Premature Bearing Failures in Wind Gearboxes and White Etching Cracks

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Wind turbine gearboxes are subjected to a wide variety of operating conditions, some of which may push the bearings beyond their limits. Damage may be done to the bearings, resulting in a specific premature failure mode known as white etching cracks (WEC), sometimes called brittle, short-life, early, abnormal or white structured flaking (WSF). Measures to make the bearings more robust in these operating conditions are discussed in this article.

Ambitious, worldwide renewable energy targets are pushing wind energy to become a mainstream power source. For example, the Global Wind Energy Council GWEC (Ref. 1) expects that the currently installed wind energy capacity of 200 GW will double within three to four years, keeping open the aspirational goal of 1,000 GW of installed capacity by 2020.

Despite high wind turbine availability (>96% depending on turbine) and a relatively low failure rate of mechanical components compared with electrical components, failures of mechanical drivetrains still create high repair costs and revenue loss due to long downtimes (Ref. 2).

In most wind turbine concepts a gearbox is commonly used to step up the rotor speed to the generator speed. Today, the actual service life of wind turbine gearboxes is often less than the designed 20 years. Failures can be found at several bearing locations, namely the planet bearings, intermediate shaft and high-speed shaft bearings (Fig. 1).

Much premature wind gearbox bearing damage results in a failure mode that is not caused by the classic rolling contact fatigue (RCF) mechanisms (Fig. 2). While these classic mechanisms are sub-surface-initiated fatigue — as well as surface-initiated fatigue — and can be predicted by standard bearing life calculation methods (see ISO 281 and ISO/TR 1281-2), premature crack failures are not covered by these methods. However, attempts to calculate bearing life have been made when detailed information of the case is available (e.g., local effect of hoop stresses) (Ref. 37).

ISO 15243 describes the visual appearance of the classic rolling contact fatigue mechanisms. White etching refers to the appearance of the altered steel microstructure when polishing and etching a microsection. The affected areas — consisting of ultrafine, nano-recrystallized carbide-free ferrite — appear white in a light optical micrograph due to the low etching response of the material.

Known to occur only occasionally in some industrial applications such as paper mills, continuous variable drives,

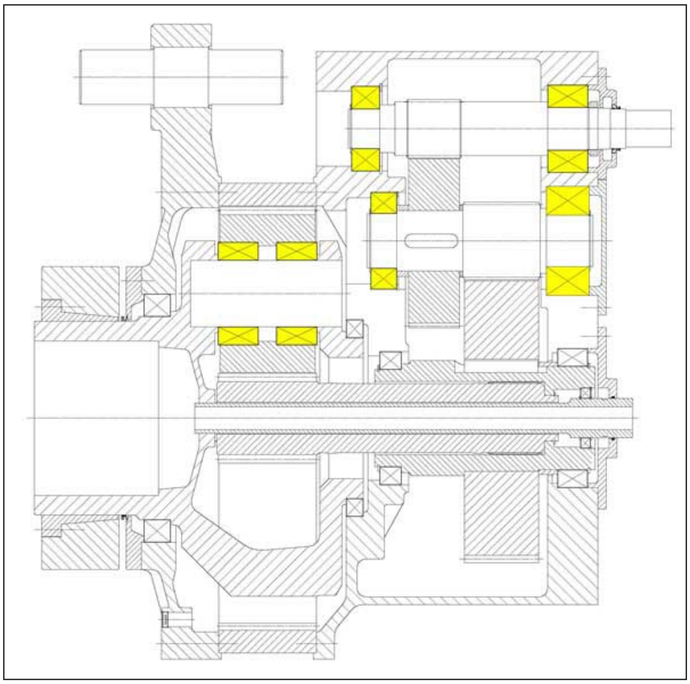

Figure 1 Standard multi-megawatt (MMW) wind gearbox (for 3-point suspension) having a low-speed planet stage and two spur wheel sections (high-speed intermediate shaft and high-speed shaft) with highlighted bearing locations that can be affected by premature bearing failures.

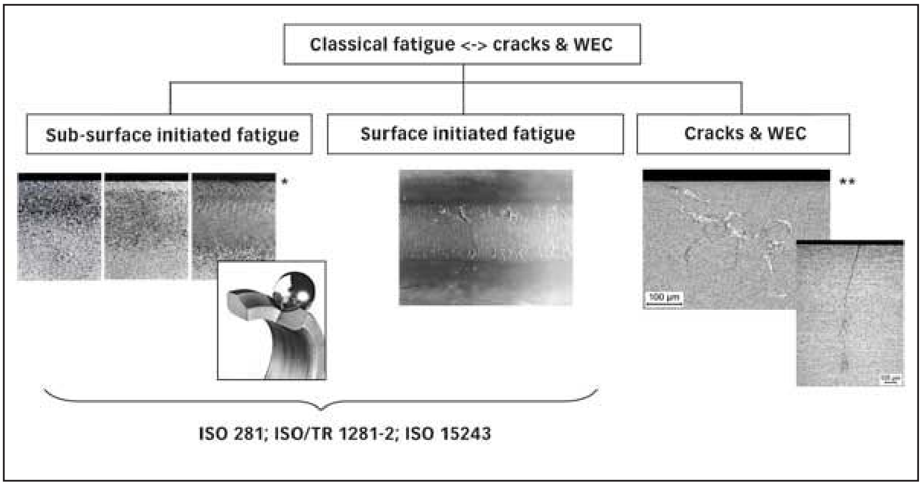

Figure 2 Classic fatigue failure modes vs. cracks and WEC *micrograph, according to Reference 5, **micrograph according to Reference 6.

