R-curve Behavior of Engineering Ceramics

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ABSTRACT

R-curve behaviors of silicon nitride, reinforced alumina,tetragonal zirconia and silicon carbide are evaluated. On the silicon nitride, large increase of the resistance of fracture is observed, and the change of the load and the resistance of fracture correspond to the analysis. On the contrary, the increase of the resistance of fracture is very small on tetragonal zirconia. It is expected that the effect of the transformation toughening of this material should be saturated on the propagation of the crack. It can be also estimated from the difference of the crack length on the maximum load and the minimum resistance of fracture. On the silicon carbide, fracture occurs at lower applied load than other materials, then the testing condition must be considered to evaluate the resistance of fracture exactly.

INTRODUCTION

Engineering ceramics are expected to use as the structural materials, but the brittleness of the ceramics is the largest problem to apply these materials to some components. Then, a lot of studies are carried out to estimate the brittleness of ceramics, especially to measure the fracture toughness, K_{IC}[1-3].

Chevron notched beam technique is one of the most common technique to measure the fracture toughness of engineering ceramics. This is good technique because the measured value of the fracture toughness is independent of the machined notch width and the data show small scattering, but in some case, the maximum of the load during the fracture may depend on the cross head speed of the bending test. Then, the change of the stress intensity factor during the fracture test should be evaluated exactly [4].

The concept of R-curve is based on the change of stress intensity factor during the fracture caused by the increase of resistance of fracture by the creation of process zone, wake, pull-out mechanism and so on [5]. In this study, we measured the slow and static fracture of the chevron notched beam and calculated the change of stress intensity factor and crack length from the change of the compliance of the specimen. Then, we discuss the character of the R-curve on each material.

EXPERIMENTAL

Tested samples are pressureless sintered silicon nitride with yttria and alumina as additives, pressureless sintered silicon carbide with boron and carbon compounds as additives, tetragonal zirconia with 3mol% yttria and reinforced alumina with 15wt% tetragonal zirconia. Table 1 shows the principal mechanical properties of each material.

Figure 1 shows the cross section of the chevron notch. Machining of the notch was carried out with a diamond cutting wheel of 0.1mm thickness. Bending test was carried out with 4-point bending of 30mm and 10mm lower and upper spans, respectively. Crosshead

Table 1 Mechanical properties of tested ceramic materials.

	Density (g/cm^3)	Young's modulus (GPa)	Flexural strength (MPa)
Si_3N_4	3.18	285	820
Al_2O_3	4.19	340	750
TZP	6.04	206	1200
SiC	3.06	410	400

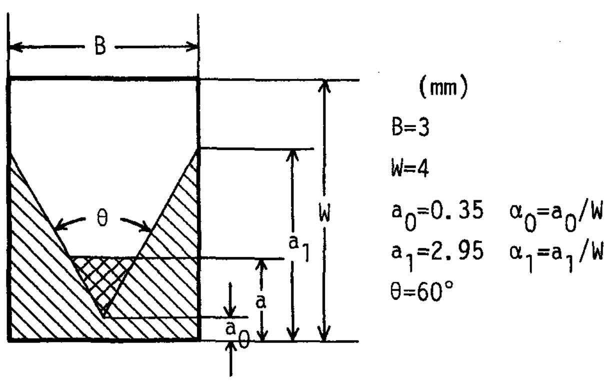

Figure 1 Cross section of chevron notch.

speed was controlled by strain gauge set under the center of the bending bar, but in this system, the deformation of the suspension rolls of the bending test should be considered to evaluate the real deflection of the specimen. Then, the real deformation of the specimen is determined by the comparison of the apparent value of the deformation and the calculated value from the load and the Young's modulus of each material. The deflection rate was 1μm/min. On each sample, fracture speed becomes faster than the deflection controlled speed when the normalized crack length, a/W, is longer than 0.5, and the instantaneous fracture occurs at this crack length. Then the data of the longer crack length region are neglected. On the other hand, the data before the resistance of fracture becomes minimum is also neglected, because on the chevron notch, it is very difficult to determine the stress intensity factor on the short crack length, and the length of the crack is not long enough compare to the width of the notch.

