Increased fatigue strength of partially stabilized zirconia achieved by shot peening

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The effects of shot peening on the fatigue strength of partially stabilized zirconia (PSZ) were studied. Smooth specimens and specimens containing a surface pre-crack with depths in the range 35-110 μm were subjected to shot peening. The cyclic fatigue tests were performed using a three-point bending setup. Shot peening introduced compressive residual stresses on the specimens and improved their fatigue strengths. The shot peened specimens with pre-crack depths ≤ 50 μm fractured outside the pre-crack area and exhibited considerably high fatigue limits, equivalent to those of the shot peened smooth specimens. Therefore, the pre-cracks with depths ≤ 50 μm could be rendered harmless by shot peening, which was confirmed by the theoretical estimations based on fracture mechanics.

Keywords: partially stabilized zirconia; shot peening; fatigue strength; residual stress; fracture mechanics

Introduction

Zirconia can exhibit superior fracture toughness than other ceramics due to the stress induced transformation from the tetragonal to the monoclinic phase,[1] which makes it suitable for applications such as mechanical components and dental materials. The mechanical components are subjected to repeated stress during their use. Accordingly, it is important to assess the fatigue strength characteristics of zirconia, and many studies have been carried out in this regard.[2-5] In the process of manufacturing of ceramic components, machining procedures such as grinding which may initiate the formation of surface cracks, are carried out. This leads to reduction in the fatigue strength if the size of the crack is larger than the acceptable size.[3, 4]

Shot peening (SP) is a surface treatment process that involves impacting a surface with shots. The main purpose of shot peening is to increase the fatigue strength and prevent the stress corrosion cracking of metals. It has been reported that shot peening on the steels containing crack-like surface defects improves the fatigue limit by increasing the acceptable defect size, in spring steels,[6-9] low-alloy steels[10] and carbon steels.[11, 12] In other words, the surface defects are rendered harmless by shot peening, from the viewpoint of the fatigue limit.

Recent studies have shown that shot peening introduces compressive residual stresses near the surfaces of ceramics such as silicon nitride,[13-16] alumina,[13, 17] and zirconia.[18-20] Moon et al. carried out shot peening on alumina and silicon nitride and reported that the fracture resistance of the sub-surface regions increased.[13] Pfeiffer and Frey reported that large compressive residual stresses up to 2000 MPa could be introduced into the near surface of alumina and silicon nitride ceramics by shot peening.[14] They showed that the static and cyclic load capacities increased by a factor of four.[14] Takahashi et al. reported that the combination of shot peening and crack healing increased the static contact strength of silicon nitride[15,16] and alumina composites[17]. Ito et al. reported that the flexural strength and the Weibull coefficient of partially stabilized zirconia (PSZ) could be improved by the beneficial effects of soft shot peening using aluminium shots.[18] Shukla and Lawrence applied micro-shot peening using glass beads and found that the method was effective in increasing the fracture toughness of zirconia-advanced ceramics.[19] Takahashi et al. reported that a compressive residual stress of 1800 MPa introduced in PSZ can improve both the wear resistance[21] and the fracture toughness.[20] It was also shown that the flexural strengths of the pre-cracked specimens were significantly improved and the pre-cracks with a depth less than 60 μm were rendered harmless by shot peening.[20] However, the effects of shot peening on the cyclic fatigue strength of zirconia have not yet been studied.

This study was carried out to analyse the effects of shot peening on the cyclic fatigue strength of PSZ containing a surface pre-crack. Smooth specimens and specimens containing a surface pre-crack were subjected to shot peening and cyclic fatigue tests were performed. The depth of the pre-crack that can be rendered harmless by shot peening was studied in terms of the cyclic fatigue limit.

