.3)

The resulting cracks propagate to the raceway surface where the damage finally occurs. They also propagate to a depth of 400 µm proving that rolling stress is of paramount importance.

Design requirements or circumstances - beyond the bearing manufacturers recommendations - may sometimes superimpose significant structural tensile stresses to the rolling stress (e.g. due to shape deviation in the bearing seat or corresponding fit selection). In those cases, the probability of WECs and ring fractures impacting service life will increase (Lai and Stadler 2016). Cracks form below the surface and likely have a purely mechanical origin. Observed in a temporal sequence, cracks form first then white etching areas appear afterwards.

Chapter 4.6 provides information on additional loads and stress peaks.

3.2. Stress resistance

The stress resistance of rolling bearings versus classical rolling fatigue correlates strongly with the purity of the materials used. This is not the case for the formation of WECs, see Fig. 3.2 (Blass et al. 2020; Loos et al. 2019a). WECs may also form from small inclusions in the material which are permissible according to steel purity requirements (e.g. ASTM E45, DIN50602).

Exposed to rolling stress, WEC form due to pure fatigue and at inclusions and precipitations below the surface. Steel purity considers both macro-inclusions (> approx. 250 µm) and micro-inclusions (approx. 15 µm to approx. 250 µm). For WECs, the relevant range for inclusions and precipitations is below approx. 50 µm (e.g. MnS (Bruce 2016), (Gould et al. 2017a) (Holweger et al. 2015), and thus within the range of naturally existing microstructural components. Such inclusions or precipitations always occur even in high-purity steels, that is why a very high steel purity cannot prevent the formation of WECs.

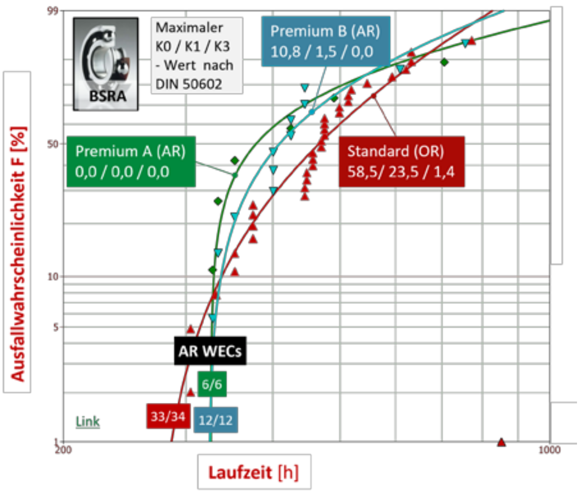

Fig. 3.2: Impact of steel purity on the failure probability of a ball bearing in WEC test (Loos et al. 2019a) (Failure probability [%] as a function of run-time [h])

A series of influencing factors listed in Chapter 4 positively or negatively affects stress resistance.

3.3. Influence of hydrogen

Conducting a desorption analysis (Richardson et al. 2018a) measures the concentration of permeable hydrogen in 100Cr6 bearing steel. Measurements found a significant correlation between WECs and hydrogen permeation. (Ruellan et al. 2015) suggests that hydrogen permeates into the material through newly forming surfaces caused by wear or by means of a non-closed tribolayer.

The question remains as to which mechanisms must be activated in the material in order to trigger WEC damage. Hydrogen plays an essential role in the ongoing debate as to whether there is a fundamental activation process for the formation of WECs.

However, atomic or ionic hydrogen must be present in sufficient concentration which cannot be quantified to this date. Common, generally acceptable influencing factors, such as current passage (Loos et al. 2021; Evans 2016), water contamination (Cantley 1977; Haque et al. 2018) and aggressive media (e.g. sour gas (Kahlman 2018)) are associated with the increased supply of hydrogen. In addition, hydrogen may be released from the ambient medium when frictional contact of two surfaces occurs (Han et al. 2016; Tanaka et al. 2017).

A permeation barrier can counteract the penetration of hydrogen into the bearing. Modifications of the boundary zone relevant for WEC formation also change the permeation barrier for elements penetrating from outside, such as hydrogen. Black oxide coating, for example, can form a conversion layer and thus mitigate WEC damage. In addition to additional tribologically beneficial properties, the oxide layer acts as permeation barrier (Ooi et al. 2019; Stadler et al. 2015a). Bare, non-oxidized surfaces (fresh fracture surfaces, friction surfaces subject to wear) not featuring such a permeation barrier, promote the formation of WECs instead.

Two common hypotheses for WEC formation summarize these observations by postulating that hydrogen concentrates in the location of maximum stress. This phenomenon locally reduces the stress resistance of the microstructure (HEDE (Hydrogen Enhanced Decohesion) (Katzarov and Paxton 2017) and HELP (Hydrogen Enhanced Local Plasticity (Birnbaum and Sofronis 1994)) and ultimately leads to WEC formation. These hypotheses are supported by experimental studies, where rolling bearings initially loaded with hydrogen ions failed prematurely due to WEC formation (Ruellan et al. 2014).

However, the hypotheses presented here have their constraints. Some studies suggest reducing the supply of hydrogen (vacuum, fluorinated lubricant), but WEC formation occurred anyway (Diederichs et al. 2016). Challenging in this context is the increased hydrogen concentration in the material which is demanding to detect. When a long period elapses between WEC formation and analysis, the original hydrogen contamination can no longer be determined, as hydrogen is a ubiquitous, extremely mobile and volatile element (Ruellan et al. 2017).

3.4. Crack formation and white areas

The white etching area (WEA) along the crack flanks is characteristic for WECs. Since also other alterations in the material can lead to the formation of WECs (see Chapter 2) and cause cracks during contact fatigue without such areas, the question arises as to what forms first - cracks according to (Manieri et al. 2019), (Gould and Greco 2016; Gould et al. 2017b) (Gould et al. 2017a; Bruce 2016) or WEA according to FVA 707 II / III (FVA 2017a, 2021), (Özel 2018; Li et al. 2017). Since there is supporting indication for both hypotheses, they are compared in Fig. 3.3.

The HELP model suggests that hydrogen accumulation is considered the origin of increased dislocation mobility (Hölzel 2004) leading to local, plastic failure and ultimately resulting in material embrittlement. As a mechanism, the HELP model correlates with the hypothesis of „microstructural alteration before crack formation“. In contrast, the HEDE model assumes that reduced cohesion between metal matrix and inclusions as a result of hydrogen accumulation propagate crack formation (Hölzel 2004). The mechanism presented by the HEDE model is applicable for the hypothesis of „crack formation before microstructural alteration“. (FVA 2022b)

Both theories have in common that hydrogen input and local accumulation of atomic hydrogen induce the formation of WECs.

