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Semi-circular surface cracks and flaking failures in silicon nitride bearings

Katsuyuki Kida*, Takashi Honda, Edson Costa Santos

Dept. of Mech. Eng., Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan

*Corresponding author. E-mail: kida@mech.kyushu-u.ac.jp

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ABSTRACT

There is a well-known pattern of flaking failure under spherical ball-on-plate contact, i.e., the network between multiple Hertzian cracks causes the surface layer's separations. Based on this pattern previous researchers studied the failures of silicon nitride bearings. However, contrary to their explanation, we found that the surface cracks did not explain the process of the flaking failure of bearing plates. In the present work we calculate the stress concentration of surface crack in order to find out which crack is more dominant in the process of the flaking failure. Copyright © 2011 VBRI press.

Keywords: Rolling contact fatigue; flaking failure; subsurface crack growth; Si_3N_4 ceramics; bearings.

K.Kida did Ph.D, M.Eng and B.Eng in Mechanical Engineering at Osaka University. His main area of research includes, (i) Rolling contact fatigue of bearings (ceramic materials, steels and polymers), (ii) Artificial joint system of humanoid robots, (iii) Scanning Hall probe microscopy, (iv) Refinement of high-carbon high-strength steels, and (v) Diesel engine's high-pressure valve. He received 'The Best Paper Prize' from 'Fatigue & Fracture of Engineering Materials & Structures' journal in 2005. After the awards he has also got seven Japanese and international awards. He is heading five projects which have been supported by the 'NEDO' and the 'Minister of Economy, Trade and Industry, Japan' in Kyushu University.

T. Honda did M. Eng. and B. Eng. in Mechanical Engineering at Kyushu University. He is working as a research fellow of the Japan Society for the Promotion of Science (JSPS) from April 2011. His main area of research includes, (i) Rolling contact fatigue of bearings, (ii) Non-destructive-testing and evaluation using magnetic microscopy, (iii) Refinement of steels, (iv) X-ray diffraction analysis, and (v) Scanning electron and laser confocal microscopy.

Edson C. Santos obtained his Master and Ph.D. degrees at Osaka University (Department of Engineering Science) in Japan and B.S. at the National University of Santa Catarina (Department of Mechanical Engineering) in Brazil. Currently a JSPS research fellow in Kyushu University in the lab of Professor K. Kida, his main research interests are: laser deposition of Ni-based superalloys, laser nitriding of titanium, heat treatment of high carbon low alloy steels and microstructure and crystallographic characterization of materials.

Introduction

The ring crack model has been investigated from the viewpoint of fracture mechanics in order to investigate the hybrid bearings [**1-8**] Hadfield et al, Wang et al. and also Chen et al.). The failures have also been studied in terms of "wear and dent" [**9-11**]. Wang and Hadfield [**2, 5-7**] extensively investigated flaking failures. They observed multiple semi-circular surface cracks around an initial ring crack and assumed these were ring cracks (secondary ring cracks). When these cracks grew inside the specimen, networks of subsurface cracks were formed between them. However, contrary to Wang and Hadfield's investigations, we concluded that the surface and subsurface crack growths under rolling contact fatigue (RCF) were not explained by the ring crack model [**12**]. It is interesting to note that the subsurface crack grew in directions forward and backward to the ball movement. Furthermore, we observed the surface and section of semi-circular surface cracks occurring around an initial surface crack. Behind the initial crack semi-circular cracks can be observed. The arcs formed by the semi-circular cracks expand outward from the initial crack. This expanding direction corresponds to the growth direction of the subsurface crack, but no cracks were formed whose arc direction is different to the growth direction of the subsurface crack. This implies that both surface and subsurface cracks are affected by each other.

In the previous paper we carried out the contact fatigue tests under lubricated contact and we concluded that the direction of semi-circular surface cracks was dominated by the subsurface main crack [**12**]. The expansion directions of arcs formed by the semi-circular surface cracks under both reciprocating-RCF and RCF correspond to the growth direction of the flaking failure [**13**]. However, no arcs expanding in an opposite direction were formed. From the observations it is not clear what causes the asymmetry in arc shapes formed by the surface semi-circular cracks. There are two possibilities.

