13th International Conference on Shot Peening

Improvement of fatigue strength of partially stabilised zirconia by shot peening

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Keywords: Partially stabilised zirconia, Fatigue strength, Shot peening, Compressive residual stress

Introduction

Partially stabilised zirconia (PSZ) can exhibit superior fracture toughness than other ceramics which makes it suitable for applications such as mechanical components and dental materials. The surface cracks induced by machinig leads to reduction in the fatigue strength if the size of the crack is larger than the acceptable size. The surface cracks in steels are rendered harmless by shot peening (SP), from the viewpoint of the fatigue limit [1]. Recent studies have shown that SP introduces compressive residual stresses near the surfaces of ceramics[2]. Takahashi et al. reported that a compressive residual stress of 1800 MPa introduced in PSZ and the apparent fracture toughness and flexural strengths were improved by SP [3]. However, the effects of SP on the cyclic fatigue strength of PSZ have not yet been studied.

Objectives

This study was carried out to investigate the effects of SP on the cyclic fatigue strength of PSZ containing a surface pre-crack. The depth of the pre-crack that can be rendered harmless by SP was studied in terms of the cyclic fatigue limit.

Methodology

The PSZ ceramic used in this study consists of 3 mol% Y_2O_3 as a stabilizer. The bending test specimens with 3×4×20 mm were prepared. The tensile surface of the specimen (4 mm wide side) was 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. The Vickers indentation loads of 30, 50, and 100 N resulted in crack depths (a) were approximately 35, 50, and 110 μm, respectively.

Shot peening was perfomed 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. Commercial ZrO_2 beads with a diameter of 180 μm and Vickers hardness of 1150 HV were used as the shot material. The peening pressure was 0.2MPa. Peening time was 30 s.

TheThe residual stresses on the surfaces of specimens were measured using the X-ray diffraction (XRD) method with a Cu-Kα beam X-ray spectrum. 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 [3]. As the depth increased to 50 μm, the compressive residual stress decreased to 100 MPa. The large compressive residual stress was induced by the local plastic deformation and the transformation of zirconia from the tetragonal to the monoclinic phase [3].

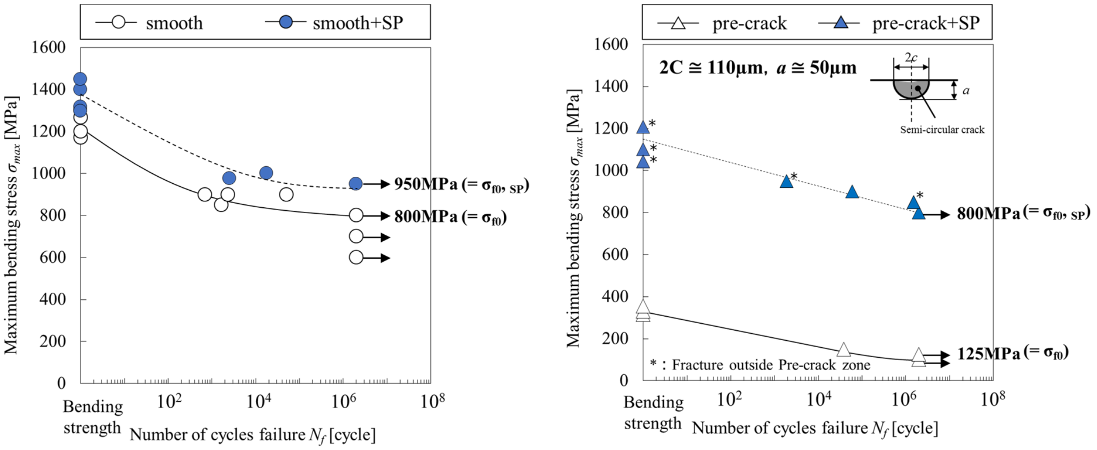
The surface roughness was determined by the maximum height of the profile (R_y) according to a profilometer scan of the specimen surface. The average values of R_y for five scans were 0.36 ± 0.04 and 0.47 ± 0.07 μm for the smooth and the smooth + SP specimens, respectively. The surface roughness after shot peening was slightly higher due to the plastic deformation caused by the impact of the shot media.

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 by the three-point bending method. The span length for the three-point bending test was 16 mm. The origins of the fractures of all the tested specimens were observed using an optical microscope and a scanning electron microscope (SEM).

Results

Effect of shot peening on the cyclic bending fatigue strength

Figure 1(a) and (b) shows the *S-N* curves for smooth and pre-cracked specimens with $a \cong 50$ μm, 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 [3] are also plotted in Fig. 1. 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.