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marine propulsion systems, crusher mill gearboxes or lifting gear drives, in wind applications the frequency of premature failures seems to be higher (but might also be related to a larger population of installed machines). Commonly, early cracks have occurred within the first one to three years of operational time or at 5 to 10 % of the calculated rating life (Fig. 3).

Mostly occurring on the inner ring (Fig. 4), the visual appearance of early cracks varies from straight or "axial cracks" to cracks in combination with small spalls and large/heavy spalling. Based on SKF's knowledge gained through increased field experience, it is concluded that early failures by cracks are neither linked to a particular type of bearing (Fig. 5), nor to a particular standard heat treatment (Fig. 6; Refs. 6 –10).

The failure appearance, however, is associated with the heat treatment (e.g., residual stress field), the stage of failure progress, and, very likely, also to the operating conditions or bearing position (e.g., stress field from loading). As can be seen in Figure 6, for early cracking in this specific application, cracks in martensite rings tend to grow straight into the material (suggesting the straight "axial" crack appearance, e.g., Fig. 6a), whereas in bainitic (Fig. 6b) as well as in carburized case-hardened rings, the cracks tend to grow circumferentially below the raceway (explaining the spalling/flaking type of appearance; e.g., Fig. 6c). Nevertheless, in a very advanced failure stage, the inner ring raceways are often heavily spalled, independent of the heat treatment.

Challenges Due to Operating Conditions in Wind Turbine Gearboxes

Wind turbine gearboxes are subjected to a wide variety of operating conditions that may push the bearings beyond their limits (e.g., with respect to load, speed, lubrication and combinations of these). The wind energy segment faces some of the toughest challenges for extending bearing life and reducing the occurrence of premature failures while at the same time reducing the overall cost of energy.

There are many opinions in the public conversation summarizing common indications of severe operating conditions in conjunction with premature failures in wind turbine applications. These include:

- Periods of heavy and dynamic loads/torques – leading to vibrations and rapid load changes (e.g., transient raceway stress exceeding 3.1 GPa, heavy loads of 15,000 per year, impact loads) (Refs. 6 – 7; 11–15;17–18).
- Depending on turbine type, additional radial and axial forces by the rotor, axial motion of the main shaft – leading to dynamical loading, higher stresses of gearbox components especially at the first stage (Refs. 19 –20).
- Occasional connecting and disconnecting of the generator from the power grid – leading to torque reversals and bouncing effects (e.g., can lead up to 2.5 – 4 times higher nominal torque, impact loads) (Refs. 12, 15, 21).
- Rapid accelerations/decelerations and motions of the gearbox shafts (Refs. 13, 15).
- Misalignment, structural deformations (nacelle hub, housings) (Ref. 11).
- Lubricant compromise between needs of gears and bearings as well as between low- and high-speed stages, insufficient oil drains and refill intervals (Ref. 22).

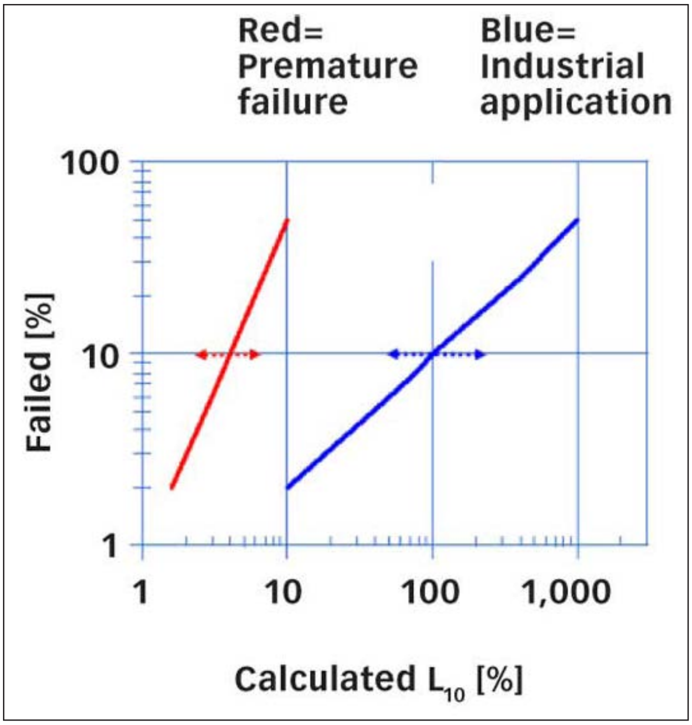

Figure 3 Typical in premature failing of industrial machinery is that bearings from identical machines in the same specific surroundings are failing within a consistent and short time period. The slope difference is a predictor of "other than classic fatigue." Those having had a short service life are likely to have a short service life again if no further actions on the bearing-shaft-housing system are taken.

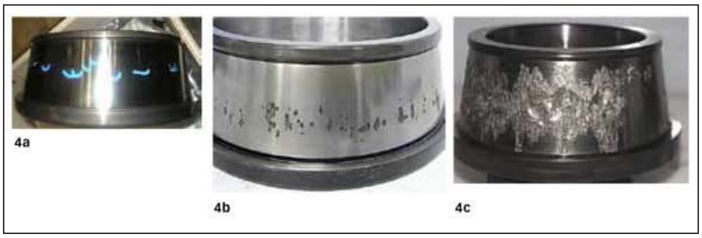

Figure 4 Failure appearance: a) straight cracks; b) straight cracks and small spalls; and c) spalls.

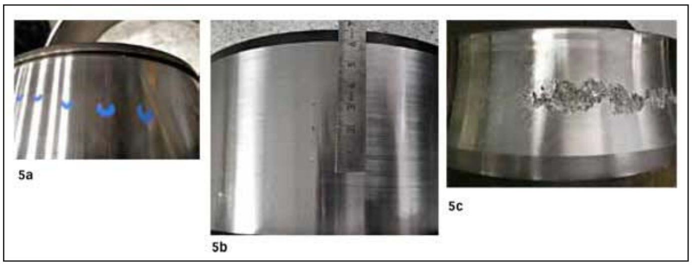

Figure 5 Examples of typical bearing types that can be affected: a) tapered roller bearing; b) cylindrical roller bearing; and c) spherical roller bearing.

