Rolling Contact Fatigue and Fracture Toughness of Rolling Element Bearing Materials*

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To clarify rolling contact fatigue strength in terms of fracture mechanics, various flaking modes in practical rolling bearings, the relationship between rolling contact fatigue life and fracture toughness in Mode I, and recent studies on crack initiation and propagation through fracture mechanics are reviewed. Surface-origin-type flaking is becoming more important than the traditional subsurface-origin type as nonmetallic inclusion in steels is reduced. A new flaking mechanism wherein tensile residual stress in the radial direction in the subsurface initiates cracking has emerged and was verified by an experiment. Another new type of flaking, referred to as brittle flaking, was reported; here cracks are remarkably numerous, large and deep, accompanied by a new type of microstructural change. The cause of the brittle flaking was assumed to be tribological reaction on the raceway which decomposes the lubricant to cause hydrogen embrittlement. To establish a new bearing life calculation equation, it is necessary to create proper models for the various failure modes and to measure fracture toughness in Mode II.

Key Words : Tribology, Fracture Mechanics, Fracture Toughness, Contact Problem, Rolling Bearing

1. Introduction

Rolling contact fatigue is a cracking phenomenon where cracks initiate and propagate by repeated contact stress and terminate with flaking or spalling. Therefore, a quantitative solution for the flaking mechanism, using fracture mechanics, would be useful. This seems very difficult, however, since the stresses are three dimensional, the fatigue phenomenon is combined with the creation of contact residual stress and microstructural changes, and lubrication effects have to be taken into account. In addition, although the flaking model (subsurface-origin type) which was established in the 1940s by Lundberg and Palmgren⁽¹⁾, is still the basic model used today, many researchers are now indicating that surface-origin flaking is more important than the traditional subsurface-origin

model. Therefore, a new precise model of surface-origin flaking must be established. Recently, with the development of computers, studies on the crack propagation mechanism of surface and subsurface cracks using fracture mechanics have been increasing. However, these seem to be only at the initial stage.

On the other hand, speaking from a practical viewpoint, bearing fatigue life has increased remarkably with improvements in steel manufacturing technology. Nonmetallic inclusions found in steel have decreased, reducing the source of stress concentrations. Today, studies aiming to prolong bearing fatigue life by modifying the chemical compositions of the materials are very active. Problems arise when we try to explain the prolonged life in terms of fracture mechanics. The relationship between rolling contact fatigue strength and fracture toughness needs to be determined. Moreover, no values have been published on the fracture toughness (K_{IIC}) of Mode II.

This paper reviews various flaking modes of practical bearings, reviews studies on crack initiation and propagation through fracture mechanics, and

* Received 8th May, 1992

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looks at the relationship between the rolling contact fatigue life and fracture toughness of Mode I, to supply references for future clarification of rolling contact fatigue strength in terms of fracture mechanics.

2. Flaking Modes

2.1 Subsurface-origin type

The theory proposed in the 1940s by Lundberg and Palmgren⁽¹⁾ states that the orthogonal shear stress acting parallel to the surface and having the largest stress amplitude is the main stress in the mechanism of rolling contact fatigue. Since cracks initiating in the subsurface at nonmetallic inclusions were found, this theory has been generally accepted. Today, though, subsurface initiated flaking seems to be less of an influence on bearing life, as the size of nonmetallic inclusions becomes smaller. Surface defects are thought to have a greater influence on crack initiation.

On the other hand, some researchers consider the maximum shear stress to have the largest influence on rolling contact fatigue life. Residual stress created during rolling contact fatigue is influenced by the maximum shear stress acting 45° to the surface. A kind of microstructural alternation, a butterfly, initi-

ates around nonmetallic inclusions at 45° angles to the surface⁽²⁾. Also, there are other microstructural changes which are associated with specific angles, such as 30° and 80° ⁽³⁾. All of these factors make it difficult to identify the stress which has the most influence on rolling contact fatigue cracking.

On the other hand, a new theory has emerged which states that a tensile residual stress in the radial direction is the reason for crack initiation. It is recognized that cracks initiate readily when contact stress is repeatedly applied to a place subjected to tensile stresses, such as hoop stress or tensile residual stress due to a grinding burn⁽⁴⁾. In the same manner, the new theory states that a tensile residual stress which is created in the subsurface to balance the residual compressive stress during rolling contact fatigue causes cracking⁽⁵⁾. Maeda et al. verified this theory using specimens, in which large compressive residual stress in the tangential direction was created in the subsurface before testing to produce tensile residual stresses in the radial direction. These tensile residual stresses in the radial direction were found to cause cracking in the subsurface during rolling contact fatigue⁽⁶⁾.