WEAs verifiably consist of nano-crystalline and carbide-rich ferrite (Grabulov et al. 2010; Grabulov et al. 2007) and feature a hardness higher than the remaining microstructure.

(Mayweg et al. 2021) study the occurrence of WECs in high carbon steels. They illustrate the nano-crystalline ferritic areas forming white etching surfaces by rubbing the crack surfaces on another thus degrading the microstructure through considerable plastic deformation. Large parts of the WEA are depleted of carbon collecting in nanoscale deposits on the crack surfaces. The lower friction of carbon on crack surfaces reduces shielding of the crack tip, increases tip displacements and allows cracks to form faster than predicted by conventional crack propagation analysis.

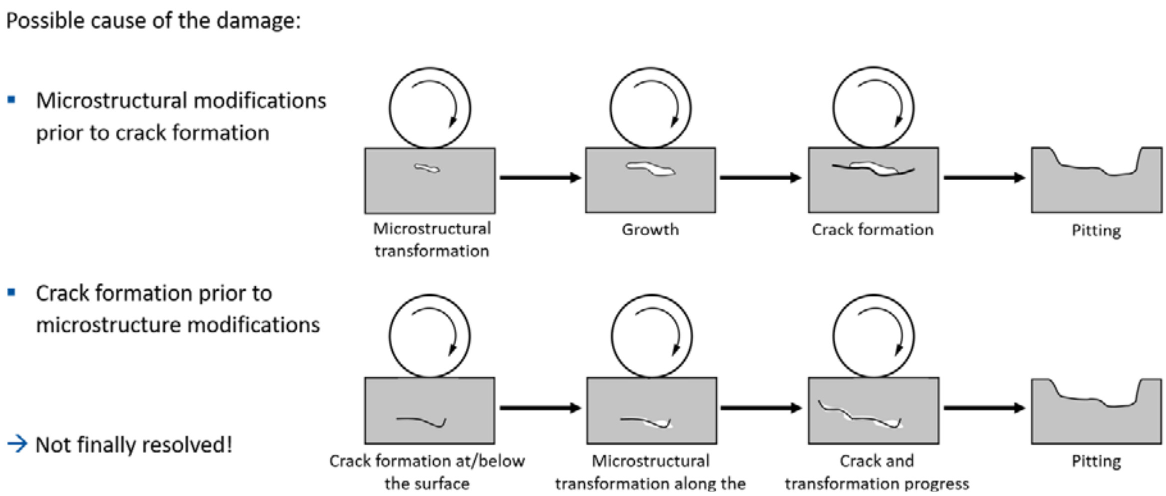

Fig. 3.3: Possible damage process responsible for WEC damage (MSE, RWTH Aachen)

4. Influencing factors

In addition to purely mechanical stress caused by Hertzian pressure, multiple influencing factors increase stress in relation to WEC formation or reduce stress resistance. As a rule, a critical state must be attained (threshold value) before WEC formation initiates.

There are a number of indications that the influencing factors mentioned in the following Chapter need to only act briefly until they trigger WEC formation (Loos et al. 2019b), (Seyfert et al. 2017), (Stadler et al. 2017).

4.1. Material

Common bearing steels differ in their WEC susceptibility. Fig. 4.1 shows the inclinations (red: very susceptible, green: largely not susceptible). WEC-susceptible materials, black oxide coating and carbonitriding significantly reduce the inclination to WEC formation. The effectiveness of the „treatment“ depends on the existing influencing parameters, such as slip, current passage, ambient medium etc. and the application. The importance of alloying elements for WEC formation has not been sufficiently determined (FVA 2022d). The user must decide whether black oxide coating or a material resistant to WEC should be selected.

With regard to WEC resistance, residual austenite content (Blass et al. 2016) and solid solution strengthening (Paladugu and Scott Hyde 2020) are the factors to be influenced by heat treatment.

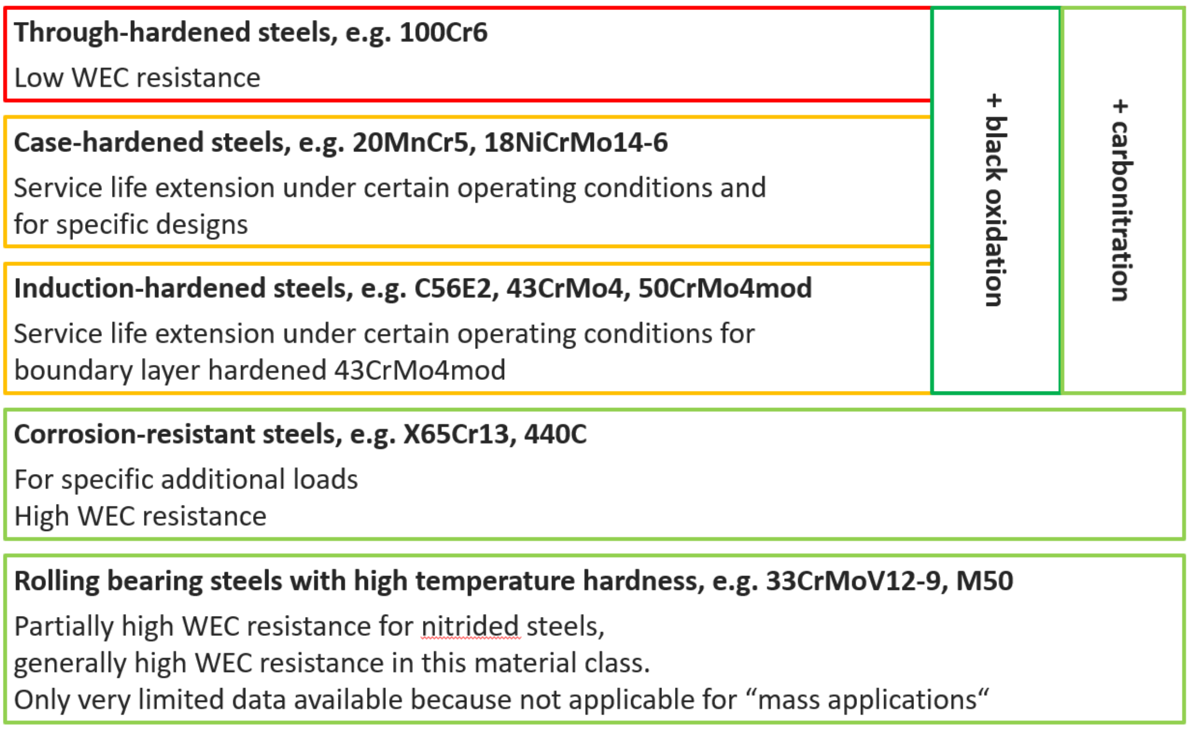

Fig. 4.1: WEC inclination of common bearing steels (GfT Task Group for WEC)

