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Rolling contact fatigue strength of shot peened zirconia composites

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In this paper, the rolling contact fatigue strength of zirconia monolithic and zirconia composites was investigated using steel balls under dry conditions. The fatigue life of zirconia monolithic with shot peening was longer than that of zirconia monolithic without shot peening. The fatigue life of SP180 was longer than that of SP300. The fatigue life of all zirconia composites was reduced by shot peening. Many fine cracks were generated on the surface of the zirconia composites due to the differences in the thermal expansion coefficient and the phase transformation. A great deal of flaking occurred caused by the rolling contact. The zirconia composites showed a crack healing ability, and a review and study of additives is thus required to improve the rolling contact fatigue strength.

Key words: Zirconia ceramics, Shot peening, Rolling contact, Fatigue strength, Surface roughness, Residual stress.

Introduction

Unlike other ceramic materials, zirconia ceramics have high strength, high toughness, excellent wear resistance, high hardness, low thermal conductivity, and good chemical and corrosion resistance. However, volume changes occur due to the monoclinic-tetragonal phase transition at about 1373 K, and the application range is thus limited. In order to overcome this problem, researchers are studying the development of zirconia composites that have a crack healing ability. That is, with the addition of SiC and TiO_2, zirconia shows a crack healing ability at about 600 ~ 800 °C, which was confirmed to improve the strength [1, 2]. However, ceramics have a lower fracture toughness than metallic materials. If a crack occurs on the surface of the material caused by rolling fatigue due to the repeated contact, the reliability of ceramics is significantly decreased. This disadvantage has a limitation for the extensive application of ceramics.

Shot peening is expected to improve the rolling contact fatigue strength [3]. Shot peened silicon nitride composites have been reported to increase the contact fatigue strength and fracture toughness of ceramics [4]. Therefore, it is expected that shot peening will improve the rolling contact fatigue strength as a sliding property.

In this study, the effect of rolling contact fatigue strength on zirconia composites with crack-healing ability and zirconia monolithic was investigated.

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Materials and Experimental Method

A powder composed of 0.026 μm ZrO_2 (TZ-3Y-E, Tosoh), 0.27 μm SiC (Wako pure chemical industries) and a sintering additive (commercially purchased anatase 0.3 μm TiO_2) was used for the experiments. Silicon carbide was added to give a crack healing characteristic. TiO_2 was added to 3 wt% to achieve the most strength recovery by crack healing. Circle plates of φ60 × 5 mm were sintered in a vacuum atmosphere for 1 h via a hot press under 30 MPa at 1723 K. The batch compositions of specimens are given in Table 1.

For shot peening (SP), a shot peening apparatus of a direct pressure system was used (FDQ type, Fuji

Table 1. Batch composition and processing conditions.

Specimen	Batch composition (wt.%)	Conditions	
		Hot pressing	Crack healing
Z	100 wt.% ZrO_2	30 MPa, 1723 K, 1 hour in vaccum	1073 K and 1173 K from 1 to 10 hour in air
ZS	90 wt.% ZrO_2 10 wt.% SiC		
ZST	87 wt.% ZrO_2 10 wt.% SiC 3 wt.% TiO_2		

Table 2. Conditions for X-ray diffraction.

Conditions for X-ray	Cu-Kα
X ray tube	Cu
Diffraction plane	Si_3N_4(323)
Diffraction angle [deg]	141.26
Tube voltage [kV]	40
Tube current [mA]	30

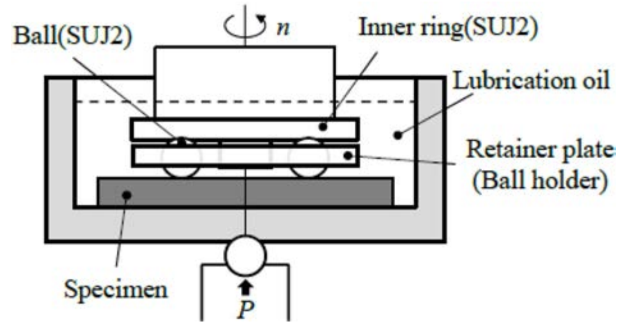

Fig. 1. Schematic diagram for rolling contact fatigue.

Seisakusho, Japan). The shot is a ZrO_2 ball (Nikkato Ltd, YTZ® ball) of φ180 and φ300 μm with a Vickers hardness of 1250 Hv. The shot projection nozzle diameter is φ5 mm, and the projection distance was 100 mm. The pressure of the projected shot was set to 0.2 MPa and the projection time was 30 s. Table 2 shows the conditions of the SP treatment. The specimens in which shot peening was carried out with φ180 μm and φ300 μm balls are named the SP180 specimen and SP300 specimen, respectively. To measure the surface roughness, a contact stylus roughness measuring instrument was used (Kosaka Laboratory Ltd., SE1200), with the measurement method based on JIS B0601. The measurement length was 160 μm (cut off 0.80 mm) and the measurement speed was set at 0.30 mm/ sec.