Materials and methods

Specimen preparation

The PSZ ceramic used in this study was ZR1 (Japan Fine Ceramics Center), which consists of 3 mol% Y_2O_3 as a stabilizer. Figure 1(a) shows the shape and the dimensions of the specimens used for the cyclic fatigue tests. The tensile surface of the specimen (4 mm wide side) was precision polished to achieve a mirror-finish. These specimens are referred to as the 'smooth' specimens. Pre-cracks were introduced at the centre of the tensile surface of the smooth specimen by Vickers indentation and these specimens are referred to as the 'pre-cracked' specimens. Figure 1(b) shows the optical micrograph of the surface of the pre-cracked specimen. The Vickers indentation loads of 30, 50, and 100 N with a loading time of 20 s resulted in surface crack lengths ($2c$) of approximately 80, 110, and 250 µm, respectively. The aspect ratio (*a*/*c*) of the pre-crack was 0.9. Thus, the pre-crack depths (*a*) were approximately 35, 50, and 110 µm, respectively. Five specimens were used for the measurements of the Vickers hardness (HV). The average values of the Vickers hardness for the SP and the non-SP specimens were 1310 ± 6.3 and 1290 ± 13.3, respectively. We believe that the hardness increased due to the plastic deformation near the surface layer.

[Figure 1 near here]

Shot peening procedure and measurement of the residual stress

We performed shot peening on the surfaces of the smooth and the pre-cracked specimens using a direct-pressure system. The specimens subjected to shot peening are referred to as 'smooth + SP' specimens and 'pre-crack + SP' specimens. Table 1 lists the conditions used for the shot peening. Commercial ZrO_2 beads (TZ-B180, TOSOH Co. Ltd., Japan) with a diameter of 180 µm and Vickers hardness of 1150 HV were used as the shot material.

The residual stresses on the surfaces of the non-SP and SP specimens were measured using the X-ray diffraction (XRD) method with a Cu-Kα beam X-ray spectrum. The details of the measurement of the residual stress are explained in the literature.[20] A large compressive residual stress of approximately 1400 MPa was introduced on the surface of the PSZ specimen, reaching a maximum of 1800 MPa at a depth of 20 µm.[20] As the depth increased to 50 µm, the compressive residual stress decreased to 100 MPa.[20] The depth of the compressive residual stress is important because the pre-crack size rendered harmless by shot peening is related to the depth of the compressive stress layer. The large compressive residual stress was induced by the local plastic deformation and the transformation of zirconia from the tetragonal to the monoclinic phase.[20] The surface textures before and after shot peening were observed using optical microscopy and scanning probe microscopy (SPM) techniques.

[Table 1 near here]

Measurement of cyclic fatigue strength

The cyclic bending fatigue tests were carried out using a hydraulic testing machine with a stress ratio $R = 0.1$ and a nominal frequency of 10 Hz, at room temperature and room humidity by the three-point bending method. The span length for the three-point bending test was 16 mm, which was identical to that of the previous study.[20] The origins of the fractures of all the tested specimens were observed using an optical microscope and a scanning electron microscope (SEM).

Results and discussion

Surface texture after shot peening

Figure 2 shows the optical micrographs of the surfaces of the smooth and the smooth + SP specimens. The surface roughness was determined by the maximum height of the profile (R_y) according to a profilometer scan of the specimen surface. The average values of R_y for five scans were 0.36 ± 0.04 and 0.47 ± 0.07 μm for the smooth and the smooth + SP specimens, respectively.

The surface roughness after shot peening was slightly higher due to the plastic deformation caused by the impact of the shot media. Figure 3 shows the SPM images of the surfaces of the smooth and the smooth + SP specimens, respectively. Nano-sized dimples were observed on the surface of the smooth + SP specimen, instead of the scratch marks on the surface of the smooth specimen. The heights of the dimples were in the range of 30–50 nm, and they had a negligible effect on the fatigue strength, as discussed in the next section.

[Figure 2 near here]

[Figure 3 near here]

Effect of shot peening on the cyclic bending fatigue strength

Figure 4 shows the *S*-*N* curves, showing the relationship between the maximum bending stress during the cyclic fatigue tests (σ_{max}) and the number of cycles to failure (N_f). The bending strengths for each specimen[20] are also plotted in Fig. 4. The asterisks (*) indicate that the specimens fractured outside the pre-crack area. The arrows indicate that the specimens endured 2×10^6 fatigue cycles. The fatigue limit (σ_{f0}) was defined as the maximum value of σ_{max} at which the specimen endured 2×10^6 fatigue cycles. Figure 5 shows the comparison of the values of σ_{f0}. The fatigue limit of the smooth specimens increased by 19% after shot peening. The fatigue limit of the pre-cracked specimens decreased with increase in the depth of the pre-crack. However, the values of σ_{f0} for the pre-crack + SP specimens increased by 200–540% compared to those of the pre-cracked specimens not subjected to shot peening. Thus, shot peening is effective in increasing the fatigue limit of PSZ. It is surprising that the fatigue limit of the pre-crack + SP specimens with $a \cong 35$ or 50 μm were close to that of the smooth specimen. Similar results have been reported for metals;[6-9, 12] however, this is the first report with regard to ceramics.

