Rolling contact fatigue strengths of shot-peened and crack-healed ceramics

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Abstract. The effects of shot-peening (SP) and crack-healing on the rolling contact fatigue (RCF) strengths of Al$_2$O$_3$/SiC composite ceramics were investigated. Non-shot-peened, shot-peened, and shot-peened + crack-healed specimens were prepared. SP was performed using ZrO$_2$ beads. The shot-peened + crack-healed specimen was crack-healed after SP. X-ray diffraction clearly showed that SP induced a compressive residual stress up to 300 MPa at the specimen surfaces. Furthermore, the shot-peened + crack-healed specimen retained a compressive residual stress of 200 MPa. The apparent surface fracture toughness of the shot-peened specimens increased owing to the positive effects of the compressive residual stress. RCF tests were performed using a thrust load-bearing test device. The RCF lives of the shot-peened specimens did not improve compared to that of the non-shot-peened specimen, because the numerous SP-introduced surface cracks could act as crack initiation sites during the RCF tests. However, the RCF life of the shot-peened + crack-healed specimen did improve compared to those of non-shot-peened and shot-peened specimens, implying that combining SP and crack-healing was an effective strategy for improving the RCF lives of Al$_2$O$_3$/SiC composite ceramics.

1. Introduction
Alumina ceramics (Al$_2$O$_3$) possess superior wear resistance, and electric insulation. Thus, they are widely used in several types of industrial equipment. However, there are few applications of alumina for rolling contact machine elements. In contrast, silicon nitride ceramics (Si$_3$N$_4$) are widely applied to contact elements such ball bearings because of their superior rolling contact fatigue (RCF) strengths [1,2]. The fracture toughness of Al$_2$O$_3$ is lower than that of Si$_3$N$_4$. Thus, surface cracks and defects decrease the structural integrity of Al$_2$O$_3$ components. We attempted to overcome the problem by shot-peening (SP) and crack-healing. SP is a surface treatment for increasing the fatigue strength of metallic materials. The propagation of fatigue cracks is retarded by the effects of compressive residual stress. Recent studies have shown that SP could introduce compressive residual stress near the surface of silicon nitride (Si$_3$N$_4$) [3,4], Al$_2$O$_3$ [4,5], and partially stabilized zirconia (PSZ) [6,7]. If surface cracks are induced during SP, the reliabilities of ceramic components will decrease.

Ceramics containing silicon carbide (SiC) particles and whiskers have crack-healing ability [8,9]. If crack-healing could be combined with SP, the surface strengths and reliabilities of ceramics could be increased. From this perspective, Takahashi et al proposed a method of combining SP with crack-healing (SP + crack-healing) to improve the surface strengths of ceramics, which was effective for increasing the bending strength [10] and contact strength [11] of Si$_3$N$_4$/SiC. Zhang et al reported that
combining SP with multiple crack-healing processes was effective for increasing the fracture resistance and bending strength of ZrB2/SiC [12]. Oki et al also reported that the SP + crack-healing process was effective for enhancing the contact strength of Al2O3/SiC [13]. However, the effects of SP and crack-healing on the RCF strengths of ceramics have not yet been investigated. Therefore, the objective of this study was to investigate the effects of SP and SP + crack-healing on the RCF strength of Al2O3/SiC. To this end, SP and SP + crack-healing were applied to Al2O3/SiC, and residual stress distributions and apparent surface fracture toughness were investigated. The RCF lives of the shot-peened and shot-peened + crack-healed specimens were also investigated.

2. Specimens and test procedure

2.1. Materials and specimens
Al2O3 reinforced by 15 vol.% SiC particles (Al2O3/SiC) was selected as the test material. Rectangular plates (90 × 90 × 6 mm) of Al2O3/SiC were hot-pressed at 1973 K for 2 h under pressure of 35 MPa in N2. The processing details have been reported by Ando et al [9]. The hot-pressed Al2O3/SiC had a relative density of 99 % and an average grain size of approximately 1 μm. Although the SiC particles were uniformly distributed in the grain boundaries, SiC nanoparticles were distributed in the alumina grain, as reported in a previous study [9]. After hot-pressing, the plates were cut into 30 × 30 × 4-mm plate specimens. One of the surface of each specimen was polished to a mirror finish. These specimens are denoted as “non-shot-peened” specimens.