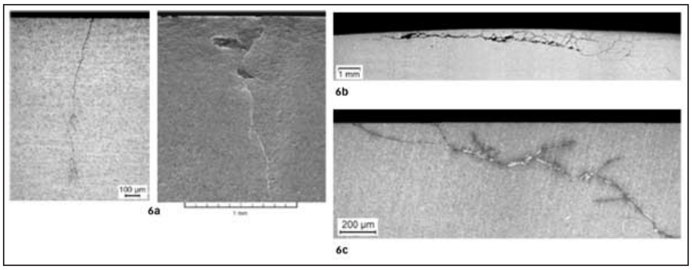

Figure 6 Crack growth patterns in standard heat treatment: a) martensite; b) bainitic; and c) case hardened (case carburized) 6.

- Harsh environmental conditions – eventual large temperature changes and consequently larger temperature differences between the bearing inner ring and housing than expected when starting up, dust, cold climate, offshore, moisture (Ref. 23).
- Idling conditions – leading to low load conditions and risk of skidding damage (adhesive wear) (Ref. 23).
- Some design requirements can be conflicting, e.g., increasing rolling element size will increase the load carrying capacity but simultaneously increase the risk of cage and roller slip and sliding damage (Refs. 6 – 7; 17, 23).

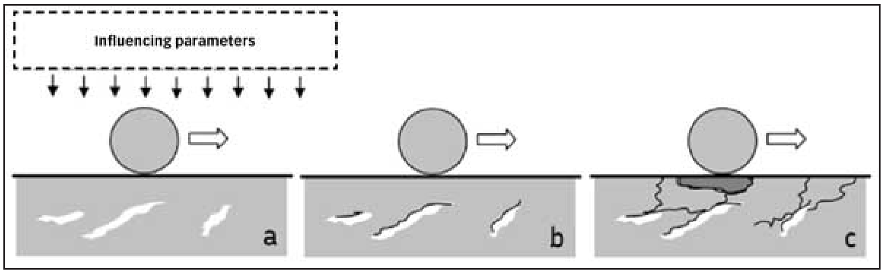

Figure 7 According to existing theories in the literature, a) certain influencing factors locally change the microstructure into white etching areas (WEAs); b) WEAs will be the starting points of white etching cracks (WECs); and finally, c) white structure flaking (WSF) due to crack propagation reaches the bearing raceway.

As stated, bearings may fail for other reasons not attributed to falling below best practice standards (Refs. 24 – 25) and from other industrial experiences. Statistical evaluations of a limited number of offshore wind turbines (Ref. 2) indicate clearly a correlation between failure rate, wind speed and heavy and fluctuating loads. The trend towards larger turbine sizes with higher power-to-weight ratios will invariably lead to more flexible supporting structures (Ref. 11) that, in turn, will influence the load sharing and load distribution within the rolling bearings as well as on other drive components. According to Reference 26, **in "young,"** heavily loaded applications having a highly innovative product design life cycle, sufficient experiences are often lacking with respect to the machine's endurance. Independent of wind turbine and gearbox manufacturers, the presence of cracks on bearings is sometimes interpreted as indicative of uncontrolled kinematic behavior (Refs. 19, 27).

Possible "Rolling Surface Crack" Drivers and Review of Hypotheses

The occurrence of premature failures is heavily discussed within the wind industry and independently investigated by wind turbine manufacturers, gearbox manufacturers and bearing suppliers as well as universities and independent institutions. Unfortunately, a consistent theory does not yet exist. To list and explain all WEC failure root cause hypotheses would go beyond the scope of this paper.

Nevertheless, many of the existing theories from literature can be briefly summarized (Fig. 7). Many papers (for example, Ref. 10) discuss a local change in the bearing material microstructure into WEC by certain influencing factors.

As influence factors, the following drivers are often mentioned:

Material. Microstructure, heat treatment, natural hydrogen content, cleanliness (different type of inclusions), residual stresses, etc.

Loading. Overloads, peak loads, impact loads, torque reversals, vibration, slip, structural stresses, electric currents, etc.

Environment. Lubricant, additives, corrosion, tribochemical effects, hydrogen generation, temperature gradients, contamination (e.g., water), etc.

Others. Mounting (e.g., scratches), transport, quality aspects, etc.

To increase the complexity, most influencing factors are also correlated.

Thus, driven by a single factor or by a combination of several factors, WEAs develop locally in the bearing steel matrix. The WEAs will then be the nucleation sites of cracks that finally propagate to the bearing raceway. As a consequence, the bearing will fail by spalling or so-called WSF.

Most common hypotheses can be further divided into hydrogen-enhanced WEC developments (Refs. 28 – 30), purely load/stress-related WEC developments preferable at inclusions (Refs. 31 – 32) or some combination of reasons (Ref. 33).

Some of the above damage mechanisms seem to influence, for example, applications such as:

- ***Paper Mills*** (e.g., water in oil – corrective action based on condition of lubrication) (Ref. 34).
- ***Marine Propulsion Systems*** (e.g., exceeding stresses – corrective action based on special through-hardened clean steel and stress reduction) (Refs. 32, 34).
- ***Alternator and Generator Bearings*** (e.g., damaging current – corrective action by use of special greases and/or hybrid bearings, special steels) (Refs. 6;35–36).

Nevertheless, in general, the relevance of the common WEC hypotheses to premature wind gearbox failures is not as yet sufficiently clear.