[Figure 4 near here]

[Figure 5 near here]

Experimental evaluation of the pre-crack size rendered harmless by shot peening

Figure 6 shows the SEM micrographs of the fractured surfaces after the fatigue test. All the pre-cracked specimens without shot peening fractured at the pre-crack region regardless of the pre-crack depth. The Vickers indentations were observed on the fracture surfaces. Among the pre-crack + SP specimens, however, those with $a \cong 110$ μm fractured at the pre-crack location, while those with $a \cong 35$ or 50 μm fractured outside the pre-crack region. There was no crack propagation from the pre-crack in the pre-crack + SP specimens with $a \cong 35$ or 50 μm, owing to the introduction of the compressive residual stress in the near-surface region by shot peening.

If the fatigue test result of a pre-crack + SP specimen meets either one of the following two conditions, the pre-crack is considered to be rendered harmless by shot peening.[8, 9]

Condition (a): The fatigue limit increased to more than 95% of that of the smooth + SP specimen.

Condition (b): More than half of the specimens fractured outside the pre-crack zone.

In the pre-crack + SP specimens with $a \cong 50$ μm, two out of the three specimens fractured outside the pre-crack zone, as shown in the data with the asterisks in Fig. 4(c). Thus, based on condition (b), it can be interpreted that the pre-cracks with depths below $a \cong 50$ μm can be rendered harmless by shot peening.

[Figure 6 near here]

Theoretical estimation of the pre-crack size rendered harmless by shot peening

The method to evaluate the crack depth, which is rendered harmless by shot peening, is based on the stress intensity factors. Here, we demonstrate that the estimated value of the crack depth is consistent with the experimental results. It was assumed that a positive value of the stress intensity factor contributes to the propagation of the fatigue crack. The apparent range of the stress intensity factor (ΔK_T), which is a driving force for the crack propagation is expressed as follows:[6]

$$\Delta K_T = K_{max} + K_r, \qquad (1)$$

where, K_{max} is the stress intensity factor induced by the maximum bending stress, calculated using the Newman–Raju equation and K_r is the stress intensity factor induced by the residual stress.[22] K_{max} was determined from the maximum bending stress, σ_{max}, corresponding to the value of σ_{f0} of the smooth + SP specimens ($\sigma_{max} = \sigma_{f0} = 950$ MPa). The equations of American Petroleum Institute Recommended Practice (API RP) 579 were used to determine the value of K_r for the surface cracks.[23] The stress intensity factor for a semi-elliptical crack is expressed as follows.

$$K_r = \left[G_0\sigma_0 + G_1\sigma_1\left(\frac{a}{t}\right) + G_2\sigma_2\left(\frac{a}{t}\right)^2 + G_3\sigma_3\left(\frac{a}{t}\right)^3 + G_4\sigma_4\left(\frac{a}{t}\right)^4\right]\sqrt{\frac{\pi a}{Q}}\,f_w, \qquad (2)$$

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65}, \tag{3}$$

$$f_w = \left[\sec\left(\frac{\pi c}{2W}\right)\sqrt{\frac{a}{t}}\right]^{1/2}, \tag{4}$$

where, G_0 to G_4 represent the influence coefficients for a semi-elliptical crack according to API RP 579. W and t are the width and the thickness of the specimens (W = 4 mm and t = 3 mm). The coefficients, σ_0 to σ_4, are obtained by the fourth-order polynomial curve fitting of the residual stress distribution, using the equation:

$$\sigma(x) = \sigma_0 + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4, \tag{5}$$

where x indicates the distance from the specimen surface in the direction of the depth. The residual stress distribution of the SP specimens[20] was approximated as a fourth-order polynomial distribution. The resulting values of K_{max}, K_r and $\Delta K_{T,}$ are shown in Fig. 7. The values of K_r were negative because the residual stress was compressive. The values of ΔK_T at the deepest point and at the surface of a semi-elliptical crack are represented by $\Delta K_{T,A}$ and $\Delta K_{T,C}$, respectively.

