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RESIDUAL STRESS ESTIMATED BY NEW EMPIRICAL METHOD AND ITS CORRELATION WITH STRENGTH IN CERAMICS

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ABSTRACT

An easier method for the residual stress estimation in ground ceramics was investigated as the alternative to the X-ray diffraction method. A new empirical procedure to evaluate grinding-induced residual stresses was described based on the indentation fracture (IF) method. The formulation to calculate the peak residual stress on the ground surface was derived from the critical equilibrium growth of the indentation-induced crack. Alumina and two kinds of silicon nitride ceramics, which were ground under different grinding conditions, were prepared for experiments. The comparison of the residual stress estimated by the present procedure with the residual stress measured by the X-ray diffraction method showed a quantitative correspondence between them. The relation between the bending strength and the grinding-induced residual stress estimated by the present procedure was also investigated. In all materials, a larger compressive residual stress was found to result in a higher strength. It was clarified that the strength normalized by using material constants, the fracture toughness and the mean grain size, was almost uniquely correlated with the estimated residual stress independently to the examined materials.

KEYWORDS

Ceramics, Residual stress, Estimation, Indentation fracture method, Bending strength, Grinding

INTRODUCTION

Residual stresses in ceramic components are generated in their grinding processes, which are inevitable to improve the accuracy of dimension in engineering applications. It should be noted that strength properties of ceramics are remarkably influenced by the grinding-induced residual stress as well as surface defects [1-7]. Although the X-ray stress measurement method has a wide applicability to the residual stress estimation in various materials, alternative simpler methods for the residual stress estimation are required considering practical needs. For ceramics, especially, a possible candidate procedure to estimate the residual stress is suggested to be the indentation fracture (IF) method [5, 8-12], which has been developed as a convenient procedure to evaluate the fracture toughness of ceramics. In the IF method, the length of an indentation-induced crack is one of dominant parameters in the fracture toughness evaluation, and the crack length may be affected by a pre-existing residual stress field. This implies that the information on residual stress can be included in the toughness value evaluated by the IF method.

In this work, an empirical procedure to evaluate the grinding-induced residual stress is introduced on the basis of the IF method. Residual stresses in alumina and silicon nitride ceramics, which are machined under different grinding conditions, are estimated by using the proposed method. The estimated results are also verified by comparison with residual stresses measured by the X-ray method. Finally, the bending strength is correlated with the estimated residual stress, and the discussion is made on the obtained relation between them.

ESTIMATION PROCEDURE OF RESIDUAL STRESS

Estimation Principle by IF Method

At a critical level for equilibrium crack growth in an indented ceramic material with a residual stress, the net stress intensity factor K_{net} remains constant as follows [9].

$$K_{net} = K_{CA} + K_R = K_{IC} , \quad (1)$$

where K_{IC} is the fracture toughness and K_R is a residual stress intensity factor associated with the residual stress field. In Eqn. 1, K_{CA} is a fracture toughness evaluated by using an IF method. It is noted that K_{CA} is an apparent fracture toughness affected by the residual stress. The evaluation procedures for K_{CA} and K_R are described in the following.

Several formulae to evaluate the fracture toughness K_C of ceramics by using the IF method have been proposed [ex. 13], though the following equation recommended in the Japanese Industrial Standard (JIS) R 1607 [14] is adopted in this work.

$$K_C = \frac{\alpha [E\,P]^{1/2} (d/2)}{a^{3/2}} , \quad (2)$$

where α, E and P are an empirical coefficient, the Young's modulus of an indented material and the indentation peak load set in a Vickers hardness tester, respectively. The coefficient α in Eqn. 2 is given as 0.026 in JIS R 1607. Other dimensions d and a are the diagonal length of a Vickers impression and the half surface-length of a crack well-developed after indentation, respectively. The measured crack length a is affected by a residual stress field as illustrated in Fig. 1. In this case, the toughness K_C calculated by Eqn. 2 should be interpreted as an apparent fracture toughness K_{CA}. Since the growth of an indentation-induced crack is restrained under a compressive stress field, the crack length a_{com} under a compressive stress is expected to be shorter than the length a_o in no residual stress field. On the contrary, it is anticipated that the crack length a_{ten} observed under a tensile stress is longer than the length a_o.