4.2. Lubricant

Whilst viscosity, additives and purity (solid impurities, particles) of the lubricant have a clearly defined impact on classic rolling element contact fatigue (see Fig. 4.2), the picture is less uniform where the formation of WECs is concerned.

In the event of massive mixed friction, increased operating viscosity (increase in viscosity grade and/or reduction in temperature) can have a positive effect. According to (Haque et al. 2018), higher viscosity can delay WEC formation, but not prevent it - but it can also increase the WEC stress due to fluid friction (λ>4) or higher EDM currents as a result of larger lubrication gap widths.

In some cases (FVA 2017b), increased oil flow was beneficial, although oil oversupply can also result in undesirable and damaging increased slip.

	"classical" rolling contact fatigue	WEC induced rolling contact fatigue
		
Viscosity	higher viscosity ⇧ lubrication film thickness -> **increased lifetime** [ISO 281 9.3.3.4]	**different,** depends on additional load [1],[2]
Additivation	**positive** at mixed friction conditions, if proven effective [ISO 281 9.3.3.3.4]	**negative**, if critical[1] in other cases fuzzy / **unknown**[2] ?
Oil cleanliness	positive [ISO 281 Annex A]	no effects reported

Fig. 4.2: Lubricant influence on classic rolling contact fatigue versus WEC inclination (Franke et al. 2020)

4.2.1. Lubricant chemistry / additives / formation of reaction layers

While suitable additives for classic rolling contact fatigue (ISO 281) offer service life extension in the mixed friction range, additives must be reconsidered when assessing WEC formation. However, exposed to certain stresses, the formation of WECs can be triggered and/or increased by such additives. The impact of temperature on the effect of additives with regard to WEC formation has not been sufficiently studied. (Surborg 2014) demonstrates that when using lubricants without additives, i.e. hydrocrack oils and synthetic oils based on PAO, rolling bearing failures due to WECs do not occur under selected operating conditions. Supplementary studies by (Gutiérrez Guzmán 2020) prove that this is also applicable for mineral oils and PFPE.

As of 2010, the impact of specific additive combinations on the formation of WECs was addressed by (Surborg et al. 2010), (Franke et al. 2014; Franke et al. 2023), (Franke et al. 2014), (FVA 2022b) and other authors (Ruellan et al. 2021). FE8-tests of these studies revealed that some combinations of certain metal-containing additives proved particularly critical for WECs (Haque et al. 2018). Metal-containing additives produced comparatively thick tribolayers (≈120 nm) associated with high friction. Haque argues that hygroscopic metal additives store water subsequently dissociating under high friction and permitting free hydrogen to permeate below the surface.

The combination of calcium sulfonates with zinc dithiophosphate (ZnDTP) can be a negative additive impact (Gould et al. 2019a), consequently also raising questions about the compatibility of lubricating oils with corrosion inhibitor (FVA 2022c), frequently containing calcium sulfonates. Studies by (Luther et al. 2014) showed no indication of WEC formation when using CLP gear oils even at high concentrations.

Due to their diversity and their interaction with other components of the lubricant formulation, no general postulations can be made regarding the impact of certain additives on WEC formation, e.g. by means of calcium sulfonate and zinc dithiophosphate.

Sulfonates in lubricants differ in basicity (from neutral to over-based), in chemical structure (type of sulfonic acids) as well as in type and particle size of inorganic alkaline additives. The latter are usually selected from the group of carbonates, hydroxides or oxides of alkali and alkaline earth metals. Particularly common are calcium sulfonates with widely varying metal content delivering alkalinity. Sulfonates inhibit corrosion, influence friction and avoid deposits. Therefore, they are suitable for the use in multiple applications.

Zinc-dialkyl-di-thio phosphates (ZnDTPs) are the most common additive group of sulfur-phosphorus compounds. In addition to anti-wear (AW) and extreme pressure (EP) properties, ZnDTPs also act as antioxidants and metal passivators.

> Due to their multifunctional properties, this additive group features diverse application options, e.g. in engine oils, shock absorber oils and hydraulic fluids.
>
> They synthesize by reaction of alcohols and phenols including phosphorus sulfide and by subsequent neutralization with zinc oxide. Due to the component diversity, ZnDTPs is a very versatile additive family characterized by multiple application properties.
>
> (Dresel und Mang 2017)

(Richardson et al. 2019) conducted 100Cr6 fatigue tests (FE8-test and micropitting rig (MPR)) with rolling contact and oil additives containing over-based calcium sulfonate (OBCaSul) used for corrosion prevention. On rollers tested with FE8, the increase in WECs correlates with the OBCaSul content in the oil. In MPR-tests, however, an OBCaSul content of only 1.4 % (ranging from 0 % in the base formulation with ZnDTP to 5.6 %) increased WEC inclination. Thermal desorption analyses (TDA) revealed permeation of hydrogen into the rollers for OBCaSul oils and for oils only formulated with ZnDTP. TDA also demonstrated a positive correlation between OBCaSul content and concentration of hydrogen available for permeation.

(Ruellan et al. 2021) demonstrated how WECs and premature bearing failures could reliably be reproduced with one oil, while another oil differing in three additives (one additive to modify friction and two additives for extremely high pressures (EP)) showed no indication of WECs and premature bearing failures, although mechanical stresses and contents of ZnDTP and OBCaSul were identical. For the oil inducing WEC damage, an increased hydrogen content in the bearing was detected (Gutiérrez Guzmán 2020; Ruellan et al. 2021).