Possibility (1) The semi-circular cracks are initiated by the tensile stress, which is increased by friction.
Possibility (2) Subsurface crack growth affects the nature of semi-circular surface cracks.

In the present work, we observed the surface at the early stage of crack growth and calculated the stress concentration occurring at the surface in order to investigate the relation between the growth directions of surface and subsurface cracks. Based on the calculation results we found out which crack is more dominant in the process of the flaking failures.

Experimental

The contact fatigue tests were carried out using a RCF (rolling contact fatigue) machine under lubricated contact. **Fig. 1** shows the schematic illustration of the contact apparatus in the machine. The lubricant was turbine oil (ISO VG46), the viscosity of which was 43.3×10^{-6} m^2/s at 40^oC. The friction coefficient was less than 0.01 during the tests and the temperature ranged from 40°C to 60°C.

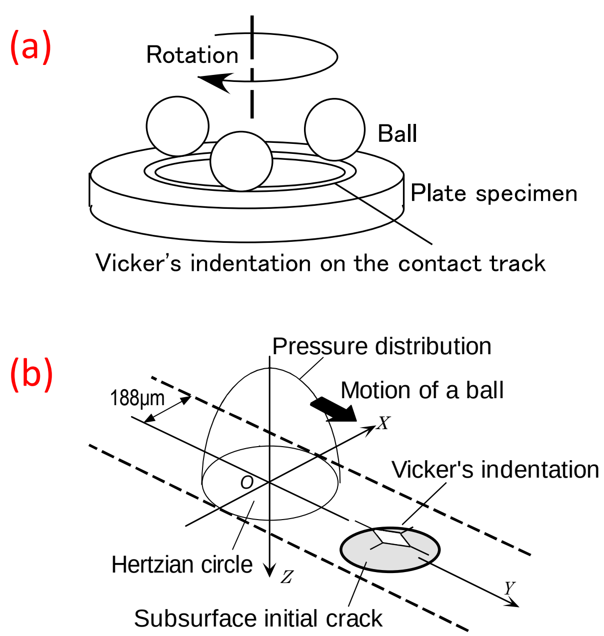

Fig. 1. Schematic illustration of RCF (rolling contact fatigue). (a) Thrust movement of balls. (b) Schematic illustrations of the subsurface initial crack and the coordinate system. Cracks occurring around a Vickers indentation (Load = 30kgf).

Ball diameter was 9.525 mm (3/8”). The thickness and diameter of the plate specimens were 11 and 60mm, respectively. The material of plate specimens and balls was HIP-Si_3N_4 (Toshiba, TSN-03) which is used in commercial ceramic bearings. **Table 1** presents its mechanical properties. This material has high wear resistance and its deformation under the present experimental conditions can be ignored. Artificial cracks were initiated by a Vickers indenter. In the present experiments, the lateral crack initiated under 30kgf (294N) was used as an initial crack. The diameter of the lateral crack was measured by using Xenon light prior to the fatigue tests. The diameter of the lateral crack was about 250μm, which was smaller than the contact diameter.

Table 1. Mechanical properties of the specimen.

Bulk density (g/cm^3)	Bending strength (MPa)	Fracture toughness K_{IC}($MPam^{1/2}$) *	Young's modulus (GPa)	Poisson's ratio
3.23	1011	6.6	294	0.27

*The value was measured by the IF method.

Table 2. Experimental conditions.

Load (N)	Hertzian maximum stress (MPa) *	Half width of contact area (μm) *	Frequency (Hz)
294	3979	188	120

*Hertzian maximum stress and half width of contact area were calculated using theoretical Hertzian equations.

Experimental conditions are shown in **Table 2**. The load is 294N, which is the same as that used in the previous research we did on rolling contact fatigue [**12**].

Results and discussion

Experimental results

In the present work, we made the observations in order to investigate the crack growth mechanins and found the following two features of semi-circular surface cracks: one is the expansion direction of the arcs formed by semi-circular surface cracks; and the radii of the arcs. **Fig. 2** shows two examples of semi-circular surface cracks occurring around Vickers indentations. The arcs formed by the semi-circular cracks expand outward from the Vickers indentations. The important point to note is that all arcs expand outward from the Vickers indentations. **Fig. 3** is a schematic illustration of the arcs formed by the semi-circular surface cracks. There were no type (a) cracks around the crack (b) in **Fig. 2**(**b**), and vice versa. This indicates that the arcs formed by the surface semi-circular cracks correspond well to the tip-shape of the subsurface main crack. If the surface cracks occurred independently of the subsurface main crack, the semi-circular surface cracks, such as the cracks of **Fig. 2**(**a**), would occur in front of the Vickers indentation in **Fig. 2**(**b**). However, no cracks occurred whose shapes were opposite to the tip-shape of the subsurface main crack (cf. **Fig. 3**).

