# EVOLUTION

A SELECTION OF ARTICLES PREVIOUSLY PUBLISHED IN EVOLUTION,
A BUSINESS AND TECHNOLOGY MAGAZINE FROM SKF

WIND POWER TECHNOLOGY KNOWLEDGE SHARING, PROVIDED BY SKF





# Contents

**A selection of articles previously published in Evolution, a business and technology magazine issued by SKF.**



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# Premature bearing failures in wind gearboxes and white etching cracks (WEC)

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.

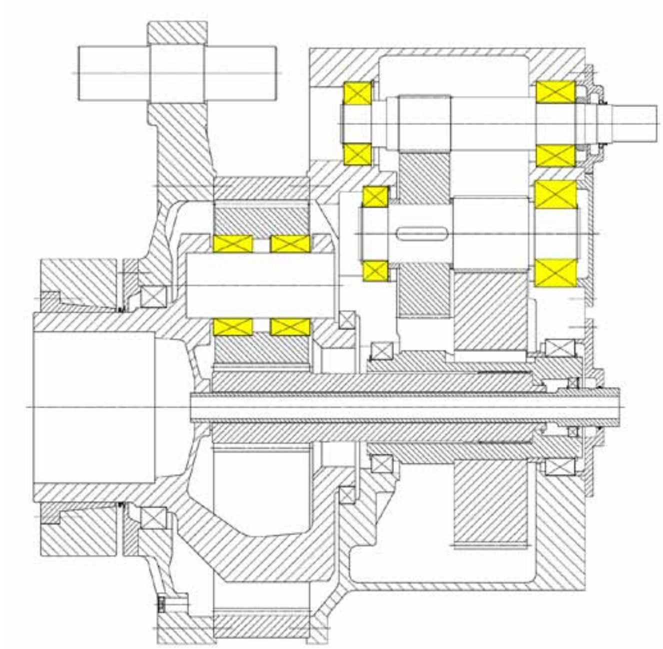


**Fig. 1: Standard Multi Megawatt (MMW) wind gearbox (for 3-point suspension) having a low-speed planet stage and two spur wheel sections (high-speed intermediate shaft and high-speed shaft) with highlighted bearing locations that can be affected by premature bearing failures.**



**AMBITIOUS WORLDWIDE** renewable energy targets are pushing wind energy to become a mainstream power source. For example, the Global Wind Energy Council, GWEC[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 on mechanical drive trains still create high repair costs and revenue loss due to long downtimes[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 subsurface initiated fatigue as well as surface initiated fatigue and can be predicted by standard bearing-life calculation methods (refer to 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)[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 ultra fine 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, marine propulsion systems, crusher mill gearboxes or lifting gear drives, in wind applications the frequency of premature failures seems to be higher (but might be also 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, as shown in fig. 4, the visual appearance of early cracks varies from straight cracks (“axial cracks”) to cracks in combination with small spalls and large/heavy spalling. Based on SKF’s knowledge from increased field experience, it is concluded that early failures by

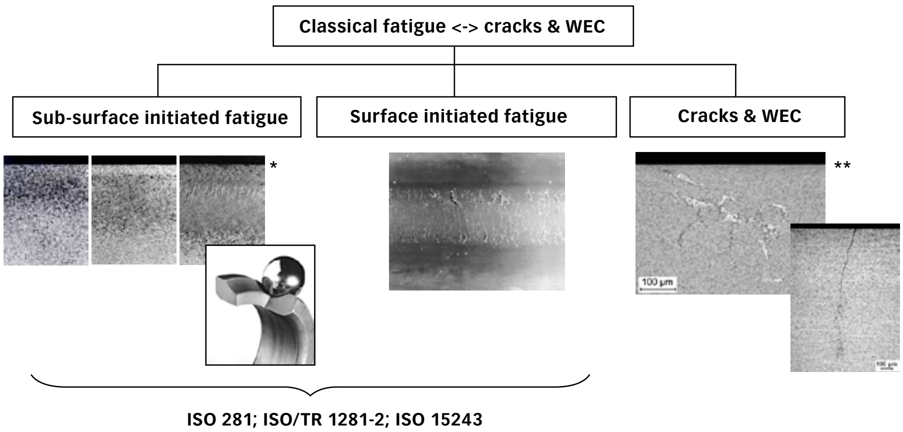



**Fig. 2: Classic fatigue failure modes versus cracks and WEC**
**micrograph according to reference 5, **micrograph according to reference 6*

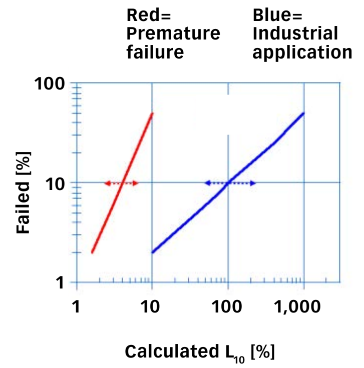



**Fig. 3: Typical in premature failing of industrial machinery is that bearings from identical machines in the same specific surroundings are failing within a consistent and short time period. The slope difference is a predictor of "other than classic fatigue". Those having had a short service life are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

cracks are neither linked to a particular type of bearing (fig. 5) nor to a particular standard heat treatment (fig. 6) [6,7,8,9,10].

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 fig. 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.


**Fig. 4: Failure appearance: a) straight cracks, b) straight cracks and small spalls, and c) spalls.**

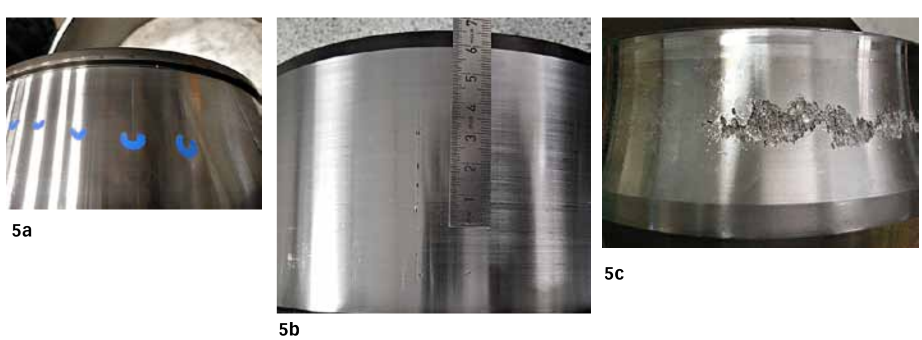



**Fig. 5: Examples of typical bearing types that can be affected: a) tapered roller bearing, b) cylindrical roller bearing, and c) spherical roller bearing.**

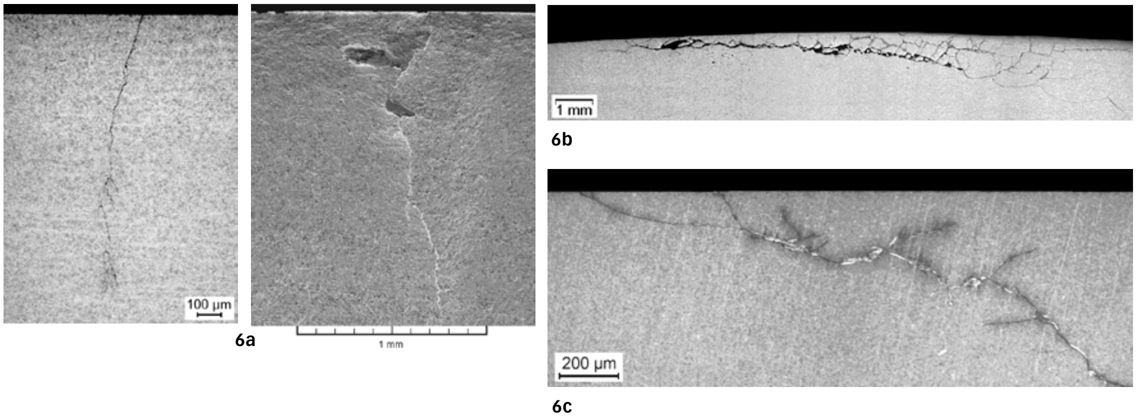



**Fig. 6: Crack growth patterns in standard heat treatments: a) martensite, b) bainitic and c) case hardened (case carburized)[6].**

## 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 domain 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)[6,7,11,12,13,14,15,17,18]
- 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[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)[12,15,21]
- rapid accelerations/decelerations and motions of the gearbox shafts[13,15]
- misalignment, structural deformations (nacelle hub, housings)[11]
- lubricant compromise between needs of gears and bearings as well as between low- and high-speed stages, insufficient oil drains and refill intervals[22]
- 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[23]
- idling conditions – leading to low load conditions and risk of skidding damage (adhesive wear)[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[6,7,17,23].

As stated, bearings may fail for other reasons not attributed to falling below best practice standards[24,25] and from other industrial experiences. Statistical evaluations of a limited number of offshore wind turbines[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[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 behaviour[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 exist today. 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 as shown in fig. 7. Many papers (for example, reference 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[28, 29, 30], purely load/stress related WEC developments preferable at inclusions[31, 32] or some combination of reasons [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)[34]
- marine propulsion systems (e.g., exceeding stresses – corrective action based on special through-hardened clean steel and stress reduction)[32, 34]
- alternator and generator bearings (e.g., damaging current –

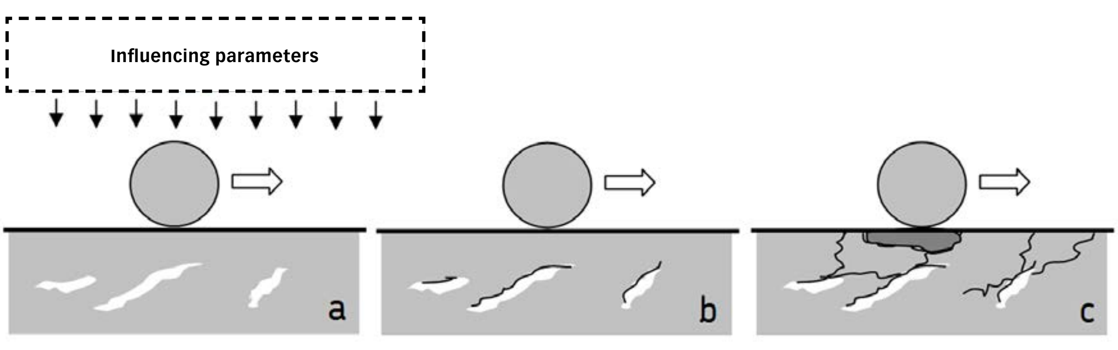



**Fig. 7: According to existing theories in the literature, a) certain influencing factors locally change the microstructure into white etching areas (WEA), b) WEA will be the starting points of white etching cracks (WEC), and finally c) white structure flaking (WSF) due to crack propagation reaches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

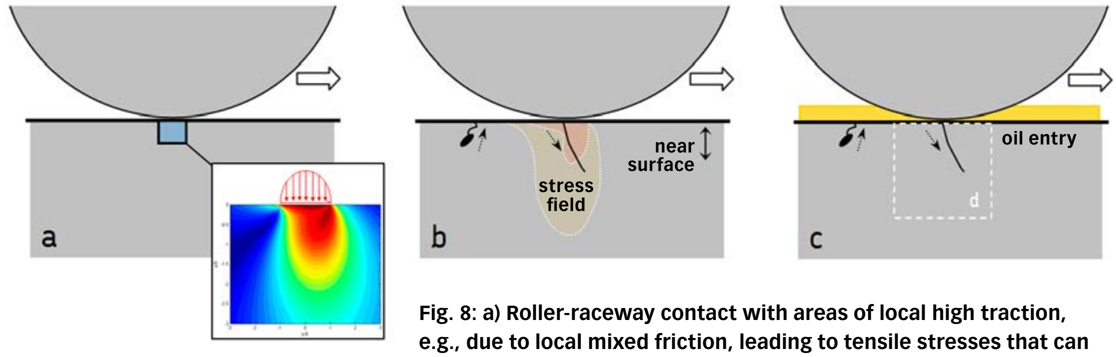



**Fig. 8: a) Roller-raceway contact with areas of local high traction, e.g., due to local mixed friction, leading to tensile stresses that can b) lead to damage such as a small crack; c) a surface crack or crack connected to the raceways allows the entry of oil; for area d, see fig. 12 for more details.**

corrective action by use of special greases and/or hybrid bearings, special steels)[6,35,36].