Research project FVA 707-VI „Impact of field-relevant lubricant formulations on the formation of white etching areas and white etching cracks“ (FVA 2022b) shows that under selected mixed friction conditions inducing WECs in the FE8 axial bearing test using currently used lubricant formulations, no WEC damage but other damage was generated. Oil contaminated with water (50 % or 90 % saturation), however, resulted in WECs. On a radial bearing test rig exposed to additional electrical currents and under full lubrication, WEC damage but also other fatigue damage occurred.

On the four-disk test rig, WECs also occurred both under mechanical and electrical loads. The authors assume that the electric current promoted the input of permeable hydrogen into the material and ultimately led to the formation of WECs (FVA 2022b). However, these studies could not deliver a uniform picture of the influence of additives.

(Kürten et al. 2022) showed in laboratory tests that conductive ionic liquids can improve the WEC tolerance during current passage. Initial tests demonstrated an increase in bearing service life by 50 %.

Altogether, the generally negative impact of metal-containing additives could not be confirmed: Various studies document that the overall lubricant formulation (exact additive types and respective concentrations) and other, non-lubricant-related parameters are more crucial. With regard to lubricants, there is clear indication that WECs are characterized by multifactorial system damage.

To date, FE8-tests with axial cylindrical roller bearings were predominantly conducted to evaluate additives used with regard to WEC inclination, e.g. according to (FVA 2019b).

However, the impact of lubricant formulation on WEC inclination strongly depends on operating conditions and/or WEC trigger (see Fig. 4.3). Common WEC tests on the FE8 lubricant tester with axial cylindrical roller bearings („high-speed mixed friction“: mixed friction at the relatively high speed of 150 rpm) suggest either early failures (< 100 h e.g. with the „FE8 Low 320“ oil) or extended service life without WEC failure (> 500 h with „R4G Low 320“ oil). The so-called R4G test by Schaeffler (WEC failure at surface separation and high rolling element slip due to churning) demonstrates that the lubricant influence is distinctly less significant and the lubricant ranking is reversed. The service life of the test bearing NU222 without WECs using „FE8 Low 320“ oil is even longer than with „R4G Low 320“ oil. These two cases are also applicable for current-induced WEC damage. With the exception of „FE8 Low

68“ oil, differing from „FE8 Low 320“ mainly in terms of viscosity (ISO VG 320 vs. 68), identical lubricants were used in WEC tests without bearing current. At very small DC currents (< 100 µA, „e-statics“) typical for electrostatic charges (e.g. induced by belt drives), the lubricant formulation has decisive influence, whereas this influence is rather insignificant for fatigue life tests at high bearing currents (> 100 mA). All tests were conducted on the same test rig (R4NN) using the same bearing type NU205.

4.3. Current passage

Electrostatic charges, e.g. between rollers of paper machines, in belt drives or on wind turbine rotors, can verifiably cause WEC damage to bearings. According to the Van de Graaf generator principle, field strengths generated in the lubrication gap filled with a liquid insulator are partially very high (> 10 kV/mm), whereas the resulting direct currents are extremely low (< 1 mA). The driver for WEC failures, always occurring at the cathode (negative pole), seems to be the electric field strength. Therefore, bearing voltage should rather be considered as stress parameter (Loos et al. 2016).

Source of bearing currents can also be inverters frequently used in variable-speed drives. Rotor earth, EDM (Electric Discharge Machining) (Tischmacher 2017) or circular currents generated in electrical machines or adjacent units can also trigger WECs. At relatively high currents (usually > 100 mA) current passage anomalies in the raceway can occur resulting from electrostatic discharges. Here, the bearing voltage is significantly lower compared to WEC damage generated by very high field strengths. Therefore, the current serves as the more useful stress parameter. In contrast to WEC damage caused by high field strengths (electrostatics), WECs can occur both at anode and cathode (Loos et al. 2016). The anode tends to be even more critical (FVA 2022b; Loos et al. 2016) for the occurrence of WECs.

Findings of the research project FVA 707-VI (FVA 2022b) yield that regardless of the examined lubricant variants, WEC damage was generated in the rolling contact when the current load superimposed the mechanical load. With additional electrical stress, an inclination towards increasing atomic hydrogen in the material was observed. Subsequently, the electric current flow induces the input of permeable hydrogen into the material and the formation of WECs, regardless of the oil formulation.

(Özel 2018) considers even moderate pressures of 1.05 GPa in combination with either current densities of 0.1 A/mm² or permeable hydrogen content of 1-2 ppm as triggering for WEC.

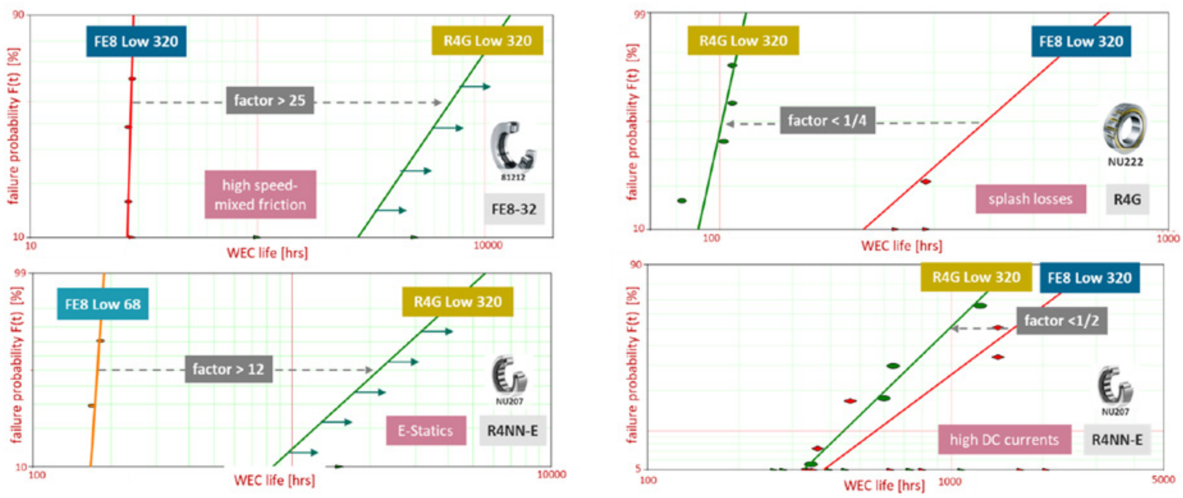

Fig. 4.3: Service life until WEC failure depending on lubricant and operating conditions (Loos et al. 2022) (Low: Oils with certain additives inducing WEC during the test procedure (mentioned in the oil name)

4.4. Water contamination

Under certain circumstances, water contamination can enhance the formation of WECs. It probably mitigates the stress resistance towards WECs. According to (Richardson et al. 2018b), tribochemical reactions play an important role here. These occur especially when slight damage due to wear had previously occurred.

