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EFFECT OF MICROSTRUCTURAL CHANGE ON THE *R*-CURVE BEHAVIOR OF AN ALUMINA MATRIX COMPOSITE REINFORCED WITH SILICON CARBIDE WHISKERS

Takashi AKATSU, Yasuhiro TANABE and Eiichi YASUDA

Materials and Structures Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori, Yokohama 226-8503, Japan

ABSTRACT

The *R*-curve of an Al_2O_3 matrix composite reinforced with SiC-whiskers typically comprises two stages in response to crack face bridging processes. The microstructural change in the composite strongly affected the bridging processes, and resulted in a significant change in the *R*-curve.

KEYWORDS

R-curve, ceramic matrix composite, whisker, crack face bridging

INTRODUCTION

Tailoring the microstructure of ceramic matrix composites reinforced with ceramic whiskers to govern the rising *R*-curve behavior is important, because the initial rising gradient of the curve strongly affects their mechanical properties. A numerical simulation based on a series of probable crack face whisker bridging processes with a sound physical basis may be quite efficient to elucidate the dependence of microstructural change in the composite on the *R*-curve behavior. In this paper, the rising *R*-curve behavior of an alumina matrix composite reinforced with silicon carbide whiskers has been experimentally examined. On the other hand, an analytical simulation for a crack face whisker bridging model has been carried out. Comparison between the experimental and the simulated *R*-curves has been made to confirm the validity of the model. Analysis to derive crack closure stress σ_b from the observed *R*-curve has been accomplished to examine the effect of microstructural change on the *R*-curve.

EXPERIMENTAL

Two kinds of SiC whiskers named as TWS-400 of rather large size and as TWS-100 of relatively small size, respectively, were used as the reinforcement of alumina matrix composites. The composites were fabricated by hot pressing [1], and were controlled to contain the whiskers with various volume fractions from 5 to 20%. Billets hot-pressed were cut into a flexural beam with a sharp single edge notch introduced to the center. Three-point flexural test of the SENB specimen was carried using an Instron-type test machine and a crack stabilizer [2] that was requisite for realizing stable crack propagation. The stable crack propagation was observed through an optical microscope to evaluate crack extension length Δa. Utilizing the crack length a, which is given by the addition of Δa to the initial crack length a_0, and the applied load P on the flexural beam with thickness B and width W, the critical stress intensity factor in mode I, K_{Ic}, as a function of a was determined.

SIMULATION FOR CRACK FACE WHISKER BRIDGING

Simulation based on a model with crack face whisker bridging was carried out in order to derive σ_b and crack tip opening displacement δ_b from an experimental R-curve. In the model, both frictional and pull-out bridging processes [3] were taken into account, and σ_b in each process was calculated on the basis of shear-lag theory. The δ_b-value was calculated in terms of the distance x from the tip using the Barenblatt relation [4] with σ_b thus calculated. The material parameters, such as the whisker volume fraction V_w, average radius of whiskers r_w, average length of whiskers l_w, elastic modulus of whiskers E_w and of matrix E_m, and tensile strength of whiskers σ_w were employed referring to the reports of the whisker supplier and of previous works [5,6]. The frictional shear stress at whisker/matrix interface τ_f was appropriately determined best-fitted to the experimental R-curve results. In the present composite system, σ_b was represented in the following formula;

$$\sigma_b(x) = \psi\, V_w \sqrt{2\, \chi\, E_w\, \sigma_w \frac{\delta_b(x)}{l_w}} \tag{1}$$

for $0 < x < d$, where ψ was the orientation efficiency factor [7], $\chi = \frac{l_w}{r_w}\frac{\tau_f}{\sigma_w}\left\{1 + \frac{V_w E_w}{(1-V_w)E_m}\right\}$ and d was determined by $\delta_b(d) = \frac{l_w}{2\chi}\left(1 - \frac{1}{2\chi}\right)^2 \frac{\sigma_w}{E_w}$, and

