White Structure Flaking in Rolling Bearings for Wind Turbine Gearboxes

By Hideyuki Uyama and Hiroki Yamada, NSK Ltd.

An investigation into the failure modes yielding white structure flaking and axial cracking in wind turbine gearbox rolling bearings

Premature failures of rolling bearings occasionally occur in wind turbine gearboxes [1]. One of the main failure modes is flaking involving a microstructural change. This type of flaking is called white structure flaking (WSF) or white etching crack (WEC) because the area of the microstructural change observed in the flaking cross sections looks white after etching. Therefore, understanding the mechanism of white structure flaking is important for wind turbine gearbox reliability.

Flaking in rolling bearings occurs due to rolling contact fatigue and it is a similar phenomenon as spalling in gears. Flaking is generally classified to subsurface originated flaking, which is initiated at nonmetallic inclusions in materials and surface originated flaking, which occurs under contaminated or poor lubrication conditions [2]. However, recently white structure flaking can be seen in several applications, which is a different type of flaking from the subsurface and surface originated flaking mentioned above. For example, it is known that white structure flaking sometimes occurs in bearings for automotive electrical accessories as shown in Figure 1 [3]. There are many studies about the failure mechanism and the countermeasure for white structure flaking in automotive bearings. Some of them suggested that this type of flaking is induced by hydrogen generated by decomposition of the lubricating oil, grease, or water in the lubricant and that this phenomenon is concerned with hydrogen embrittlement [4] [5] [6] [7] [8] [9] [10] [11].

Axial cracks are also observed in failed bearings for wind turbine gear boxes [12]. This failure mode is very unique and it is seldom found in other applications. The same microstructural change as seen in white structure flaking is often observed in the cross sections around the axial cracks. However, it is unclear whether the mechanisms of white structure flaking and axial cracking are the same or not. In this study, rolling contact fatigue tests were performed in order to reproduce white structure flaking and axial cracking by using specimens charged with hydrogen. From the view of hydrogen theory, influ-

encing factors in operating conditions were discussed and effects of materials on bearing life were suggested as the countermeasure.

Observation results of failed bearings for wind turbine gearboxes

Failed bearings used in wind turbine gearboxes have been observed and two types of failures were mainly observed, which are classified as white structure flaking and axial cracking.

Figure 2 shows the observation results of a failed cylindrical roller bearing, which were used on the high speed shaft in wind turbine gearboxes. A small flaking was seen in the raceway surface as shown in Figure 2a. Figure 2b shows the cross section of the

ALSO IN THIS SECTION:

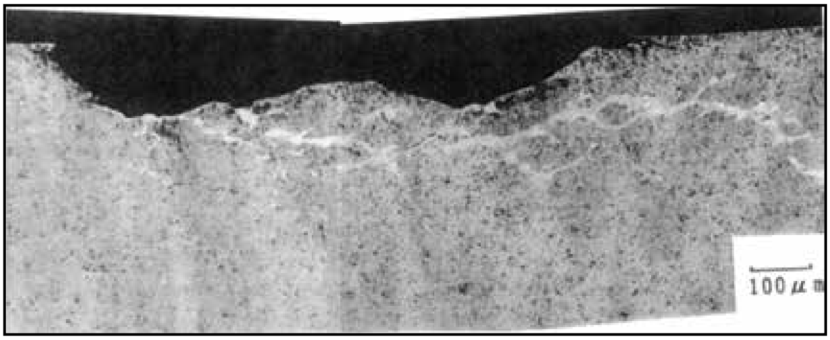

Figure 1: An example of the cross section of white structure flaking in an automotive electrical accessory bearing [3]

flaking area at the dotted line in Figure 2a. A microstructural change called white structure was observed at the flaking. Flaking morphology of failed bearings in wind turbine gearbox and automotive electrical accessories seem to be very similar as shown in Figure 1 and Figure 2b although bearing types and size are quite different. Namely, small size ball bearings are used for automotive electrical accessory and large size roller bearings are used for wind turbine gearboxes. Figure 2c shows the cross section of an area without flaking in the same bearing as shown in Figures 2a and 2b. White structure was observed even in this area, which is most likely to be the prior stage to flaking. Therefore it is presumed that this type of flaking in wind turbine gearboxes is initiated at the white structure.