The method for determining the size of the pre-crack which is rendered harmless is described as follows. If ΔK_T is less than the threshold stress intensity factor range, ΔK_{th}, the surface crack is considered to be harmless. The values of ΔK_{th} were calculated from the fatigue limits (σ_{f0}) of the pre-cracked specimens and are shown in Fig. 8. The figure also shows the relationship between ΔK_T and a. The fatigue cracks are initiated at the deepest point in the pre-crack (point A) and the values of $\Delta K_{T,A}$ increase with the crack depth. Thus, the intersection between $\Delta K_{T,A}$ and ΔK_{th} gives the maximum defect size a_{max}, that can be rendered harmless by shot peening. From Fig. 8, the value of a_{max} was estimated to be 53 μm. The experimental results indicated that the surface cracks with depth $a \leq 50$ μm were rendered harmless by shot peening. Thus, the theoretical result obtained using fracture mechanics is consistent with our experimental result. Shot peening is therefore a useful technique for improving the fatigue strength of PSZ and rendering the detrimental surface cracks harmless.

[Figure 7 near here]

[Figure 8 near here]

Conclusion

The effects of shot peening on the fatigue strength of PSZ and the pre-crack depth that could be rendered harmless by shot peening were investigated. The following conclusions were obtained:

(1) The fatigue limits of the pre-cracked specimens after shot peening were significantly increased, by 200–540%, compared to those of the pre-cracked specimens without shot peening. The compressive residual stress induced by the local plastic deformation and the transformation of zirconia from the tetragonal to the monoclinic phase contributed to the improvement in the fatigue limits.

(2) In the pre-crack + SP specimens with $a \cong 35$ and 50 μm, majority of the specimens fractured outside the pre-crack zone. Thus, according to the experimental results, the surface cracks with a depth ≤ 50 μm could be rendered harmless by shot peening.

(3) The maximum crack depth (a_{max}) that could be rendered harmless by SP was also estimated based on fracture mechanics. The value of a_{max} was found to be 53 μm, which was consistent with our experimental results.

(4) Shot peening is a useful surface treatment method for improving the fatigue properties of PSZ and rendering detrimental surface cracks harmless.

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Table captions

Table 1. Conditions used for the shot peening of PSZ.

Figure Captions

Figure 1. (a) The shape and the dimension of the specimen used in the present study (unit: mm) and the schematic of the pre-crack position. (b) Optical micrograph of the surface of the pre-cracked specimen (indentation load: 50 N, pre-crack length $2c \cong 110$ μm, pre-crack depth $a \cong 50$

μm).

Figure 2. Optical micrographs of the surfaces of the (a) smooth and the (b) smooth + SP specimens.

Figure 3. SPM images and profiles of the surfaces of the (a) smooth and the (b) smooth + SP specimens

Figure 4. *S*-*N* curves for the following specimens: (a) Smooth, (b) Pre-cracked with $a \cong 35$ μm, (c) Pre-cracked with $a \cong 50$ μm, and (d) Pre-cracked with $a \cong 110$ μm. The open and solid symbols represent the non-SP and SP specimens, respectively.

Figure 5. Comparison of the fatigue limits for the smooth specimens, and for the pre-cracked specimens with varying crack depth (a).

Figure 6. SEM micrographs of the fractured surfaces obtained after the fatigue tests, showing the origin of fracture in the different specimens.

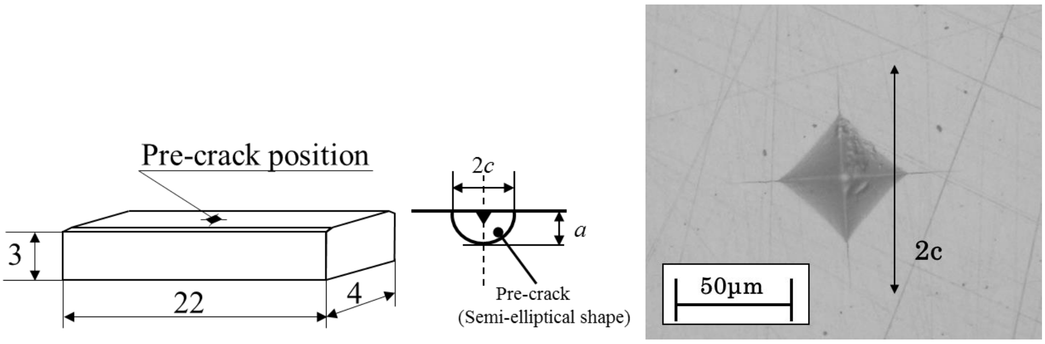
Figure 7. Distribution of the stress intensity factors as a function of the crack depth.