Potential Root Cause of WEC in Wind Gearboxes According to SKF Experience

According to SKF experience, most early bearing failures are related to lubrication or other surface-related issues and can partly be estimated by the SKF advanced bearing-life model. SKF internal investigations have revealed that many cracking failure modes in wind gearbox bearing positions most likely have their origin at or near the surface (0 –150 µm) and propagate into the material under the influence of a corrosion fatigue process (Refs. 6 –7,16).

There are several indicators that can support this hypothesis:

Wind gearbox bearings are relatively large, and for larger bearings the crack initiation and propagation mechanism can differ compared to small bearings (Refs. 6, 16). For instance, a deeper radial cracking is reported in larger bearings at moderate loads due to the residual stresses and higher hoop stress (Ref. 37). In case of premature wind gearbox bearing failures, the failure occurrence suggests fast crack propagation. The fast branching and spreading crack propagation can be explained by the presence of chemical influencing factors such as oxygen and ageing products of the lubricant at the crack faces/tips (Refs. 6, 16, 38). In a completely sub-surface crack system, we have vacuum conditions and consequently significantly slower crack growth from pure mechanical fatigue (Ref. 38). In other words, already at an early stage the cracks or crack systems must be connected to the surface to allow the entrance of oxygen and lubricant.

Hydrogen-assisted fatigue can lead to similar effects (Refs. 28, 33), or to accelerated classic rolling contact fatigue (Refs. 6, 35 – 36); however, this would require, for example, aggressive corrosive environment or continuous high-frequency electric current passage. The presence of free water leads, likewise, to a highly corrosive environment (Ref. 34), but elevated water contents in the lubricants are claimed to be under control by the turbine manufacturers. Moisture corrosion in wind gearboxes is usually not seen during SKF investigations. If that can be excluded, then regenerative passivating tribolayers usually provide a barrier to corrosion and hydrogen absorption into the steel, if continuous and intact. All told, if hydrogen absorption occurs in the steel, it is detrimental; however, the available evidence of this failure mechanism in wind gearboxes is relatively weak.

Nevertheless, SKF tribochemistry studies confirm the local generation of hydrogen in severe mixed friction contacts. To continuously generate hydrogen, fresh, interacting metallic surfaces are needed. This could lead to a local weakening effect on the surface, facilitating a surface crack generation. However, in wind gearboxes, severe wear is hardly seen on the failed bearing raceways, which would allow hydrogen permeation. Thus, hydrogen permeation through the bearing raceway (without any additional factor) seems not to be likely. A potential additional factor could be the relative aggressive wind oils, eventually in combination with contaminants (Refs. 39 – 41). In SKF's experience, the performance of wind gearbox oils can be distinguished from surface initiated failure mechanisms (Ref. 39) (e.g., surface distress). To quantify the relevance, further investigations are needed. At the moment, the role of hydrogen generation is seen as a local effect generated in the crack systems due to lubricant entry leading to the mechanism of corrosion fatigue cracking (CFC) (Refs. 6, 16).

The normally moderate bearing load conditions in wind gearboxes, the absence of compressive residual stress buildups (in the area of the maximum von Mises equivalent stress) as well as the decrease in the X-ray diffraction line broadening close to the raceways in failed bearings (e.g., due to mixed friction – shear stresses and vibrations) shown by material response analyses further support a surface or near-surface failure initiation (Refs. 6 – 7, 16). Lately, it is known that not only inadequate lubrication conditions, but also certain vibration effects at higher frequencies, are able to reduce the film thickness and consequently increase the risk for conditions of local mixed friction (Refs. 42 – 43).

According to Reference 44 the generation of WEC networks is less influenced by Hertzian pressures, and most influencing factors are surface based. The often-disputed role of butterfly crack generation at inclusions, which show a similar altered microstructure as seen in WEC, is considered as part of the classic fatigue mechanism that is well covered in the bearing-life model (Refs. 7, 44 – 45). Little experimental evidence is reported that supports butterfly cracks propagating into WEC networks (Ref. 10).

A high butterfly density is a sign of overstress or very heavy loading (>3 GPa), but excessive loads are claimed not to exist by the turbine manufacturers. This seems to be supported by standard gearbox HALT tests. A highly accelerated life test (HALT) is a stress testing methodology for accelerating product reliability during the engineering development process. There, the metallurgical investigations often show an elevated number of butterfly formations in the bearings due to heavy-load test conditions, but failed bearings from the field often do not show a significant increase in butterfly formations [6, 7]. Especially at the high-speed stages, the loads are usually moderate, but bearings can still fail by cracks / WEC without showing a significant population or even individual exemplars of butterflies [6, 7]. It seems that standard gearbox HALT tests do need further adaptations to reflect the early failure mechanisms as seen in the field.

Nevertheless, the occurrence of unexpected high subsurface stress-induced bearing damage [32] also by inclusions cannot be fully excluded as long as the exact contribution of transient running conditions is not fully understood. The exact loading of wind gearbox bearings in the field is very much based on wind field simulations, later on further reduced to quasi-static load assumptions; and moderate bearing loads are assumed at nominal conditions. Non-steady-state conditions should be kept in mind and are increasingly taken into account by the wind industry.

Potential Mechanism for Damage Propagation

There is a general agreement that it is not nominal wind gearbox operating conditions but rather transient, partly unknown, conditions that lead occasionally to disturbed bearing kinematics, loading and lubrication. Basically, it is assumed that high surface stress concentrations can be reached, e.g., by vibration-induced local mixed friction 6, 16, 47, misalignment or other events as already mentioned. At boundary lubricated patches at asperity level, the stress concentration of the tensile stresses can increase and open a crack under repeated cycles (areas of high stresses just below the roughness) 48, 49.