2.2 Surface-origin type

Peeling and crevasse-type cracks are the most important types of surface-origin flaking. Peeling is an accumulation of cracks which initiate on a surface of a specimen when the mating specimen is rough. The cracks are less than 50 micrometers in length and less than 10 micrometers in depth (Photo 1). However, the mechanism for cracking is not well understood. Peeling initiates rather readily on needle rollers, which usually roll on the rough surface of a shaft. According to Akamatsu, the early stages of peeling damage occur very soon after a smooth surface comes into contact with a rough surface⁽⁷⁾. Even if the smooth surface is then brought into contact with another smooth surface, peeling will occur because the initial damage was done when the sample was in contact with the rough surface. A quantitative mea-

Photo 1(a) Appearance of peeling ($\times 100$)

Photo 1(b) Cross section of Photo 1(a) ($\times 500$)

surement of the damage to the material before peeling was initiated is needed. An investigation regarding crack directions has been done using X-ray measurement⁽⁸⁾, but further investigation is necessary.

Photo 2(a) Crevasse-type crack ($\times 100$)

Crevasse-type cracks are cracks which initiate in front of debris indentations, as in Photo 2⁽⁹⁾. The crack always seem to initiate at the front of the indentation and not at the side of the indentation. Ball bearings are more apt to fail from this type of flaking. Shimizu et al. are investigating the mechanism of this type of cracking by evaluating three-dimensional residual stress in terms of X-ray diffraction measurements⁽¹⁰⁾.

2.3 Brittle flaking

Maeda et al. published a paper concerning a different type of flaking which was initiated in the stationary ring of a grease-lubricated ball bearing when it was operated under specific conditions⁽¹¹⁾. A new type of microstructural change occurred in the subsurface, resulting in short life. This new type of flaking mechanism will be referred to as brittle flaking in this paper.

A circumferential cross section of an outer ring from a ball bearing is shown in Photo 3 and is an example of brittle flaking. Although the flaking size is small, the cracks within the material are remarkably numerous, large and deep. To elucidate the progress of this type of flaking, bearing tests were performed. Photos 4(a)-(d) are the results of the tests. When

Photo 2(b) Cross section of Photo 2(a) ($\times 500$)

Photo 3 An example of brittle flaking, cross section ($\times 100$)

the test time was relatively short, an easily etched microstructure was randomly generated. The microstructures are called "black needles". The black needles have a crack in them, as shown in the magnified view in Photo 4(b). After extended running time, the black needles increased in number and accumulated in areas, as in Photo 4(c). When the bearing was heated to over 300°C, the black needles turned into a constituent that was barely etched. It is necessary to clarify the true structure of these easy- and hard-to-etch constituents.

This type of microstructural change was reproduced in a rolling contact fatigue test using a specimen which had been charged with hydrogen by electrolysis of water. It was also found that the microstructural change could be prevented by applying an oxide treatment to the raceway prior to testing. Therefore, the cause of this phenomenon was believed to be a tribochemical reaction on the raceway which decomposed the grease and generated hydrogen, which penetrated into the steel to cause hydrogen embrittlement⁽¹¹⁾.

The fact that black needles turn to a white etching structure upon heating to 300°C, as mentioned above, appeared to be related to the formation of butterflies. Therefore, further studies were attempted. Photo 5(a) shows microstructure of a chromium-

plated specimen after rolling contact fatigue testing. Black needles are initiated around nonmetallic inclusions. This specimen was heated to 300°C in an electric furnace and slowly cooled (Photo 5(b)). Butterflies were observed. Butterflies are thought to be a rehardened structure. However, in spite of the facts that in this case the temperature was not high enough for rehardening and the cooling was as slow as furnace cooling, butterflies were formed. A new explanation is needed for the formation of a butterfly.

3. Fracture of Bearings

The inner ring of a bearing can often have a hoop stress created as a result of being press-fitted onto a shaft. When the press fit is tight, even if the load is light, the inner ring can fracture⁽⁹⁾. Fracture of rolling elements, such as balls and rollers, is rare. Carburized rollers, though, used under excessive loads can crack in their core and then fracture (Photo 6)⁽¹²⁾. Outer rings can fracture under excessive load by the tensile residual stress created in the core to balance the compressive residual stress in the subsurface⁽⁹⁾.