Figure 8. Estimation of the maximum crack size that can be rendered harmless by shot peening.

Table 1. Conditions used for the shot peening of PSZ.

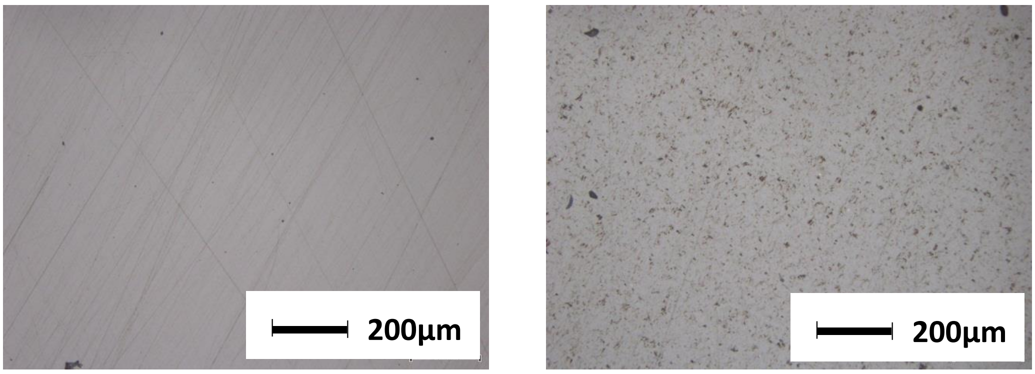
Shot system	Direct pressure system, FDQ-2
Shot material	ZrO_2 beads, TZ-B180
Shot Vickers hardness [HV]	1150
Shot diameter [μm]	180
Shot pressure [MPa]	0.2
Projector distance [mm]	100
Time [s]	30
Coverage [%]	300

Figures



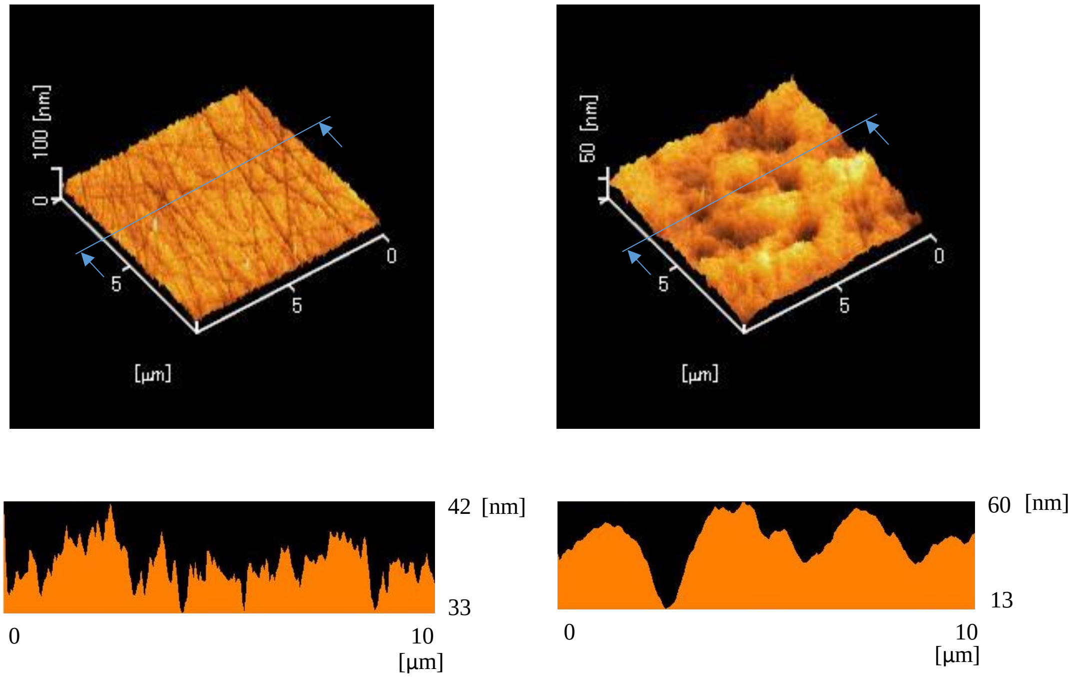
(a) (b)

Figure 1. (a) The shape and the dimension of the specimen used in the present study (unit: mm) and the schematic of the pre-crack position (b) Optical micrograph of the surface of the pre-cracked specimen (indentation load: 50 N, pre-crack length *2c* ≅ 110 μm, pre-crack depth *a* ≅ 50 μm).