(a) smooth

(b) $a \cong 50$ μm

Figure 1. *S-N* curves for the following specimens: (a) Smooth, (b) Pre-cracked with $a \cong 50$ μm. The open and solid symbols represent the non-SP and SP specimens, respectively.

Figure 2 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 [1]; however, this is the first report with regard to ceramics.

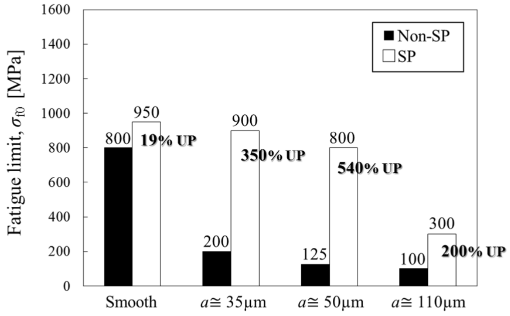


Figure 2. Comparison of the fatigue limits for the smooth specimens, and for the pre-cracked specimens with varying crack depth (a).

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

Figure 3 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.[1]

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.

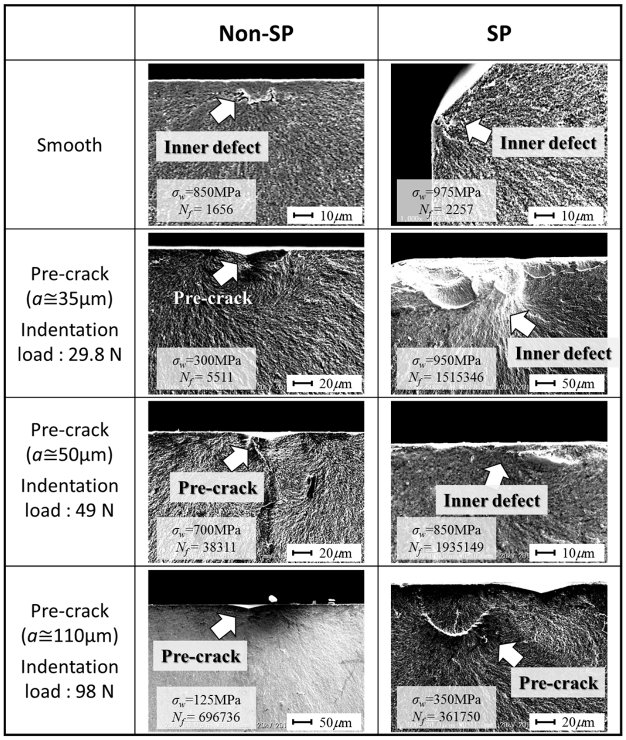


Figure 3. SEM micrographs of the fractured surfaces obtained after the fatigue tests, showing the origin of fracture in the different specimens.

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. 1(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.

Discussions

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 [1]:

$$\Delta K_T = K_{max} + K_r, \tag{1}$$

where, K_{max} is the stress intensity factor induced by the maximum bending stress, calculated using the Newman–Raju equation [4] and K_r is the stress intensity factor induced by the residual stress [5]. K_{max} was determined from the maximum bending stress, σ_{max}, corresponding to the value of σ_{f0} of the smooth + SP specimens (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 [5]. The stress intensity factor for a semi-elliptical crack is expressed as follows.

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

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

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

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 [3] was approximated as a fourth-order polynomial distribution.

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. 4. 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. 4, 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.

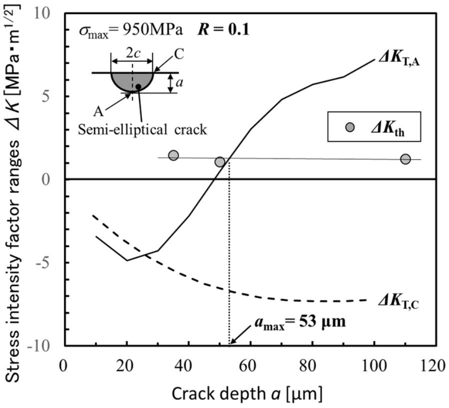


Figure 4. Estimation of the maximum crack size that can be rendered harmless by shot peening.

Conclusions

(1) The fatigue limits of the pre-cracked specimens after SP were significantly increased, by 200–540%, compared to those of the pre-cracked specimens without SP. The large compressive residual stress induced by SP 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 SP.
(3) The predicted value of a_{max} was found to be 53 μm, which was consistent with our experimental results.

Considering the above results it can be concluded that SP is a useful surface treatment method for improving the fatigue properties of PSZ and rendering detrimental surface cracks harmless.

Acknowledgments

This study was supported by JSPS KAKENHI Grant Numbers 25289003 and 16H04231.

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