Regarding the inner ring, identification of the applied stress is easy, and the presumption of the cause of a fracture using fracture mechanics has been tried as follows. Photo 7 shows the fracture surface of a spherical roller bearing inner ring⁽¹³⁾. The origin of

(a) Black needle

(b) Magnified view of black needle

(c) Accumulation of black needle

(d) Hard-to-etch white structure, changed from (c) by heating to 400°C

Photo 4 Microstructural change leading to brittle flaking

Photo 5(a) Microstructural change during rolling contact fatigue of chromium-plated specimen ($\times 200$)

Photo 5(b) Butterflies (arrow) in the specimen in Photo (a), produced by heating to 300°C ($\times 400$)

Photo 7(a) Fracture in axial direction of spherical roller inner ring ($\times 0.8$)

Photo 6 Cracking in the core of 12 mm diameter roller ($\times 5$)

Photo 7(b) Magnification of the origin (arrow) in Photo 7 (a) ($\times 5$)

the fracture is a smear on the raceway. The crack propagated to 69 mm in an axial direction and 16 mm in the depth direction before rapid fracture occurred. From the condition of rapid fracture, $K_{Ic} = F\sigma\sqrt{\pi a}$, the fracture stress is estimated. The initial crack propagation is a zigzag pattern (Photo 7(b)), which agrees with the theoretical estimate for crack propa-

gation when shear stress and hoop stress are applied, as will be discussed in section 6.

4. Fracture Toughness Values of Various Bearing Materials

In order to quantitatively estimate the conditions which caused the fracture of an inner ring through the use of fracture mechanics, as mentioned in section 3, fracture toughness values of various bearing steels were obtained⁽¹⁴⁾. The results are shown in Table 1. The K_{Ic} value of a fractured bearing can be estimated from the residual stress value measured on the fracture surface, using X-ray diffraction. As an example, the relationship⁽¹⁵⁾ between residual stress on the fractured surface and K_{Ic} for through-hardened ball bearing steels (JIS SUJ 2 and SUJ 3) is shown in Fig. 1.

5. Relationship between Fracture Toughness and Rolling Contact Fatigue Life

If we consider the mechanism of flaking as fatigue due to repeated shear stress, the fracture toughness of Mode II (K_{IIc}) is necessary. However, it is very difficult to fracture high-hardness steel by Mode II shear stress, as mentioned before. Recently, Otsuka tried to measure the K_{IIc} of high-hardness materials⁽¹⁶⁾. No other reports have been published thus far. Therefore, the relationship between fracture toughness in Mode I and rolling contact fatigue life was examined.

Using specimens made from SUJ 3 and varying the cooling rate of the quench, a rolling contact fatigue test was conducted⁽¹⁷⁾, and the results are shown in Table 2. This test was conducted 15 years ago. The test lives were very low compared to those of today's steels because of a large difference in nonmetallic inclusion content, which had a significant effect on the rolling contact fatigue life. The rolling contact fatigue life varied widely with the rate of quenching. The life was much longer for specimens quenched at a lower quench rate. The relationship between crack sensitivity⁽¹⁸⁾, which relates to fracture toughness, and quench rate is shown in Fig. 2. As the quench rate is reduced, the crack sensitivity becomes lower and therefore, fracture toughness increases. On the basis of the information in Table 2 and Fig. 2, it is thought that there may be a relationship between fracture toughness K_{Ic} and rolling contact fatigue life for certain steels.

However, the K_{Ic} values listed in Table 1 for various kinds of steels cannot be correlated with rolling contact fatigue life. This is because as hardness increases, fracture toughness decreases, but rolling contact fatigue life increases. If K_{IIc} increased

with an increase in hardness, then it might be possible to correlate the rolling contact fatigue life with K_{IIc} . Thus, the K_{IIc} measurement is necessary.

Table 1 Fracture toughness K_{Ic} of various bearing steels and residual stress measurements taken on the fracture surface

Type of steel	Test temperature	Hardness (HRC)	K_{Ic} (MPa $m^{1/2}$)	Residual stress on fracture surface
SUJ 2	Room temp.	61-62.5	16.3 (n=8)	+270, +200 (MPa)
SUJ 3	Room temp.	62.5-63	15.7 (n=5)	+100
	-195°C		16.5 (n=3)	-
	100°C	60	16.3	+240
	200°C	58	17.8	+340
	300°C	50	21.3	+720
M 50	Room temp.	60-60.5	16.5 (n=5)	+290, +290
	100°C		18.5 (n=2)	+480, +540
	200°C		22.5 (n=2)	+540, +640
	300°C		24.5 (n=2)	+540, +740
	400°C		26.0 (n=2)	-
T 1	Room temp.		16.4 (n=2)	+190, +240
	100°C		17.5 (n=2)	+280, +440
	200°C		20.0 (n=2)	+240, +340
	300°C		21.6 (n=2)	+340, +440
SUS 440C	Room temp.	58-58.5	21.1 (n=6)	+240, +220
SKH 9	Room temp.		17.7 (n=2)	+140, +240
	100°C	60-60.5	20.4 (n=2)	+280, +290
	200°C		22.8 (n=2)	+280, +340
	300°C		21.4 (n=2)	+350, +440