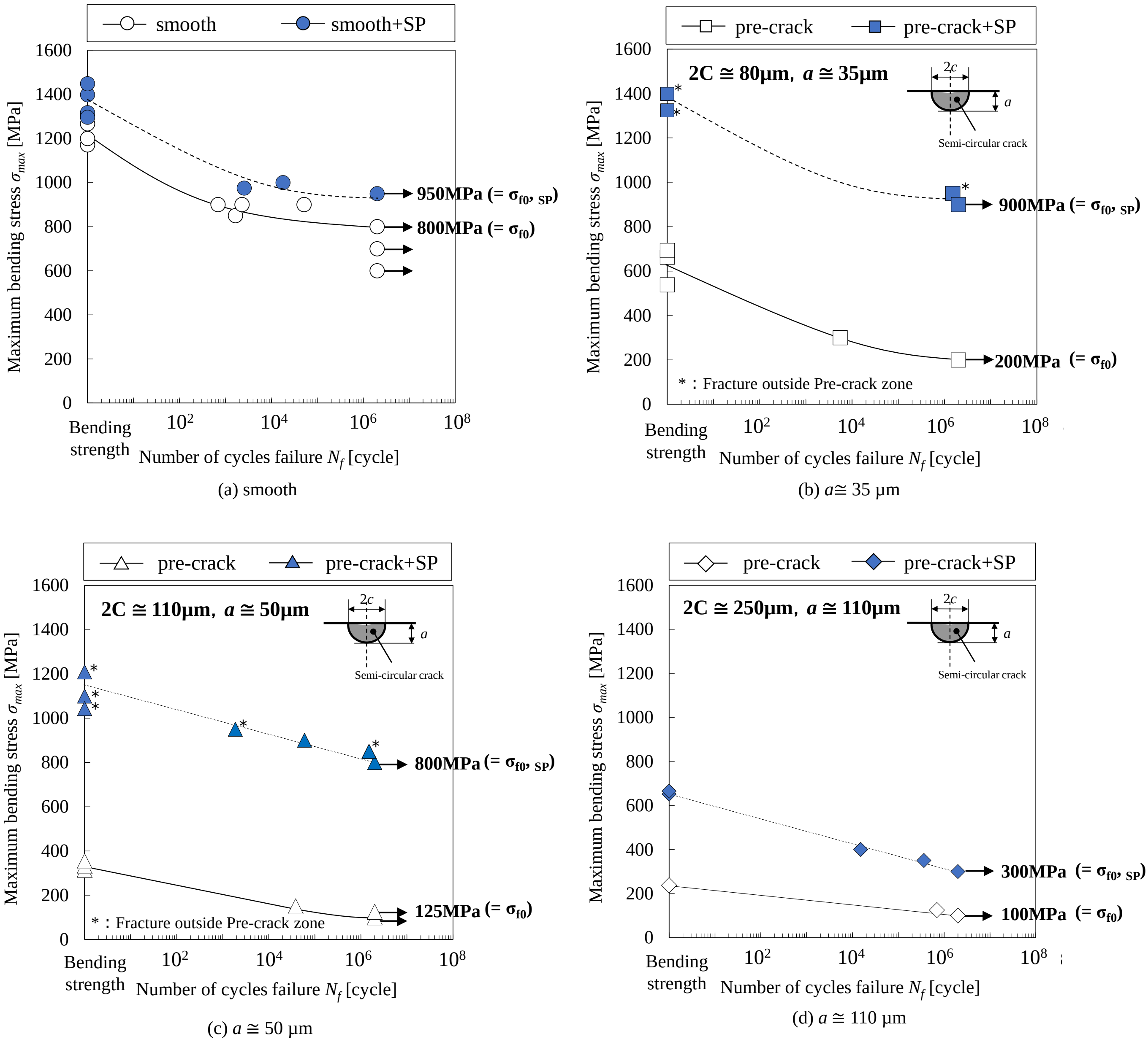
(a) Smooth (b) Smooth + SP

Figure 2. Optical micrographs of the surfaces of the (a) smooth and the (b) smooth + SP specimens.