The radii of the semi-circular cracks are 176μm in **Fig. 2**(**a**) and 124μm in (**b**). These values are smaller than the contact radius. This means that the radii of the semi-circular cracks are much smaller than those of the ring cracks which are about 1.1 times as large as contact radius. From these features we concluded that possibility (2) explains the nature of the surface cracks under RCF.

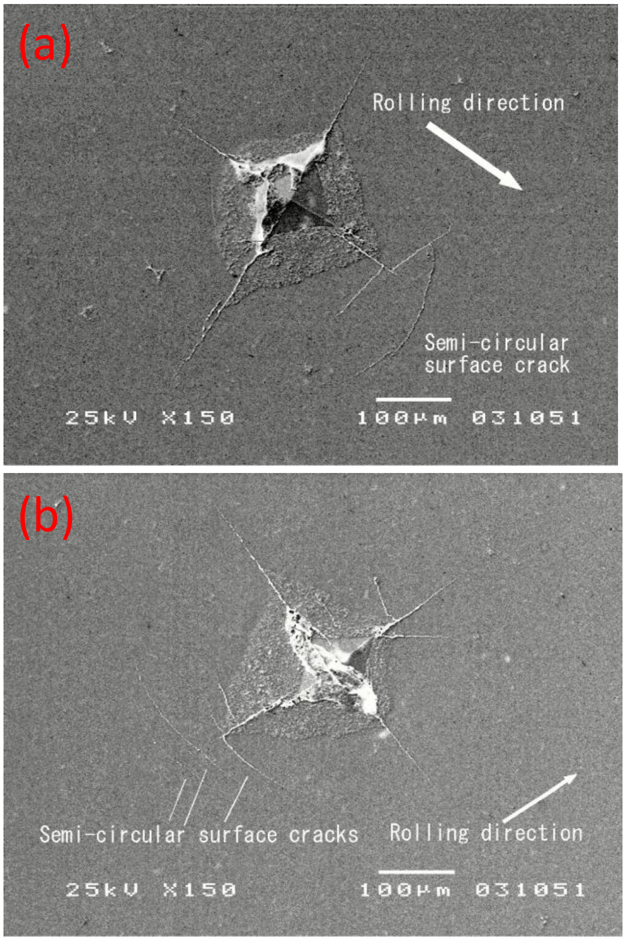

Fig. 2. Semi-circular surface crack occurring around a Vickers indentation. The arcs formed by the cracks expand outward from the Vickers indentations. (**a**) and (**b**). Arcs formed by the semi-circular cracks expand forward (**a**) and backward (**b**) to the rolling direction. Center squares in (**a**) and (**b**) are the Vickers indentations.

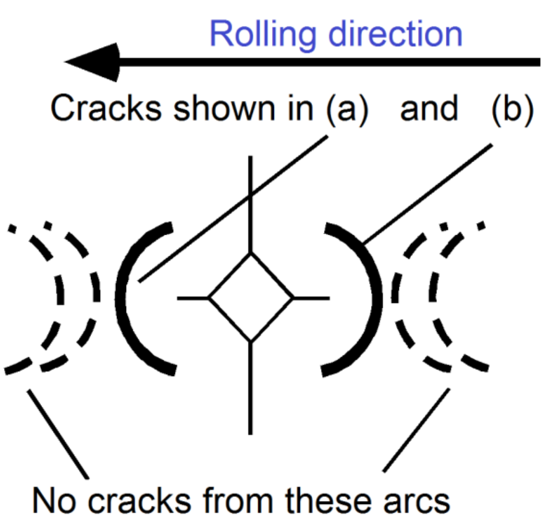

Fig. 3. Schematic illustration of the possible arcs formed by the semi-circular surface cracks. Note that no cracks (dashed arcs) were found whose expansion directions were opposite to the arcs observed in **Fig. 2**(**a**) and (**b**).