Figure 3 shows the observation results of the other failed bearing, which is also a cylindrical roller bearing and used on the high speed shaft in wind turbine gearboxes. There were several large cracks longer than 10 mm and many small cracks around 1-3 mm in the axial direction on the raceway surface of the inner ring. Figure 3a shows two small cracks chosen of many axial cracks, which were observed on the raceway surface. The small cracks seem to be an early stage of crack propagation. A small axial crack was chosen for the cross section observation because small cracks

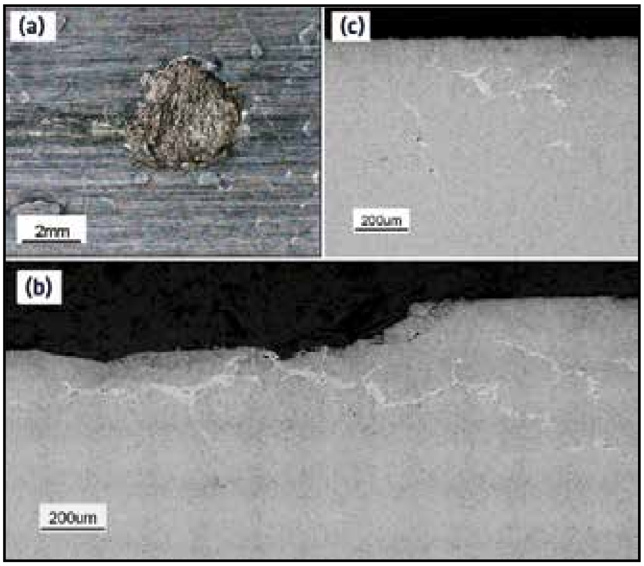

Figure 2: The raceway and the cross section of a failed bearing with white structure. a) Raceway surface of flaking area b) Cross section of the dotted line in Figure 2a c) Cross section of no flaking area

are easier than large cracks to find the location of the crack initiation. Figure 3b shows the cross section including the small axial crack area. White structure was seen and it is seemed that a crack propagated along the white structure and reached the raceway surface. This crack is seen as the axial crack on the raceway surface.

Rolling Contact Fatigue Tests to Reproduce White Structure Flaking and Axial Cracking

Reproduction of the bearing failure mode is important to know the failure mechanism and to find the most appropriate countermeasure. We carried out two kinds of rolling contact fatigue tests in order to reproduce white structure flaking and the axial cracks. Hydrogen is utilized in these tests because microstructural changes called white structure were seen in both of these failure modes.

Experiment to Reproduce White Structure Flaking

Flat disk type specimens with a diameter of 65 mm and a thickness of 6 mm were used in rolling contact fatigue test. The specimens were made of JIS-SUJ2 bearing steel, equivalent to SAE52100 and DIN-100Cr6. The specimens were quenched and tempered to produce a final hardness of 740 HV and the surface was ground and then lapped.

Before rolling contact fatigue testing, the specimens were charged with hydrogen by immersing them inNH4SCN aqueous solution at 323 K for 24 h.

The specimens were immediately assembled into the thrust bearing test machine after having been charged with hydrogen as shown in Figure 4. The upper race was a 51305 thrust bearing ring and the lower race was the specimen mentioned above. The rolling elements were 6 balls with a diameter of 9.525 mm. The retainer used was made of brass. The lubricating oil used was ISO-VG68. The maximum contact pressure was 3.8 GPa and the rotating speed was 1000 min-1.