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

### 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[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[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[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 [6,16,38]. In a completely sub-surface crack system, we have vacuum conditions and consequently significantly slower crack growth from pure mechanical fatigue[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[28,33], or to accelerated classic rolling contact fatigue[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[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[39, 40, 41]. In SKF's experience, the performance of wind gearbox oils can be distinguished from surface initiated failure mechanisms[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)[6, 16].

The normally moderate bearing load conditions in wind gearboxes, the absence of compressive residual stress build-ups (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[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[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[7, 44, 45]. Little experimental evidence is reported that supports butterfly cracks propagating into WEC networks [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.

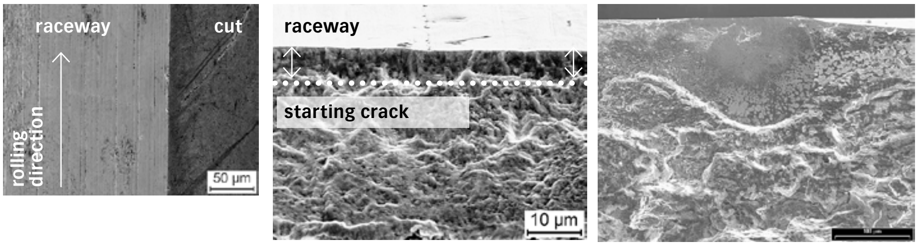
Nevertheless, the occurrence of unexpected high sub-surface stress-induced bearing damage[32] also by inclusions cannot be fully excluded as long as the exact contribution of transient running conditions is not fully understood. The exact loading of wind gearbox bearings in the field is very much based 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].

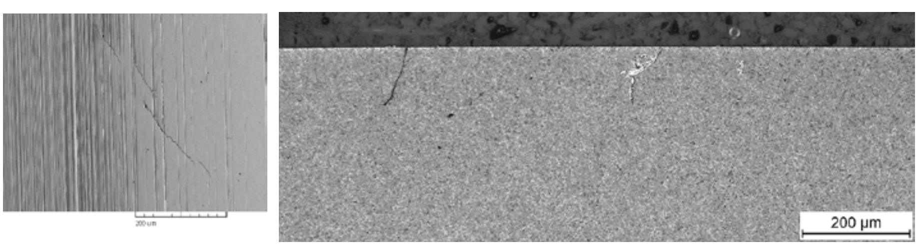
As schematically shown in fig. 8, transient conditions can trigger surface cracks, possibly accelerated by tribochemical effects[6, 16, 39, 40, 41], or sub-surface cracks that reach the raceway when starting at weak points such as inclusions close to the surface (< 150 µm)[6].

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 cracks[6, 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].




9a 9b 9c

**Fig. 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, taken from reference 6).**




10a 10b

**Fig. 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).**

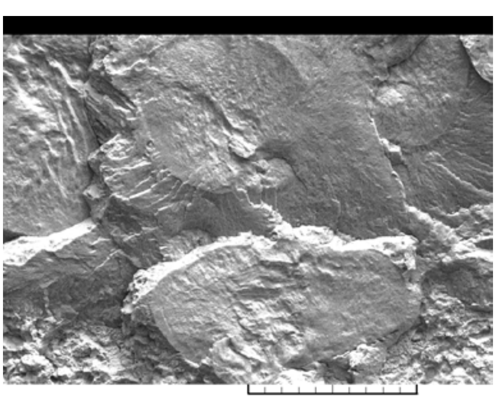



**Fig. 11: Opened fracture face (cf. fig. 10a) revealing two cracks (similar to fig. 9c), surrounded by the CFC structure (scanning electron microscope fractograph, backscattered electron mode).**

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 GPa[18].

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.

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 intercrystalline 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 transcrystalline 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, WEC 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.

## 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

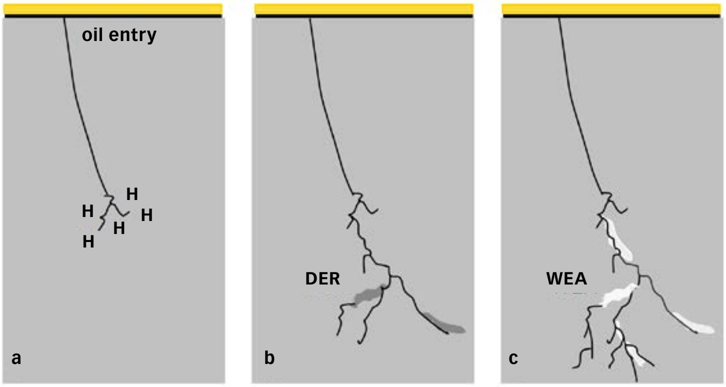
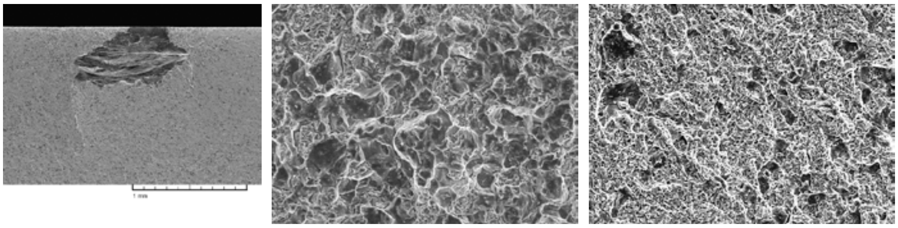



**Fig. 12 (continuation of fig. 8): a) After penetration, oil and additives react in the crack flanks locally producing hydrogen, b) and c) the hydrogen transforms locally the microstructure close to the crack system into white etching cracks WEC (from dark etching regions, DER, to white etching areas, WEA)[6, 7, 16].**



13a 13b 13c

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

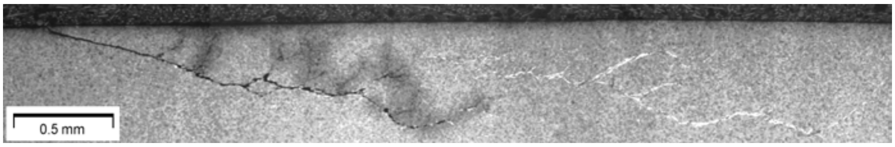



**Fig. 14: Irregular white etching decorated crack network (from reference 6).**

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:

- SKF special passivation
  - to stabilize the near surface microstructure
  - to make the bearing more resistant to chemical attack and hydrogen
  - to reduce micro friction under peak loading
  - to improve running-in
- SKF special clean steel for the most stressed component
  - to 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)
  - to allow a conditioning of the component (shake down – the nominal loading in wind is relatively moderate)
  - to 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. ●

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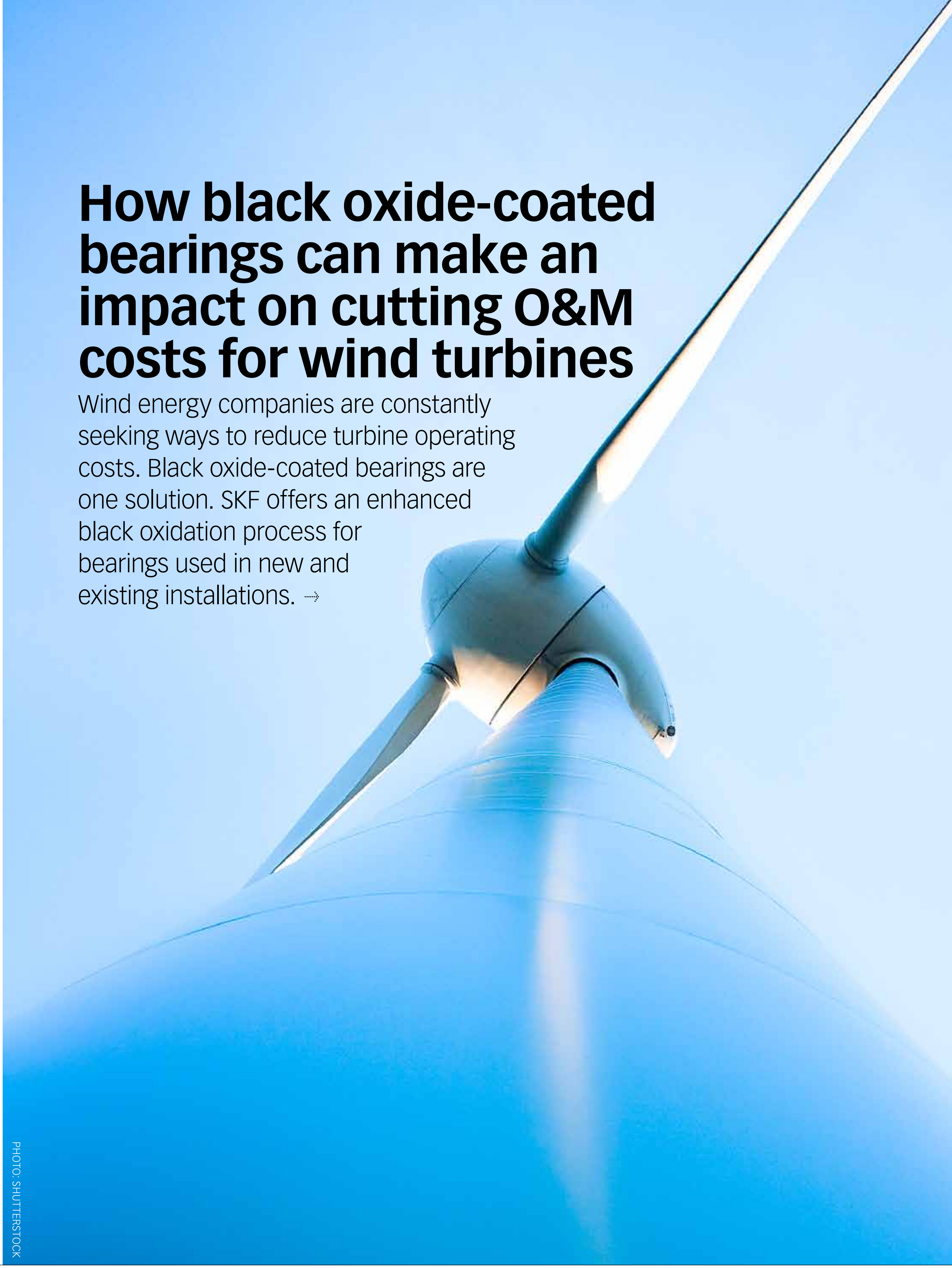
**Summary** The rapid growth of the wind industry and its increasing size and power-generation capacity combined with the harsh operating conditions create a challenging operating environment for wind turbines. Understanding mechanisms, particularly in bearing systems, that can lead to early turbine 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.