Contamination of the lubricant with water can be very problematic with regard to WEC formation; flame-retardant hydraulic fluids containing water (HFC oils) can also enhance WEC formation (Ruellan et al. 2014), (Iso et al. 2005), (Peter Kohl 2015).

The presentation by (Strandell et al. 2010) shows how standstill corrosion, induced by the addition of small amounts of water, can shorten bearing life to 1 % of the nominal L10 life. The authors present comparable results of hydrogen-charged bearings in component tests and postulate that the test results support the theory of permeable hydrogen with associated, significantly reduced fatigue life of bearings.

Already back in the 70s, (Cantley 1977) clearly demonstrated that water in concentrations of 25 ppm, 100 ppm and 400 ppm in SAE 20 oil had a detrimental effect on the life of tapered roller bearings and correlated these results to the oil additives used. For synthetic oils, the limits are significantly higher.

(Haque et al. 2018) demonstrate that metal-containing additives massively induce WEC inclination by forming tribolayers with high friction coefficients and by increasing the water content in the lubricant. In addition, they show that water is a significant source of hydrogen contributing to WEC formation. By using heavy water (D_2O) in the oil, water contamination could be identified as the cause of hydrogen formation in the rolling contact. „Water dissociation“ through frictional forces in the tribolayer or water bound in the reaction layer is suggested as hypothesis for hydrogen formation.

4.5. Hydrogen

Solutions are available for bearing applications in hydrogen-rich atmospheres. (Kahlman 2018) demonstrates that hybrid bearings with ceramic rolling elements, PEEK cages and bearing rings made of very tough stainless bearing steel (X30CrMoN15-1) are suitable for the operation in corrosive sour gas with high H_2S content.

4.6. Additional loads

Stress peaks in the rolling contact (all the way to plastic deformation) are frequently discussed mechanical stress parameters. Stress peaks do not necessarily occur throughout the entire operating time (Manieri et al. 2019; Stadler et al. 2017). They can be caused by extreme operating conditions or by inconsistent load distribution in the bearing (edge loading).

On a micropitting test rig (MPR), (Manieri et al. 2019) subjected test specimens to a permanent load of 1.9 GPa. They selected this test geometry to deliberately expose roller edges to very high initial loads (ensuing possible subsequent plastic deformation), which are reduced by wear. (Stadler et al. 2017) exposed spherical roller bearings to very high loads in a brief minute range, resulting in local plastic deformation due to the purely axial load on the radial bearing. After subsequent „normal“ radial loading (service life > 1000 h) of the bearings, extremely large WEC networks were found below the outer ring surface (even without surface spalling) in both of the previously overloaded areas.

(Franke et al. 2020) showed that, in addition to high stress peaks, the two aforementioned sources displayed high friction energy density also relevant to damage.

A series of rolling bearing tests were conducted to determine whether a brief overload (below 4 GPa) reduces the service life of rolling bearings. Both FVA projects: 541-I “Rolling bearing service life - wind turbine gearboxes” (FVA 2011) and 866-I “Brief overloads” (FVA 2022a)” conducted multiple fatigue tests with cylindrical roller bearings of different sizes. They demonstrated that initially high overloads for 1 to 10 h at to up to 3800 MPa Hertzian pressure did not cause premature failures.

As demonstrated by (Bruce et al. 2018) in tribometer tests (2-disc test pHz > 2.4 GPa and slip > 5 %), increased simultaneous slip accelerated the formation of WEA due to high pressures.

(Lai and Stadler 2016) provoked local tensile stresses by deliberately introducing waviness in the bearing inner ring seat. Very high tensile stresses initiated axial cracks with significantly accelerated propagation but without WEA decoration. Lower tensile stresses generated axial cracks, but did not lead to immediate failure. As a result, crack propagation with accompanying crack flank friction formed the typical staircase-shaped cracks (see Fig. 4.4) with WEA decoration. However, both cases resulted in premature failure of the bearing inner ring.

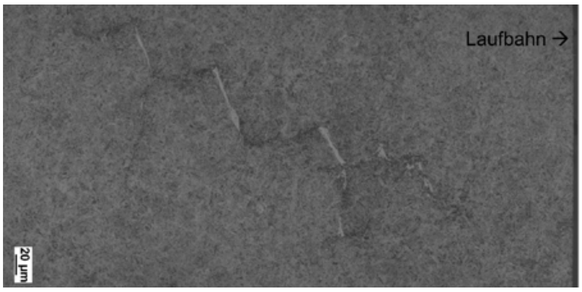

Fig. 4.4: Staircase-shaped crack propagation (raceway →) (Source SKF)

In the explanatory approaches of the aforementioned studies, experts have not yet reached complete consensus as to whether stress peaks alone or the combination with friction/slip thereof are crucial for WEC formation.

4.7. Vibrations

There are multiple indications that torsional oscillations and vibrations, such as in belt drives (Tamada and Tanaka 1996) or CVT transmissions, pose critical additional WEC stress. (Tamada and Tanaka 1996), for example, induced WECs in ball bearings through high, forced torsional dynamics. (Holweger et al. 2015; Loos et al. 2015) produced WECs on the outer ring of pulleys as a result of high-frequency oscillations (vibrations). The excitation was caused by a toothed belt whose back rested on the pulley. The WEC service life of the test bearings depended strongly on the belt type and correlated with the acceleration (vibration) measured at the screw connection of the pulley.