2.2. SP and crack-healing
We performed SP on the surfaces of the non-shot-peened specimens using a shot-peening system at a 0.2-MPa shot for 30 s. Commercial 180-μm-diameter ZrO2 beads (Vickers hardness = 1150 HV) were used as the shot material. Subsequently, the shot-peened specimens were heated at 950°C for 100 h to heal any SP-induced surface cracks. The crack-healing conditions were selected because the SP-introduced surface cracks could be healed while maintaining the SP-introduced compressive residual stress. The shot-peened + crack-healed specimen surfaces were repolished to a depth of 1–2 μm to reduce the surface roughness since the friction coefficient was expected to increase owing to the oxide films formed on the sample surfaces.

2.3. Residual stress and apparent fracture toughness
The residual stresses of the shot-peened, shot-peened + crack-healed, and non-shot-peened specimens were measured using X-ray diffraction (XRD) with a Cr-Kα beam and the 2θ-sin^2Ψ relationship. The X-ray beam spot diameter was 2.0 mm. The diffraction plane of Al2O3 [146] and the diffraction angle 2θ = 139° were selected to measure the residual stress. The residual stress distributions of the polished specimens were measured. The residual stress was successively measured for each layer. The apparent fracture toughness, Kc, was estimated by indentation-fracture (IF) method. The Kc can be calculated using the following equation [14]:

\[ K_c = 0.018(E/HV)^{0.5}(P/c)^{1.5} \]  

where HV is Vickers hardness, E is Young’s modulus, P is the indent load, and c is half the surface crack length. The material had the following properties: E = 324 GPa and HV = 18.6 GPa (1898 HV). Vickers indentations were introduced on the polished surfaces by applying P = 49 N for 20 s.

2.4. Rolling contact fatigue tests
The RCF strengths were evaluated using a thrust load-bearing test device. The tests were conducted using six 4.0-mm-diameter bearing-steel balls (JIS-SUJ2) as the rolling element, and the rotation speed was set at n = 500 rpm. A commercial spindle oil was used as the lubricant. The test loads per ball were P = 0.21, 0.33, and 0.46 kN. A vibrometer on the test machine was adjusted to automatically
stop in response to test specimen surface failure. The number of contact loadings at the automatic stop was evaluated as the RCF life, $N_f$.

3. Test results

3.1. Residual stress distribution

Figure 1 shows the distribution of the residual stress induced on each specimen. Compressive residual stresses were induced near the surfaces of the shot-peened and shot-peened + crack-healed specimens. Approximately 300 and 200 MPa of compressive residual stresses were induced on the outermost surfaces of the shot-peened and shot-peened + crack-healed specimens, respectively. Since the compressive residual stress near the surface of the shot-peened + crack-healed specimen was lower than that near the surface of the shot-peened specimen, indicating that the SP-induced lattice strain was relieved by heating. However, the heating-induced relief in the residual stress was not evident at or deeper than 5 μm. Therefore, the compressive residual stress remained on the shot-peened specimen surface even after heating the specimen in air at 950°C for 100 h.

![Residual stress distributions of surface-treated Al$_2$O$_3$/SiC specimens.](image1)

![Apparent fracture toughness ($K_c$) of surface-treated Al$_2$O$_3$/SiC specimens.](image2)

3.2. Apparent fracture toughness

Figure 2 shows $K_c$ of each specimen. The $K_c$ of the shot-peened and shot-peened + crack-healed specimens improved by 96 and 50%, respectively, compared with that of the non-shot-peened specimen because the compressive residual stress prevented the development of indentation-fracture-induced cracks. The $K_c$ of the shot-peened + crack-healed specimen was lower than that of the shot-peened specimen owing to the heating-induced decrease in the compressive residual stress, as described in section 3.1.

3.3. RCF life

Figure 3 shows the RCF test results. The RCF life of the shot-peened specimen was equivalent to that of the non-shot-peened one. In contrast, the RCF life of the shot-peened + crack-healed specimen was higher than that of the non-shot-peened and shot-peened ones. The crack initiation loads of the monotonic indentation tests [13] are plotted on the left in the figure. Although SP increased the crack initiation loads in the monotonic indentation tests, it did not increase the RCF life in the RCF tests. The reasons for the extended rolling fatigue life achieved by combining SP and crack healing are...
discussed based on the damage behaviors.

