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R-CURVE BEHAVIOR OF WHISKER-REINFORCED CERAMIC COMPOSITES

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Ceramics have attracted great interest for advanced heat engines and industrial applications as a result of their stiffness, light weight, corrosion resistance, and superior performance at high temperatures. However, their utilization in engineering applications is severely limited by their brittleness. One approach toward substantially reducing this brittleness is by incorporating strong whiskers into the ceramic matrix. Studies of whisker-reinforced ceramic composites have shown both rising fracture resistance with crack extension (i.e. *R*-curve behavior) and a three- to four-fold increase in steady-state toughness (Becher *et al.*, 1988). The primary toughening mechanism is bridging of the crack surface by whiskers.

Based on the characteristics of various types of crack bridging, the following mechanism has been proposed (Hsueh and Becher, 1991). From the crack tip to the end of the bridging zone, the mechanism shows transitions from elastic bridging to frictional bridging and to pullout bridging. Immediately behind the crack tip, the bridging stress results from elastic stretching of the whisker while the interface remains intact. The bridging stress and the corresponding interfacial shear stress increase rapidly with increasing crack opening and, hence, the distance from the crack tip. When the interfacial shear stress reaches the interfacial shear strength, interfacial debonding followed by frictional bridging occurs. While frictional sliding occurs along the partially debonded interface, the whisker is subjected to tension and remains intact. With frictional bridging, the bridging stress in the whisker increases with further increase in the distance from the crack tip until it reaches the whisker strength. At this point and beyond, whisker fracture and pullout occur up to a distance behind the crack tip where the crack-opening becomes greater than the pullout length.

It has previously been discussed that the rapid increase of the bridging stress in an elastic bridging-whisker with the crack-opening limits the development of the elastic bridging zone, and the contribution of elastic bridging to the toughening effect is negligible (Hsueh and Becher, 1991). Hence, contributions from both frictional bridging and pullout bridging are examined in the present study.

Prediction of the *R*-curve involves the following steps. (1) The relations between the bridging stress in the whisker and the crack-opening are derived for both frictional bridging and pull-out bridging. (2) The crack profile is defined which is a function of both the applied load and the bridging stress. (3) The distribution of the bridging stress along the crack surface is obtained from the bridging stress versus crack-opening relation and the crack profile. (4) The sizes of both the frictional and the pullout bridging zones are determined. Whereas comparison of the fictional bridging stress with the whisker strength defines the end of the frictional bridging zone, comparison of the pullout length with the crack opening displacement gives the end of the pullout bridging zone. (5) The toughening effect due to the bridging stress along the crack surface is calculated.

Based on the prediction, the *R*-curve can be tailored by manipulating the whisker properties and content. To examine effects of diameter and volume fraction of whiskers on the *R*-curve behavior, two sets of hot-pressed composites were used. One set of composites containing 1, 4, 10, and 20 vol. % whiskers were made by mixing ~0.8 μm diameter SiC whiskers from the same source (SC-9 whiskers, Advanced Composite Materials Corporation, Greer, SC) with alumina powder (CR-10 powder, Baikowski International, Charlotte, NC). Additives of Y_2O_3 and MgO were used to achieve similar grain size for these composites. A second set of composites containing 20 vol. % whiskers were made using whiskers of different average diameters from different sources: ~ 0.4 μm diameter whiskers (SCW-300, ALCAN International, Ltd., Jonquiere, Canada), ~ 0.8 μm diameter whiskers, and ~ 2 μm diameter whiskers (Los Alamos National Lab., Albuquerque, NM).

The *R*-curve response of the composites was measured using an applied moment double cantilever beam (DCB) geometry with the crack plane oriented parallel to the hot pressing direction. Details of the specimen preparation and experimental setup are described in a separate publication

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(Becher *et al.*, 1995). Both predicted and measured *R*-curves are shown in Figs. 1 and 2, respectively, at different volume fractions and diameters of the whisker. The toughening effect increases with the increase in either the content or the diameter of whiskers. Whereas excellent agreement between the predicted and the measured results is obtained in Fig. 1 for different volume fractions of whiskers, some deviation was observed in Fig. 2 for different whisker diameters. This deviation can be due to different whisker sources, which could result in different whisker properties or interfacial properties.

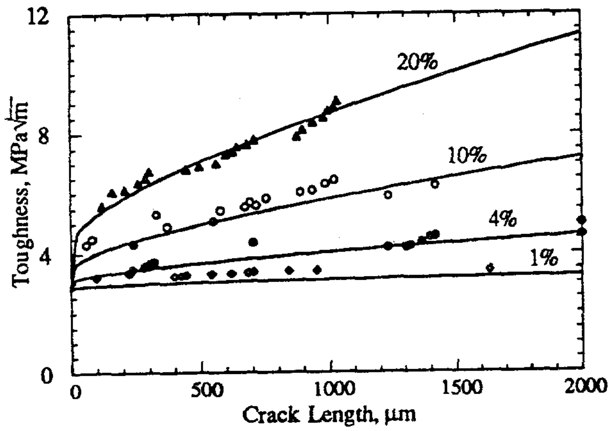

Fig. 1 The predicted (solid line) and the measured (symbols) *R*-curves for SiC whisker-reinforced Al_2O_3 composites with whisker diameter of ~0.8 μm, showing effects of whisker content.

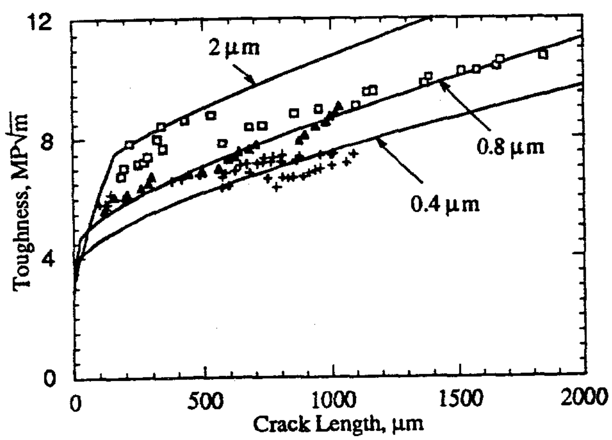

Fig. 2 The predicted (solid line) and the measured (symbols) *R*-curves for SiC whisker-reinforced Al_2O_3 composites with the whisker content of 20%, showing effects of whisker diameter.

Theoretical prediction shows that the *R*-curve behavior is controlled by frictional bridging and pullout bridging, respectively, at short and long crack extensions. Hence, the *R*-curve is expected to be consisted of two segments with the first segment controlled by frictional bridging and having a steeper slope than the second segment, which is controlled by pullout bridging. Figure 1 shows that the slopes of both segments increase with the increase in the whisker content. Figure 2 shows that the slope of the first segment decreases with the increase in the whisker diameter, and the slope of the second segment is insensitive to the change in the whisker diameter. However, the first segment extends to a longer crack length when the whisker diameter increases which, in turn, results in an increase in the toughening effect.

It is worth noting the additional factors which could modify the *R*-curve. When the interfacial frictional stress is increased (e.g. by a rougher interface or stronger residual clamping at the interface), the bridging stress increases which is accompanied by a decreasing frictional bridging zone size, and the net toughening effect decreases. Hence, it is desirable to have small interfacial friction to achieve optimum toughening. However, the reinforcement is required to be of sufficient length. Otherwise, whisker pullout would occur before whisker fracture, and the *R*-curve effect would be diminished.

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