4.8. Friction

A series of publications state that WECs increasingly form in areas of increased slip (Ruellan et al. 2015). Therefore, they are the product of pressure and (relative) velocity (the p*v value) and can be regarded as mechanical driver for WEC formation. Detailed tests results conducted by (Bruce et al. 2018) report WECs below the surface, starting from a Hertzian load of 2.42 GPa and a slide-to-roll ratio (SRR) of 5 %. Fig. 4.5 (Richardson et al. 2018b) shows that WECs occur in areas of high sliding energy (p*v) in mixed friction, whereby areas of negative slip (outside) show significantly increased WECs, possibly due to higher friction on the crack flanks under compressive stress. (Gutiérrez Guzmán 2020)

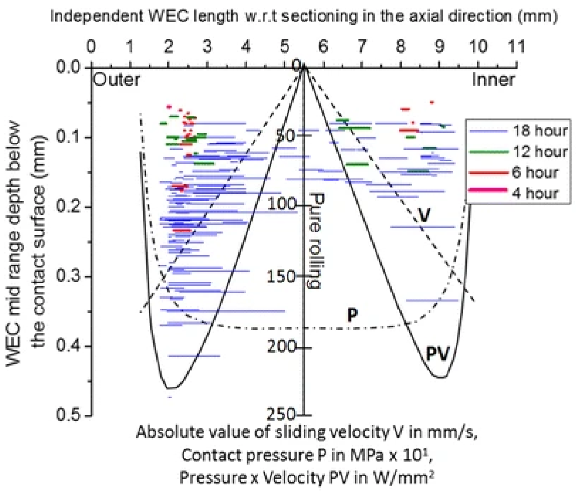

Fig. 4.5: The evolution of White Etching Cracks (WEC) in cylindrical roller thrust bearings (CRTBs) made of 100Cr6 Steel exposed to rolling contact fatigue tests. (Richardson et al. 2018b)

Based on this approach, (Kruhöffer and Loos 2017) devise a criterion of accumulated frictional energy for the assessment of WEC risks. In order to calculate the local solid contact pressure and the regeneration time between contacts at roughness level, this approach considers the local p*v value and the relative lubricant film thickness λ. This approach also enables to describe WEC life as function of speed and location of increased WEC inclination (see Fig. 4.5) in the tested axial cylindrical roller bearings.

However, several experimental studies (Seyfert et al. 2017; FVA 2022b) found no correlation between the total friction measured for various lubricants and failure in the FE8-test. The friction coefficient in FE8-tests is not a parameter for the WEC criticality of the lubricant formulation.

5. Methods of damage analysis and risk assessment

5.1. Damage analysis

Generally, two scenarios can serve as the motivation for conducting a risk assessment. Damage to an existing field or series bearing can require an examination, and also the question may arise regarding the risk of WECs occurring when developing a new design.

Work program in bullet points:

1. Collection of facts
   - Documentation of the operating/system conditions
   - Visual inspection
2. Analysis with testing instruments
   - Ultrasonic examination
   - Metallographic examination
3. Determining the origin of the damage
   - System analysis („fishbone“)
   - Risk assessment

First, the bearings affected should be documented as installed in machine or system, taking into account the ambient conditions. The service life history (life cycle, over-rolling, lubricants) including unusual events and measured values should be recorded. If possible, lubricant samples should be taken at various locations and should subsequently be analyzed. Broken-out fragments, wear or dirt particles are also to be documented. After disassembly, the entire bearing should be inspected (complete bearing, inner ring, outer ring, rolling elements, cage) and documented. Initial indications of possible WEC damage may be axial cracks across the bearing width or „small“ axial cracks with multiple small distributed break-outs (see Fig. 2.2 and Fig. 2.5).

Ultrasonic testing (frequency > 20 MHz and high-resolution methods required) may help detecting the areas with crack networks or assist in identifying the areas for sectioning the rings. In order to analyze the microstructure, axial and circumferential sections (Fig. 2.3 and Fig. 2.4) must be subsequently cut in the laboratory, both in the damage area and in its vicinity. Etching with nital or pikral is required for the detection of white etching areas (WEA).

This type of etching can also help visualizing the current passage in the bearing (re-hardening Fig. 5.1, white layer & current passage ISO 15243). For WECs generated by high field strengths (Loos et al. 2016) or in applications with high mixed friction contents (Loos et al. 2019b), classic melting structures, such as pearls and craters, could not be detected.

It is extremely demanding to determine the hydrogen content relevant to the damage of bearings in operation. Determining the material quality (e.g. chemical composition, degree of purity, hardness, microhardness) can be supplementary to ruling out other causes of damage. With this information in mind, an analysis of the influencing factors on system level (e.g. fishbone, see Fig. 5.2) can be conducted, and damage hypotheses can be sketched and verified. If damage occurs in series type bearings, the statistical evaluation of the service life and the analysis of other (also damage-free) bearings is recommended. A subsequent quantitative risk assessment can then be created on this basis.

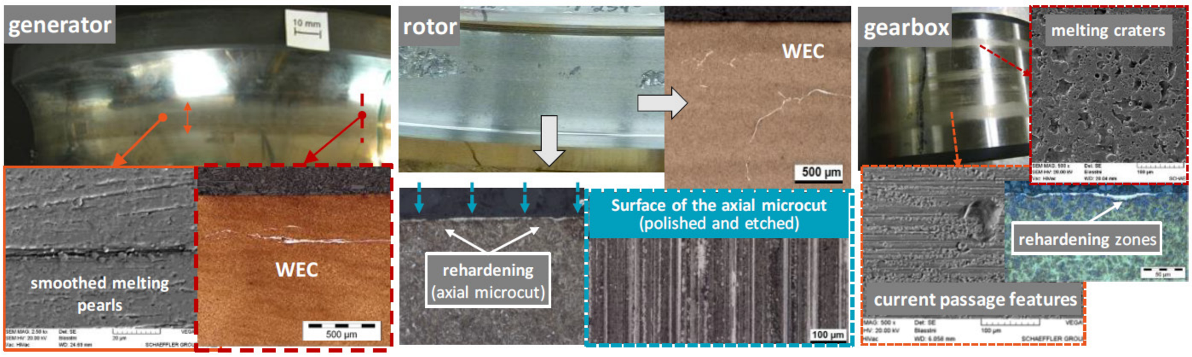

Fig. 5.1: Wind turbine bearing with current passage features (Loos et al. 2019b)