The residual stress of the shot peened surface was evaluated using an X-ray residual stress measurement apparatus. Table 2 shows the X-ray residual stress measurement conditions. Vickers hardness was measured under a load of 49 N.

The rolling contact fatigue strength was evaluated using a trust bearing tester (Fuji Testing Machine Ltd, MJ-1 type). Fig. 1 shows a schematic diagram of the rolling contact fatigue. The rolling bearings were six steel balls (SUJ2) of φ4 mm. The rolling speed was 500 rpm and spindle oil was used as the lubricant. Using a stepwise method, the load was increased by 0.5 kN per 10^5 times starting from 1 kN. In each step of the experiment, the SUJ2 bearing was replaced. Specimen damage was detected using an acceleration type vibrometer. The vibration was occurred by separation. The test load, P, and the damage life are shown by NR_f.

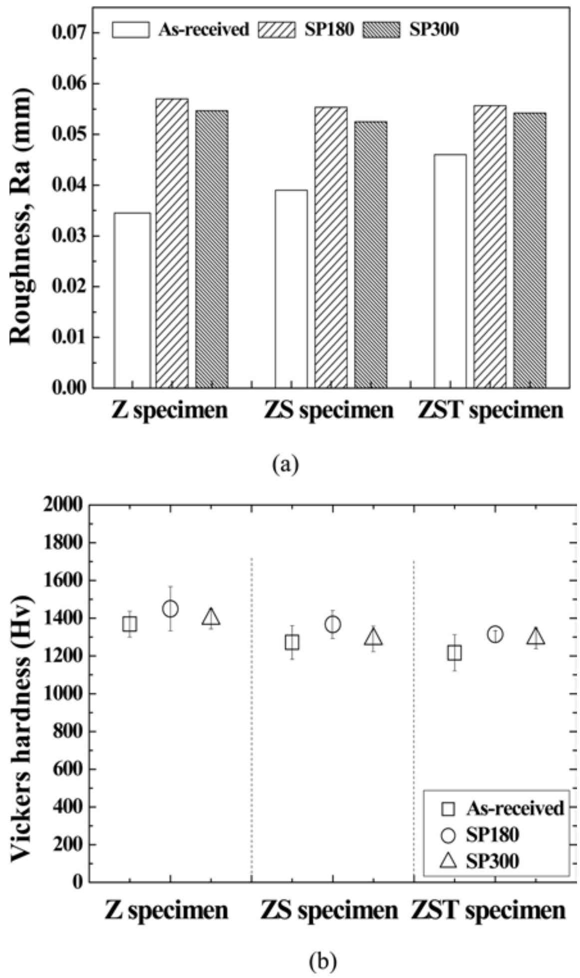

Fig. 2. Surface roughness and Vickers hardness in Z, ZS and ZST specimens according to shot peening.

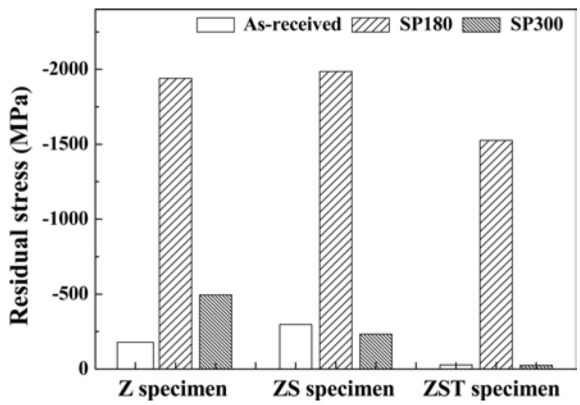

Fig. 3. Residual stress by SP treatment.

Results and Discussion

Roughness after SP treatment

Rolling contact fatigue is related to the surface roughness or the hardness. Fig. 2(a) and 2(b) show the surface roughness and Vickers hardness, respectively. The roughness of the as-received specimen showed ZST specimen > ZS specimen > Z specimen. However, the roughness after shot peening was similar to that of the other three specimens. It was observed that the roughness of the SP180 and SP300 specimens was increased more than that of the as-received specimen. In addition, the roughness of the SP180 specimen was slightly greater than that of the SP300 specimen. The Vickers hardness was slightly increased or similar with shot peening. The crack propagation of the specimen was small according to deformation suppression caused by compressive residual stress [5]. Moon *et al*. reported that the compressive residual stress introduced on an alumina single crystal by shot peening is due to the introduction of a micro-crack or dislocation occurring near the surface [6]. However, the rolling contact fatigue of the zirconia composite is affected by the phase transformation of the surface layer.