## References


1. GWEC, *Global wind report, Annual market update 2010,* April 2011
2. Y. Feng, 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. H. Swahn, P.C. Becker, O. Vingsbo (1976a), *Martensite decay during rolling contact fatigue in ball bearings.* Metallurgical Transactions A, Vol. 7A, No. 8, pp. 1099–1110
6. J. Gegner, *Tribological aspects of rolling bearing failures.* In: Tribology – Lubricants and Lubrication, Kuo, C.-H. (Ed.), *InTech*, Rijeka, Croatia, 2011, Chap. 2, pp. 33–94, http://www.intechopen.com/articles/show/title/tribological-aspects-of-rolling-bearing-failures
7. J. Gegner, *Frictional surface crack initiation and corrosion fatigue driven crack growth,* NREL workshop, Broomfield, November 2011
8. J. Luyckx, *Hammering wear impact fatigue hypothesis WEC/irWEA failure mode on roller bearings,* NREL workshop, Broomfield, November 2011
9. W. Holweger, *Influence on bearing life by new material phenomena,* NREL workshop, Broomfield, November 2011
10. M.H. Evans, *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. J.P. Molly, *Wind energy – Quo vadis?* DEWI Magazine No. 34, February 2009
12. D. Heidenreich, *A lean solution to the gearbox life problem in wind turbine drive systems*, Hannover Messe 2011
13. J. Rosinski, D. Smurthwaite, *Trouble-shooting wind gearbox problems,* Gearsolutions 2010
14. A. Heege et al., *Matching experimental and numerical data of dynamic wind turbine loads by modelling of defects,* SAMTECH, EWEC 2009
15. D. Aguglia, 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
16. J. Gegner, 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
17. W. Nierlich, J. Gegner, *Einführung der Normalspannungshypothese für Mischreibung im Wälz-Gleitkontakt. Gleit- und Wälzlagerungen: Gestaltung, Berechnung, Einsatz,* VDI-Berichte 2147, VDI Wissensforum, Düsseldorf, Germany, 2011, pp. 277–290 (in German)
18. M.N. Kotzalas, G.L. Doll, *Tribological advancements for reliable wind turbine performance,* Phil.Trans.R.Soc. A 368, 2010
19. T. Thomas, *Schäden durch Schwingungen noch nicht im Griff,* VDI Nachrichten, 26.Feb.2010, No. 8
20. T. Korzeniewski, *Gearbox protection concept for wind turbine generator systems,* DEWI No. 36, 2010
21. FVA 541 I, *Wälzlagerlebensdauer-Windgetriebe,* 2010
22. B. Kamchev, *Wind energy encounters turbulence,* Lubes'n'greases 2011
23. R .Heemskerk, *Challenges on rolling bearings in wind turbines*, VDI Gleit- und Wälzlagerungen 2011
24. IEC/ISO 61400-1 to 25, *Design requirements for wind turbines*
25. ANSI/AGMA/AWEA 6006-A03, *Standard for design and specification of gearboxes for wind turbines*, 2003
26. O. Klempert, *Belastungen im Getriebe werden zum Streitthema,* VDI Nachrichten, 14.Mai.2010, No. 19
27. W. Musial, S. Butterfield, B. McNiff, *Improving wind turbine gearbox reliability*, NREL, 2007
28. H. Uyama, *The mechanism of white structure flaking in rolling bearings,* NREL workshop, Broomfield, November 2011
29. N. Kino, K. Otani, *The influence of hydrogen on rolling contact fatigue life and its improvement,* JSAE Rev., 24, 2003
30. K. Tamada, H. Tanaka, *Occurrence of brittle flaking on bearings used for automotive electrical instruments and auxiliary devices*, Wear, 199, 1996
31. T. Lund, *Subsurface initiated rolling contact fatigue – Influence of non-metallic inclusions, processing conditions and operating conditions,* J. ASTM Int., 7, 2010
32. T. Lund, *SABB 1309,* ASTM conference, Tampa, 2011
33. R. Vegter, J. Slycke, *The role of hydrogen on rolling contact fatigue response of rolling element bearings,* J. ASTM Int., 7, 2009
34. I. Strandell, C. Fajers, T. Lund, *Corrosion – One root cause for premature failures,* 37th Leeds-Lyon Symposium on Tribology, 2010
35. J. Gegner, W. Nierlich, *Sequence of microstructural changes during rolling contact fatigue and the influence of hydrogen.* Proceedings of the 5th International Conference on very high cycle fatigue, Berger, C. and Christ, H.-J. (Eds.), German Association for Materials Research and Testing (DVM), Berlin, 2011, pp. 557–562
36. J. Gegner, W. Nierlich, *Hydrogen accelerated classical rolling contact fatigue and evaluation of the residual stress response,* Material Science Forum Vol. 681, 2011
37. T.H. Kim, A.V. Olver, P.K. Pearson, *Fatigue and fracture mechanism in large rolling element bearings*, Tribology Transaction, 44, 2001
38. 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
39. R. Pasaribu, 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
40. I. Nedelcu, E. Piras, A. Rossi, 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
41. B. Han, Bo.X. Zhou, R. Pasaribu, *C-Ring hydrogen induced stress corrosion cracking (HISCC) tests in lubricating liquid media,* European Corrosion Congress, Stockholm, 2011
42. A. Félix-Quiñonez, G.E. Morales-Espejel, *Film thickness fluctuations in time-varying normal loading of rolling elastohydrodynamically lubricated contacts*, Proc. IMechE Vol. 224 Part C, 2010
43. A. Félix-Quiñonez, G.E. Morales-Espejel, *Film thickness in EHL rolling contacts with transient normal load*, ITC Hiroshima, 2011
44. W. Holweger, J. Loos, *Beeinflußung der Wälzlagerlebensdauer durch neue Werkstoffphänomene in speziellen Anwendungen,* Antriebstechnisches Kolloquium Aachen, ATK, 2011
45. M. Brueckner, J. Gegner, A. Grabulov, W. Nierlich, J. Slycke, *Butterfly formation mechanisms in rolling contact fatigue,* D.Verb.für Materialfor. und -prüf. e.V., 2011
46. J. Lai, J. Wang, E. Ioannides, *Fluid-crack interaction in lubricated rolling-sliding contact,* Proceedings of the STLE/ASME, IJTC 2008
47. J. Gegner, W. Nierlich, *Operational residual stress formation in vibration-loaded rolling contact.* Advances in X-ray Analysis, Vol. 52, 2008, pp. 722–731
48. G.E. Morales-Espejel, V. Brizmer, *Micropitting modelling in rolling-sliding contacts: Application to rolling bearings,* Trib. Trans. Vol. 54, pp. 625–643, 2011
49. K. Stadler, G.E. Morales-Espejel, V. Brizmer, *Micropitting in rolling bearings: influence of lubrication, roughness, wear and ways of prevention,* Antriebstechnisches Kolloquium Aachen, ATK 2011



# How black oxide-coated bearings can make an impact on cutting O&M costs for wind turbines

Wind energy companies are constantly seeking ways to reduce turbine operating costs. Black oxide-coated bearings are one solution. SKF offers an enhanced black oxidation process for bearings used in new and existing installations. →

PHOTO: SHUTTERSTOCK

**OPERATION AND MAINTENANCE** (O&M) costs can constitute a significant proportion of running a wind turbine, up to 25 % over the lifetime of a machine[1]; thus manufacturers and maintenance service providers are keen to adopt any technology that makes a contribution to reduced maintenance and downtime. With this in mind, SKF is championing a surface treatment based on an enhanced black oxidation process for bearings used in wind turbine applications.

Black oxide-treated bearings can replace conventional units as part of wind farm maintenance routines, as well as being specified for new installations. This means that the benefits of black oxidation can be applied across the entire wind energy industry.

SKF, as a global engineering company and a leading bearing supplier to the wind energy industry, has extensive experience with wind turbine applications, from bearing design through to broad services covering condition monitoring, lubrication systems, asset management and the provision of spare parts. Through SKF's long involvement with the wind energy industry, the company has identified a number of opportunities to improve operational reliability through new products and processes such as the specially designed black oxidation treatment. This is a surface refinement process that can deliver significant performance improvements at an acceptable cost.

## Increasing demands on installations

Wind turbines are subject to widely varying temperatures, speeds and loads. This, combined with contamination, moisture and chemical effects due to highly AW doped oils, means these conditions can sometimes considerably shorten the bearing life cycle, if no preventive measures are taken. Also, as wind turbines have increased in size and generating power, further demands are placed on key systems such as the gearbox.

The black oxidation process used by SKF offers enhanced protection against damage to bearing components, particularly for the challenging operating conditions created by a shift from onshore to offshore installations and for those constructions sited in increasingly harsh environments around the world.

While damage and failure rates of wind turbine gearboxes may vary according to the source of published data, a benchmark has been reported by the EU-funded Reliawind study, which came out around 6 % per year. That study also quoted publicly available data on the failure rate and downtime from large reliability surveys performed by Landwirtschaftskammer in Schleswig-Holstein, Germany, and the Wissenschaftliches Mess- und Evaluierungsprogramm of the Fraunhofer Institute in Kassel, Germany, and noted failure rates of around 10 %. While these figures may be considered low when compared with other causes of breakdowns in the field, such as electrical systems, the consequence of that failure can be heavy; damage and failures in mechanical drive trains can result in high costs due to long downtimes.

As an example, a bearing failing on a high-speed shaft of an onshore turbine can incur repair costs in the region of several thousands of euros, assuming it is exchanged up-tower. However, if a planet bearing fails, then the whole gearbox needs to be replaced, and the cost can easily exceed hundreds of thousands of euros when all costs are factored in.

## The main failure mechanisms

The types of damage that can be alleviated by the addition of a black oxide treatment to bearing components such as the rings and rollers generally fall into categories such as cracks, sliding (smearing) and surface distress, as well as environmental effects, such as moisture and chemical attack.

### 1. Cracks

Many premature wind gearbox bearing damages result in a failure mode that does not follow classical rolling contact fatigue (RCF) mechanisms. These classical mechanisms are subsurface initiated fatigue as well as surface initiated fatigue and can be predicted by standard bearing-life calculation methods, whereas premature white etching crack (WEC) failures experienced in wind turbine bearings are not covered (fig. 1a). WEC refers to the appearance of the altered steel microstructure when polishing and etching a microsection. Failures can be found at several bearing locations, namely the planet bearings, intermediate shaft and high-speed shaft bearings.

The occurrence of premature failures due to WEC is widely discussed within the wind industry and is being independently investigated by wind turbine manufacturers, gearbox manufacturers and bearing suppliers as well as universities and independent institutes. Current hypotheses are focused on either hydrogen-enhanced WEC developments or purely load/stress-related WEC developments, preferably at inclusions as well as at the surface, or combinations of these.

**2. Smearing (adhesive wear)**
In lightly loaded roller bearings, pure sliding between rolling elements and inner ring can occur when there is a large mismatch between the inner ring and roller set rotational speed. For demanding applications such as wind gearbox high-speed shafts, idling conditions and changing of load zones can sometimes lead to high sliding risk.

In radially loaded roller bearings, the most critical zone where sliding can occur is the entrance of the rollers into the load zone. While rotating, the rollers slow down in the unload zone of the bearing because of friction and subsequently have to be suddenly accelerated as they re-enter the load zone. Resultant conditions can cause smearing (fig. 1b). The microstructure of rollers and raceways is altered, and this results in local stresses that ultimately cause spalling and bearing failure.

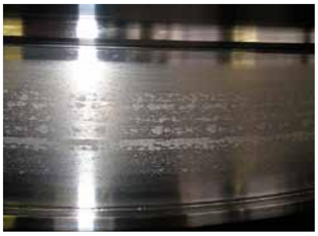
Full complement cylindrical roller bearings do not always have a separating lubricant film built up between the contacting rollers due to opposing surface speed. Thin film or even mixed lubrication under high roller-to-roller contact pressures leads to metallic contact between neighbouring rollers, and this then increases →

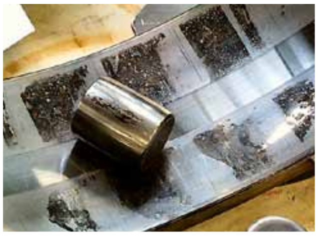


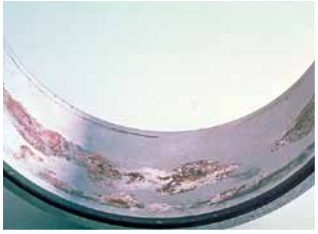
## Fig. 1: Types of bearing damage that can occur in wind gearboxes:


a) cracks/spalls;


b) sliding damage/smearing;


c) surface distress/ microspalling;


d) moisture/standstill corrosion on a raceway;


e) fretting corrosion in the bore of an inner ring.

friction, which consequently can lead to smearing and surface destruction.