Table 2 Rolling contact fatigue life of specimens, 12 mm in diameter and 22 mm in length, made from SUJ 3, quenched with various cooling rates

Cooling rate	Hardness (HRC)	No. of specimens	Life (loading cycles, $\times 10^4$)	
			10% life	50% life
$t_p = 350 - 500 \text{ mV}$	61.0-62.0	16	164	4920
$t_p = 700 - 900 \text{ mV}$	61.0-62.0	18	975	8010
$t_p = 1000 - 1100 \text{ mV}$	61.0-62.0	18	2190	9350
$t_p = 1300 - 1500 \text{ mV}$	61.0-62.0	16	4620	9690

Fig. 1 Relationship between residual stress on the fracture surface and fracture toughness K_{Ic} for SUJ 2 and SUJ 3

Fig. 2 Relationship between crack sensitivity and cooling rate. The quench rate was changed by changing oil temperature and severity of quench. t_p (in mV) indicates cooling rate. Cooling rate increases as t_p increases.

6. Research on Crack Initiation and Propagation

Material fracture is divided into two stages, crack initiation and crack propagation. Zhou et al.⁽¹⁹⁾, using SAE 52100 and 4118 steels, performed pitting experiments to obtain necessary material constants and then calculated strain energy based on dislocation theory. He assumed that a surface crack initiates when the strain energy reaches a critical value. When crack propagation was calculated from the strain energy release rate, the number of loading cycles to crack initiation was found to be three times as great as the number of loading cycles from crack initiation to flaking when the contact stress was small ($P_{\max} = 1.75$ GPa). When the contact stress was large, the number of loading cycles for crack propagation was larger than the number of loading cycles for crack initiation. However, it is generally thought that crack initiation occupies the majority of the life in the case of subsurface flaking⁽²⁰⁾.

Keer and Bryant⁽²¹⁾, and Bower⁽²²⁾ separately used dislocation theory to calculate the two-dimensional crack propagation of a surface crack inclined to the surface, considering crack surface friction and oil hydraulic pressure inside of the crack. Kaneta and Murakami⁽²³⁾, using a body force method, calculated three-dimensional crack propagation. They claimed that cracks propagated parallel to the crack plane in Mode II, then turned direction in Mode I due to the action of oil pressure.

Miller⁽²⁴⁾ calculated the propagation direction of a two-dimensional crack parallel to the surface, using dislocation theory. The important factor for crack propagation was found to be $\Delta K_{II}/\Delta K_{I \max}$.

Ghosn⁽²⁵⁾ used a multidomain integral equation to calculate the propagation of a surface crack by applying centrifugal force as it applies to a bearing rotated at high speeds. $K_I \times \Delta K_I$ was found to be the most important factor in crack propagation. Surface cracks propagate in a zigzag pattern in the initial stage. This result may explain the zigzag pattern seen on the fracture surface in the initial stage of the fracture in Photo 7(b).

Muro⁽²⁶⁾ considered the contact residual stress created during rolling contact and analyzed crack propagation. Otsuka et al.⁽¹⁶⁾, using aluminum and mild steel, performed an experiment using four-point shear loads to study crack propagation, and compared their results to calculated values.

Kumar et al.⁽²⁷⁾ calculated plastic deformation due to rolling contact fatigue by using elastic plastic theory including work hardening. Their report gives some suggestions as to the nature of the crack initiation mechanism.

7. Concluding Remarks

Recently, new bearing-life calculation equations⁽²⁸⁾ were proposed. However, the equations do not appear to be completely reliable. To complete these equations it will be necessary to develop precise models of rolling contact fatigue phenomenon, obtain fracture toughness values in Mode II of various materials and apply them to the models with fracture mechanics considerations. The final objective of researchers mentioned in section 6 is to be able to perform life prediction in bearing design. The theme to be solved for the moment in order to achieve this goal is to create proper models for the various failure modes of practical bearings and to measure fracture toughness in Mode II.

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