Resistance of fracture (K_{IR}) and crack length are calculated by the equation presented by Munz [6] under the concept of the slice model by Bluhm [7]. First of all, the change of the compliance of the bending bar from the straight through crack is calculated from equation (1) to (3).

$$dC'/d\alpha=2Y^2 \tag{1}$$

$$Y=[(S_1-S_2)/W]\{(3\Gamma_M\sqrt{\alpha})/[2(1-\alpha)^{3/2}]\} \tag{2}$$

$$\Gamma_M=1.9887-1.326\alpha-\frac{(3.49-0.68\alpha+1.35\alpha^2)\alpha(1-\alpha)}{(1+\alpha)^2} \tag{3}$$

where $\alpha=a/W$, S_1 and S_2 are outer and inner spans, respectively.

Then, with the shear factor obtained by Bluhm, the compliance of the chevron notched specimen, C_{tr}, is obtained from equation (4).

$$\frac{1}{C_{tr}}=\left(\frac{\alpha-\alpha_0}{\alpha_1-\alpha_0}\right)\frac{1}{C(\alpha)}+\frac{k}{n}\sum_{i=m+1}^{n}\left(\frac{1}{C(\xi)}\right)_i \tag{4}$$

where $\alpha_1=a_1/W$ and $\alpha_0=a_0/W$, k is the interlaminar shear factor and C(a) and $C(\xi)$ are the slice compliances.

Finally, the change of the resistance of fracture is obtained from equation (5) and (6) by using the change of the compliance which is obtained from the load and the strain on the experiment.

$$K_{IR}=(P/B\sqrt{W})Y^* \quad (5)$$

$$Y^*=[\frac{1}{2}(dC'_{tr}/d\alpha)(\alpha_1-\alpha_0)/(\alpha-\alpha_0)]^{1/2} \quad (6)$$

where P is the load and the C'tr is the dimensionless compliance.

The change of the crack length is also calculated from the change of the compliance.

RESULTS

Figure 2 shows the R-curve on the silicon nitride. The crack length at that the resistance of fracture becomes minimum corresponds to the crack length at that the applied load during the test becomes maximum. The resistance of fracture just before the instantaneous fracture is 20% larger than the minimum resistance of fracture (= fracture toughness, K_{IC}).

Figure 3 shows the R-curve of the reinforced alumina. Same as the silicon nitride, the crack length of the minimum resistance of fracture corresponds to that of the maximum load. The increase of the resistance of fracture is 15%.

Figure 4 shows the R-curve of tetragonal zirconia. The crack length of the minimum resistance of fracture and maximum load shows large difference, and the degradation of the load occurs on the shorter crack length region. Moreover, the increase of the resistance of fracture is very small. The resistance of fracture just before the instantaneous fracture is only 4% larger than that of the minimum value.

Figure 5 shows the R-curve of silicon carbide. On the silicon carbide, the increase of the resistance of fracture and the difference of the crack length on maximum load and minimum resistance of fracture are observed. However, the testing condition should be considered on this material, because the fracture load is very small compare to other materials. The apparent increase of the resistance of fracture is 30%.