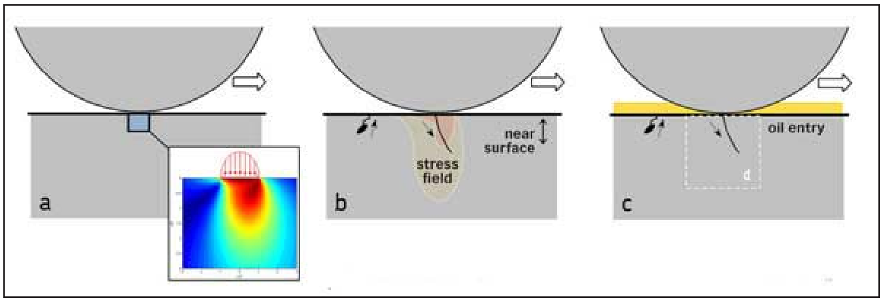

Figure 8 **(A) Roller-raceway contact with areas of local high traction due, for example, to local mixed friction, leading to tensile stresses that can, b) lead to damage such as a small crack; c) surface crack or crack connected to the raceways allows the entry of oil; (for "area d" details, see Fig. 12).**

As schematically shown in Fig. 8, transient conditions can trigger surface cracks, possibly accelerated by tribochemical effects 6, 16, 39, 40, 41, or sub-surface cracks that reach the raceway when starting at weak points such as inclusions close to the surface (<150 µm) 6.

The inclusions can be soft MnS or hard oxides that naturally exist in any bearing steel. In addition, small MnS lines at the raceway can sometimes be dissolved by the lubricant and act also as potential surface cracks6, 16 and/or environmental corrosive cracks. Examples of a shallow surface crack are shown in Figs. 9 and 10, and often it requires significant effort and experience to find them at an early stage 6, 7, 16.

The cracks shown in Figs. 10 and 11 are generated in an automotive rolling-sliding contact at high traction and contact pressures, similar to potential wind load situations of around 3 GPa18.

Once the bearing raceway is locally damaged, the highly EP doped lubricant will penetrate into the crack. Depending on the crack orientation, hydraulic effects will additionally push the crack propagation 46. As indicated in Fig. 12, the lubricant (often aged and/or contaminated with water) will react inside the material at the fresh metallic crack flanks. In other words, a corrosion fatigue crack propagation process, CFC, is triggered.

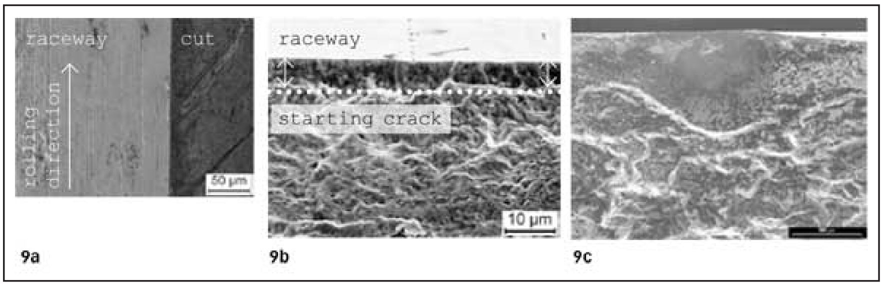

Figure 9 (A) Small shallow crack at the raceway and further crack propagation, smoothed machining marks indicate potential mixed friction conditions; b) opening of a shallow surface crack; c) surface crack triggered by near-surface inclusion (scanning electron microscope fractographs (Ref. 6).

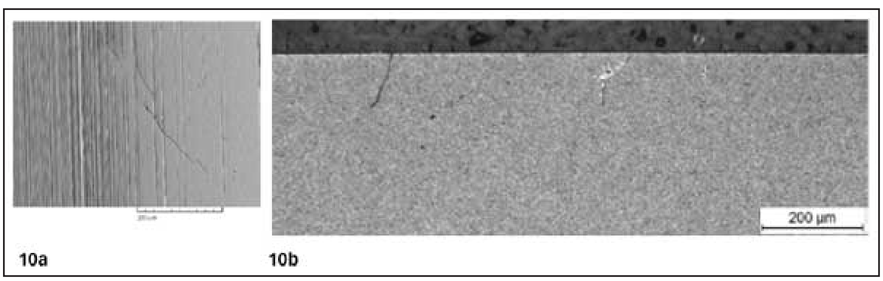

Figure 10 Cracks on rolling-sliding components from an automotive application: a) small, friction-induced cracks on the raceway–smoothed machining marks indicate mixed-friction conditions; b) circumferential microsection (SKF Material Physics, Schweinfurt) showing a non-decorated crack (left) and white etching-decorated crack (right).

This leads to a hydrogen induced microstructure transformation by means of hydrogen release from decomposition products of the penetrating oil (additives, contaminants) on the rubbing blank metal crack faces that in turn further accelerate the crack propagation 6, 7, 16. This conclusion is also supported by spatially resolved determinations of the hydrogen content in damaged bearing rings, which confirm that hydrogen absorption occurs late in the damage process 7, 16. As shown in Fig. 13, a fractographic investigation in the preparative opened forced fracture face close to the inner ring crack reveals an inter-crystalline microstructure that indicates material embrittlement by hydrogen, released from the ageing lubricant products 6, 7, 16, 41, whereas distant from the CFC crack, a normal largely trans-crystalline fracture face is seen. Further indication of such a CFC mechanism is found by EDX analysis of lubricant and additive residuals within the opened crack system 6, 7, 16.

Inside the crack system, the mechanism of CFC will then transform the microstructure locally into white etching areas and lead to the typical appearance of an irregular WEC network (e.g., Figs. 2, 6, 14). Thus, WECs are considered as secondary; a by-product of the CFC mechanism, as the hydrogen released and energy dissipated at the crack flanks result in a local change of the microstructure then appearing as a white etching crack decoration.