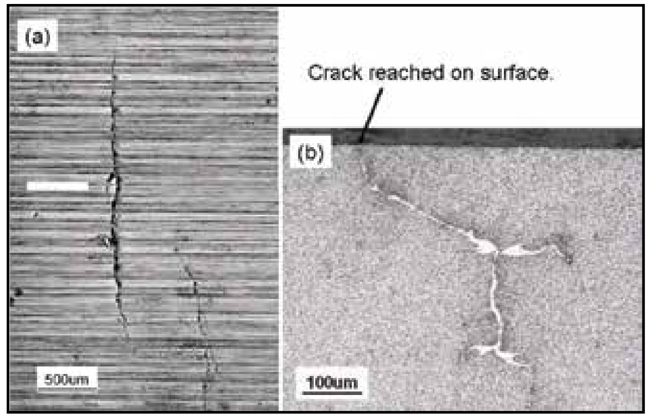

Figure 3: The raceway surface and the cross section of a failed bearing with axial cracks. a) Axial cracks on the raceway surface b) The cross section through the cracks

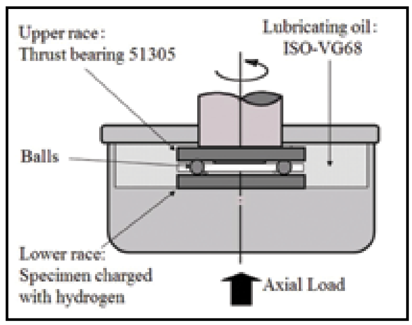

Figure 4: Schematic of the thrust type rolling contact fatigue test machine

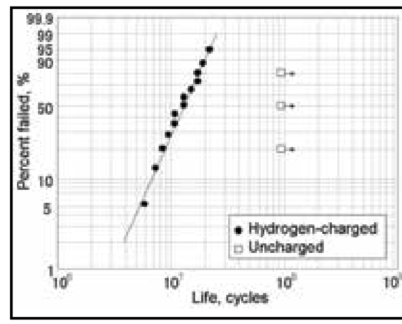

Figure 5: The results of thrust type rolling contact fatigue tests

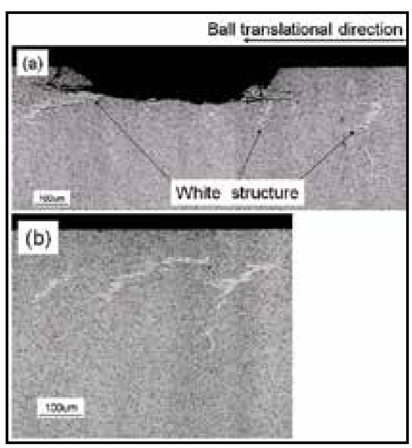

Figure 6: The cross section of hydrogen-charged specimen a) Flaking area b) No flaking area

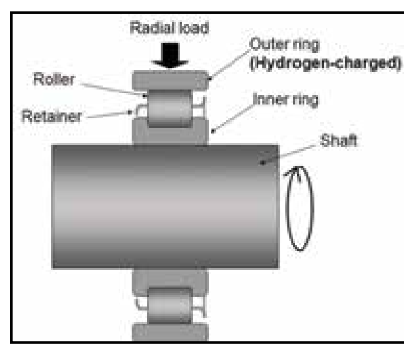

Figure 7: A schematic of radial type bearing test machine

Test Result of Rolling Contact Fatigue to Reproduce White Structure Flaking

Figure 5 shows the result of thrust type rolling contact fatigue tests using the hydrogen-charged specimen and uncharged specimen. Flaking occurred in the hydrogen-charged specimens, and the rolling contact fatigue life was much shorter than in the uncharged specimen.

Figure 6a shows the microstructure of the flaking cross section in the hydrogen-charged specimen. White structure was observed around the flaking area. White structure was observed also in the cross section of an area without flaking as shown in Figure 6b. Therefore, it is presumed that this flaking was initiated from white structure formed subsurface. On the other hand, flaking did not occur and the tests were suspended in the uncharged specimen. There was no microstructural change in the uncharged specimen. Therefore, it is presumed that hydrogen induced microstructural change and decreased rolling contact fatigue life.