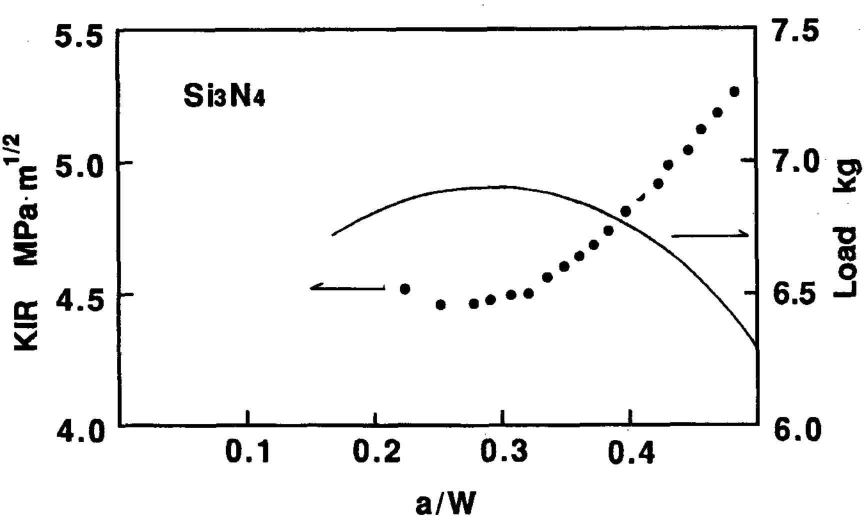

Figure 2 R-curve of silicon nitride (solid circle: resistance of fracture, solid line: applied load).

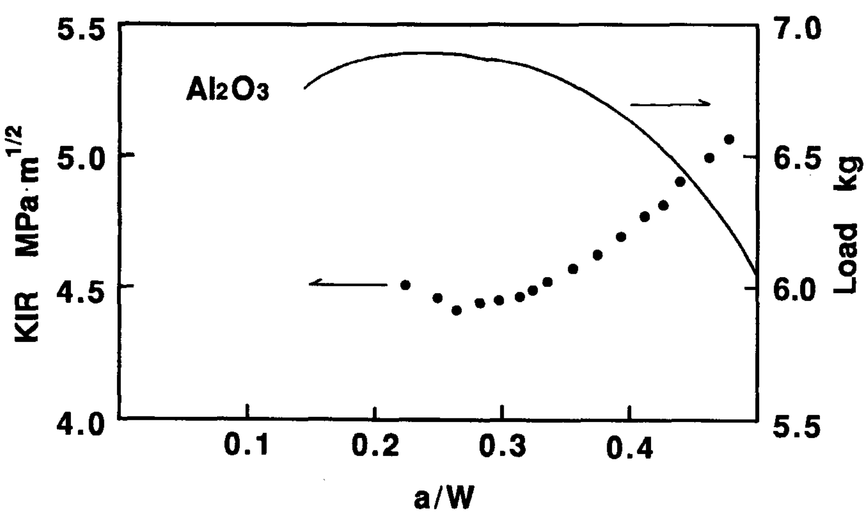

Figure 3 R-curve of reinforced alumina (solid circle: resistance of fracture, solid line: applied load).

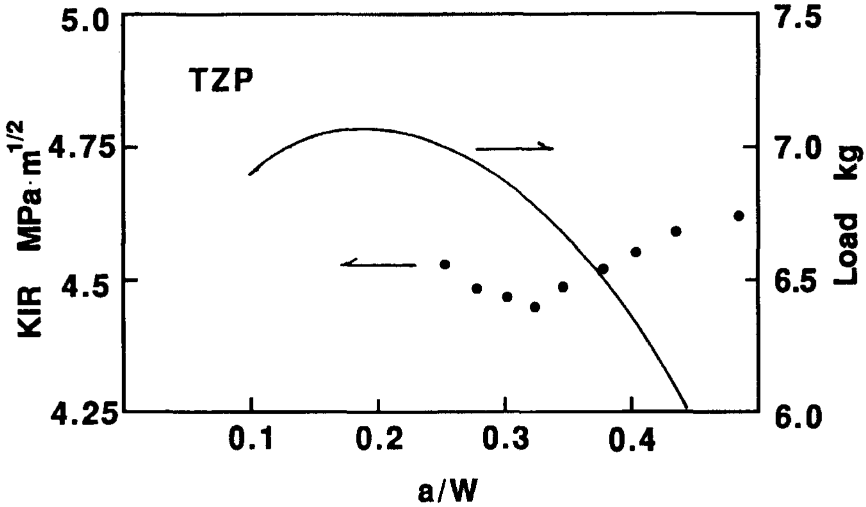

Figure 4 R-curve of tetragonal zirconia (solid circle: resistance of fracture, solid line: applied load).