(a) Smooth (b) Smooth + SP

Figure 3. SPM images and profiles of the surfaces of the (a) smooth and the (b) smooth + SP specimens



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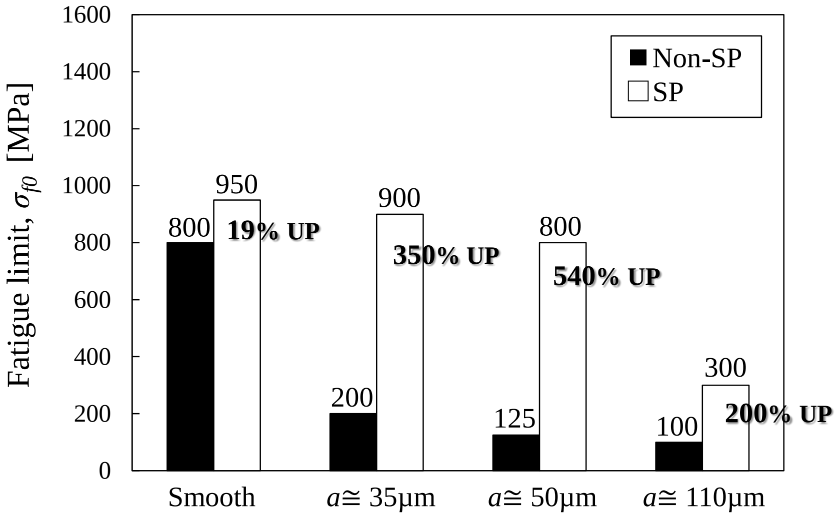

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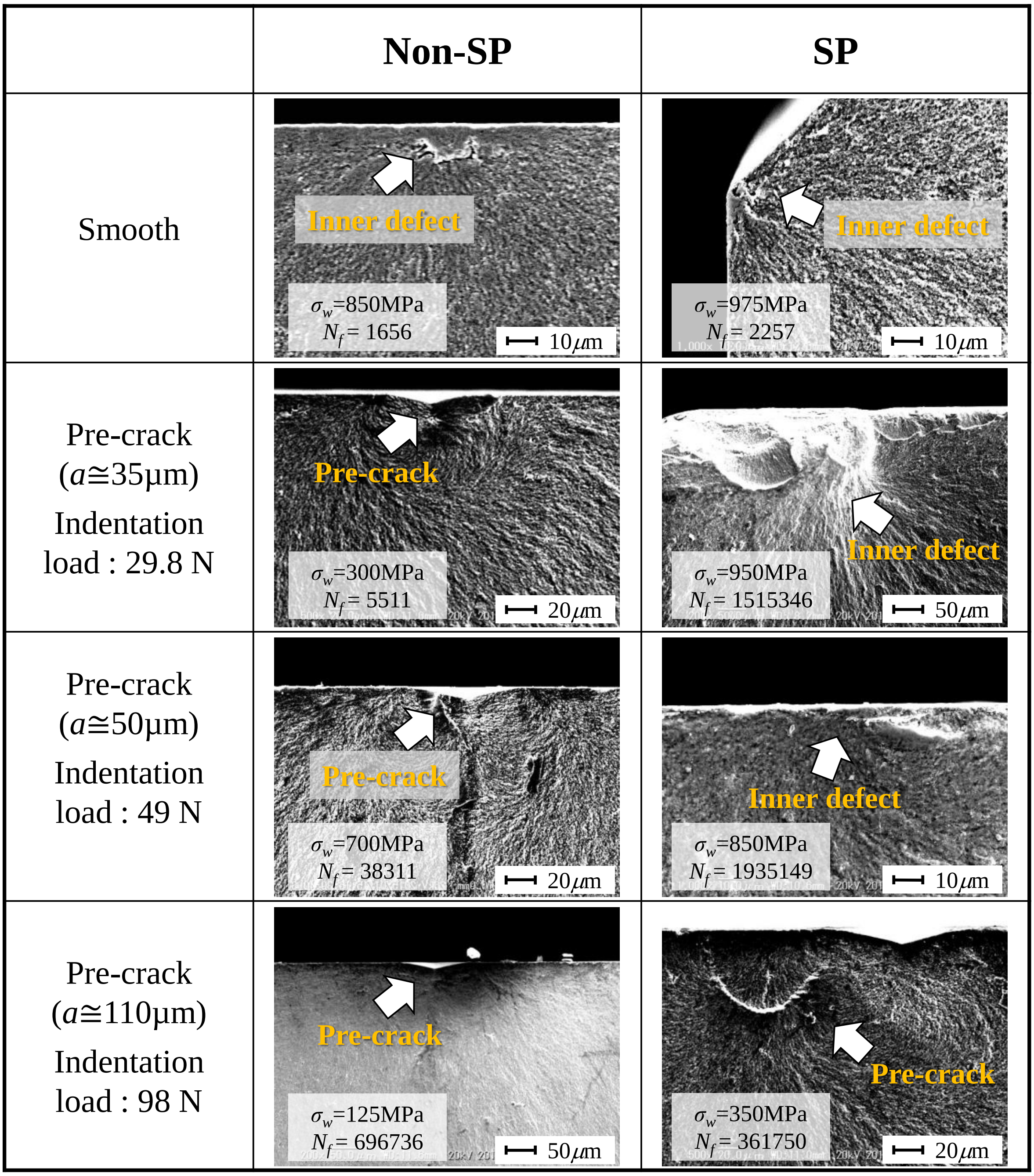