![Image](image_url)

**Figure 3.** Results of RCF tests for surface-treated Al$_2$O$_3$/SiC specimens.

Figures 4-6 show the surface images of the test specimens subjected to a test loading of $P = 0.21$ kN. The surface images taken at $N = 2.4 \times 10^6$ cycles and at failure ($N_f$), are shown in figures 4(a)-6(a) and 4(b)-6(b), respectively. Figure 7 shows the schematic images of the RCF mechanisms in each specimen.

![Image](image_url)

**Figure 4.** Optical microscopy images of non-shot-peened specimen ($P = 0.21$ kN).

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**Figure 5.** Optical microscopy images of shot-peened specimen ($P = 0.21$ kN).
**Figure 6.** Optical microscopy images of shot-peened + crack-healed specimen ($P = 0.21$ kN).

**Figure 7.** Schematic images of rolling contact fatigues in specimens.

Figure 4 shows optical microscopy images of the non-shot-peened specimen. After a certain number of contact cycles, arc-shaped ring cracks were initiated at the wear race on the specimen surface, as shown in figure 4(a). The cracks led to flaking damage, as shown in figure 4(b). Figure 7(a)
shows the schematic images of the RCF mechanisms in the non-shot-peened specimen. The damage mechanism of the non-shot-peened specimen can be divided into five stages: (1) surface layer wear, (2) ring cracks initiating from minute cracks remaining after polishing, (3) ring cracks propagating in the tensile mode (mode I), (4) subsurface main cracks propagating in shear modes (modes II and III) and developing upward and downward branches from their tips, and (5) upward cracks reaching the surface and causing flaking. This flaking process is quite similar to the one for Si$_3$N$_4$, as reported by Kida et al [2].

Figure 5 shows optical microscopy images of the shot-peened specimen. Although figure 5(a) shows numerous SP-induced minute dents, the wear race of the shot-peened specimen subjected to the same number of contact cycles as the non-shot-peened specimen did not show any arc-shaped ring cracks. Figure 7(b) shows the schematic images of the RCF mechanisms in the shot-peened specimen. The small cracks that initiated from the SP-induced dents presumably led to several small points of flaking damage, which coalesced resulting in the final failure, as shown in figure 5(b). Although the compressive residual stress inhibited the propagation of the ring cracks, the RCF life ($N_i$) of the shot-peened specimen was approximately the same as that of the non-shot-peened one owing to the negative effects of the SP-induced small dents and cracks.

Figure 6 shows optical microscopy images of the shot-peened + crack-healed specimen. As shown in figure 6(a), the shot-peened + crack-healed specimen did not show any SP-induced dents or any ring cracks. All the SP-induced surface cracks had healed by crack-healing, as shown in figure 7(c). Thus, the RCF life increased owing to the positive effects of the compressive residual stress, implying that applying additional heating to heal SP-induced surface cracks was an effective strategy for improving the RCF lives of Al$_2$O$_3$/SiC composites.

4. Conclusion
The effect of combining SP and crack-healing on the RCF strength of an Al$_2$O$_3$/SiC composite was investigated. Residual stress distributions and apparent fracture toughness ($K_c$) were also measured for non-shot-peened, shot-peened, and shot-peened + crack-healed specimens, and the following results were obtained:

- SP induced a compressive residual stress up to 300 MPa at the specimen surfaces. Furthermore, the shot-peened + crack-healed specimen retained a compressive residual stress of 200 MPa.
- The apparent surface fracture toughness of the shot-peened and shot-peened + crack-healed specimens increased by 96 and 50%, respectively, compared with that of the non-shot-peened specimen. The compressive residual stress prevented the development of indentation-fracture-induced cracks.
- The RCF life of the shot-peened specimen did not improve compared with that of the non-shot-peened specimen because the SP-introduced surface cracks could act as crack initiation sites during the RCF tests.
- The RCF life of the shot-peened + crack-healed specimen improved compared with those of the non-shot-peened and shot-peened specimens, implying that applying additional heating to heal SP-induced surface cracks was an effective strategy for improving the RCF lives of Al$_2$O$_3$/SiC composites.

Acknowledgments
This work was supported by JSPS KAKENHI Grant Numbers 22686013 and 16H04231.

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