$$\sigma_b(x) = \frac{2}{\chi}\psi\, V_w \frac{\frac{l_w}{4\chi} - \delta_b(x)}{r_w}\left\{1 - \frac{\frac{l_w}{4\chi} - \delta_b(x)}{r_w}\frac{\tau_f}{E_w}\right\}^{-1} \tau_f \tag{2}$$

for $d < x < b$, where b was given by $\delta_b(b) = \frac{l_w}{4\chi}$. Equations (1) and (2) were only available for the condition of $\chi \geq 1$. Finally, the critical stress intensity factor of the composite was estimated as a function of relative crack length α given as $\alpha = a/W$ under the condition that the length of bridging zone, l_b, is assumed to be much smaller than the total crack length a, as follows:

$$K_{Ic}(\alpha) = K_{Ic}{}^0 + \sqrt{\frac{2}{\pi}}\int_0^{\Delta a} \frac{\sigma_b(x)}{\sqrt{x}}\, dx \tag{3}$$

Details of the bridging model and the procedure of calculation are given in Ref.8.

RESULTS

The R-curves of the composites reinforced with the large whiskers (TWS-400) with various V_w were experimentally obtained as shown with closed circles in Fig.1. Each R-curve behavior typically comprised two stages divided at a bend in the curve. At the first stage of R-curve, $K_{Ic}(\alpha)$ steeply increased from $4\pm0.2\mathrm{MPa}\sqrt{\mathrm{m}}$ without a visible crack extension. The initiation of R-curve was, however, sensitively detected through the onset of nonlinear load-displacement relation in the bend test of SENB specimens. At the second stage beyond the bend, $K_{Ic}(\alpha)$ gradually increased as the crack macroscopically extended. The value of $K_{Ic}(\alpha)$ at the bend increased with V_w. In addition, the plateau of R-curve increased with V_w. The R-curves simulated for various values of V_w were shown as the solid lines in Fig.1. Good agreements between observed and simulated R-curves were confirmed, while the fitting is relatively insufficient for the composites having lower V_w-values. In addition, the bend was successfully reproduced in our R-curve simulation. The R-curve behavior of another composite reinforced with the small whiskers (TWS-100) of 20vol.% referred to as Compo-sw was shown with the closed squares in Fig.2 along with that of a composite with the large whiskers (TWS-400) of 20vol.% referred to as Compo-lw (closed circles) for comparison. A significant deference in their R-curves was seen: At the second stage of R-curve behavior, $K_{Ic}(\alpha)$ of Compo-lw showed a steeper increase and reached a higher plateau than that of Compo-sw, though the differences in $K_{Ic}(\alpha)$ at the initiation and at the bend in each R-curve are insignificant. The R-curves simulated for both the composites were shown as the solid lines in Fig.2. Good agreements between observed and simulated R-curves were demonstrated not only for Compo-lw but also for Compo-sw.

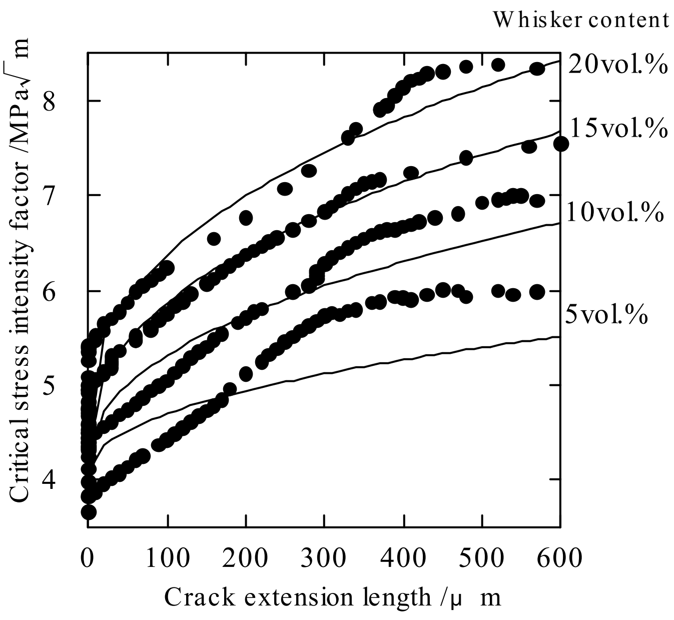

Figure 1: R-curves of an alumina matrix composite reinforced with silicon carbide whiskers (TWS400) for various whisker volume fractions. Closed circles are experimental and solid lines are simulated R-curves.