It seems that these microstructural changes observed in the rolling contact fatigue tests using hydrogen- charged specimens are the same microstructure as seen in failed bearings of wind turbine gearboxes and automotive electrical accessories. It is reported that hydrogen enhances localized plasticity and this mechanism is known as the HELP theory [13]. Therefore, it is supposed that white structure represents a local-

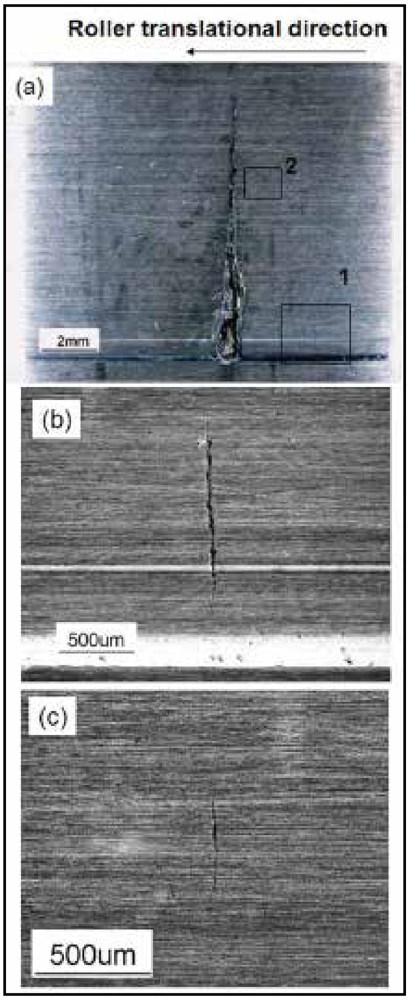

Figure 8: The raceway surface of the hydrogen-charged outer ring a) Large axial crack b) Magnification of position 1 in Figure 8a c) Magnification of position 2

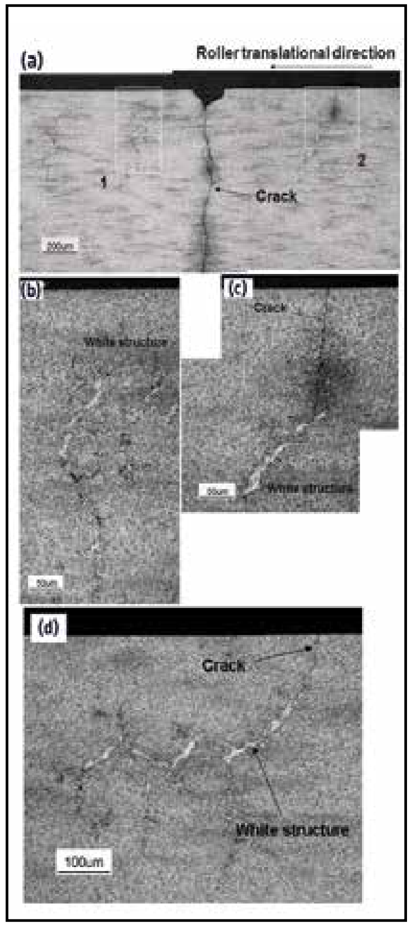

Figure 9: The cross section of the cracked area of a hydrogen-charged outer ring a) The cross section of position 2 in Figure 8a; b) Magnification of position 1 in Figure 9a; c) Magnification of position 2 in Figure 9a; d) The cross section of the small crack in Figure 8b

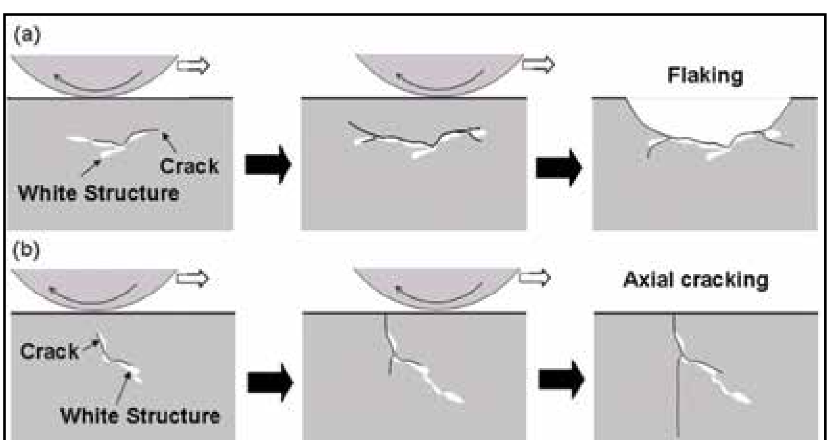

Figure 10: Schematics of the failure process of white structure flaking and axial cracking a) The case of flaking b) The case of axial cracking

ized microstructural change by interaction between cyclic plasticity and hydrogen in the rolling contact fatigue process [11].

