EFFECTS OF NOTCH ROOT RADIUS ON BOTH CRACK INITIATION SITES AND FRACTURE TOUGHNESS OF CERAMICS AND STEEL

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In this study, fracture toughness tests using three-point bend specimens of Al_2O_3 , Si_3N_4 and mild steel with a notch were carried out to study the effects of notch root radius on fracture toughness and crack initiation sites. The notch radius was varied in size ranging from 0.1 to 1.0mm. The tests were also conducted at room temperature(RT) and high temperature(1000℃) to examine the influence of temperature. The test temperature for mild steel was –170℃. The results were discussed based on the process-zone-size failure criterion. The relationships between notch root radius and fracture toughness measured at both RT and 1000℃ were in good agreement with the theoretical relations deduced from the criterion. In mild steel, the crack initiation sites are distributed in the vicinity of the eleastic-plastic boundary.

INTRODUCTION

Recently, much research has been performed on the strength and reliability of structural ceramics. Ceramics are typical brittle material, and have the following two features, (a)Fracture toughness is not constant, and decreases with decreasing defect size similar to elastic-plastic materials such as steels and polymers, (b)Fracture toughness depends on crack size, notch root radius. Therefore, it is important to quantitatively clarify their strength characteristics in order to ensure safety and reliability when ceramics are used as a structural material. Iwasa et al.[1] have paid much attention to the process zone that occurrs in the crack tip zone of ceramics and they have proposed a process-zone-size failure criterion. Furthermore, the effects of crack length, notch root radius and grain size on the fracture toughness of Si_3N_4, SiC and Al_2O_3 ceramics have been successfully explained using this failure criterion. However, the physical meaning of this failure criterion is not yet established. It seems that it is useful to discuss the relation between the crack initiation sites and the critical process zone size for

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clarifying this problem. In this study, the effects of notch root radius on fracture toughness values at room temperature and at high temperature(1000℃) were investigated using Al_2O_3 and Si_3N_4 specimens with various size of notch radius. We analyzed the effects of temperature and the notch root radius on the distance from the notch tip to the crack initiation sites.

MATERIALS AND TESTING METHOD

The specimens used here are HP(Hot Pressing) sintered Al_2O_3, Si_3N_4 and mild steel. The shapes and dimensions of specimens were of a square bar of 10×10×55mm(Al_2O_3) and 3×4×45mm(Si_3N_4) the loading mode was three-point bending over a span length of 40mm. The fracture tests were conducted at room temperature(R.T) and high temperature(1000℃), and the notch root radius ρ was varied from 0.1 to 1.0mm. In order to remove residual stresses, the Al_2O_3 specimens were annealed for 1h at 1230℃ and the Si_3N_4 specimens for 2h at 1200℃ in advance of the test. In the case of the mild steel(JIS G3106 SM400C), the shapes and dimensions of the test specimens were 30×15×150mm and the loading mode was the same as for ceramics. The notch radius ρ was varied from 0.1 to 1.0mm and the test temperature was –170℃. The chemical composition of the steel(%wt) was 0.16% carbon, 0.24% silicon, 0.88% manganese, 0.016% phosphorus, and 0.004% sulphur. The yield strength was 700MPa and the ultimate strength was 810MPa at the test temperature. The residual stress relieving was done by heat treatment at 630℃ for 2h in a vacuum. The cross-head speed in the all tests ranged from 0.5 to 1.0mm/min. The fracture toughness values were estimated according to JIS R1067[2] for Al_2O_3, Si_3N_4 while the ASTM standard E399[3] was used the mild steel. The crack length and notch length were measured using a binocular stereoscopic microscope and the distance from the notch tip to the crack initiation sites were investigated in detail using a scanning electron microscope.

A PROCESS-ZONE-SIZE CRITERION FOR FAILURE

The elastic stress distribution ahead of a notch is given by the following equation proposed by Creager[4].

$$\sigma_{yy}=K \cdot 2(r+\rho)/\pi^{1/2}(2r+\rho)^{3/2} \quad \text{-- (1)}$$

where, r is the distance from the notch tip, K is the stress intensity factor and ρ is the notch radius. Ando[5] calculated that plastic zone size ahead of a notch as a function of notch radius ρ, yield stress σ_Y and the stress intensity factor K for the cases of plane stress and plane strain.