**3. Surface distress/microspalling**
Many machine elements having rolling and sliding contacts (e.g., rolling bearings, gears and cam-followers) can sometimes suffer from various types of damage. Amongst these are mild abrasive wear and microspalling. Surface distress or microspalling occurs because of an insufficient oil film to separate the moving contacts; it is a form of localized surface damage that occurs on both gear teeth and in bearings and is a common phenomenon found in wind turbine gearboxes. Gear teeth are usually more affected than bearings. Nevertheless, if it happens to bearings, it can be particularly detrimental to the bearing function. It alters the geometry of rollers and raceways, increasing internal clearance and resulting in local stresses that ultimately cause spalling and bearing failure (fig. 1c). Contamination by water in wind turbine gearboxes could also be a contributing factor.

**4. Moisture corrosion**
The water content of wind gearbox oils is often underestimated. The large temperature gradients in combination with highly saturated water content (depending on oil type) can lead to the risk of "free water" and standstill corrosion (fig. 1d). Whereas the high risk to the application by free water is well known, the risk of different levels of dissolved water in gearbox oil is still unclear. SKF investigations indicate a negative impact on bearing performance whenever a certain amount of dissolved water is present.

**5. Fretting corrosion**
When the bearing shaft interface (inner ring bore – shaft seat) or the bearing housing interface (outer ring outside surface – housing seat) are subjected to micro movements under varying loading conditions, the native oxide on the steel surfaces can be removed. Furthermore, surface asperities can corrode and are torn off. These particles become trapped in the contact, and if oxidizing agents such as moisture are also present, further corrosion happens at the surface (fig. 1e) . Under load, the trapped air and moisture corrode the surface further and can lead sometimes to further particle generation. These particles will act as grinding paste resulting in further loss in interference and increased ring creep, or in the worst case (if corrosion particles remain trapped at the seat) to ring through cracking by increased and too high local stress.

## The black oxidation process used by SKF

For all these potential failure modes, applying a specially designed black oxide coating on the bearing functional surfaces provides a significant degree of protection. This layer adds beneficial properties to the bearing operation, such as an improved running-in phase, and results in equally improved surface properties after running-in, better performance under poor lubrication regimes (low κ conditions) and better lubricant adhesion, as well as enhanced smearing resistance. The risk of

**Fig. 2:**
**Black oxidized wind turbine gearbox bearings: cylindrical roller bearings without outer ring, used in planetary wheels.**

**Fig. 3:**

**Black oxidized wind turbine gearbox bearings: separable high capacity cylindrical roller bearings, e.g. used in high-speed intermediate and high-speed output shafts.**



# Black oxide treatment

**BLACK OXIDE** is a surface treatment that is formed by a chemical reaction at the surface layer of the bearing steel and is produced when parts are immersed in an alkaline aqueous salt solution operating at a temperature of approximately 150 °C. The reaction between the iron of the ferrous alloy and the reagents produces an oxide layer on the outer surface of bearing components consisting of a well-defined blend of FeO, $Fe_2O_3$, resulting in $Fe_3O_4$. The result is a dark black surface layer of approximately 1–2 μm in thickness.

The benefits of black oxide have to be judged for the individual application, but no detrimental effects of this treatment are known at this time. It has been successfully applied to bearings in other industries with particular operational challenges, such as paper machine rolls, machine tools and industrial fans.

The black oxidation process involves a wide variety of parameters. The total process consists of about 15 different immersion steps; in many of these it is possible to vary chemical content, concentration, temperature, immersion time and fluid behaviour within the tanks.

SKF has performed extensive research on this process since 2006 to define optimized treatment specifications for the black oxide process, also extending it to the treatment of large bearings. The black oxidation processes from SKF are designed and individually tailored for each bearing type and application to provide maximum performance and can deal with a broad range of bearing sizes used in wind turbines currently up to 2.2 m outside diameter, with the weight of individual bearing components up to 1,000 kg. The treatment method as well as the size and weight range is proprietary to SKF.

SKF recommends that both inner and outer rings as well as the rolling elements are coated for the best performance. The black oxide can be applied to all bearing types used in key wind turbine systems. Cylindrical and tapered roller bearings in particular have been successfully treated and put into operation in recent years (figs. 2 and 3).

The black oxide treatment process used by SKF is carefully specified and precisely monitored, producing high-quality bearings that can be accessed through the company's global network, making the benefits of black oxide bearings available to wind turbine manufacturers, end users and service providers worldwide. ●

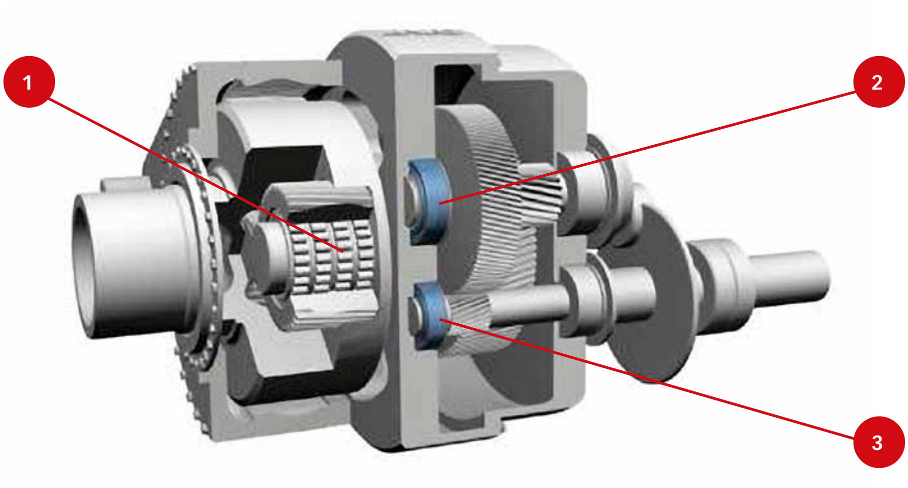



**Fig. 4:**
**Black oxide-coated bearings from SKF in wind turbine gearboxes:**
**1) planetary wheels (fig. 2)**
**2) high-speed intermediate shaft (fig. 3)**
**3) high-speed output shaft (fig. 3).**

fretting, microspalling and crack formation can be reduced. Furthermore, the black oxide layer offers an elementary corrosion resistance as well as an enhanced chemical resistance when compared with untreated surfaces. The moderate corrosion resistance of black oxide is sufficient to suppress standstill corrosion and fretting corrosion, and the chemical resistance reduces detrimental effects from aggressive oil ingredients. It improves friction behaviour and reduces wear, particularly under mixed lubrication conditions. Recent R&D results indicate that black oxide acts as a barrier to hydrogen permeation into the steel.

To give a comparison of the potential improvement in failure rates, a wind gearbox manufacturer has reported, in a sample of 1,000 standard cylindrical roller bearings in a gearbox application, a failure rate ranging from 40 % to 70 % (after two years). Subsequently, in a sample of 1,150 black oxidized cylindrical roller bearings for a similar application, the failure rate was 0.1 % over the same period[2].

In summary, compared with untreated bearings, black oxide-coated bearings from SKF in windmill turbine gearbox applications (fig. 4) can offer the following benefits:

- improved running-in behaviour
- better corrosion resistance
- improved resistance against smearing damage
- better performance in low lubrication conditions
- increased oil and grease adhesion
- reduction of chemical attack from aggressive oil additives on the bearing steel
- reduced hydrogen permeation in the bearing steel
- decrease of fretting corrosion risk in the fits.

With more than 50,000 black oxide-coated bearings in the field, SKF has accumulated a wealth of evidence that this cost-effective process can deliver appreciable performance improvements for the wind energy industry that can result in fewer early failures and hence contribute to lower overall O&M costs. ●

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## Note

1. For a new turbine, O&M costs may easily make up 20–25 % of the total levelized cost per kWh produced over the lifetime of the turbine. If the turbine is fairly new, the share may be only 10–15 %, but this may increase to at least 20–35 % by the end of the turbine's lifetime. Figures from Wind Energy – The Facts (WindFacts), a European project financed by the Intelligent Energy, Europe programme of the Executive Agency for Competitiveness and Innovation.
2. J.Luyckx, Hammering Wear Impact Fatigue Hypothesis WEC/irWEA failure mode on roller bearings, NREL workshop, Broomfield, Colorado, USA, November 2011.

**Summary**

Wind turbines are increasingly sited in harsh environments, and manufacturers and operators are faced with trying to reduce operating and maintenance costs while improving machine availability. SKF is making its contribution to improving turbine performance through its proprietary black oxidation process, which provides extra protection to bearings used in key components in this challenging industry.

# Flexible choice for reliable gear-box solutions

SKF's high-capacity cylindrical roller bearings are specifically designed for wind turbine gearbox applications. The new separable design provides high performance and improved reliability and facilitates assembly, maintenance and repair operations.



Wind turbine drivetrain concepts are special. There are turbines with or without gearboxes, and there are hybrid turbines that actually do have a gearbox but only one or two stages of gearing and do not use a high-speed generator. Looking back in history, the majority of turbines – about 80 % – are gearbox-equipped; the remainder are direct-drive or hybrid. Currently, there is considerable discussion in the industry about whether the trend will shift towards more direct-drive turbines. The cost of energy is the key, and the question remains as to which turbine concept is better able to achieve the lowest cost of energy. This means having good control of life-cycle costs, which involves initial investment costs as well as operating and maintenance costs. The fact is that all turbine concepts have their advantages and disadvantages, meaning that gearboxes will still play a very important role, with the ultimate goal being to further improve reliability and operational safety. Bearings in gearboxes often suffer from premature damage and failures, leading to unplanned stops and high maintenance cost. To avoid these, SKF can help by supplying appropriate products.

### Situation in brief

The planetary stages of gearboxes are often equipped with full complement cylindrical roller bearings. These bearings, which have a high load-carrying capacity, typically generate more friction than a caged bearing does, due to direct roller-

PHOTOS: SHUTTERSTOCK

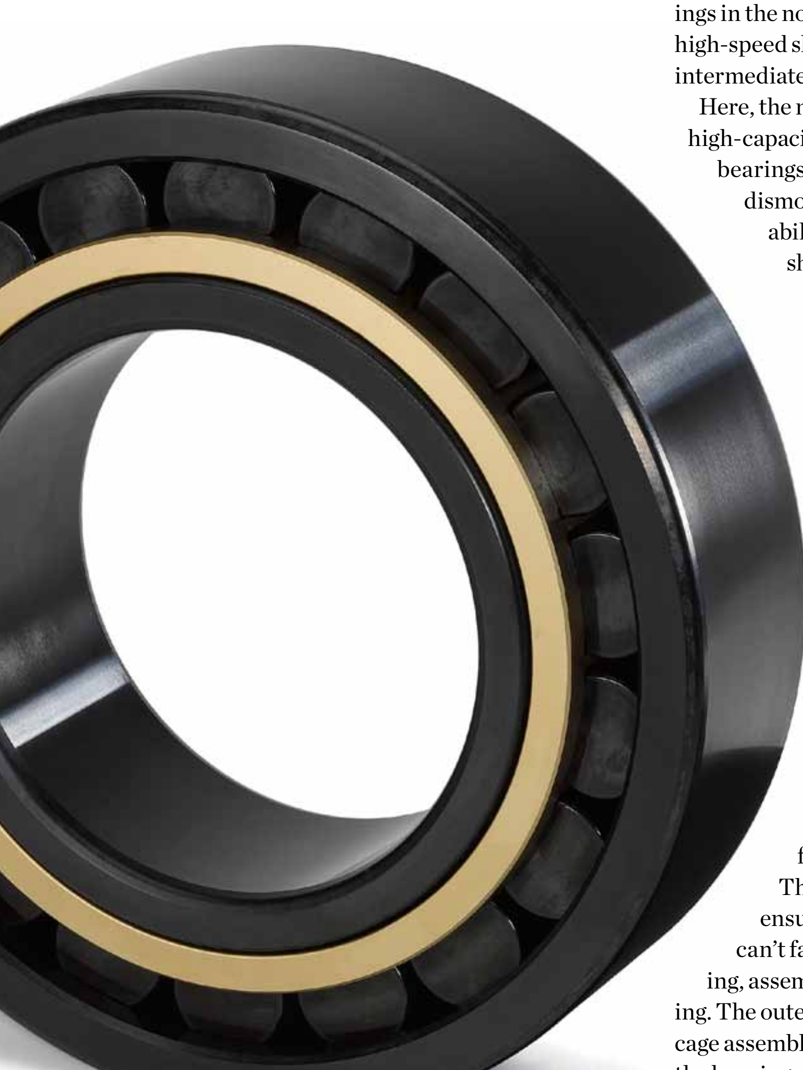
View of a windmill drivetrain from the top of the nacelle.

to-roller contact. In smaller gearboxes, these bearings seem to work satisfactorily. However, as wind turbines have become larger, there is an ever-increasing risk that these bearings will fail prematurely, due to smearing and wear.