Compressive residual stress before and after SP treatment

Fig. 3 shows the compressive residual stress introduced to the surface by the shot peening. Of the three specimens, the compressive residual stress of the SP180 specimen was significantly increased, but that of the SP300 specimen was sharply decreased. As such, it was found that with the zirconia monolithic and zirconia composites, the effect of compressive residual stress introduced by the SP treatment was greater for the SP180 specimen than for the SP300 specimen.

Rolling contact fatigue of SP specimen

Figs. 4(a), 4(b), and 4(c) show the relationship between the test load of specimens and the rolling contact fatigue life for the Z specimen, ZS specimen, and ZST specimen, respectively. The rolling contact fatigue life showed SP180 specimen > SP300 specimen > as-received specimen in Fig. 4(a) and as-received specimen > SP300 specimen > SP180 specimen in Figs. 4(b) and 4(c). Zirconia monolithic shows a longer life with an increase of the compressive residual stress [7]. Zirconia composite was the opposite phenomenon [5]. That is, the rolling contact fatigue life of the Z specimen is proportional to the compressive residual stress, but that of the ZS and ZST specimens is shortened in proportion to the magnitude of surface roughness. The rolling contact fatigue life was not related to the compressive residual stress with shot peening. On the other hand, the rolling contact fatigue strength of the Si_3N_4 ceramic increased with shot peening [7].

Honda *et al*. studied the flaking crack propagation behavior in the rolling contact fatigue of Si_3N_4 ceramics, and reported results as follows [8, 9]. (a) The generated ring crack mainly propagates to mode I under tensile stress. (b) A surface crack that was propagated a certain amount is generated branches by the shearing stress according to the ball contact, is propagate to mode II in parallel with against the surface. Such a crack is connected to the surface crack, separated from the surface, and separation damage then occurs.

Fig. 5 and 6 show the macro surface flaking phenomenon after the rolling contact fatigue of the zirconia composites. Fig. 5 shows a ZS specimen and Fig. 6 shows a ZST specimen. In Fig. 5, Figs. 6(a-c) indicate the as-received specimen, SP180 specimen, and SP300 specimen, respectively. A great deal of flaking was observed in the as-received specimen and shot peened specimen after rolling contact. Flaking occurred due to the phase transformation and the differences in the thermal expansion coefficient of the additives of the zirconia composites. The synthesized ceramic generated many fine cracks on the surface due to the differences in

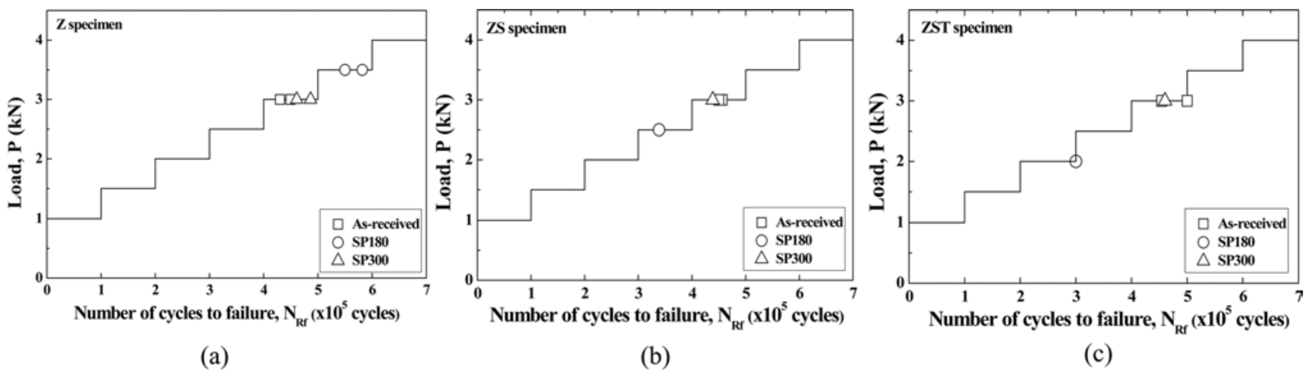

Fig. 4. Results of rolling contact fatigue test of Z, ZS and ZST specimen.