For the case of ceramics, innumerable microcracks are formed or phase transformation is induced in the process zone. These events are assumed to be different from the yielding process in metals. In this paper, their formation are assumed to obey a maximum stress criterion[1]. Consequently, stress in the process zone is constant value $\sigma_P = \sigma_F$ [1].

The elastic stress distribution ahead of the notch is given by AM in Figure 1. In the process zone, the material can not sustain a stress higher than σ_F, and so the stress redistributed ; See BGN in Figure 1. By using the load-balance concept, area ACEF must be equal to area BCHG[5]. Hence the process zone size D is given by

$$D / \rho = \pi^2 \alpha_Y (1+2\alpha_Y) / 8(1+\alpha_Y) \quad \text{-------------------------------------(2)}$$

Here α_Y is r_Y / ρ and r_Y is the distance from the notch tip to the point where σ_{yy} is equal to σ_F. It follows that α_Y is (see the following equation) a function of K, ρ and σ_F, where, $\pi^2/8$ is a correction factor to match the D value calculated by the Dugdale model when $\rho = 0$ and $\sigma = \sigma_F$. Thus

$$K / \sigma_F \sqrt{\rho} = \pi^{1/2} (1+2\alpha_Y)^{3/2} / 2(1+\alpha_Y) \quad \text{---------------------------------(3)}$$

By using equations(2) and (3), the process zone size is given as a function of K, σ_F and ρ. The stress intensity factor is a function of applied stress σ and notch radius ρ. Thus, fracture toughness are given as a function of ρ and σ_F by using the process-zone-size failure criterion.

RESULTS AND DISCUSSION

Effect of Notch Root Radius on Fracture Toughness

Figure 2 shows the effect of notch root radius $\sqrt{\rho}$ on the plane strain fracture toughness at RT and 1000℃ in the notched Al_2O_3 and Si_3N_4 specimens. In Al_2O_3 specimens, the $K_{IC}(\rho)$ value at both RT and 1000℃ decreases with decreasing ρ and $K_{IC}(\rho)$ becomes equal to the K_{IC} value when ρ is less than 0.1mm at RT. However, this tendency cannot be found at 1000℃. The $K_{IC}(\rho)$ of the Si_3N_4 decreases with decreasing ρ similar to the Al_2O_3. The solid lines were obtained from equation(3) which is based on the process-zone-size failure criterion by using the K_{IC} and σ_F values. From the figure, it can be seen that the theoretical values are in good agreement with the experimental results. The semi-solid marks in the figure indicate the apparent fracture toughness values of specimens in which slow crack growth was observed at 1000℃. The dependence of fracture toughness, $K_{IC}(\rho)$, on the notch root radius, $\sqrt{\rho}$, is shown in Figure 3. Although the material characteristics of mild steel is different from that of ceramics, the relationship between $K_{IC}(\rho)$ and $\sqrt{\rho}$ showed similar to that of Al_2O_3 and Si_3N_4. If the fracture criterion for steel involves a maximum stress criterion to determine the elastic-plastic boundary, $K_{IC}(\rho)$ and $\sqrt{\rho}$ are in proportion to each other[6]. From the figure, however, it is evident that $K_{IC}(\rho)$ is not linearly proportional to $\sqrt{\rho}$. Therefore, the maximum stress criterion cannot be applied as the criterion for cleavage crack initiation in mild steel.

Relationship between Crack Initiation Sites and Process Zone

The values of X/Dc and $X/\overline{Dc}$ versus $\sqrt{\rho}$ in Al_2O_3 at 1000℃ are shown in Figure 4. In accordance with the process-zone-size failure criterion, the condition of $X/\overline{Dc} \leqq 1.0$ must be satisfied. The crack initiation sites existed randomly in vicinity of the notch front. The X measured were $10 \sim 40\,\mu m$ and was smaller than 85% of Dc. From those results, it is considered that the crack initiation sites are affected not only by the stress distribution but also by the strain distribution of the notch front. One the other hand, in mild steel, the crack initiation sites are distributed in the vicinity of the elastic-plastic boundary, and the value of X/R_{YF} is between about 0.75 and 1.25. Here R_{YF} is theoretical plastic zone size at fracture. The R_{YF} was assumed to be a plane strain condition, and was evaluated using the method presented in Ref.[5]. The crack initiation sites are also independent of $\sqrt{\rho}$.

CONCLUSIONS

The main results obtained were followings:

(1) The dependence of $K_{IC}(\rho)$ of both ceramics on a notch root radius was very well described by the process-zone-size failure criterion.

