Theoretical and Experimental Analysis of the Toughening Behavior
of Whisker Reinforcement in Ceramic Matrix Composites

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SiC whisker reinforcement of ceramics can result in substantial improvements in fracture toughness and resistance to wear, slow crack growth, and thermal shock of ceramics with the incorporation of strong, small diameter ceramic whiskers¹⁻⁵. For example, the critical toughness of very fine grained alumina can be increased from $\leq 3 \text{ MPa m}^{1/2}$ to $\sim 9 \text{ MPa m}^{1/2}$ with the addition of 20 vol. % SiC whiskers. Comparable increases in toughness have been observed in a variety of other whisker reinforced ceramics³⁻⁴. In addition, the increased fracture toughness is retained with increasing temperature, e.g. up to $\sim 1100^\circ\text{C}$ in the SiC whisker reinforced alumina composites⁶. When compared to the continuous fiber reinforced ceramics at the same reinforcing phase contents, the whisker reinforced composites exhibit similar toughness values, but have the advantage of composite fabrication by more conventional powder processing techniques.

The mechanisms responsible for such whisker toughening include crack deflection and both whisker bridging and whisker pullout within a zone immediately behind the crack tip^{1,5}. Such processes are noted in fracture surface observations and scanning and transmission electron microscopy studies of cracks in these composites, Figure 1. Crack tip bridging processes are of considerable interest in fracture processes. A classic example of the formation of a bridging zone is that noted in continuous fiber reinforced ceramics where toughness is enhanced by the extensive pullout of the fibers in this zone.

As noted in Figure 1, the establishment of a whisker bridging zone in the crack tip wake results in increased toughness, dK^{wr} which is defined as:

$$dK^{wr} = 2\sigma^c (2D_B/\pi)^{1/2} \quad (1)$$

where σ^c is a closure stress imposed on the crack by the bridging whiskers over a zone of length D_B ¹. In the case of aligned whiskers, the closure stress is the sum of the stress [$\leq$ the whisker tensile fracture strength (σ_f^w)] exerted by each whisker in the bridging zone and is equal to:

$$\sigma^c = V_f \sigma_f^w \quad (2)$$

where V_f is the volume fraction of whiskers.

When there is a strong toughening contribution from whisker reinforcement, the crack opening displacement (u) at the whisker at the end of the bridging zone can be reduced to the form:

$$u = 8(1-\nu^2)\sigma_f^w V_f D_B/\pi E^c \quad (3)$$

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where ν is the Poisson's ratio of and E^C is the Young's modulus of the composite for the whiskers uniaxially aligned parallel to the tensile stress axis¹. The crack opening displacement at the end of the bridging zone will equal the maximum tensile displacement (dl) in the debonded whisker at that point. Thus the crack opening displacement (u) can be related to dl and the whisker-matrix interface debond length (l_{DB}) as follows:

$$dl = u = \sigma_f^W l_{DB}/E^W \quad (4)$$

where E^W is the Young's modulus of the whisker. Using the analytical solutions for interface separation versus whisker fracture of Budiansky et al.⁷, the debonded length of the whisker-matrix interface is:

$$l_{DB}/r = \gamma^m/6 \gamma^i = \beta \quad (5)$$

where r is the whisker radius and γ^m and γ^i are the fracture energies of the matrix and interface, respectively. By substitution of equations 4 and 5 into equation 3, we obtain the definition of D_B :

$$D_B = (\gamma^m E^C/\gamma^i E^W) [\pi r/48(1-\nu^2)V_f] \quad (6)$$

for bridging whiskers in the region immediately behind the crack tip. The toughening contribution from whisker bridging dK^{WR} is then defined by substitution of equations 2 and 6 into equation 1:

$$dK^{WR} = \sigma_f^W \{ [V_f r/6(1-\nu^2)] (E^C/E^W) (\gamma^m/\gamma^i) \}^{1/2} \quad (7)$$

for the case where whisker bridging imposes a uniform closure stress over the bridging zone.

These and companion analytical solutions are found to accurately describe the experimentally observed toughening behavior in a variety of whisker reinforced ceramics (e.g., alumina, mullite, and glasses) as shown in Figure 2. In addition, they provide important insights into the whisker, matrix, and interface properties required to obtain further increases in toughness by whisker reinforcement of ceramics. However, the solutions derived explicitly consider the case of whisker bridging involving strong interfaces where whisker pullout is minimized. Further studies are underway to examine the role of interface properties and the toughening contributions derived from extensive whisker pullout in brittle matrix systems.

Acknowledgments

The research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences, and the Office of Transportation Systems, Ceramics Technology for Advanced Heat Engines Project of the Advanced Materials Development Program under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Crack Propagation Direction

Figure 1. Toughening By Whisker Reinforcement Is Associated With The Formation of A Zone Of Bridging Whiskers Behind The Crack Tip. As the crack tip reaches the whisker, debonding/fracture occurs along the whisker-matrix interface (A) which allows the crack tip to advance leaving the whiskers intact and bridging the crack (B,C). At some distance behind the crack tip, whiskers fracture and/or are pulled out of the matrix (D) establishing the whisker bridging zone (E).

Figure 2. The Fracture Toughness of Ceramics Increases with the Addition of Strong SiC Whiskers. The toughness increase due to whisker bridging predicted by the analytical models (curves) describes that observed experimentally in alumina (▲), mullite (■), and glass (●) based composites. The calculated toughening curves are shown for l_{DB}/r ratios observed experimentally, i.e., 5:1, 2:1, and 1:1 for the alumina, mullite, and glass matrices, respectively.