To meet the need to increase power density and reliability in wind turbines, in 2006 SKF launched a range of high-capacity cylindrical roller bearings. These caged high-capacity cylindrical roller bearings are available for a number of sizes in the 22 and 23 dimension series. Depending on the cage variant, bearings in the 23 series can have up to two extra rollers; bearings in the 22 series can have up to three or more extra rollers, when compared with a standard bearing of the same size.

Bearings made to the high-capacity designs provide increased radial load-carrying capacity to cope with heavy load conditions.

**Separable high-capacity cylindrical roller bearing with black oxidized rings and rollers.**



## New bearing design

SKF has now introduced a new version of its high-capacity cylindrical roller bearings in a separable design that enables separate mounting of inner and outer rings. The new SKF separable high-capacity cylindrical roller bearing combines the advantages of separate mounting and high load-carrying capacity. In launching this version, SKF builds further on the success of its high-capacity cylindrical roller bearings in wind turbine applications.

The new bearing design has been developed as a response to OEM and user requirements for bearings in the non-locating position on high-speed shafts and high-speed intermediate shafts.

Here, the new SKF separable high-capacity cylindrical roller bearings offer easy mounting, dismounting and maintainability for high-speed shafts in the spur gear section, coupled with improved reliability and operational safety.

The design comprises a one-piece solid brass cage incorporating a high-capacity cage pocket design that is guided on the inner ring.

Separate mounting is achieved by a cage design that features a retaining function of the rollers. This retaining function ensures that the rollers can't fall out during mounting, assembling and dismounting. The outer ring with roller and cage assembly can be mounted into the housing, while the inner ring is separately mounted on the shaft to ease assembly afterwards.

During mounting, the rolling elements are protected by the cage, reducing the risk of handling damage. The cage design also features an optimized roller drop, which helps to facilitate assembly. The inner-ring guided cage counteracts the risk of slip damage at high speeds for which the bearing may have to cope with minimum load conditions. The rotating inner ring, which is in contact with the cage in the adjacent area outside the contact zone of the rollers, drives the cage, resulting in improved kinematics of the roller set.

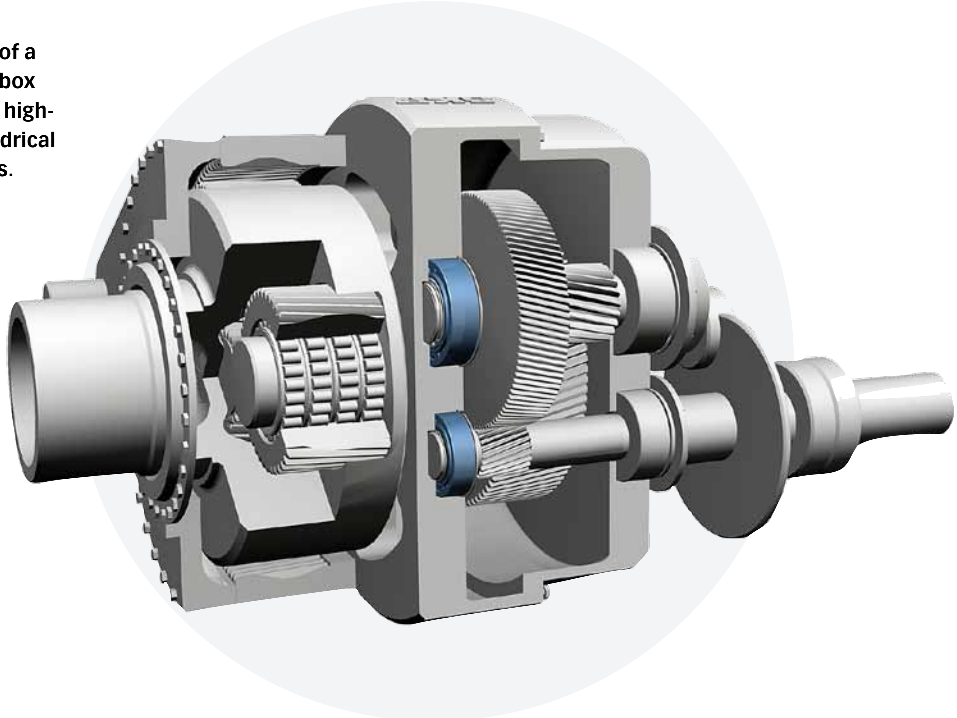
Various tests on roller slip have been made, particularly under very light load conditions. Compared with widely used NU design bearings, a significant reduction of roller slip of up to 40–50 % was measured, proving that the new SKF separable high-capacity cylindrical roller bearings can cope with this demand of minimum load requirements. Combined with increased load-carrying capacity, they lead to reduced risk of premature bearing damage or failure and increased operational safety.

## Meeting increased demands

Turbines are getting continually larger in size, with higher power ratings – up to 7.5 MW, with 10 MW in the planning stages. Coupled with this, wind farms are located offshore or in remote locations and harsh environments, putting added emphasis on reliability. Gearbox failures are regarded as one of the most serious causes of breakdown in wind turbines because of the high cost of repairing or replacing the gearbox and the resulting long downtime.

For bearings in wind turbine gearboxes, these demands require

CAD drawing of a windmill gearbox incorporating high-capacity cylindrical roller bearings.



better performance through higher operational reliability to comply with heavier loads and keep the design as compact as possible. The high-capacity cylindrical roller bearing versions offer substantial performance improvements and increased operational safety on the different bearing positions in a wind turbine gearbox.

The newly developed separable high-capacity version is suitable for use by original equipment manufacturers in new designs and as a retrofit solution, where turbines suffering gearbox bearing failures could benefit from an improved bearing design. The boundary dimensions of the new bearing conform to the ISO 15 standard, making replacement straightforward.

## Applications

The existing SKF range of high-capacity cylindrical roller bearings has been successfully used in planetary stages of wind gearboxes. The new separable bearing meets maintenance and inspection requirements, such as when the dismounting of high-speed shafts must be carried out directly on top of the turbine. In this situation, a separable cylindrical roller bearing design facilitates the task considerably.

SKF separable high-capacity cylindrical roller bearings are available in two dimension series for the two different shaft positions (the 22 series bearings are mainly for high-speed shafts, and the 23 series bearings are mainly for high-speed intermediate shafts). Bearings in both series have been designed to meet the various requirements of higher load-carrying capacity, along with reducing slip and risk of wear and having a separable bearing design. Both the 22 and the 23 series cover bore diameters ranging from 100 mm to 240 mm.

The increased load-carrying capacity enables higher operational safety margins by keeping the same geometrical size or by maintaining the current load-carrying capacity safety level built into a smaller and more compact bearing. SKF separable high-capacity cylindrical roller bearings and high-capacity cylindrical roller bearing versions help customers achieve high reliability, excellent performance and easy maintainability in their applications. ●

**Summary**

The trend towards wind turbines with larger generating capacity puts tremendous strain on gearbox designs. To support OEMs and operators of windpower generators and facilitate maintenance, inspection and repair, SKF has introduced a new version of its high-capacity cylindrical roller bearings in a separable design that combines the advantages of separate mounting with high load-carrying capacity. With this product, SKF offers easy mounting, dismounting and maintainability for high-speed shafts in the spur gear section, coupled with improved reliability and operational safety.


**Fig.1: Inspection of 47.625 mm diameter ceramic balls (right) used for windmill generator bearings.**

# Developments in **ceramic bearing balls**

The need to provide solutions for high-performance applications in advanced gas turbines initially drove the development of ceramic rolling elements for use in bearings. This was followed by the use of ceramic rolling elements in other applications, such as machine tool spindles, electric motors and generators.

**HYBRID ROLLING BEARINGS** incorporating ceramic rolling elements are used for many challenging applications. Some recent applications include the railway industry and renewable energy business such as windmill generators.

Bearing grade silicon nitride, $Si_3N_4$, is the current standard material for rolling bearings and meets international standards, and testing and inspection methods (fig.1) have been established, all of which accommodate the trend towards larger-size ceramic balls. High-quality silicon nitride bearing balls up to a diameter of 47.625 mm (1 7/8") are now commercially available.

Ceramic, stone and marble balls have a long history of use as cannonballs and jetsam and, of course, in children's games. The development of synthetic engineering ceramics in the 1960s and 1970s led to high-performance silicon nitride ceramic bearing balls becoming the state of the art for use in such diverse applications as jet engines, machine tool spindles, electric motors, Formula 1 racing cars, pumps, etc. Further development work is still under way, especially in the larger ball size range.

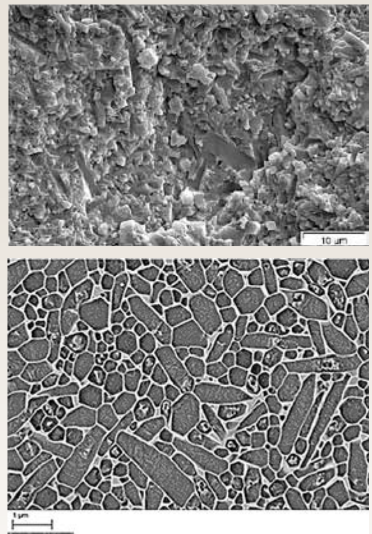


**Fig. 2: Bearing-grade silicon nitride fractured surface (top) and plasma etched microstructure (bottom) showing the long needles of the beta-silicon nitride improving the toughness.**

## Development of ceramic bearing balls and applications

An important driving force behind the development of modern engineering ceramics has been the dream of developing a very efficient gas turbine engine. The operating conditions for the main shaft bearings of such engines are extremely demanding, with shaft speeds in excess of 30,000 r/min and predicted bearing temperatures higher than 650 °C [1]. At gas temperatures above 1,100 °C, only high-performance ceramic materials with a higher hardness than bearing steels or even high cobalt-based stellites and high tungsten alloy tool steels are considered. The primary use of gas turbines has been in jet engines. This application demands materials that are low in weight (low density) and high in strength and can withstand high temperatures, as well as meet many additional requirements such as stiffness, processability and availability.

Ceramic materials were known to fulfil the first two requirements, high temperature and low density, but they were also known to be weak and brittle. Research efforts in the space and defence sectors were applied to understand why ceramics were weak and how this property could be improved. The resultant theories, methods and processes yielded improved ceramics and new synthetic ceramics, such as silicon nitride. The SKF Engineering and Research Centre (ERC) in the Netherlands has worked extensively with ceramic materials from a very early stage of their development.

Silicon nitride is a special type of ceramic material that provides self-reinforcing properties. Its two ceramic phases, alpha-silicon nitride and beta-silicon nitride, have different crystal shapes, one of which forms elongated needles (fig. 2). During processing, the balance between the two phases can be adjusted to obtain a tough material. The first silicon nitride that became commercially available with a strength and toughness suitable for bearing applications was hot pressed or hot isostatic pressed (HIP) silicon nitride.

During the 1960s and 1970s the SKF Company Marlin Rockwell Corp. (MRC) in the United States designed the first ceramic bearings. The hybrid bearing , which had a split inner ring, was manufactured by MRC for a test programme financed by the US government. The long-term operation of the silicon nitride material in a bearing using solid lubricants at temperatures above 500 °C was demonstrated during 1984 [1] by SKF.