The distribution and intensity of the WEC decoration effect is relatively complex. It depends very much on the distribution of lubricant residuals inside the crack network, the local rubbing effect in the crack faces and the local equivalent stress fields.

Finally, fast three-dimensional crack propagation/branching in combination with crack returns will lead to a fast failure of the concerned rolling bearing surfaces.

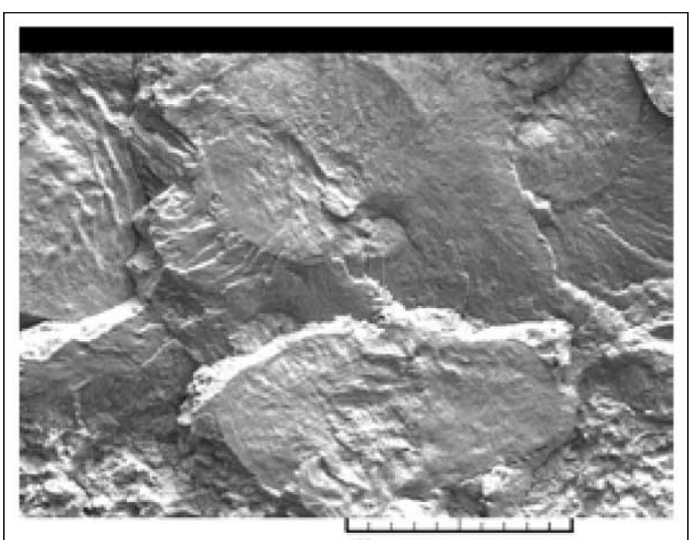

Figure 11 Opened fracture face (cf. Fig. 10a) revealing two cracks (similar to Fig. 9c), surrounded by the CFC structure (scanning electron microscope fractograph, backscattered electron mode).

Conclusion and SKF Prevention Strategy

The fast growth of the wind industry as well as the trend to increasing turbine sizes erected at locations with turbulent wind conditions puts significant challenges on the rolling bearings in the drive train. One consequence of this evolution of a relatively young industry has been premature gearbox bearing failures. Over the years, the discussion in the industry was mainly focused on the influence of bearing material and heat treatments. Recently, there is a general agreement that specific wind conditions can lead to disturbed bearing kinematics, loading and lubrication. In other words, the root cause failure will not be found inside the bearing only. The complete application interfaces between the bearing and the gearbox / turbine need to be considered.

The phenomenon of wind gearbox bearing failures by cracks / WEC has been described. A failure hypothesis has been introduced. SKF investigations reveal that cracking failure modes in critical wind gearbox bearing positions most likely have their origin at the surface or near surface and propagate further into the material under the influence of a corrosion fatigue process.

Due to the high complexity of a wind turbine as well as the very different bearing locations that can be affected, it is very unlikely that there is only one application condition root cause. However, it can be stated that any condition that leads to disturbed bearing kinematics, such as high vibration levels and high sliding friction, should be avoided in order to reduce micro-wear and high tensile stresses.

To effectively support the wind industry, SKF as a bearing manufacturer is focusing on bearing modifications that aim to reduce the risk of premature bearing failures and increase bearing robustness under the specific conditions of wind gearbox applications. The solution strategy takes into account mainly the hypothesis introduced, but also addresses the common theories on WEC.

Most failure prevention strategies have been positively confirmed by internal investigations and SKF field experience. Today's state-of-the-art failure prevention measures are:

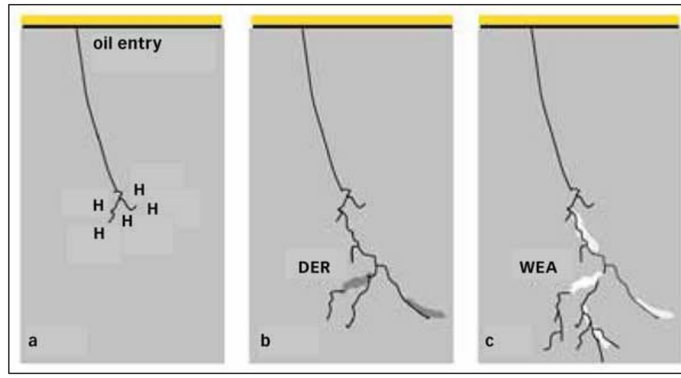

Figure 12 (Continuation of Fig. 8): a) After penetration, oil and additives react in the crack flanks locally, producing hydrogen — b and c; the hydrogen transforms locally the microstructure close to the crack system into white etching cracks WECs (from dark etching regions (DER), to white etching areas, WEAs) 6, 7, 16.

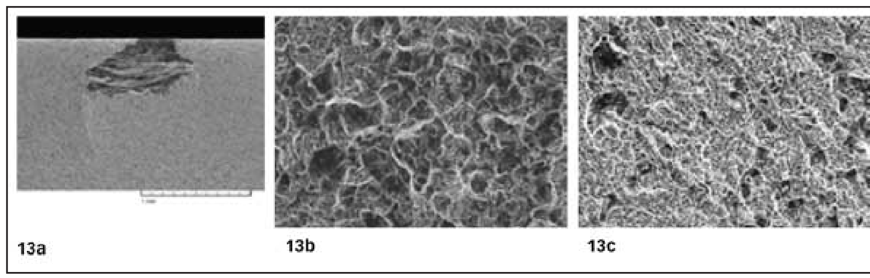

Figure 13 Axial opening of a crack connected to the surface, b) intercrystalline microstructure close to the crack system, c) transcrystalline microstructure elsewhere.