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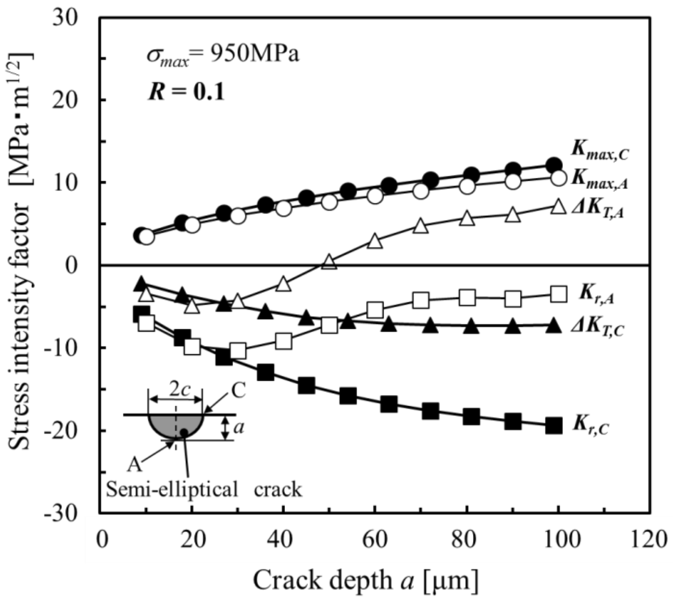

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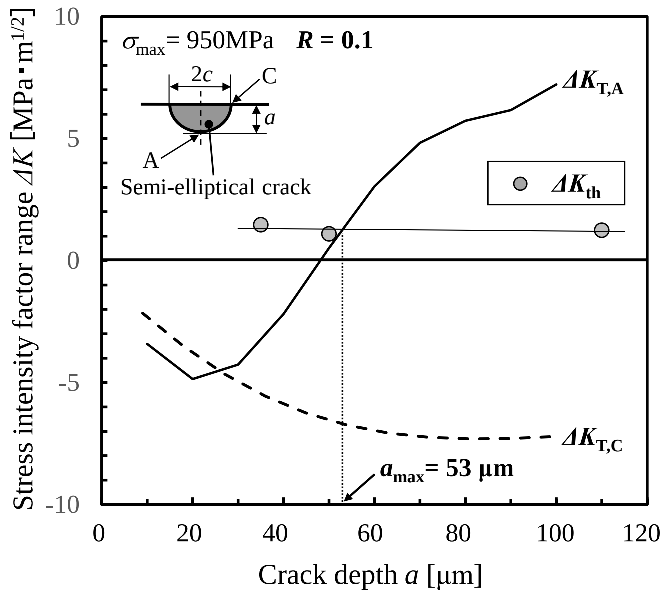

Figure 8. Estimation of the maximum crack size that can be rendered harmless by shot peening.