# Toughening Mechanisms in $Al_2O_3$-$SiC_w$ Composites

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**ABSTRACT**

$Al_2O_3$-$SiC_w$ (Silicon carbide whiskers) composites were fabricated by incorporating 25 vol.% $SiC_w$ in $Al_2O_3$ matrix. The resulting composites yielded an average toughness value of 7.5 MPa $\sqrt{m}$, average strength of 550 MPa and Young's modulus of 410 GPa. Micrographs revealed that crack path is deflected by the second phase. Crack bridging also takes place. The experimentally obtained values were compared with the predictions of models. While the crack deflection model overestimated the increase in toughness, the predictions of the crack bridging model fell short of the experimental data. Pull out did not seem to be of consequence.

**KEY WORDS**

$Al_2O_3$-$SiC_w$ composites; Bridging; Pull out; Crack deflection.

**INTRODUCTION**

$Al_2O_3$-$SiC_w$ composites have recently become very important ceramic materials. The advantages of these materials are quite obvious-while they retain the high hardness of alumina, these composites possess higher toughness values as compared to alumina (Becher and Wei, 1984; Tiegs and Becher, 1987a). Because of this enhanced toughness, these composites are wear and thermal shock resistant (Tiegs and Becher, 1987b). Furthermore, they retain their properties at higher temperatures (Porter et al. 1987; Becher and Tiegs, 1988). There are several studies in the literature, which identify toughening mechanism(s) in these composites (Becher et al. 1986, Homeny et al. 1987 and Ruhle et al.1987). It is now known that in non-transformation toughened materials such as $Al_2O_3$-$SiC_w$ composites several toughening mechanisms can occur e.g. deflection, bridging and pull out. Models of each of these mechanisms are available in the literature (Faber and Evans, 1983a; Marshall and Cox, 1988; Thouless and Evans, 1988). In this paper, we report the mechanical property data of the samples fabricated by us. We also critically evaluate the present data in terms of the various mechanisms which we describe below.

## TOUGHENING MECHANISMS

Crack Deflection:

This mechanism was proposed by Faber and Evans (1983a, 1983b) in $Si_3N_4$ and glass ceramics. Whenever the propogating crack encounters a second phase particle, it is deflected from the original course. These deflections displace the original plane of the crack. The problem is eventually treated in terms of mixed mode crack propagation, even though mode I opening takes place at the far end of the tip. The modelling of crack deflection is simplified by assuming two basic configurations : 1) Tilt and 2) Twist (Figure 1). Stress intensity factors can be calculated by coordinate transformation and applying mixed mode criterion. The salient features of the model are:

1) The greater the aspect ratio of the second phase, the greater is the increase in toughness;

2) The median angle of deflection should correlate with increase in toughness.

Crack Bridging:

In a composite containing high strength whiskers, crack extension should take place through the matrix phase initially. However, near the crack tip whiskers may not break due to their high strength. These unbroken whiskers tend to bridge the wake of the crack tip consequently reducing the stresses in the nearby matrix area (Figure 2). The problem may be tackled by evaluating the stress intensity factors associated with the bridging zone. Alternatively, an energy balance criterion can be used. Both the approaches give equivalent results (Marshall and Cox, 1987).

A particularly useful description of bridging effect can be made in terms of crack shielding phenomenon in the sense that the crack tip cannot feel the entire stress applied at the further end. By applying path independent 'J' formulation, the increase in toughness can be given as

$$\frac{K_p}{K_c} = \left[ 1 + 4 \left\{ \frac{S^3 Rf\ (1-f) E_m^3}{12 \tau K_0^2 (1-\upsilon^2) E_f E_c^2} \right\} \right]^{1/2} - 1 \qquad \cdots\cdots\cdots (1)$$

where $K_p$ represents the increase in toughness due to the whisker bridging, $K_c$ is the intrinsic toughness without bridging, S is whisker strength, f is volume fraction of whiskers, $\tau$ is interfacial shear strength, R is whisker radius and E is Young's modulus. Subscripts w, m and c represent whisker, matrix and composite respectively.

Pull Out:

This mechanism takes place particularly in composites containing high strength whiskers. During loading applied stresses may be greater than the critical interfacial shear strength of the interface to dislodge the whiskers from the matrix. This case has been described by Becher et al. (1986) to some extent. Axial stresses generated during pull out is

$$\sigma = 2\tau ( L_c/R) \qquad \cdots\cdots\cdots (2)$$

where $\tau$ is the interfacial shear strength of the whisker matrix interface, R is the whisker radius and $L_c$ is the critical length of the whisker. The additional work required for pull out is $(2\pi R L_c)\tau L_c$. For multiple axially aligned whiskers



with mean length $L^*$, the total increase in toughness is

$$[\ E(L_c/L^*)\pi R(\tau/12)\ \ f]^{1/2} \qquad \cdots\cdots\cdots (3)$$

where $E_c$ is Young's modulus of the composite and f is the volume fraction of the second phase.