Discussion

It is generally known that surface circular cracks occur under spherical Hertzian contact and they are therefore called 'Hertzian cracks (ring cracks and cone cracks).' These cracks are of a similar shape to the contact circle. Previous researchers explained flaking failures from the viewpoint of ring cracks [**5-7**]. The semi-circular cracks occurring around the initial surface cracks were also observed on the ball surface by Wang and Hadfield [**7**]. They referred to them as secondary ring cracks, but did not discuss the failures caused by them in detail. These secondary ring cracks are very similar to the semi-circular cracks we observed under RCF. However, while they appear similar on the surface the underlying cracks are different. The major differences between the features of secondary ring cracks and semi-circular surface cracks are as follows:

1. When we compared our research with that of Wang and Hadfield we found that the shape and distribution of the cracks were very similar. However, the secondary ring cracks investigated by Wang and Hadfield were the surface cracks generated around an initial semi-circular ring crack and caused a 'shallow spalling' which we did not observe in the present work.
2. Wang and Hadfield also reported that when the initial ring cracks caused general types of flaking failure on the ball surface there were no surface cracks [**7**]; however, we observed them in our experiments. Although the flaking failures occurring on the ball surface which they observed were very similar to what we observed, we found the mechanisms causing flaking failures to be different. Wang and Hadfield observed semi-circular cracks on their flaking surface after the surface layer separation; however, they found no surface cracks before the separation.

When comparing the features of flaking failures in the present work to those of the flaking failures which were investigated by Wang and Hadfield, we notice that the patterns of crack growth are different. This indicates that even when the features of surface circular cracks are very similar, the underlying cracks are not necessarily the same.

Direction of arcs formed by semi-circular surface cracks

In **Fig. 2**, which shows semi-circular surface cracks under RCF, all arcs formed by the semi-circular surface cracks expand outward from the initial crack. We compare the expansion direction of arcs formed by semi-circular surface cracks and the initial subsurface cracks. If the surface cracks were not affected by the subsurface cracks, arc shapes formed by surface cracks could be explained from the viewpoint of surface stress alone. Therefore, we checked whether the change of the surface stress caused by the ball movement has an influence on the nature of the semi-circular surface cracks.

The expansion directions of arcs formed by the semi-circular surface cracks under RCF correspond to the growth direction of the flaking failure. However, no arcs expanding in an opposite direction were formed. From the observations it is not clear what causes the asymmetry in arc shapes formed by the surface semi-circular cracks.

The tests were carried out under rolling contact fatigue, and the value of the friction coefficient was lower than

0.01. This means that we do not need to discuss the nature of cracks caused by friction. However, in order to consider possibility (1), we assume that the friction coefficient is 0.10 and calculate the surface stress distribution. **Fig. 4**(**a**) is the distribution of the normal stresses on the surface, which was calculated using Hanson's equations [**14**]. When calculating the stress, the mechanical properties of the specimens shown in **Table 2** were used. As the Hanson's equation is for transversely isotropic materials, our test material was assumed to have 1.0×10^{-6} of transverse isotropy value and the results are not different from the results obtained through the theoretical Hertzian contact calculation.

The tensile stress has two peaks around the circumference of the contact area. The value of the tensile stress of the back peak is larger than that of the front peak. If the tensile stress was increased by friction it would initiate a semi-circular crack around the back peak of the contact area (see **Fig. 4**(**b**)). When we assume that a ball turns back, the peak value of the tensile stress decreases but that of the other peak increases (**Fig.** 4(**c**)). This would initiate another semi-circular crack at the opposite side of the circumference of the contact area (**Fig. 4**(**d**)). However, contrary to the assumption, the ball does not turn back.

Therefore, this makes possibility (1) unlikely. We can apply this explanation to the case when the value of the friction coefficient is about zero. If the tensile stress around a back peak affects the formation of semi-circular surface cracks during a cycle, this stress also would initiate the other cracks around the back peaks. However, no arcs were formed whose arcs were opposite to the shapes of the subsurface crack tip. Therefore we concluded that the asymmetrical shapes of the arcs formed by the surface cracks are not fully explained from the viewpoint of surface tensile stress. More evidence for our conclusion comes from the experiments done by Yoshioka *et. al.* They observed that the semi-circular cracks were formed under static spherical contact [**15**].