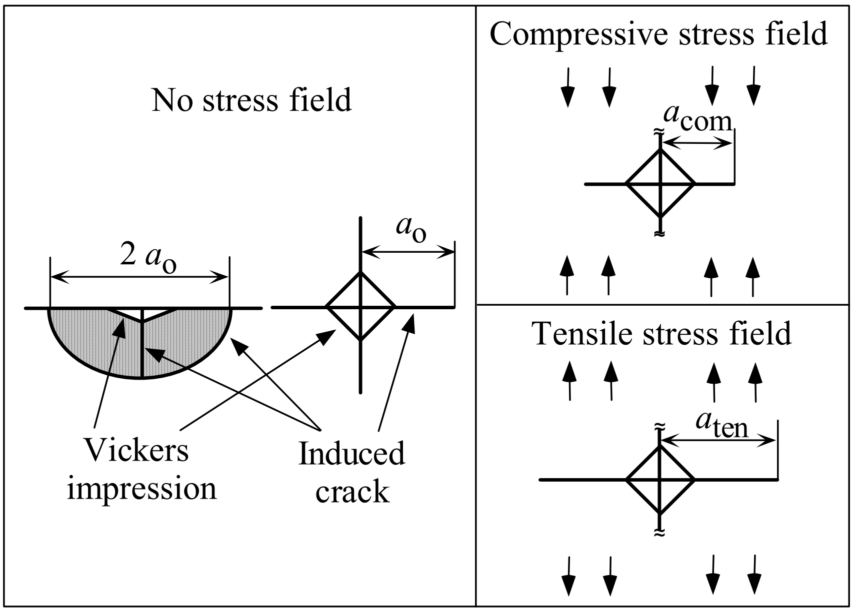

Figure 1: Illustration of indentation-induced crack

A grinding-induced residual stress σ_R is generally known to be compressive. In experimental studies [4-6, 15], it is also reported that the compressive residual stress σ_R has its peak σ_{RO} on or near the ground surface of a ceramic specimen and vanishes toward the specimen-depth direction. Since the well-developed crack induced by an indentation is usually approximated as a semi-elliptical crack, K_R for the crack in a residual stress filed can be expressed by the typical form as

$$K_R = \frac{\sigma_{RO}(\pi \lambda a)^{1/2}}{\Phi(\lambda)} M_R \, . \tag{3}$$

In Eqn. 3, λ is the aspect ratio defined as the ratio b/a of the crack depth b to the surface half length a, and $\Phi(\lambda)$ is the complete elliptic integral of the second type depending on λ. The parameter M_R in Eqn. 3 is a magnification factor determined by a given residual stress distribution, λ and b/t, where t is the specimen thickness.

Residual Stress Estimate by IF Method

By substituting Eqn. 2 with $\alpha = 0.026$ and Eqn. 3 into Eqn. 1, we have the following equation to estimate the peak residual stress σ_{RO}.

$$\sigma_{RO} = \frac{K_{IC}(\pi a)^{-1/2} - 0.026(E P/\pi)^{1/2}(d/2)\, a^{-2}}{\lambda^{1/2} M_R} \Phi(\lambda) \, . \tag{4}$$

Recently, using the IF method, the standard JSMS-SD-4-01 for the evaluation of grinding-induced residual stresses in ceramics has been established by the Society of Materials Science, Japan (JSMS). In this standard, the peak residual stress is evaluated by using the formulation:

$$\sigma_{RO} = \frac{K_{IC}(\pi a)^{-1/2} - 0.026(E P/\pi)^{1/2}(d/2)(a)^{-2}}{M} \, . \tag{5}$$

The coefficient M in Eqn. 5 is found to be equivalent to $\lambda^{1/2} M_R/\Phi(\lambda)$ by comparison with Eqn. 4. This means that M may be calculated if the parameters λ and M_R are known. Usually, however, it is difficult to get the information about λ and M_R. In the standard, therefore, $M = 1.4$ is empirically determined on the basis of the result obtained in the round robin test which was conducted by the working group organized by JSMS Committee on Fatigue of Materials.