Experiment to Reproduce the Axial Cracks

Cylindrical roller bearings are used for the experiment to reproduce the axial cracks, because they are often used for wind turbine gearboxes and the axial cracks have not been seen in ball bearings. Although, white structure flaking has been observed in ball bearings. Bearing number of N308 made of JIS-SUJ2 bearing steel, equivalent to SAE 52100, were used as the test bearings with a bore diameter of 40 mm and an outside diameter of 90 mm. Only the outer ring was separated and charged with hydrogen by the same method mentioned previously and the inner ring and the rollers were uncharged, and then the test bearing was set on the radial type bearing test machine as shown in Figure 7. The reason why the outer ring was chosen for hydrogen charge is that hydrogen in the outer ring is more difficult to diffuse out of the steel than the inner ring as the temperature of outer rings are normally lower than of inner rings. The lubricating oil used was ISO-VG150. The maximum contact pressure on the outer raceway was 2.1 GPa and the rotating speed was 3000 min-1.

Test Result of Bearing Life Test to Reproduce Axial Cracks

Bearing life test of the hydrogen-charged bearing was stopped by detecting the vibration at the testing time of 280 h. On the other hand, the test of the uncharged bearing was suspended at the testing time of more than 1000 h because there was no sign of bearing failure.

Figure 8 shows the outer ring raceway surface which was charged with hydrogen. One large crack and two small cracks were observed. These cracks propagated straight in the axial direction and were identical to the axial cracks in the failed bearings of wind turbine gearboxes.

Figure 9a shows the cross sections of the cracking area including the position 2 in Figure 8a. The large crack propagated in the depth direction. White structure was observed independently in Figure 9a position 1 to the left of the large crack magnified in Figure 9b. And also, Figure 9c is the magnification of the position 2 in Figure 9a and including the small axial crack

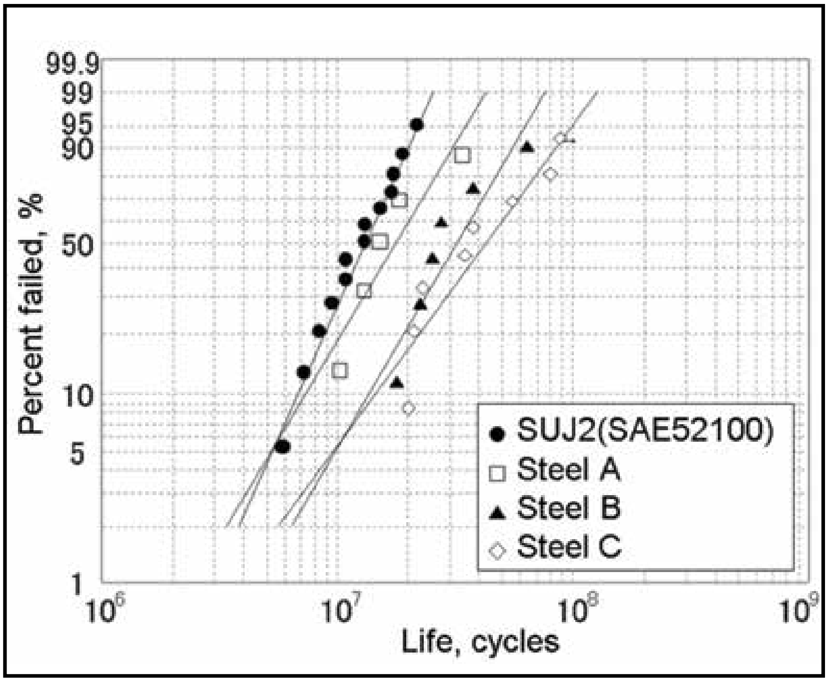

Figure 11: The effect of the chemical composition of steel on white structure flaking life