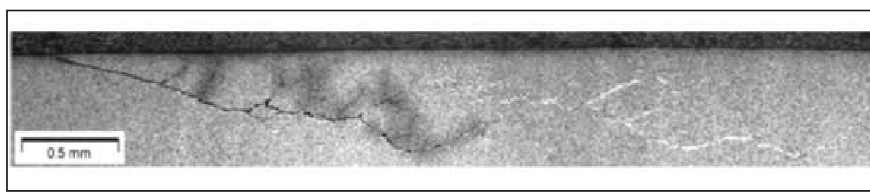

Figure 14 Irregular white etching decorated crack network (Ref. 6).

SKF Special Passivation to:

- Stabilize the near surface microstructure
- Make the bearing more resistant to chemical attack and hydrogen
- Reduce micro friction under peak loading
- Improve running-in

SKF Special Clean Steel for the Most Stressed Component

- Reduce further the amount of inclusions that can act as stress raisers in the material or on the surface

SKF Deep Surface Strengthening Process on the Most Stressed Component (Prototypes)

- Allow a conditioning of the component (shake down – the nominal loading in wind is relatively moderate)
- Increase the resistance against surface crack initiation and sub-surface crack propagation

In summary, a bearing modified as described above can reduce premature failures but needs to be combined with further improvements of the total design in light of the actual application conditions. Therefore, collaboration between all partners in the design process is needed and advanced calculation tools should be used to analyze the operating conditions to identify critical operating conditions and to eliminate the potential damaging ones. A stronger focus on component testing combined with real-size dynamic tests (e.g., in research institutes such as NREL, NAREC, Fraunhofer, etc.) should enable reproduction of damaging operating conditions and the testing of potential solutions.

Summary

- The rapid growth of the wind industry and its increasing size and power generation capacity, combined with the harsh operating conditions, create a challenging operating environment for wind turbines.
- Understanding mechanisms, particularly in bearing systems, that can lead to early turbine failures is crucial to delivering equipment that can support the industry's need for reliable generation combined with cost-effective operation.
- Failure mechanisms are complex, and mitigating the effects of these mechanisms requires not only in-depth research but also collaboration between all sectors of the industry. **PTE**