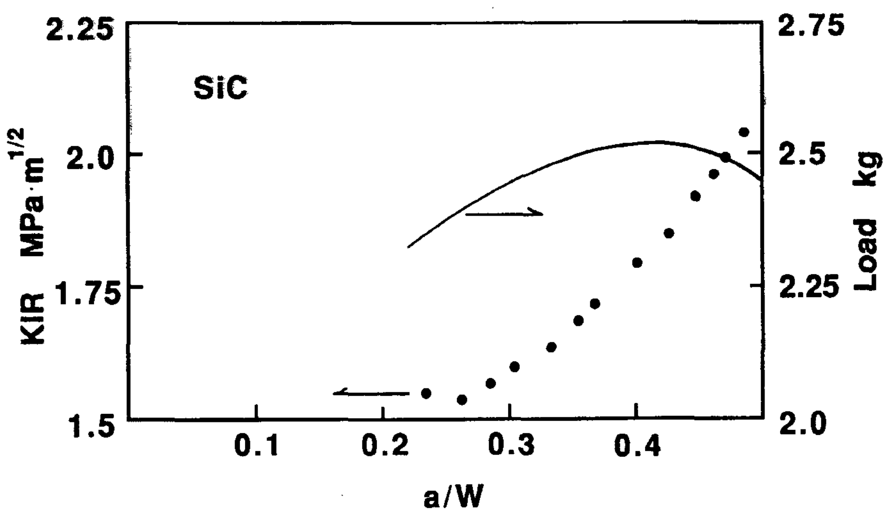

Figure 5 R-curve of silicon carbide (solid circle: resistance of fracture, solid line: applied load).

DISCUSSION

(1) R-curve of silicon nitride and reinforced alumina

On these materials, the crack length of the maximum load almost corresponds to that of the minimum resistance of fracture. As these two values are equal on the analysis, the testing condition is good in this load region. On the silicon nitride, the increase of the resistance of fracture is large. On the macroscopic meaning, the crack of silicon nitride is hard to go straight. Then, the increase should represent this phenomenon. The increase of the resistance of fracture is larger than the data obtained by Okada [8], but we cannot make simple comparison with these data, because the shape of the specimen and the notch are different. Moreover, they reported that the resistance of fracture can be changed with sintering conditions.

(2) R-curve of tetragonal zirconia

Tetragonal zirconia is well known of its characteristic reinforcement mechanism by transformation toughening. Then, the increase of the resistance of fracture is expected because the fracture of this material needs more energy than for the fracture surface creation. Although, the increase of the resistance of fracture is very small on this material. This is considered that the length of the crack is already long enough at the beginning of this experiment. Then, on this material, the transformation toughening does not affect in increasing the resistance of fracture with crack propagation from a certain length of the crack, and the critical crack length may be shorter than 0.5mm. On the other hand, the transformation mechanism may affect the initiation of the crack because there is a difference of the crack length of the maximum load and minimum resistance of fracture. These results and discussion do not conflict with the analysis by McMeeking 9.

(3) R-curve of silicon carbide

As silicon carbide has smaller fracture toughness, the load on the fracture becomes smaller than that of other materials. Then, the effect of the relaxation of the suspension roll of the bending test cannot be neglected. Moreover, at the initiation of the fracture, pop-in occurs before the static fracture. Then, it should be considered that the regular analysis can be applied on this type of the fracture. From the former reason, increase of the resistance of fracture should be considered, and from the latter reason, the difference of the crack length of maximum load and minimum resistance of fracture should be considered.

CONCLUSIONS

R-curve behavior of the representative four kinds of engineering ceramics are evaluated. The followings are concluded.

(1) On the silicon nitride, the large increase of the resistance of fracture is observed. It may be related to the difficulty of the straight propagation of the crack on this material.

(2) Tetragonal zirconia shows little increase of the resistance of fracture, although it has transformation toughening mechanism. This mechanism may affect on the initiation of the crack.

(3) On the silicon carbide, increase of the resistance of fracture is observed, but the testing condition needs further considerations.

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