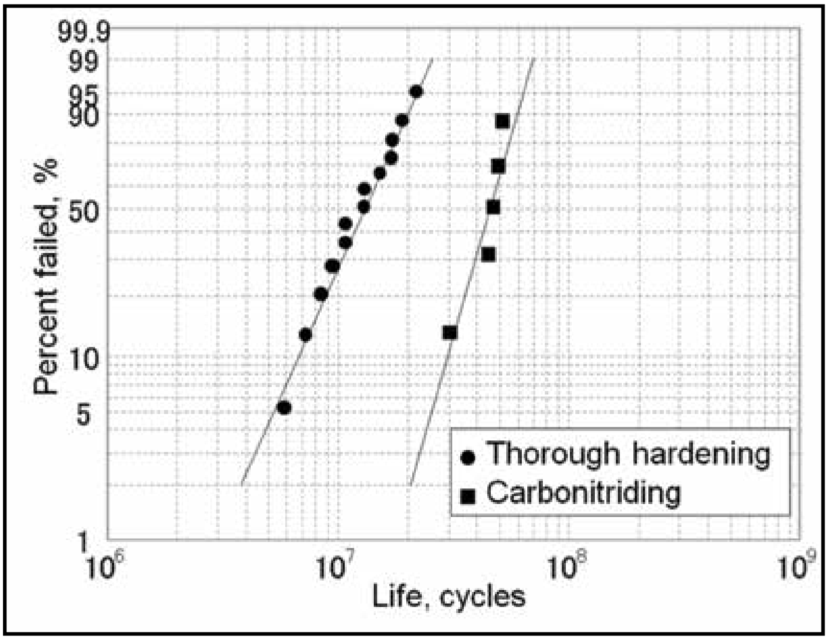

Figure 12: The effect of heat treatment on the white structure flaking life.

in Figure 8c. The small crack connected with white structure. Therefore it is supposed that white structure was formed first such as in Figure 9b and then a small crack initiated from the white structure and propagated to the raceway surface such as Figure 9c and finally the crack propagated in the axial and depth directions such as is visible in Figure 8a and Figure 9a. Figure 9d shows the cross section including the small axial crack in Figure 8b. White structure was observed also in this area and it seems that the crack initiated at the white structure and propagated to the surface.

However, white structure was not observed on the cross section of the large axial cracks. This reason is supposed that the initiation of the large axial crack would be white structure, but it is difficult to observe the cross section pinpointing the crack initiation. It is much easier to observe the cross section of the crack initiation in the small axial cracks.

Failure mode of the axial cracks is very unique and is seldom seen in other applications except for wind turbine gearboxes. However, it seems that the hydrogen-charge method does reproduce it. This method is very simple and the other effects on rolling contact fatigue are small. Therefore, it is supposed that axial cracks seen in wind turbine gearbox bearings are also caused by hydrogen. The patterns of white structure due to hydrogen are random, so that cracks along the white structure can propagate in various directions. It is supposed that some cracks mainly propagate in a horizontal direction to the rolling elements' translational direction and finally cause flaking, and that other cracks mainly grow in the vertical direction to the rolling element's translational direction and results in the axial cracks on the raceway surface as shown in Figure 10.

Operating condition inducing white structure flaking

The bearing failures in wind turbine gearboxes are more likely to be caused by hydrogen as shown in the rolling contact fatigue tests to reproduce white structure flaking and axial cracking. Therefore, it is important to know the causes of hydrogen generation and penetration into the bearing steel, although there is no direct evidence that hydrogen is generated and penetrated into the steel in wind turbine gearbox bearings. It is reported that hydrogen is generated by decomposition of lubricant and it is enhanced by the type of lubricant, water in the lubricant, slip, vibration, and electric current [3] [4] [5] [6] [7] [8] [9] [14]. These previous studies are mainly conducted for automotive bearings. However, influencing factors are basically common also to wind turbine gearbox bearings.