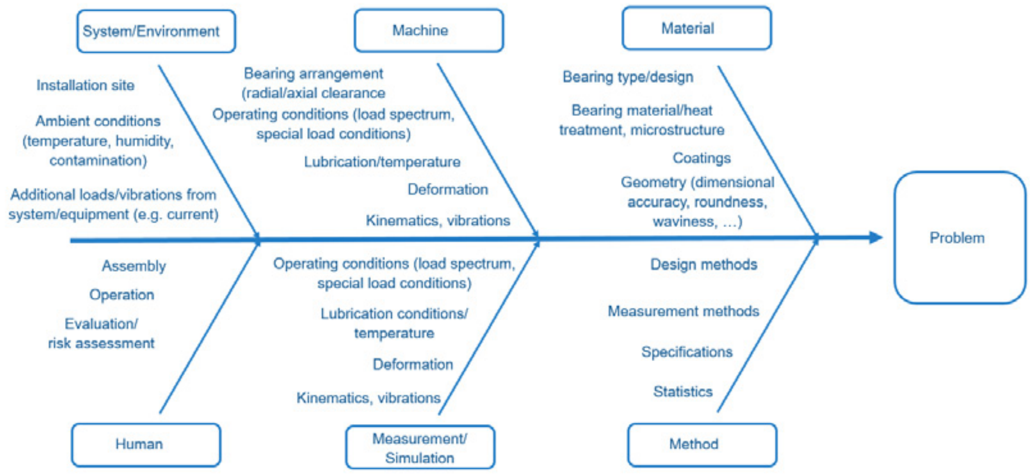

Fig. 5.2: "Generic fishbone" for component damage (HT - heat treatment)

5.2. Risk assessment

For a general assessment of WEC risks, it is advisable to verify all relevant influencing parameters in accordance with Chapter 4.

The contact pattern should be inspected for any anomalies. Available information on lubricant (data sheet) and lubricant history should be consulted, paying special attention to operating and application conditions, such as temperature, filling quantity, mixed friction, water content, etc. The comparison with bearings of related machines or test results may provide important information.

Failure statistics and know-how of comparable systems or other bearings in the same machine should be consulted for an evaluation.

The use of a WEC-susceptible material (composition, heat treatment, surface treatment, see Fig. 4.1) should be verified.

The possibility of bearing currents occurring (current path?) should also be checked and respective measurements should be conducted, if necessary.

High sliding friction (slip), possibly caused e.g. by churning losses in the bearing, should be evaluated and high vibrations (e.g. induced by belt drives) must be considered.

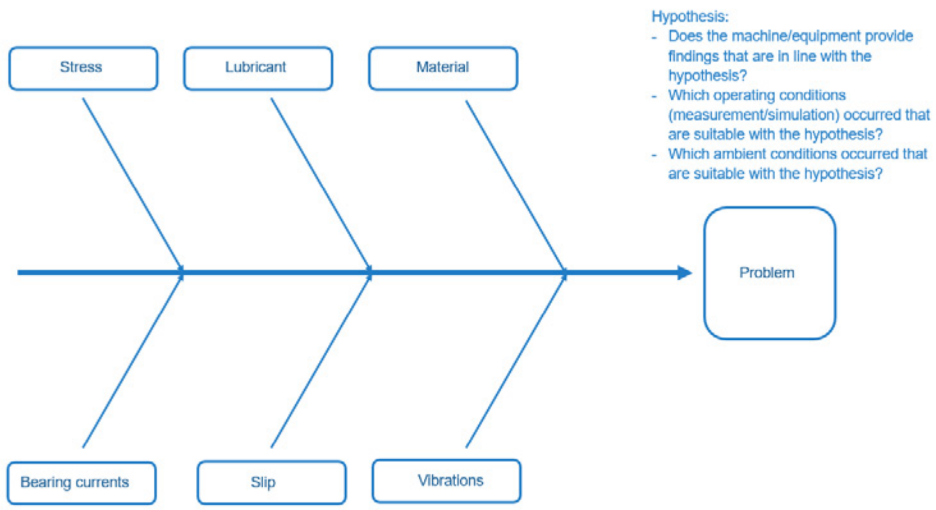

Fig. 5.3: "WEC Fishbone" (blueprint)

6. Remedies

Literature provides various remedies to counteract the formation of WECs. Following, remedies with regard to material, heat treatment, coating and lubricant are categorized and the effective mechanisms are described (see Fig. 6.1).

Material

The material is paramount for the formation of WECs in rolling bearings. Unstable microstructures may induce the formation of white etching, nanocrystalline microstructures and accelerate the microstructural transformation during the fatigue process. To counteract such effects, alloys aim to influence the microstructure (stabilization and matrix strengthening, avoidance of nanocrystalline microstructure), to reduce crack formation by mitigating embrittlement inclination and to passivate the surface.

Various alloy concepts offer the potential to mitigate embrittlement inclination and thus achieve longer service life until hydrogen-induced WEC failure occurs. (Yamada and Uyama 2015) confirmed these studies. Alloying elements, such as manganese, silicon, chromium and molybdenum were added to various bearing steels.

By reducing the carbon content, the formation of a white etching, nanocrystalline structure can be prevented. (Blass et al. 2017a) achieved an increase in service life by using carbon-reduced steels (SAE 4320 and 50CrMo4). Enrichment with carbonitrides (FVA 2022d) can contribute to avoiding nanocrystalline microstructures.

Adding the alloying elements nitrogen, silicon and nickel strengthens grain boundaries and ultimately the matrix (Evans 2012; Matsumoto et al. 2002). Increased resistance of M50NiL steel to plasticization (compared to 100Cr6) delays WEC formation (Braza et al. 1993).

According to (Evans 2016), surface passivation leading to low input of hydrogen, can be achieved by using steels with increased chromium content. (Evans 2016) and (NSK Ltd. 2004) state that an increased proportion of homogeneously distributed chromium carbides (e.g. in SHJ5 and ES1) is an effective countermeasure against hydrogen release and ultimately reduces the risk of WEC formation (NSK Ltd. 2004).

Supplementary to the material-specific remedies listed here, common bearing steels and their WEC inclination are illustrated in Fig. 4.1.

Heat treatment

The surface heat treatments described here introduce residual compressive stresses into the microstructure and increase the residual austenite content therein. This decelerates hydrogen permeation leading to extended service life until WEC damage occurs.