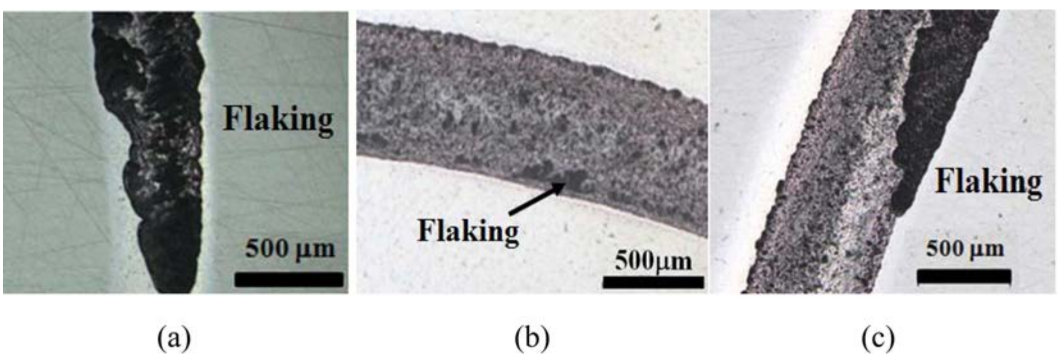

Fig. 5. Flaking after rolling contact fatigue test from ZS specimen. (a) As-received specimen, (b) SP180 specimen, (c) SP300 specimen.

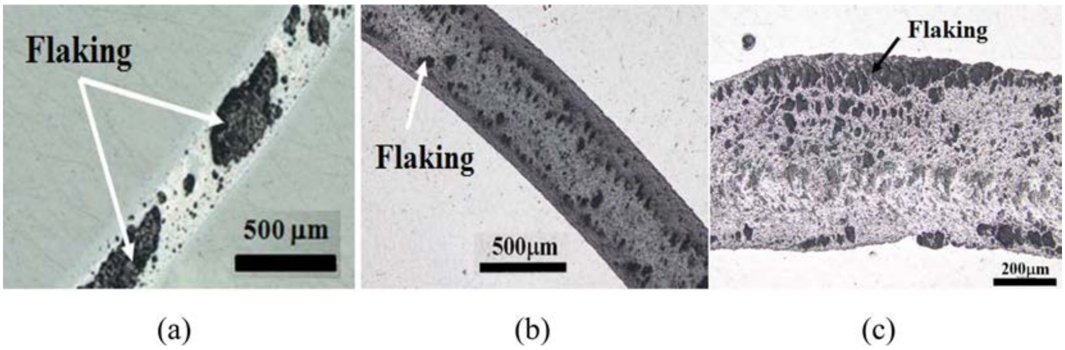

Fig. 6. Flaking after rolling contact fatigue test from ZST specimen. (a) As-received specimen, (b) SP180 specimen, (c) SP300 specimen.

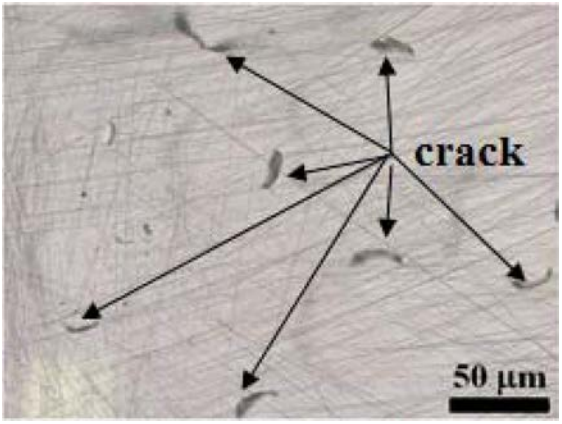

Fig. 7. Typical micro-cracks on the surface of ZS specimen after heat treatment of 1173 K-10 hrs.

the thermal expansion coefficient. Fig. 7 shows an example. Despite the compressive residual stress, flaking occurred due to the rolling contact fatigue caused by the micro-cracks, thus reducing the rolling contact fatigue life. Therefore, in zirconia composites having crack healing, improvement in the rolling contact fatigue strength by shot peening was not observed. That is, to improve crack healing ability, a review and study of additives that have the effect of improving the rolling contact fatigue strength are required.

Conclusions

The roughness by shot peening was shown to be similar in the three types of specimens, and was increased more in the SP180 and SP300 specimens than in the as-received specimen. In addition, the roughness of the SP180 specimen was slightly greater than that of the SP300 specimen. However, the Vickers hardness was similar or slightly increased in all specimens by shot peening. The zirconia composites showed compressive residual stress as a result of the shot peening. The effect of compressive residual stress in the SP180 specimen was greater than that for SP300. The rolling contact fatigue life of zirconia monolithic was increased according to the magnitude of compressive residual stress, but that of the zirconia composites was reduced due to shot peening. Therefore, shot peening increases the crack healing ability of ziconia monolithic, and a review and study of additives that can improve the rolling contact fatigue strength are required.

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