(2) Most cracks of both ceramics initiated in an area within about 85% of critical process zone size (Dc).

(3) The crack initiation sites are distributed in the vicinity of the elastic-plastic boundary, and the value of X/R_{YF} is between about 0.75 and 1.25.

SYMBOLS USED

D = process zone size(μm)

Dc, $\overline{Dc}$ = critical process zone size and its mean value, respectively(μm)

K =stress intensity factor(MPam$^{1/2}$)

K_{IC} = plane strain fracture toughness(MPam$^{1/2}$)

$K_{IC}(\rho)$ = plane strain fracture toughness of a notched specimen(MPam$^{1/2}$)

R_{YF} = theoretical plastic zone size at fracture in mild steel(μm)

R_β = plastic zone size at maximum constraint(μ m)

r = distance from the notch tip (μ m)

r_Y = distance from the notch tip to the point where applied stress σ_{yy} is equal to σ_F (μ m)

X = distance from notch tip to crack initiation site in ceramics and mild steel(μ m)

σ = applied stress (MPa)

σ_C = critical stress of notched sample(MPa)

σ_F = fracture stress of a plain specimen(MPa)

σ_P = process zone formation stress(MPa)

σ_Y = yield stress(MPa)

$\sqrt{\rho}$ = notch root radius(mm)

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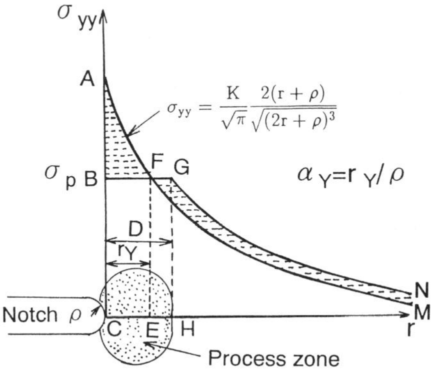

Figure 1 Process zone size and stress distribution ahead of notch tip

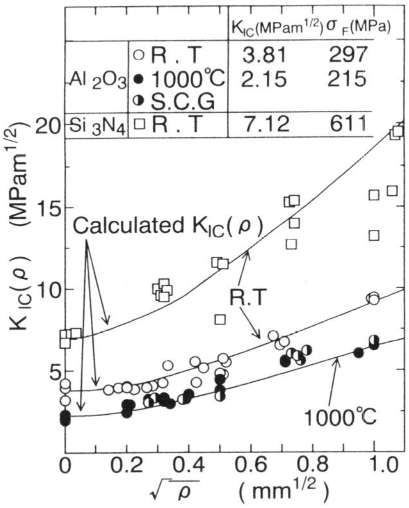

Figure 2 Effect of notch root radius on fracture toughness of Al_2O_3 and Si_3N_4

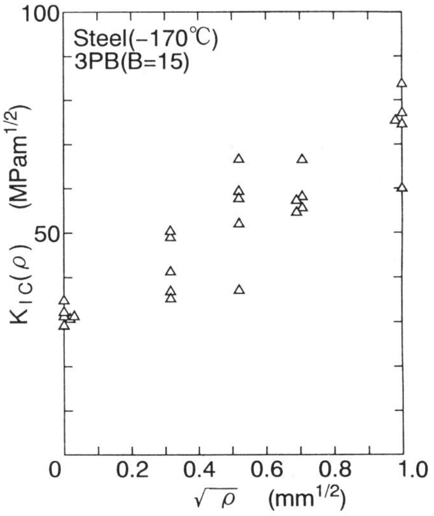

Figure 3 Effect of notch root radius on fracture toughness of mild steel

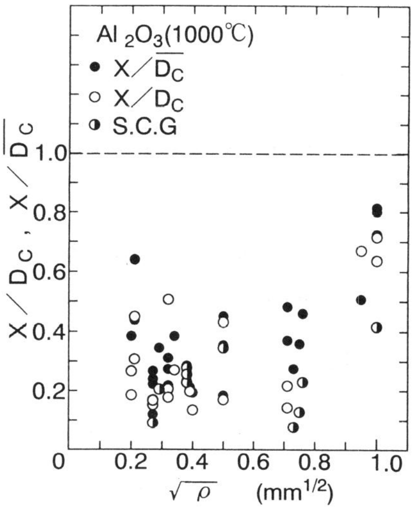

Figure 4 Relationship between notch root radius and $X/Dc, X/\overline{Dc}$ of Al_2O_3