Type of Lubricant

It is reported that lubricant is decomposed by a chemical reaction with a fresh metal surface, which is formed by local metal-to-metal contact and thereby generates hydrogen [4] [5] [6] [7] [8] [9] [14]. Bearing life of white structure flaking is depending on additives included in the lubricant [4] [5] [8] [9] [14]. Some additives decrease bearing life and other additives increase it. The effect of extended life is more likely due to the oxidation film formed by a tribochemical reaction. Oxidation film can prevent a fresh metal surface from being exposed to lubricants and keeping the raceway surface chemically stable as some kinds of additives enhance to form the oxidation film on the fresh metal surface.

Slip and Vibration
Slip between rings and rolling elements and bearing vibration can cause local metal-to-metal contact resulting in the exposure of a fresh metal surface. In the study about automotive ball bearings, it is reported that white structure was not formed at the bottom center of the raceway where maximum contact pressure was subjected, but instead near the raceway shoulders where large differential slip occurred [6] [7] [9].

Slip between rings and rollers are relatively small in cylindrical roller bearings and tapered roller bearings, which are normally used for wind turbine gearboxes. However large slip may occur during rapid acceleration and deceleration of a rotating shaft.

Electric Current
The problem of white structure was well known first in bearings for automotive electrical accessories. Static electricity was believed as the cause of hydrogen generation because frictional electrification can occur between the pulley and the drive belt made of rubber. It is reported that ceramic ball and an insulated pulley to shut out electric current prevented white structure flaking and that the grease containing nano-carbon powders with conductivity was also very effective because it can keep static electricity neutralizing and prevent the electric discharge at metal-to-metal contact [8]. Electric discharge forms a fresh metal surface where the steel surface is locally melted by a spark.

Electrical corrosion in rolling bearings only occasionally occurs in generators of wind turbines [1]. Stray currents from the generator may affect gearbox bearings.

Effects of material on white structure flaking

Hydrogen is most likely to be a concern with bearing failures in wind turbine gearboxes as mentioned previously. Prevention of hydrogen generation and penetration into the bearing steel is very effective countermeasures for white structure flaking; however it is currently unclear which operating conditions induce wind turbine gearbox white structure failures. Material improvement with a strong resistance to hydrogen is also a candidate as another countermeasure.

Effect of Chemical Composition of Steel
Figure 11 shows the result of a rolling contact fatigue test using the flat disk specimens charged with hydrogen and the thrust type rolling contact fatigue test machine in the same way as shown in Fig. 4. Four kinds of steels were used for the specimens; JIS-SUJ2 equivalent to SAE52100, steel A , B and C. Chemical compositions were different in them; steel A contains more Mn, steel B contains more Si and steel C contains more Cr. Rolling contact fatigue life of steel A, B and C were extended comparing to JIS- SUJ2. This result suggests that white structure flaking life can be extended by improvement of chemical composition of steel and it can delay formation of the white structure.

Effect of Heat Treatment
Figure 12 shows the result of a rolling contact fatigue test using hydrogen-charged specimens in the same way. Two kind of specimens with the same chemical composition of steel (JIS-SUJ2) and a different heat treatment were used, namely one data set used was through hardened specimens and the other was carbonitriding specimens. The rolling contact fatigue life of the carbonitriding specimens was longer than the through hardened specimens. It is supposed that compressive residual stress and larger amounts of retained austenite near the surface, which were formed by the carbonitriding heat treatment were effective against white structure flaking. Compressive residual stress can delay crack propagation initiated at the white structure, resulting in an extended time from crack initiation to flaking. Retained austenite can delay hydrogen from concentrating in high subsurface shear stress areas because the hydrogen diffusion rate in an austenitic structure is much slower than in a martensitic structure [15].

These results suggest that an optimum combination of chemical composition of the steel and heat treatment condition can produce long life bearings resistant to the formation of white structure flaking.

Conclusions

The following conclusions were obtained from investigating failed bearings in wind turbine gearboxes, conducting rolling contact fatigue tests to reproduce the failure modes, and estimating material effects on the flaking life.