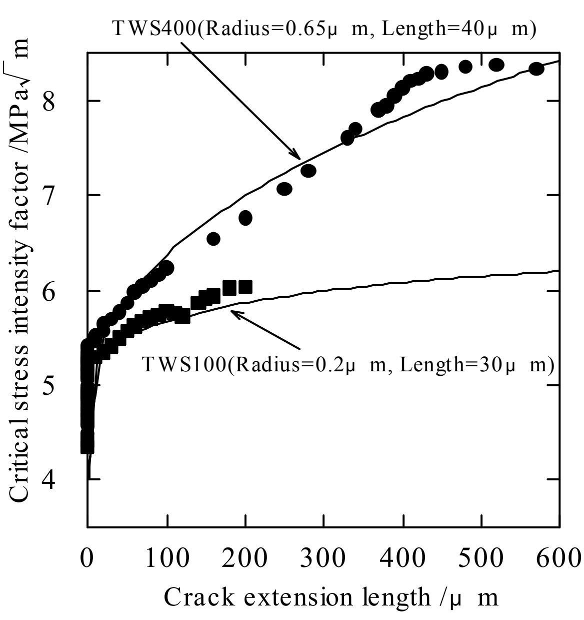

Figure 2: R-curves of the composite reinforced with whiskers of small (TWS100) and large (TWS400) sizes. The former and the latter are denoted with closed squares and circles, respectively. Solid lines are R-curves simulated for each composite.

DISCUSSION

Effects of whisker volume fraction on R-curve

The distribution of σ_b has been calculated for various values of V_w using the same whisker dimensions as TWS-400, as shown in Figs.3(a) and 3(b). As shown in Fig.3(a) where the relations of σ_b in the vicinity at a crack tip are demonstrated , the peak value of σ_b in Frictional Bridging (FB) [3,8] increases with V_w simply owing to the increase in the number of whiskers bridging a crack in FB. That is the main reason why $K_{Ic}(\alpha)$ at the bend of *R*-curve of the present composite system increases with V_w, as shown in Fig.1. In Fig.3(b) where a wide range view of bridging is depicted, the maximum σ_b in Pull-out Bridging (PB) [3,8] increases but the zone length l_b decreases with the increase in V_w. The former is also due to the increase in the number of whiskers bridging a crack in PB. In order to investigate the latter, we take δ_b into consideration, because l_b, which significantly affects $K_{Ic}(\alpha)$ at the second stage of *R*-curve as much as σ_b does, is geometrically determined through the combination of l_w and δ_b at the trailing edge of a bridging zone under crack propagation. The δ_b-values within the zone for various values of V_w have been calculated for the same whisker dimensions as TWS-400 in terms of the distance from crack tip. It is found that there is almost no difference in δ_b with various V_w at very close range from the tip; however, the δ_b-value of the composite with high V_w increases more progressively with the increase in the distance from the tip than that of the composite with low V_w. The progressive increase in δ_b is caused by the increase in nominal $K_{Ic}(\alpha)$ with V_w due to the stress shielding effect of σ_b, and results in the decrease in l_b with the increase in V_w at a constant l_w. The negative effect of the decrease in l_b on toughening is entirely overcome by the positive effect of the increase in σ_b with V_w. As a result, the minute increase in rising *R*-curve gradient at the second stage with V_w has been observed, as shown in Fig.1. We conclude that the increase in V_w is fairly effective for toughening the present composite system.