We consider that (2) fits our observations best because the changes in the diameter of semi-circular cracks correspond well to changes in the tips of the subsurface main crack. Furthermore, we found that surface semi-circular cracks did not occur when subsurface cracks did not grow under RCF. If semi-circular cracks were observed prior to the subsurface main crack we could not conclude that the direction of semi-circular surface cracks was dominated by the subsurface main crack. However, no semi-circular surface cracks occurred when the subsurface main crack was initiated before the RCF tests.

Conclusion

We observed the relation between surface semi-circular and subsurface initial cracks. We carried out rolling contact fatigue (RCF) tests and compared their shapes in order to find out which crack was more dominant in the process of the flaking failure. Our conclusions concerning flaking failure are as follows:

1. Subsurface cracks were more dominant in the process of the flaking failure than surface cracks.
2. Ball movement direction has little effect on the shapes of flaking failures.
3. The direction of arcs formed by semi-circular surface cracks was dominated by subsurface crack growth direction.

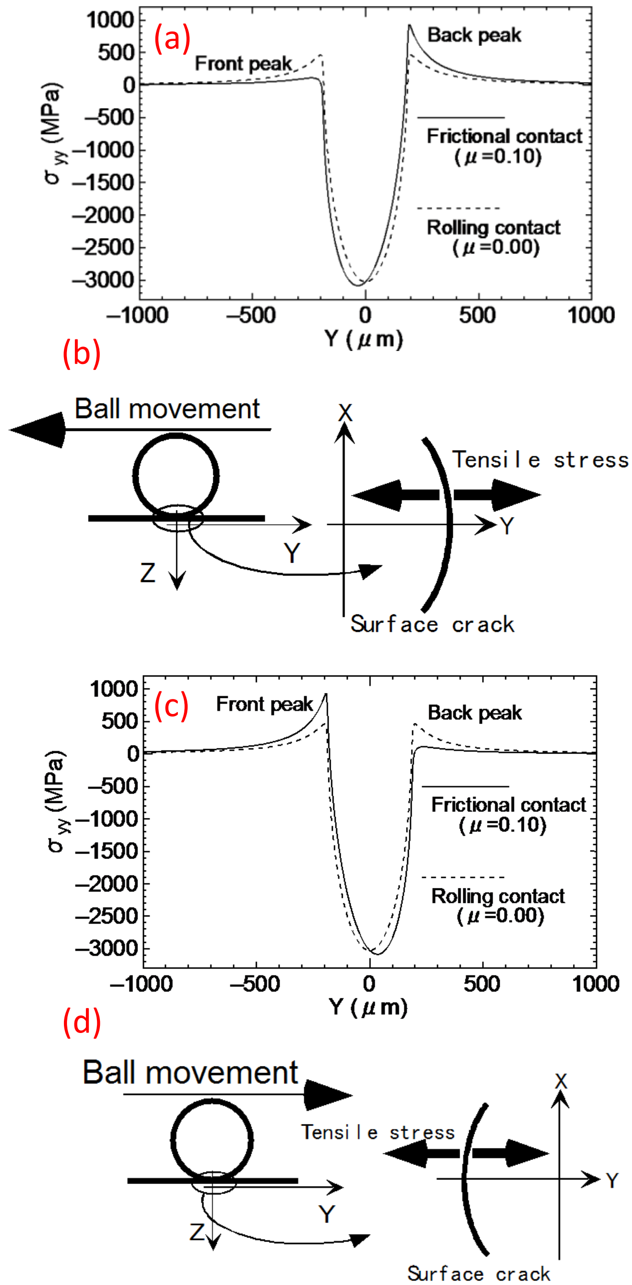

Fig. 4. Possible mechanism initiating surface cracks.(**a**) Distribution of normal stress on the surface when a ball moves forward. (**b**)Surface crack initiated by tensile stress occurring around a circumference of the contact circle. (**c**)Distribution of normal stress on the surface when a ball moves backward. (**d**) Surface crack initiated by tensile stress occurring around the opposite side of the circumference.

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