1. Failure modes of wind turbine gearbox bearings were mainly

classified as white structure flaking and axial cracking on the raceway. Both of them were involving a microstructural change called white structure.
2. White structure flaking and the axial cracking were reproduced by using specimens charged with hydrogen in rolling contact fatigue tests. The axial cracks also seem to be initiated at the white structure. Therefore it is supposed that both failure modes in wind turbine gearbox bearings were caused by hydrogen.
3. Additives in lubricants, slip, vibration and electric current can induce hydrogen generation by decomposing lubricant and penetrating into the bearing steel, although there is no direct evidence of this in wind turbine gearbox bearings.
4. Improvement of the chemical composition of steel can extend the white structure flaking life and it is supposed that the suitable addition of the alloying elements delays the progression of microstructural change. Carbonitriding heat treatment was also effective against the formation of white structure flaking, because it is presumed that compressive residual stress near the surface can delay crack propagation and larger amounts of retained austenite can delay hydrogen concentration in areas of high shear stress.

References

1. Evans, M.H., White structure flaking (WFS) in wind turbine gearbox bearings: effects of butterflies and white etching cracks (WECs), Material Science and Technology, 28, 1, pp.3-22 (2012).
2. Furumura, K., Murakami, Y., Abe, T., The Development of Bearing Steels for Long Life Rolling Bearings under Clean Lubrication and Contaminated Lubrication, Proceedings of 4th International Symposium on Bearing Steels, San Diego, Creative Use of Bearing Steels, ASTM STP 1195, pp.199-210 (1993).
3. Murakami, Y., Long Life Bearings for Automotive Alternator Applications, SAE Technical Paper Series, 950944, pp. 1-14 (1995).
4. Kohara, M., Kawamura, T., Egami, M., Study on Mechanism of Hydrogen Generation fromLubricants, Tribology Transactions, 49, pp. 53-60 (2006).
5. Tamada, K., Tanaka, H., Occurrence of Brittle Flaking on Bearings Used for Automotive ElectricalInstruments and Auxiliary Devices, Wear, 199, pp. 245-252 (1996).
6. Kino, N., Otani, K., The Influence of Hydrogen on Rolling Contact Fatigue Life and Its Improvement, JSAE Review, 24, pp. 289-294 (2003).
7. Fujita, S., Mitamura, N., Murakami, Y., Research of New Factors Affecting Rolling Contact FatigueLife, Proceedings of WTC 2005, Washington, 63400 (2005).
8. Iso, K., Yokouchi, A., Takemura, H., Research Work for Clarifying the Mechanism of White Structure Flaking and Extending the Life of Bearings, SAE Technical Paper Series, 2005-01-1868, pp. 1-11 (2005).
9. Tanaka, S., Pulley Support Bearings for Push-Belt CVTs, NSK Technical Journal Motion & Control,19, pp. 13-19 (2006).
10. Fujita, S., Uchida, H., Tanaka, S., Long-Life Materials Countering White Structure Flaking, NSK Technical Journal Motion & Control, 19, pp. 20-26 (2006).
11. Uyama, H., Yamada, H., Hidaka, H., Mitamura, N., The Effects of Hydrogen on Microstructural Change and Surface Originated Flaking in Rolling Contact Fatigue, Tribology Online, 6, 2, pp. 123-132 (2011).
12. Gegner, J., The Bearing Axial Cracks Root Cause Hypothesis of Frictional Surface Crack Initiation and Corrosion Fatigue Driven Crack Growth, NREL Work Shop, Wind Turbine Tribology Seminar, Broomfield, November 2011.
13. Birnbaum, H.K., Sofronis, P., Hydrogen Enhanced Localized Plasticity – a Mechanism for HydrogenRelated Fracture, Materials Science and Engineering, A176, pp.191-202 (1994).
14. Lu, R., Nanao, H., Kobayashi, K., Kubo, T., Mori, S., Effect of Lubricant Additives on Tribochemical Decomposition of Hydrocarbon Oil on Nascent Steel Surfaces, Journal of the Japan Petroleum Institute, 53, 1, pp.55-60 (2010).
15. Fisher, D.J., Hydrogen Diffusion in Metals, Scitec Publication, Switzerland (1999).