Case hardening introduces beneficial residual compressive stresses into the material via solid solution strengthening (Gould et al. 2019b; Paladugu et al. 2019; Paladugu and Hyde 2020) also enabling to adjust an increased residual austeni-

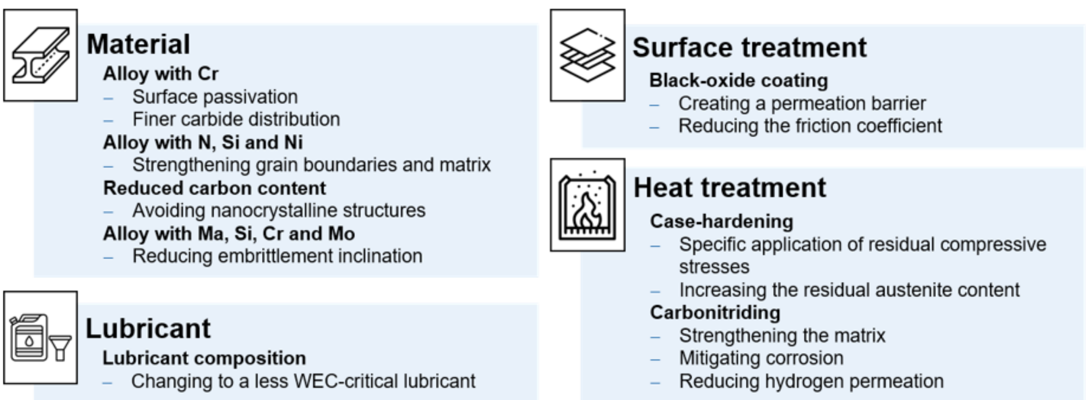

Fig. 6.1: Possible remedies and their hypotheses for reducing WEC risks based on FVA 707 VII (FVA 2022d).

te content (content >20 %). Both measures increase the resistance to fatigue damage and to the formation of WEC damage (Errichello et al. 2013; Roy et al. 2019). Tests provided indications that using case-hardened bearings instead of through-hardened bearings significantly reduced the WEC failure rate from 40 % to 2.7 % (Luyckx 2012; Luyckx 2011).

Carbonitriding delivers further resistance to WECs (NSK Ltd. 2004; Xiangduo et al. 2008; Tanaka et al. 2002). In addition to matrix strengthening which counteracts the mechanical decohesion of the microstructure, carbonitriding inhibits corrosion and hydrogen permeation. (Yamada and Uyama 2015) demonstrated in deep groove ball bearing tests that, compared to conventional 100Cr6 steel, alloyed, carburized (SAE5210) and carbonitrided steels enable an extended service life before WECs occur. Bench tests confirmed the stabilizing effect of (carbo)nitrides and their impact on the WEC resistance of carbonitrided steel (X30CrMoN15 1) (Blass et al. 2017b; Qin et al. 2020). Since bearing manufacturers offer bearings made of different materials and different heat treatments, it is highly recommended to consult the manufacturer in the event of WEC damage in order to determine which combination of material and heat treatment is most suitable for the affected bearing type.

Surface treatment

In addition to the direct influence of alloying elements or heat treatments on the material, coating can also contribute to mitigating the risk of WEC formation. Creating a surface barrier reduces the permeation of hydrogen into the bearing material. Friction-reducing coatings can also help to lower WEC-inducing shear stresses in the surface.

Coating the surface with a black oxide layer is common practice of creating a barrier preventing hydrogen permeation. By applying such a black oxide layer (Evans et al. 2015; Ooi et al. 2019; Stadler et al. 2015a), friction coefficient and ultimately surface friction between rolling element and bearing surface can be mitigated. This results in a partial reduction of the shear stresses in the material which are associated with the formation of WECs (Dhanola and Garg 2020).

Lubricant

Depending on multiple factors, the formation of WECs and their damaging effect constitutes a complex system phenomenon. „WEC-critical“ lubricants alone are only one of many important factors.

For certain applications (e.g. wind turbine and automotive gearboxes), lubricants containing high proportions of additives induce WEC formation through interactions in the tribocontact. In some applications, the formation of WEC damage was prevented by using a different lubricant less critical to WECs without requiring further design alterations. However, when using a different lubricant, the overall application functionality must be considered to avoid provoking other damage patterns (e.g. gray staining). Important note: A change of lubricant does not remedy any previous bearing damage.

Lubricants less critical to WECs are available on the market for almost all applications purposes. The current state of research does not allow a clear allocation to the respective chemical composition. Therefore, verification can only be achieved through test results. Test methods include FE8 according to FVA 707-V (FVA 2019a), VW-pitting-test (PV1483) or ZF-pitting-test (0000 702 232).

Design measures

Due to the multitude of influencing factors and their interaction, generally valid recommendations for suitable design measures cannot be given. These must always be verified on a case-by-case basis and assessed according to their potential risks.

As discussed in chapter 4, high surface friction due to increased slip amounts or insufficient hydrodynamic surface separation, e.g. in transient operating conditions, causes additional shear stress in the material. Changing bearing type or bearing arrangement, operating viscosity or the lubricant may lead to improvements, however, it is advisable to consult the respective manufacturer for recommendations.

If current passage through the bearing is suspected, earthing concept and possible insulation should be inspected and adjusted.

Conclusion

WEC damage occurs due to a multitude of influences. Many influencing factors and currently ongoing research rule out the one universal defense measure. However, coating the rolling bearing raceway with black oxide, case-hardening or carbonitriding bearings and using different lubricants less critical to WECs, have all proven to be particularly effective measures which have already become part of industrial practice. In addition to the outlined remedies, FVA project 707 VII „WEC: Heat treatment and materials - countermeasures" (FVA 2022d) delivers more options to minimize the risk of WEC.

7. Summary

White etching cracks (WEC) are crack networks, predominantly detected in rolling bearings, flanked by white etching areas in the metallographic section which ultimately lead to premature failures. WECs occur in the area of maximum equivalent stresses in the rolling contact below the surface, where potentially high hydrogen concentrations occur. Cracks often originate from very small non-metallic inclusions, which are permissible and technically unavoidable, even in the context of high steel cleanliness. It can be assumed that in applications showing WEC bearing damage, the WEC stress was either unexpectedly higher than the design permitted, and/or the WEC stress resistance of the bearings was compromised by various factors. In the ongoing debate of the possible origins for WECs, difficult-to-detect and volatile hydrogen is of crucial importance. Current passage, high friction, water contamination and aggressive media may increase the hydrogen supply whereas a permeation barrier (e.g. through black oxide coating) can mitigate this supply. For certain steels and surface treatments, the WEC inclination is more significant than for others. Acceptable influencing parameters for the formation of WECs include additional loads, slip, current passage, vibrations and water in the lubricant. Depending on the operating conditions, oil additives can also play a major role.

WECs constitute a systemic phenomenon with complex, not yet fully understood cause-and-effect relationships. Therefore, a clear allocation to one singular „root cause" is not feasible.

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