EXPERIMENTAL PROCEDURES

Materials and Specimen Preparations

Materials to be used in experiments have been investigated in other works; i.e. two lots of a pressureless sintered alumina produced by Japan Fine Ceramics Center (AL-PL1 [16] and AL-PL2), a gas pressure sintered silicon nitride produced by NGK Spark Plug Co. Ltd. (SN-GP [16]), and two kinds of pressureless sintered silicon nitrides (SN-PL1 [5] and SN-PL2) by TOTO Ltd. and Japan Fine Ceramics Center, respectively. The bulk density ρ, the Young's modulus E and the fracture toughness K_{IC} of the materials are as follows; $\rho = 3.93$ Mg/m^3, $E = 380$ GPa and $K_{IC} = 4.4$ MPa·m$^{1/2}$ for AL-PL1 and AL-PL2, $\rho = 3.23$ Mg/m^3, $E = 320$ GPa and $K_{IC} = 6.0$ MPa·m$^{1/2}$ for SN-GP, $\rho = 3.23$ Mg/m^3, $E = 310$ GPa and $K_{IC} = 5.7$ MPa·m$^{1/2}$ for SN-PL1 by TOTO, and $\rho = 3.23$ Mg/m^3, $E = 259$ GPa and $K_{IC} = 7.1$ MPa·m$^{1/2}$ for SN-PL2 by Japan Fine Ceramics Center. The fracture toughness of each material was obtained by the standard method specified in JIS R 1607 or its equivalent procedure.

Geometry of specimen machined in this work was of a square rod type with a dimension of 4×3×36 mm^3 which is specified for the bending specimen in JIS R 1601 [17]. In all cases, the grinding direction was set in the longitudinal direction of specimen. For AL-PL1 and SN-GP, two types of specimens were finally prepared by grinding with wheels of #400 and #800 grit sizes. The cutting depth per one pass was set to be 4 μm for #400 grinding and 2 μm for #800 grinding, respectively. Another series of AL-PL2 and SN-PL2 specimens were also prepared by using grinding wheels of #80, #200 and #800 grit sizes. In this series, the cutting depths per pass in the conditions using #80, #200 and #800 grinding wheels were respectively 20 μm, 8 μm and 2 μm, while surfaces of specimens ground by using #80 wheel were slightly polished so that the indentation-induced crack could be more easily observed. On the other hand, specimens of SN-PL1 were machined under six different conditions as follows. Three distinct grit sizes of grinding wheel, #170, #270 and #600, were adopted. Two values of the cutting depth were selected for each grit size; i.e. 5 μm and 40 μm for #170 and also for #270, and 1 μm and 25 μm for #600.

Testing Procedures

In the present study, specimens were indented by using an ordinary Vickers hardness tester, and the indentation force was set to be in the range from 196 to 490 N. The surface length $2a$ of the crack was measured through an optical microscope, while the crack tip was sometimes identified by using a laser scanning microscope with a higher resolving power.

Bending strength has been obtained for AL-PL1 [16], SN-GP [16] and SN-PL1 [5], respectively. Smooth specimens of AL-PL1 and SN-GP were loaded by four-point bending with an outer span of 30 mm and an inner span of 10 mm, while bending tests for smooth specimens of SN-PL1 were conducted under three-point mode with a span length of 20 mm. In each case, tests were carried out under load-controlled condition, and the loading rate was controlled so that the rate of the maximum tensile stress in a specimen might be about 100 MPa/s.