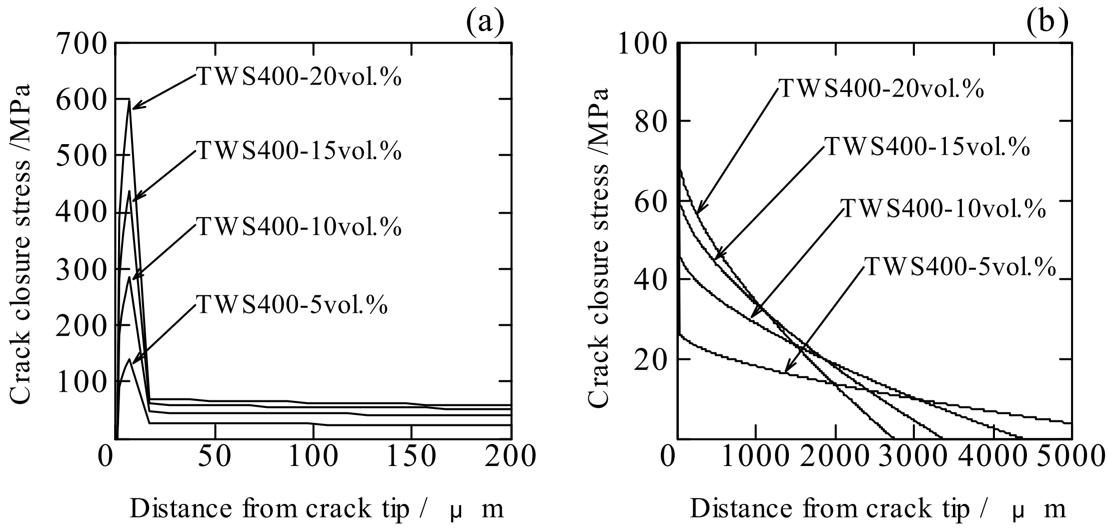

Figure 3: Distribution of crack closure stresses in the composite for various whisker volume fractions in the vicinity of a crack tip (a) and throughout bridging zone (b).

Effects of whisker dimensions on R-curve

As shown in Fig.2, there is a negligible small discrepancy in $K_{Ic}(\alpha)$ at the bend in *R*-curve between Compo-sw and Compo-lw, because of the insignificant difference between their peak values of σ_b. The simulation reveals that much larger values of σ_b and l_b in PB of Compo-lw than those of Compo-sw cause the significant difference in the rising behavior at the second stage of their *R*-curves. In order to examine the difference in *R*-curve between Compo-sw and Compo-lw in detail, the effect of the size and the aspect ratio A_w of whiskers on the *R*-curve behavior of the present composite system should be taken into account individually, because they are expected to effect on the *R*-curve in different ways. The effect of whisker size on the rising *R*-curve behavior has, first, been examined with V_w of 0.2 and a constant A_w of 8.7 resulting in the constant χ-value of 1.0, where the effect of whisker bridging on the toughening of the present composite system has been optimized, as well as demonstrated in Fig.4. The increase in r_w and l_w with a constant A_w enhances the rising *R*-curve behavior in the second stage, while the difference in $K_{Ic}(\alpha)$ in the first stage of *R*-curve is hardly detected owing to the insignificant effect of whisker size on the peak value of σ_b in FB. The effect of whisker size on the maximum σ_b in PB is also insignificant, because it is principally given in terms of χ, V_w and σ_w. The simulation reveals that the increase in l_b with r_w and l_w at constant A_w is caused by the compensation of the increase in l_w for the increase in δ_b at the trailing edge of the bridging zone. Therefore, the increase in whisker size with constant A_w increases l_b, and results in the enhancement of rising *R*-curve behavior at the second stage in the present composite system. The effect of A_w on the rising *R*-curve behavior is, then, examined through the χ-value, because the use of χ, which is simply proportional to A_w, properly gives a general description of the change in *R*-curve behavior. The χ-value is given in terms of the ratio of l_w to r_w. Accordingly, we have employed r_w as a variable of χ. *R*-curves simulated for various values of χ with V_w of 0.2 were depicted in Fig.5. It is found that the decrease in χ down to χ=1 remarkably enhances the rising *R*-curve behavior at the second stage. However, the $K_{Ic}(\alpha)$-value at the bend in curve is very insusceptible owing to the insignificant dependence of χ on the peak value of σ_b in FB. The simulation of σ_b-values in PB for various values of χ with V_w of 0.2 reveals that both the maximum σ_b in PB and l_b increase with the decrease in χ down to χ=1. The increase in the maximum σ_b is caused by the increase in the number of bridging whiskers intact at the transition from FB to PB process; the tensile stresses on bridging whiskers decreases with the decrease in χ. Moreover, the decrease in the tensile stress increases the pulled-out whisker length resulting in the increase in l_b. We conclude that the decrease in A_w with the increase in r_w at constant l_w significantly enhances rising *R*-curve behavior at the second stage in the present composite system through the increase in both the maximum σ_b in PB and l_b. A significant difference in rising gradient at the second stage of *R*-curve between Compo-sw and Compo-lw is attributed to the difference in whisker size as well as aspect ratio.