Around 1990, beside aerospace test programmes, the machine tool industry started to exploit the advantages of the lightweight, high-speed features of ceramic balls. In the mid-1990s, frequency converters for electric motors started to use fast-switching electronics, which caused electric current damage in standard bearings. Hybrid bearings offer a very robust alternative for electrical insulation solutions. At about the same time, several hybrid-bearing solutions were introduced for Formula 1 racing cars, making use of their robustness under very demanding conditions (marginal lubrication, heavy loads and high speeds). The use of hybrid bearings in pumps and compressors arrived in about 2000, allowing marginal lubrication conditions and applications where fluids with lower viscosity than lubrication oil, such as refrigerants, were acceptable as lubricants. Also, the excellent corrosion resistance of ceramics drove their use in sour gas compressor applications. More recently, in the renewable energy business, ceramics have found applications in wind turbine generators. For this purpose, large (47.625 mm diameter) ceramic balls are required (fig. 1). Another growing application is the railway industry, where ceramic rolling elements are used in traction motors (fig. 3). Electrical insulation and the better performance of ceramic rolling elements under relatively light loads (they generate less frictional heat) are increasing the grease life in this application.

## Qualification of high-performance ceramic bearing balls

A broad range of rolling bearing applications can benefit by the introduction of ceramic balls. To make sure that ceramic materials perform optimally in an application, a careful assessment of the materials used for bearing balls is necessary. Test procedures have been established over time for this purpose.

In general, a first material assessment can be done by checking the macrostructure (fig. 4, top), microstructure and homogeneity (fig. 4, middle) on sectioned samples from blank or finished ball materials by sample mounting and polishing. Also hardness and indentation fracture resistance for a possible bearing material candidate can be determined relatively quickly (fig. 4, bottom).

New methods for testing the strength of finished ceramic balls have been developed. Especially in high-strength materials, it has been seen that the surface quality has a significant influence on strength. And the surface quality of a bearing ball is much better than that of a reference sample bending bar. The “notched ball” test (fig. 5) has the advantage that strength can be evaluated on real bearing balls and not on bending bars as specified at ⇢

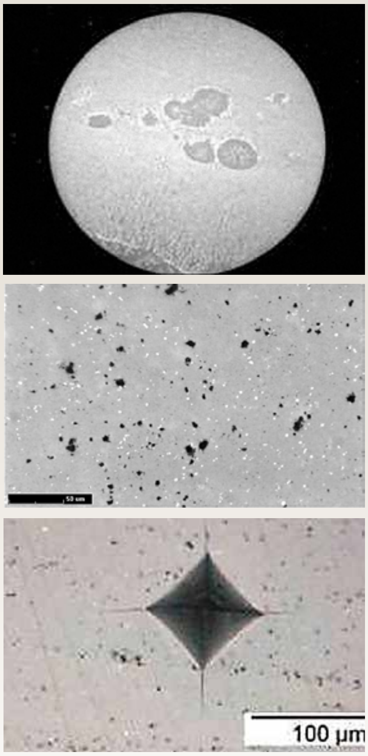



**Fig. 4: Macrostructure (top), microstructure (middle), hardness and indentation fracture resistance (bottom) evaluated on a cut and polished section of a ceramic bearing ball.**

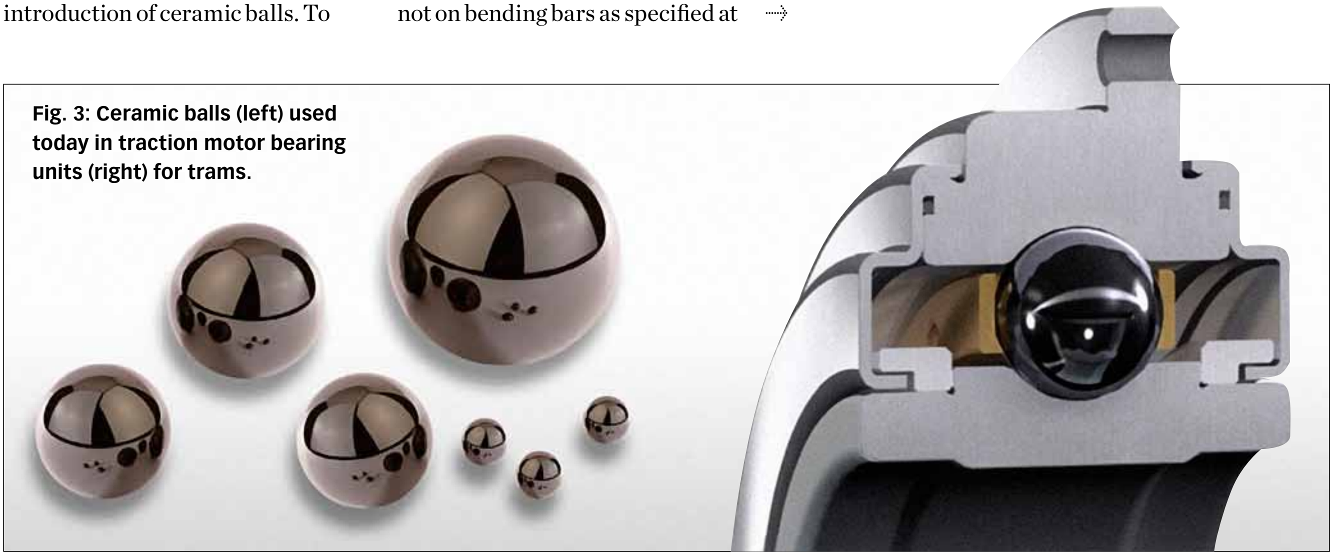


**Fig. 3: Ceramic balls (left) used today in traction motor bearing units (right) for trams.**

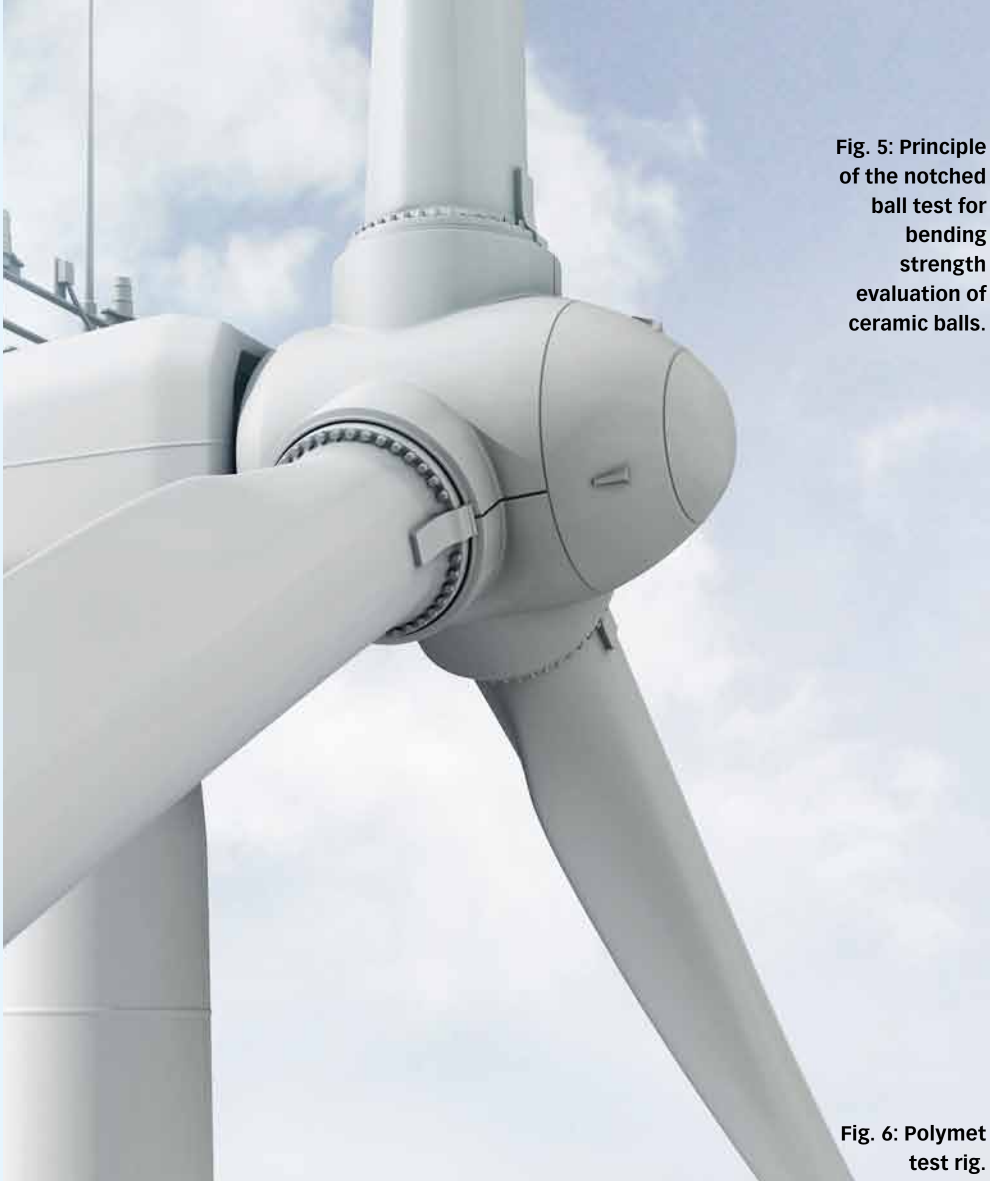


PHOTO: GETTY IMAGES

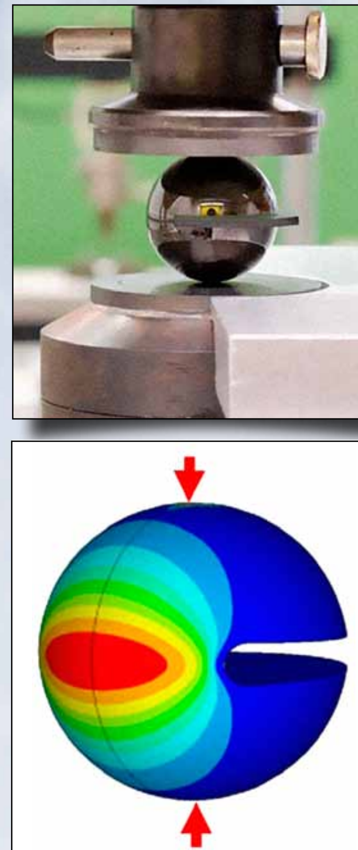


Fig. 5: Principle of the notched ball test for bending strength evaluation of ceramic balls.

Fig. 6: Polymet test rig.

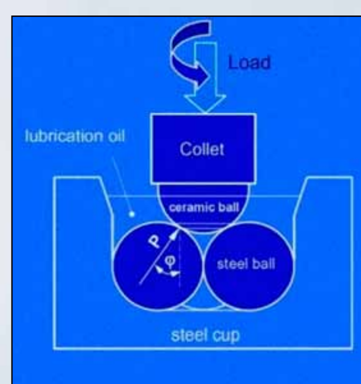



Fig. 7: Four-ball test.

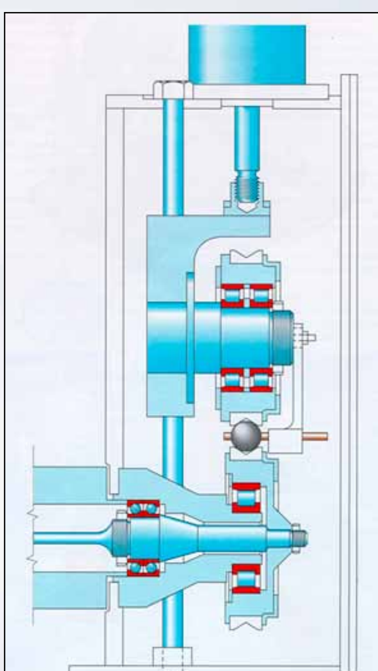


Fig. 8: V-groove test.