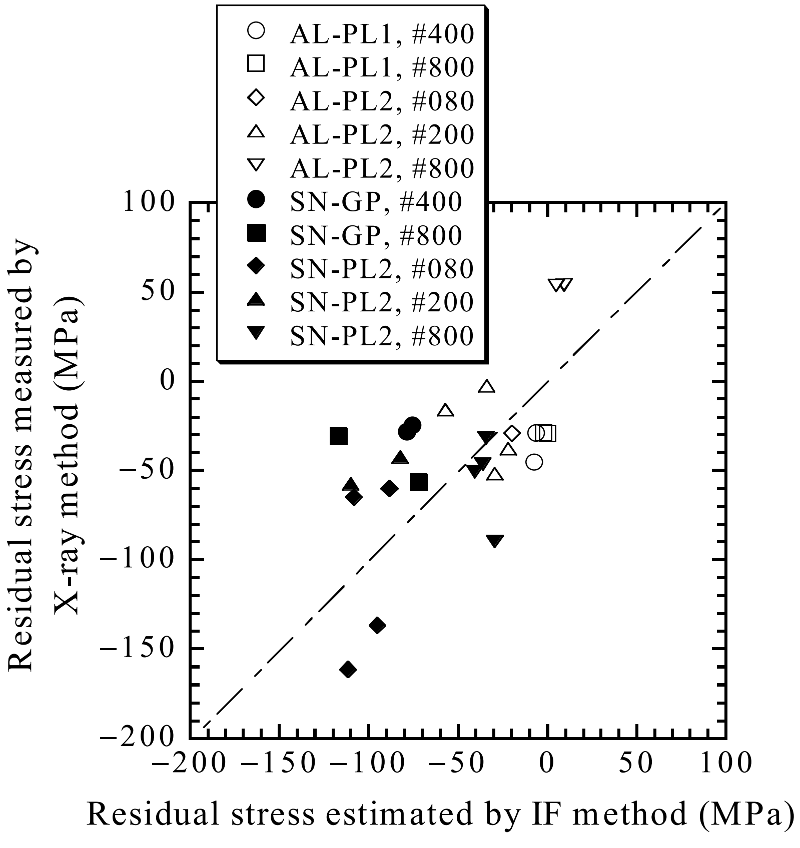

Figure 2: Comparison between residual stresses evaluated by X-ray and IF methods

EXPERIMENTS AND DISCUSSIONS

Comparison between Residual Stresses Measured by Proposed and X-Ray Procedures

Grinding-induced residual stresses in AL-PL1, AL-PL2, SN-GP and SN-PL2 specimens were also measured by using an X-ray diffraction method. For the materials, the residual stress measured by the X-ray diffraction method is compared with that estimated by the present procedure in Fig. 2. Although a little bit large scatter is seen in the figure, a good coincidence is found between the residual stresses by the X-ray and the IF methods. Consequently, it may be concluded that the proposed procedure gives a quantitative correspondence to the

X-ray measurement. This implies that the proposed procedure is applied as a simpler estimation of grinding-induced residual stress in ceramic materials.