References

1. GWEC. "Global Wind Report;" "Annual Market Update;" 2010-2011.
2. Feng, Y. and P. Tavner. "Introduction to Wind Turbines and Their Reliability & Availability," Durham Side Event at the *EWEC Conference*, Warsaw, April 2010.
3. ISO 15243:2004. *Rolling Bearings: Damage and Failures; Terms; Characteristics and Causes*.
4. ISO 281. *Rolling Bearings: Dynamic Load Ratings and Rating Life; ISO/TR 1281-2. Rolling Bearings: Explanatory Notes on ISO 281- Part 2: Modified Rating Life Calculation, Based on a Systems Approach to Fatigue Stresses, and SKF General Catalogue.*
5. Swahn, H., P.C. Becker and O. Vingsbo. "Martensite Decay During Rolling Contact Fatigue in Ball Bearings," *Metallurgical Transactions A*, Vol. 7A, No. 8, 1976, pp. 1099–1110.
6. Gegner, J. "Tribological Aspects of Rolling Bearing Failures," *Tribology – Lubricants and Lubrication*, Kuo, C.-H. (Ed.), In Tech, Rijeka, Croatia, 2011, Chap. 2, pp. 33–94, *www.intechopen.com/articles/show/title/tribological-aspects-of-rolling-bearing-failures.*
7. Gegner, J. "Frictional Surface Crack Initiation and Corrosion Fatigue-Driven Crack Growth," NREL Workshop, Broomfield, November 2011.
8. Luyckx, J. "Hammering Wear Impact Fatigue Hypothesis WEC/irWEA Failure Mode on Roller Bearings," NREL Workshop, Broomfield, November 2011.
9. Holweger, W. "Influence on Bearing Life by New Material Phenomena," NREL Workshop, Broomfield, November 2011.
10. Evans, M.H. "White Structure Flaking (WSF) in Wind Turbine Gearbox Bearings: Effects of 'Butterflies' and White Etching Cracks (WECs)," *Material Science and Technology*, Vol. 28, No. 1, 2012.
11. Molly, J.P. "Wind Energy – Quo Vadis?" *DEWI* Magazine, No. 34, February 2009.
12. Heidenreich, D. "A Lean Solution to the Gearbox Life Problem in Wind Turbine Drive Systems," Hannover Messe 2011.
13. Rosinski, J. and D. Smurthwaite, "Troubleshooting Wind Gearbox Problems," *Gear Solutions* 2010. Heege, A., et al. "Matching Experimental and Numerical Data of Dynamic Wind Turbine Loads by Modelling of Defects," SAMTECH, EWEC 2009.
14. Aguglia, D. and R. Rebeschini. "Power Transformer Role for Gearbox Mechanical Stress Mitigation During Voltage Dips Applied to Doubly Fed Induction Generator-Based WT," *EWEC* Warsaw, April 2010.
15. Gegner, J. and W. Nierlich. "Mechanical and Tribochemical Mechanisms of Mixed Friction-Induced Surface Failures of Rolling Bearings and Modelling of Competing Shear and Tensile Stress-Controlled Damage Initiation," *Tribologie und Schmierungstechnik*, Vol. 58, 2011, No. 1, pp. 10–210.
16. Nierlich, W. and J. Gegner. "Einführung der Normalspannungshypothese für Mischreibung im älzleitkontakt," Gleit- und Wälzlagerungen: Gestaltung, Berechnung, Einsatz, VDI-Berichte 2147, VDI Wissensforum, Düsseldorf, Germany, 2011, pp. 277–290.
17. Kotzalas, M.N. and G.L. Doll, "Tribological Advancements for Reliable Wind Turbine Performance," *Phil.Trans. R. Soc*. A. 368, 2010.
18. Thomas, T. "Schäden Durch Schwingungen Noch Nicht im Griff," VDI Nachrichten, 26, Feb. 2010, No. 8. Korzeniewski, T. "Gearbox Protection Concept for Wind Turbine Generator Systems," *DEWI* No. 36, 2010.
19. FVA 541 I. *Wälzlagerlebensdauer-Windgetriebe*, 2010.
20. Kamchev, B. "Wind Energy Encounters Turbulence," *Lubes'n'Greases* 2011.
21. Heemskerk, R. "Challenges on Rolling Bearings in Wind Turbines," VDI Gleit-und Wälzlagerungen 2011.
22. IEC/ISO 61400-1 to 25. *Design Requirements for Wind Turbines.*
23. ANSI/AGMA/AWEA 6 0 0 6 -A0 3. *Standard for Design and Specification of Gearboxes for Wind Turbines,* 2003.
24. Klempert, O. "Belastungen im Getriebe Werden zum Streitthema," VDI Nachrichten, 14, Mai, 2010, No. 19. Musial, W., S. Butterfield and B. McNiff. "Improving Wind Turbine Gearbox Reliability," NREL, 2007.
25. Uyama, H. "The Mechanism of White Structure Flaking in Rolling Bearings," NREL Workshop, Broomfield, November 2011.
26. Kino, N. and K. Otani. "The Influence of Hydrogen on Rolling Contact Fatigue Life and its Improvement," *JSAE* Rev., 24, 2003.
27. Tamada, K. and H. Tanaka. "Occurrence of Brittle Flaking on Bearings Used for Automotive Electrical Instruments and Auxiliary Devices," *Wear*, 199, 1996.
28. Lund, T. Subsurface-Initiated Rolling Contact Fatigue — Influence of Non-Metallic Inclusions, Processing Conditions and Operating Conditions, *J. ASTM Int*., 7, 2010.
29. Lund, T. SABB 1309, *ASTM Conference*, Tampa, 2011.
30. Vegter, R. and J. Slycke. "The Role of Hydrogen on Rolling Contact Fatigue Response of Rolling Element Bearings, *J. ASTM Int*., 7, 2009.
31. Strandell, I., C. Fajers and T. Lund. "Corrosion: One Root Cause for Premature Failures," *37th Leeds-Lyon Symposium on Tribology*, 2010.
32. Gegner, J. and W. Nierlich, "Sequence of Microstructural Changes During Rolling Contact Fatigue and the Influence of Hydrogen."
33. J. Gegner and W. Nierlich. "Hydrogen-Accelerated Classical Rolling Contact Fatigue and Evaluation of the Residual Stress Response," *Material Science Forum* Vol. 681, 2011.
34. T.H. Kim, A.V. Olver and P.K. Pearson. "Fatigue and Fracture Mechanism in Large Rolling Element Bearings," *Tribology Transaction*, 44, 2001.
35. J. Lai, et al. "The Fatigue Limit of Bearing Steels – Part I: A Pragmatic Approach to Predict Very High Cycle Fatigue Strength," *International J.O. Fatigue*, 37, 2012.
36. R. Pasaribu and P. Lugt. "The Composition of Reaction Layers on Rolling Bearings Lubricated with Gear Oils and its Correlation with Rolling Bearing Performance," *Tribology Transaction*, STLE, 2012.
37. Nedelcu, I., E. Piras, A. Rossi and R. Pasaribu. "XPS Analysis on the Influence of Water on the Evolution of Zinc Dialkyldithiophosphate-Derived Reaction Layer in Lubricated Rolling Contacts," ECASIA Special Issue Paper, Surf. Interface Anal. 2012.
38. Han, B., X. Bo, R. Zhou and R. Pasaribu. "C-Ring Hydrogen-Induced Stress Corrosion Cracking (HISCC) Tests in Lubricating Liquid Media," *European Corrosion Congress,* Stockholm, 2011.
39. Félix-Quiñonez, A. and G.E. Morales-Espejel. "Film Thickness Fluctuations in Time-Varying Normal Loading of Rolling Elastohydrodynamically Lubricated Contacts," *Proc. IMechE*, Vol. 224, Part C, 2010.
40. Félix-Quiñonez, A. and G.E. Morales-Espejel. "Film Thickness in EHL Rolling Contacts with Transient- Normal Load," *ITC Hiroshima*, 2011.
41. Holweger, W. and J. Loos. Beeinflußung der Wälzlagerlebensdauer durch neue Werkstoffphänomene in Speziellen Anwendungen, Antriebstechnisches Kolloquium Aachen, ATK, 2011.
42. Brueckner, M., J. Gegner, A. Grabulov, W. Nierlich and J. Slycke. "Butterfly Formation Mechanisms in Rolling Contact Fatigue," D.Verb. für Materialfor und -prüf. e.V., 2011.
43. Lai, J., J. Wang and E. Ioannides. "Fluid-Crack Interaction in Lubricated Rolling-Sliding Contact," *Proceedings of the STLE/ASME*, IJTC 2008.
44. Gegner, J. and W. Nierlich. "Operational Residual Stress Formation in Vibration-Loaded Rolling Contact," *Advances in X-ray Analysis*, Vol. 52, 2008, pp. 722–731.
45. Morales-Espejel, G.E. and V. Brizmer. "Micropitting Modelling in Rolling-Sliding Contacts: Application to rolling bearings," *Trib. Trans*., Vol. 54, pp. 625–643, 2011.
46. Stadler, K., G.E. Morales-Espejel and V. Brizmer. "Micropitting in Rolling Bearings: Influence of Lubrication, Roughness, Wear and Ways of Prevention," Antriebstechnisches Kolloquium Aachen, ATK 2011.

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