**Fig. 9: Endurance life test rig with two sets of four axially loaded 7318 BEMA/HC5DBBVE5752 hybrid angular contact ball bearings.**

present in ISO 26602:2009. The balls are notched and loaded vertically. They act in a similar way to bending bars. Details about this test are published [2, 3]. It has been shown [4] that surface defects such as Hertzian "C" cracks have a significant influence on ball strength.

An initial idea of cyclic rolling contact fatigue can be evaluated by a Polymet disc on a rod machine (fig. 6). A rod is loaded between two rotating steel discs. Typically $40 \times 10^6$ cycles at contact pressures of 3 or 4.8 GPa are run as an acceptance test. Cyclic rolling contact fatigue on finished balls can be tested with a modified four-ball test machine. The top ceramic ball drives three bottom steel balls in a ball socket, simulating a very simple bearing (fig. 7). A similar test can also be performed as a five-ball test, using four balls at the bottom. Another possibility for assessment of rolling contact fatigue on finished ceramic balls is the V-groove test (fig. 8). A ball is loaded between two V-grooved rings at contact pressures between 1.5 to 5.5 GPa. With the standard shaft speed, 28.6 mm diameter balls have to withstand about 6 million stress cycles per hour.

The endurance life of hybrid bearings is tested under different lubrication conditions. The typical bearing for endurance testing is a 7209 angular contact ball bearing, having 12.7 mm diameter balls. A hybrid bearing life test with grease lubrication in larger 7318 angular contact ball bearings, having 31.75 mm diameter balls, is shown in fig. 9.

## Conclusion

With these formal methods of qualifying ceramic rolling elements in hybrid bearings, end users can be assured of the performance of these materials in advanced applications. With continued development of ceramic materials tailored to high-performance applications, it is certain that hybrid bearings will continue to find uses in new industries with performance demands. ●

By *Oskar Schöppl, SKF Österreich AG, Steyr, Austria*

### References

[1] Pallini, R.A.: *"Turbine engine bearings for ultra-high temperatures"*, SKF Ball Bearing Journal 234, September 1989.
[2] P. Supancic, R. Danzer, S. Witschnig, E. Polaczek, R. Morrell, *"A new test to determine the tensile strength of brittle balls — The notched ball test"*, Journal of the European Ceramic Society 29 2447–2459 (2009).
[3] P. Supancic, R. Danzer, W. Harrer, Z. Wang, S. Witschnig, O. Schöppl, *"Strength Tests on Silicon Nitride Balls"*, Key Engineering Materials Vol. 409 pp 193-200 (2009).
[4] P. Supancic, R. Danzer, Z. Wang, S. Witschnig, O. Schöppl, *"The Notched Ball Test – A New Strength Test for Ceramic Spheres"*, 9th Symp. on Ceramic Materials, Shanghai (2008).

**Summary**

More than 400 years ago, the first industrially produced ceramic balls were marble balls used as cannonballs, jetsam and children's toys. The advent of new engineering ceramics in the 1960s and 1970s transformed these humble marble balls into high-performance ceramic bearing balls, which are being tested in jet engines and commercialized for machine tool spindles, electric motors, Formula 1 racing cars and pumps.

Recent new hybrid bearing business can be found in railway applications and renewable energy applications such as windmill generators. SKF remains in the forefront of ceramic bearing ball development, industrial-ization, application and standardization. Development work is still going on, especially in the larger ball size range. Silicon nitride bearing balls up to a 47.625 mm diameter are already commercially available. On the ceramic material side, there are opportunities to better tailor new materials to specific applications. This will save cost and also help the environment, as less energy-consuming processes are established for new production units to fulfil the growing demands for these new materials.

# Wind powering THE US

For more than 150 years, the United States has been drawing the bulk of its energy from below ground. But the country is increasingly looking for energy from the opposite direction – the skies.

**TEXT** ANNA ALBIEN **PHOTO** GETTY IMAGES, CHENG KWOK-KEUNG

Two pairs of eyes are laser-focused on the big screen monitor providing minute-by-minute data about the state of the Highland wind farm in southwestern Pennsylvania, in the United States.

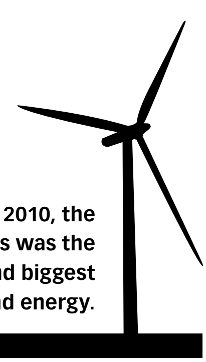
Plant operators John Bennett and Bradley Foy are working in the wind farm's control centre, situated a few minutes' drive away. From here they monitor and manage 25 turbines generating more than 62 megawatts of installed capacity.

"What we do is make sure these turbines are running when the wind is blowing," says Bennett. "We fix any kind of defects with the turbine – figure them out so we have a dependable machine that can run when we have good winds and make some power."

Highland, a project run by US wind energy company EverPower, generates enough power to provide electricity to more than 20,000 homes.

In fact, the US, a country accounting for about 20 percent of the world's total energy-related emission of carbon dioxide, is increasingly looking to the skies for power. By the end of 2010, the country was the second biggest producer of wind energy in the world. Around 2 percent of its electricity is now generated by wind power, but the potential is much greater. In 2008, the US Department of Energy published a report exploring a scenario in which wind provides 20 percent of the country's electricity by 2030, and President Barack Obama's 2009 stimulus bill included a strong focus on renewable energy. The development of wind power also enjoys strong support among the US public. According to the American Wind Energy Association, polls recently showed that nine out of 10 voters believed that it was a good idea to increase the amount of energy the US gets from wind. And in spite of the recent economic crisis, installed wind power capacity more than doubled from the first quarter of 2010 to the first quarter of 2011.

EverPower wants to play a key role in realizing the US's future wind power goals. "Hopefully we can be one of the main providers," says Daniel Lagiovane, project communication manager at EverPower. "We currently have one operational wind farm, and this year [2011] we're constructing two wind farms. We have four more in the development stage, which hopefully will be in construction this time next year."



**By the end of 2010, the United States was the world's second biggest producer of wind energy.**

Lagiovane adds that a wind farm generates more than environmental benefits. The New York City-based company puts a lot of emphasis on involving the local community, not least by giving it a boost economically. From the very outset EverPower plans its new development in close cooperation with local communities. Landowners get royalty payments, townships receive payments, and there is the tax revenue.

"The Highland wind farm is about a 150 million US dollar investment in a local community," says Lagiovane. "That's what EverPower has put into the area, with most of it staying locally in jobs and the purchase of local goods and services." The project also adds economic benefit nationally in the purchase of products used to build the wind farm, he says.

> "The Highland wind farm is about a 150 million US dollar investment in a local community."
>
> DANIEL LAGIOVANE, PROJECT COMMUNICATION MANAGER AT EVERPOWER

**The control centre of the Highland wind farm.**

**IN ORDER FOR** EverPower to run a productive and profitable operation, downtime must be reduced to a minimum. And in making sure that the Highland wind turbines are spinning when winds are strong, Bennett and Foy look to the SKF WindCon remote monitoring system, which is installed in all 25 turbines, monitoring, analyzing and compiling the mechanical data and providing a performance overview.

"The SKF WindCon system gives us foresight," says Foy. "We can know a problem before it happens, whether it will be three or six or even 12 months down the road."

Lagiovane adds: "If something happens, you can't run down to the local hardware store for parts. It can take days to get the parts, so the better we are at maintenance, the fewer major breakdowns we have, and we can keep the turbines going and operating as efficiently as possible and for as long as possible." ●

**The EverPower Highland wind farm is located in the US countryside in southwestern Pennsylvania.**


## SKF WindCon benefits include:

- Extended maintenance intervals
- Consolidated maintenance activities and prolonged repairs
- Reduced operating costs and costs per kWh
- Reduced risk of unplanned shutdowns and lost energy production
- Ability to predict remaining service life by turbine
- Remote monitoring of operating conditions via the Web
- Interface with SKF automatic lubrication system, WindLub, for monitoring lubrication conditions
- Display of particle size distribution according to ISO standards, which enables online oil condition monitoring
- Integrated software with new displays and tools, providing easier review of data.

SKF WindCon can be installed on all turbine sizes and types, on land and sea.

### SKF WindCon at the hub

By enabling operators to monitor and track deteriorating component conditions in real time, SKF WindCon enables maintenance decisions to be based on actual machine conditions rather than arbitrary maintenance schedules. Along with the possibility that maintenance intervals can be extended, the system provides a powerful tool for managing day-to-day maintenance routines and consolidating risky, costly maintenance activities.

Engineering company Sincro Mecánica helps to make sure ageing turbines stay productive at Spain's leading wind farms.

A wind farm in Galicia in northwestern Spain.



# Spin doctors

**TEXT AND PHOTOS** RICHARD SURMAN

In Spain, many wind farms are situated in remote, rugged, mountainous terrain, where generators are subjected to harsh environmental conditions. Improved pitch technology – the ability to alter the angle of the blades to deal with variable wind speed and power demands – places increasing strain on turbine powertrains, as does the installation of higher towers to take advantage of stronger winds. The need for top-quality, time-responsive maintenance and repair is paramount, especially for the mechanisms that translate rotation into power generation. Meanwhile, as Spain's wind turbine installations mature, many of the turbines are coming out of warranty. This is where Sincro Mecánica comes in.

Sincro Mecánica specializes in maintenance and repair of out-of-warranty wind power drivetrains, carrying out complex gearbox repairs both on-site and at the company's state-of-the-art plant in Narón, A Coruña. "There are close to 19,000 wind turbines installed nationally," says Operations Director Carlos Garabato Gándara. "Our growth is directly related to the number of generators that are coming out of warranty."

Sincro Mecánica is fully equipped to dismantle, ship and reinstall turbine machinery from the most remote sites, providing a total evaluation, strip-down and rebuild service that includes load testing

## SKF and wind power maintenance

**With the largest global network of authorized distributors, SKF is uniquely positioned to deliver tailor-made solutions for customers quickly and effectively. SKF supplies powertrain components and seals to Sincro Mecánica through its Certified Maintenance Partner (CMP) Epidor. SKF also delivers training solutions to Sincro Mecánica engineers.**

**With the SKF WindCon 3.0 condition monitoring system, operators can monitor the true condition of major wind turbine components in real time and implement cost-effective maintenance. SKF has applied this proprietary technology to more than 3,000 wind turbines worldwide.**

## SINCRO MECÁNICA

Sincro Mecánica, together with its sister companies Neodyn, Intaf, Evolventia and Tecman, is part of a multidisciplinary engineering group with origins in the 1940s.

The group first entered the wind-sector engineering field in 1985, with Intaf and Neodyn manufacturing components.

Tecman became involved in 2007, providing a comprehensive engineering management service for wind farms in Spain.

In 2009, an increase in the amount of repairs and servicing carried out by Tecman led to the founding of Sincro Mecánica, which specializes in the repair and servicing of wind turbine transmission equipment.

The company recently opened a state-of-the-art engineering plant and head office in Ferrol-Narón, where it employs a staff of 170 and has capacity to repair 200 machines per year.

The average turnover of the group in 2010 and 2011 was about 13 million euros.

*www.sincromecanica.es*

**Above: The repair hall at Sincro Mecánica.**
**Left: Operations Director Carlos Garabato Gándara.**

and reverse engineering (for cases in which original specifications and plans are not available). The company's engineers also provide on-site predictive maintenance using visual and remote inspections, vibration analysis and thermography to identify potential problems.

**SINCRO MECÁNICA'S** current capacity for turbine repairs is about 200 machines a year, and its management is optimistic about the future. Juan José Taibo, Sincro Mecánica's general manager, points out, "With the economic uncertainty in 2011 and 2012, maintenance and repair are better placed than manufacturing."

The market is becoming more aggressive and competitive, Taibo continues. "Since 2011 we have seen an increase in the turnover of operators of wind farms, and there is more competition in international manufacturing. But there are opportunities. We are developing strategic partnerships with wind turbine manufacturers with a view to undertake warranty repairs as well as expand our market share of out-of-warranty servicing and repairs."