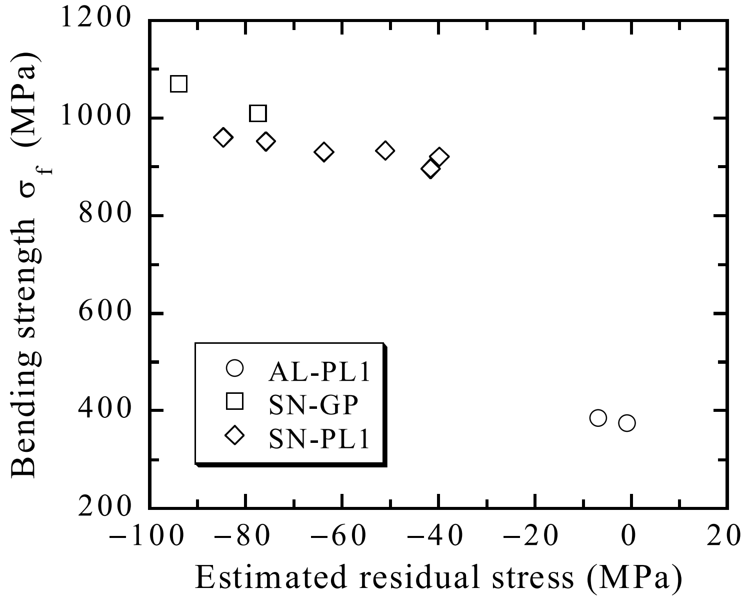

Figure 3: Relation between estimated residual stress and bending strength

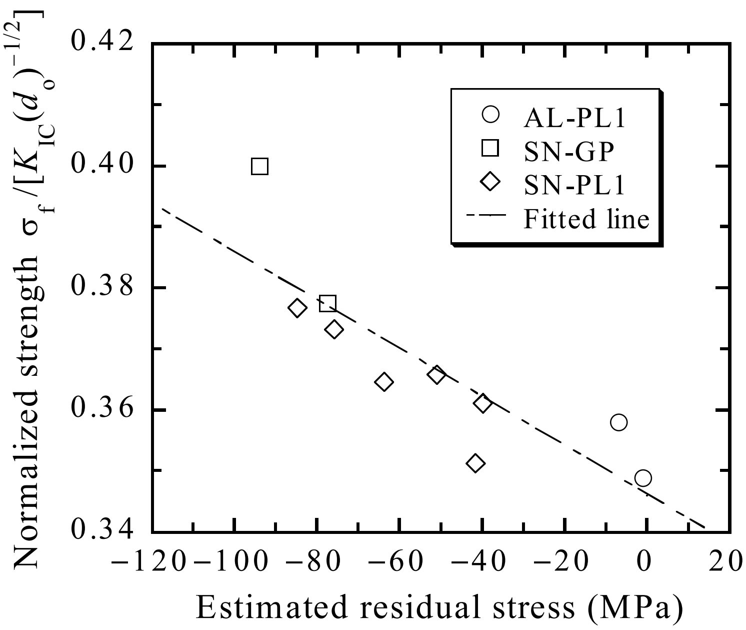

Figure 4: Relation between estimated residual stress and bending strength normalized by using material constants

Relation between Strength and Estimated Residual Stress

As mentioned in the introduction, the strength of ceramic materials is affected by the residual stress. In this section, the strength is correlated with the grinding-induced residual stress estimated by the proposed procedure. Figure 3 shows the relation of the mean strength σ_f depending on the grinding condition with respect to the estimated peak residual stress σ_{RO}. Using the fracture toughness K_{IC} and the mean grain size d_o, the strength is normalized by a stress parameter K_{IC} $(d_o)^{-1/2}$, and the normalized strength is also correlated with the estimated residual stress in Fig. 4. As seen in Fig. 4, the relation between the normalized strength and the estimated residual stress is well fitted by the linear relationship as depicted with the dot-dash line, and the relation is found to be independent of the examined materials.

As shown in Fig. 3 and Fig. 4, a larger compressive residual stress is found to result in a larger strength. This result is reasonable, because the compressive stress restrains the crack growth from inherent and grinding-induced defects, and improves the material strength.

CONCLUDING REMARKS

In this work, a new empirical procedure to estimate grinding-induced residual stresses based on the indentation fracture method was described for ground ceramic materials. The peak residual stress appeared on the ground surface was formulated from the critical equilibrium growth of an indentation-induced crack. The proposed procedure was applied to a pressureless sintered alumina, a gas pressure sintered and pressureless sintered silicon nitrides, which were ground under different grinding conditions. The residual stress estimated by the present procedure was almost coincided with the residual stress measured by the X-ray diffraction method. It was revealed that estimated residual stresses were compressive in the investigated materials. A reasonable correlation was also seen between the estimated residual stress and the bending strength; i.e. a larger compressive residual stress increased the strength. It was also clarified that the strength normalized by using material constants, the fracture toughness and the mean grain size, was almost uniquely correlated with the estimated residual stress independently to the examined materials. Consequently, it was concluded that the proposed procedure was effective in the estimation of residual stresses generated in ground ceramic materials.

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