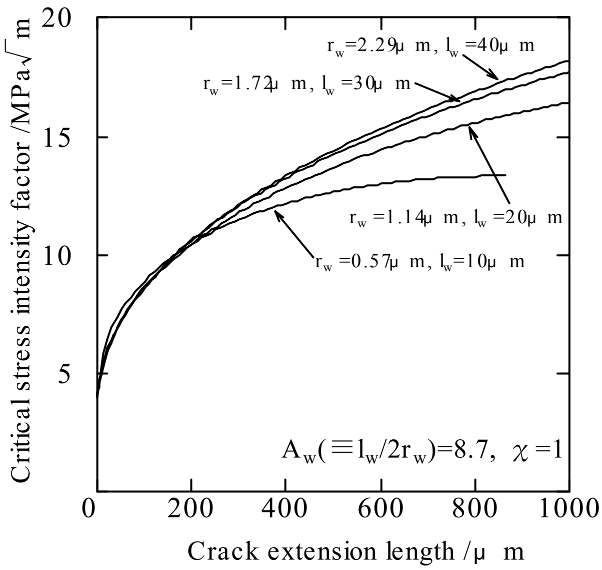

Figure 4: *R*-curves simulated for various whisker sizes with a constant whisker aspect ratio of 8.7 resulting in the constant χ-value of 1.0 and whisker volume fraction of 20%.

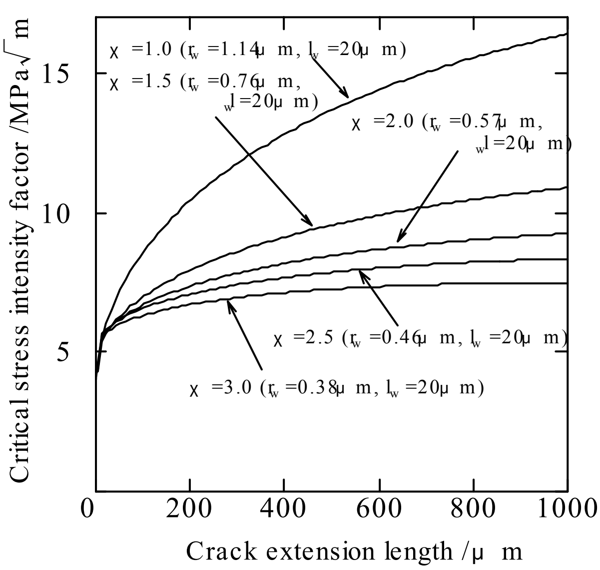

Figure 5: *R*-curves simulated for various values of χ with whisker volume fraction of 20%.

CONCLUSIONS

The effect of microstructural change on the *R*-curve behavior was examined for alumina matrix composites reinforced with silicon carbide whiskers, leading to the following conclusions:

(1) The increase in the volume fraction of whiskers increases crack closure stresses in both frictional and pull-out bridging processes through the increase in the number of whiskers bridging a crack, and results in the enhancement of rising *R*-curve behavior at both the first and the second stages.

(2) The increase in whisker size increases bridging zone length, whereas it does not cause any change in the maximum bridging stresses. In the present composite system, the decrease in whisker aspect ratio increases the maximum bridging stress as well as the zone length in pull-out bridging process. Therefore, the composite reinforced with whiskers of large size and small aspect ratio has an advantage for realizing the enhancement of rising *R*-curve behavior.

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