"We've come a long way from the days of small mechanical projects in the 1940s," says the group's CEO, José Ramón Franco Caaveiro, "and although our emphasis at the moment is on the domestic market, our vision is to seize the potential of the global market. Our policy of long-term investment in plant, training and technological innovations is one from which all our customers will continue to benefit. Repairs and servicing are parallel to manufacturing, and with increasing efficiency we are able to stay competitive." ●

## Spanish wind power at full blast

**Spain has become a global leader in the growth of onshore wind-generated power, with a stable rate of growth that continues to defy global economic uncertainty. Spanish firms Acciona, Iberdrola and Gamesa Eolica – all Sincro Mecánica customers – are among the world's largest wind farm developers and operators. With steady annual growth in capacity (excluding a sharp downturn in 2009), Spain generated about 43,600 GWh of electricity from wind power in 2010, with the sector turning over almost 3 billion euros. Spain overtook Germany that year in terms of installed generating capacity and currently ranks fourth after China, India and the United States.**

**Challenges for the industry in Spain include improving and integrating the distribution system and developing offshore wind farms. Denmark and Britain, with a wider area of continental shelf than Spain, currently lead the offshore wind sector. They are putting considerable effort into developing the viability of floating generator towers.**

PHOTO: GETTY IMAGES

# Centralized lubrication system for wind turbines offers improved efficiency

A successful cooperation of companies within the SKF Group has led to the development of an improved pump unit for centralized lubrication systems for wind turbine applications.

Lubrication requirements for bearings in wind turbines have triggered a series of developments that further enhance the operation of SKF centralized lubrication systems. This has culminated in SKF developing a lubrication package for wind farms worldwide that increases the lifetime and reliability of these systems.

Some bearings in wind turbines require lubrication at predetermined intervals (fig. 1). To achieve this effectively, automatic centralized lubrication systems are required (fig. 2). A centralized lubrication system contains an KFG series pump unit from SKF, an electric filling pump, a pressure switch and a pump for the used lubricant (fig. 3).

## The KFG pump unit

The KFG pump unit (fig. 4) is a key component of the centralized lubrication system. Many aspects of the pump have been specifically optimized to meet the demands of the wind industry.

A significant improvement in the design is the option to fill the pump from the top. This feature enables a homogenous exchange of the lubricant, based on the “first in, first out” principle. The lubricant is fed into the system from the top and pumped out at the bottom. In earlier versions, the grease entered the system from the bottom, which meant that unused grease was able to accumulate in the upper part of the pump. A patent application for this top-filling design has been filed by SKF Lubrication Systems, Germany.

The new top-filling design also required a new concept for the grease follower piston (fig. 5), necessary for the correct operation of the rotary pump. The piston feeds highly viscous grease continuously to the pump contained in the pump housing. This new grease follower piston design, in turn, demanded a new concept for a customized, machined sealing solution . This was developed together with SKF Economos Deutschland GmbH, part of the SKF seals platform.

In order to implement this innovative filling method, both a new grease follower piston and the new K01-R ECOVAR sealing system were developed. The piston was designed so that the lubricant is fed through a distributor duct into the system with precise centricity from the top into the grease reservoir. This new design and the customized K01-R ECOVAR sealing system enable the grease follower piston to operate using various viscous lubricants suitable for different temperature ranges.

The new concept was the result of a unique SKF programme “Innovation in a Day”, in which components

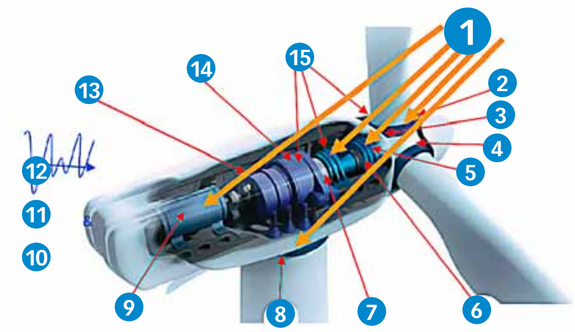



**Fig. 1: Key lubrication components and SKF’s contribution to optimize efficiency.**

**1** Automatic lubrication systems
**2** Pitch bearings
**3** Sealing solutions
**4** Plain bearings
**5** Main shaft bearing(s)
**6** Main shaft housings and locknuts
**7** Couplings
**8** Yaw bearing
**9** Generator bearings
**10** Maintenance tools and grease
**11** Mechanical repairs and refurbishment
**12** Monitoring and diagnostic services
**13** Condition monitoring SKF WindCon/WebCon
**14** Gearbox bearings
**15** Engineering consultancy services

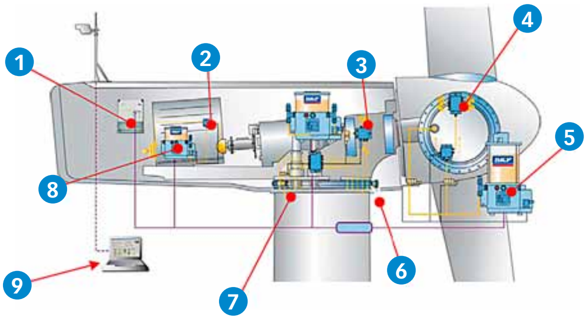



**Fig. 2: Inside view of a wind turbine, position of the central lubrication units.**

**1** SKF WindCon online condition monitoring system
**2** Progressive feeder with piston detector
**3** Progressive feeder with 2/2 direction valve and piston detector
**4** Progressive feeder
**5** Pump unit
**6** Pump unit
**7** Pump unit
**8** Lubrication pinion
**9** Remote monitoring visualization/ parameterization

KFG pump

Electric filling pump

Pressure switch

Pump for used lubricant

**Fig. 3: Main components of the central lubrication system.**

can be designed and produced within one day. This made it possible to quickly and effectively respond to challenges encountered during the trial phase.

## Benefits of the new design

The modular concept of the new KFG pump allows easy pump installation, as does the new reservoir concept, which enhances reliability, even when used in extreme conditions. Forcibly actuated pistons supply adequate volumes with substantial lubricants also at extremely low temperatures. This reduces maintenance requirements and increases reliability.

The exterior pump design was upgraded with aluminium profiles, which considerably improve the pump's stability and permit larger pump designs without problems. Currently, versions with reservoir sizes from 4 to 15 kg are available for rotary applications and in sizes up to 20 kg (fig. 6) for stationary operations.

## Demand-driven developments

The development of the pump was necessary to meet the increasing requirements of the wind industry. This new pump design meets corrosion requirements according to C5M, requested by offshore wind farm operators.

Design, material conformance and respective standards in compliance with C5M requirements have been confirmed by the issuance of the "Germanischer Lloyd Certification", DAA-GL-426-2010, on 14 September 2010 (fig. 7).

During the development of the pump, a large number of experiments were carried out to test the new functions. Various NLGI class 1 and 2 lubricants were tested for their continuous transport properties in temperature ranges between –30 °C and +70 °C. For example, it confirmed the constant functionality of the grease follower piston with the K01-R ECOVAR customized seal, irrespective of whether the pump rotates, is upside down

**Fig. 4: Top-filling KFG pump design.**


**1** Filler connection
**2** Filler tube
**3** Grease follower piston
**4** Magnetic tape
**5** Piston seal
**6** Aluminium profile

## Key improvements made to the new KFG pump:

- **Top-filling design of the pump units**
- **Grease follower piston featuring the K01-R ECOVAR customized sealing solution with integrated magnetic tape and receptacle for the filling tube**
- **Sturdy design using aluminium profiles also for very large pumps**
- **New reservoir concept with inserted pump elements enable an operating range from –30 °C to +70 °C and resistance up to –40°C**
- **Special flanges support the modular concept and allow easy pump installation**
- **The fluid level in the lubrication reservoir can be monitored using up to three external magnetic switches.**

or is in a horizontal position. After various prototypes were found to function without any problems, the pump was presented at the 2010 HUSUM WindEnergy trade fair in Germany. Almost concurrently, for a pilot project in China, a first run of 40 KFG pumps was delivered to Sinovel, China's largest wind turbine manufacturer.

As a supplement to the KFG pump, an electric filling pump has been developed that makes refilling the KFG pump from the top quick and easy (fig. 8). The electric filling pump requires an electric power supply, is mobile and can be transported easily by service teams from one wind turbine to the next. It significantly improves service and maintenance operations.

In conjunction with the other previously mentioned innovative SKF WindLub products, the development of the new KFG pump marks an important milestone in the development of centralized lubrication systems for wind power.

Special considerations for wind power applications include:

- C5 – corrosion protection
- Special approval for offshore use
- Convenient refilling with an electric pump
- Patented top-filling design
- Extensive temperature range from –30 °C to +70 °C
- Highly stable design.

## Conclusion

An efficient and successful cooperation between SKF Sealing Solutions and SKF Lubrication Systems has resulted in a new pump unit with outstanding and reliable lubrication capabilities for bearing applications in wind turbines, thus providing long service life and reducing maintenance requirements. ●

By *Stefan Schürmann, Manager Development Centre Hockenheim, SKF Lubrication Systems, Hockenheim, Germany*
*Peter Beckenbach, Technical sales, SKF Economos Germany, Erbach, Germany*
*Thomas Mayer, Seals business and Marcom manager, SKF Service Division, Judenburg, Austria*

**Summary**
SKF has developed a special pump unit that supplies the centralized lubrication system in wind turbines. The main component of the system consists of the KFG pump, an electric filling pump and a pressure switch. Unlike in earlier pump versions, the lubricant can be fed into the modified KFG pump unit from the top, avoiding an accumulation of grease in the upper part of the pump. The modular concept of the new KFG pump is suitable for use in a wide temperature range, enables larger pump designs and is easy to install.

The KFG pump unit also contains a new machined sealing concept for the grease follower piston. This new K01-R ECOVAR sealing concept was developed by SKF Economos Deutschland GmbH in cooperation with SKF Lubrication Systems Germany. The KFG pump can be refilled with a specially designed portable electric filling pump, thus significantly improving service and maintenance operations.

**Fig. 5: Grease follower piston with lubrication flow during the filling process.**

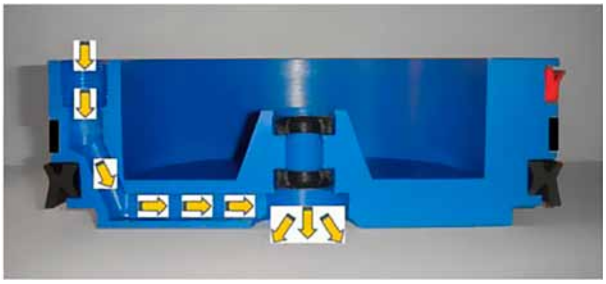
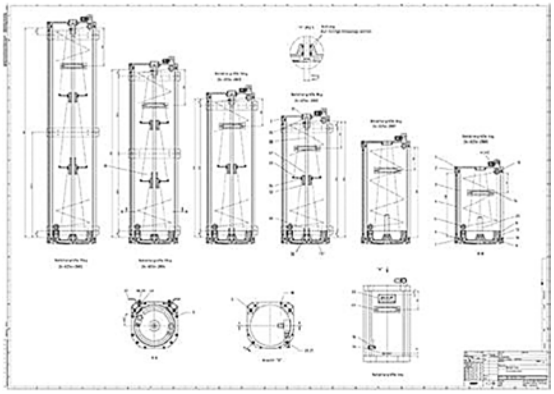


**Fig. 6: The modular concept enables the use of different reservoir sizes.**




◀ **Fig. 7: GL certificate.**

▶ **Fig. 8: Electric filling pump.**


# Reduce total cost of ownership at every stage of your turbine life cycle

SKF Life Cycle Management is a proven approach to maximizing machine productivity and minimizing total cost of ownership over every stage, from specification and design to operation and maintenance. Importantly, the knowledge gained from end user stages is fed back into this continuous improvement loop to benefit next generation assets.

Whether you're responsible for designing, operating or maintaining wind turbines, you can take advantage of SKF engineering and application knowledge to optimize designs and extend service life, maximize productivity, minimize maintenance, improve reliability and safety, and reduce total cost of energy production.

For more information about SKF solutions for the wind energy industry, visit **skf.com/wind.**

**The Power of Knowledge Engineering**