## EXPERIMENTAL PROCEDURE

Flow chart for the entire processing is shown in Figure 3. Briefly speaking, the as-received whiskers were milled in an agate mill to decrease the aspect ratio somewhat. The milled whiskers were ultrasonicated at a pH value of 9.5. The as-dispersed whiskers were added to alumina doped with $Y_2O_3$. The mixture was milled further in an agate mill. The milled material was dried and hot pressed in vacuum using gaphite die between temperature of 1700-1800°C for one hour. Control samples of $Al_2O_3$ ($Y_2O_3$) were hot pressed at 1600°C for 1 hr. The as-hot pressed material came out in the form of disc of about 12 cm. in diameter. These were cut into bars, which were ground and polished. Bend strength values were determined in a 3 point bend jig in a universal testing machine (INSTRON 1185) fitted with a compression load cell. The same jig was used for determining toughness values from single edge notched beam (SENB) specimens. The microstructure was examined in scanning electron microscope (SEM). The Young's modulus of the composite was measured using a resonance technique.

## RESULTS AND DISCUSSIONS

The bulk densities of all the samples reached 98% of the theoretical density. The average bend strength of $Al_2O_3$-$SiC_w$ composites was 550 MPa. The average bend strength of control samples was 275 MPa. Single Edge Notched Beam (SENB) technique yielded a toughness value of 7.5 MPa $\sqrt{m}$. For the control sample, fracture toughness was 2.5 MPa $\sqrt{m}$. Young's modulus of the composite was 410 GPa, while that of the control sample is 272 GPa. Toughness values are comparable or higher than those reported in the literature (Homeny et al. 1987; Tiegs and Becher, 1987b). Since the composites are hot pressed they are quite anisotropic. In the present case the crack plane was parallel to the hot pressing direction (perpendicular to the whisker plane). Becher and Wei (1984) reported that when the crack plane is perpendicular to the whisker plane, there is substantial increase in toughness. Therefore, this high toughness value can be reported as a result of uniaxial hot pressing and the particular geometry of testing.

It is of interest to note here that ARCO whiskers were used in fabricating composites in the above cases (Homeny et al. and Tiegs,Becher). In the present case, the source of the whiskers is a different one. These whiskers may influence the properties of fabricated composites by affecting whisker-matrix interface. Becher et al. (unpublished) have conclusively proved that Oxygen content of the whiskers have a very important role to play in altering the characteristics. If the oxygen content of the whiskers is high they form glassy phase at the grain boundary, thus achieving a stronger bond. This, in turn, would decrease p ull out and lead to lesser increase in toughness. One may therefore, argue that the whiskers used in the present experiment may contain less oxygen.

Figure 6 shows the crack path in the composite. These cracks originated from the indentations emplaced on the material by Vicker's indentation. The figure clearly shows that the crack gets deflected as well as bridged. However similar experiments could not be conducted on control samples. Without this piece of information, it is difficult to conclude on the effect of deflection on the increase in toughness. The crack path was analysed to obtain the average deflection angle. The frequency vs deflection angle is shown in Figure 7. The median deflection angle is around 46 degrees. The aspect ratio of the whiskers used in this work is 20. According to Faber and Evans (1983a,b), the increase in toughness should have been around 4 fold for 25 vol.% of whiskers. However, in the present case the increase in toughness is only 3 fold.

Becher et al. (unpublished) reported that in fine grained alumina (similar to what we have here) the extent of deflection and the median angle of deflection is similar to the $Al_2O_3$-$SiC_w$ composites having fine grained matrix. This means appreciable crack deflection was not taking place. Physically speaking, when the elastic constants of the whisker phase is much larger than the matrix phase, possibility of crack deflection increases. This is not so in the present case. All these considerations tend to rule out deflection as a major mechanism in the present case.

Next, toughening effect of crack bridging is discussed. Equation(1) can be applied to crack bridging. $E_c$, $E_w$ and $E_m$ are taken as 410, 490 and 272 GPa respectively. Average whisker radius (R) is 0.3 μm and the poisson's ratio is 0.3. The average strength of Tateho whisker is taken as 21 GPa (Gadkaree and Chyung, 1986). The average friction stress is taken as 800 MPa (Homeny et al. 1987). Equation(1) yields a value of 1.96 as the ratio of enhanced toughness to original toughness. Therefore, crack bridging underestimates the increase in toughness.

Calculations were also carried out for the pull-out case. The increase in toughness due to pull out is 3 MPa $\sqrt{m}$. However, fracture surfaces did not reveal many pull out locations. Hence, the effect of pull out on toughening, if any, may not be substantial.

While comparing predictions of the model to the experimental data, one should bear in mind that all the mechanisms listed above work simultaneously in the material. Therefore, some synergistic effect is expected. It is known that deflection mechanism can operate alongwith transformation toughening and microcrack toughening. Since the present system does not contain any $ZrO_2$, phase transformation toughening does not take place here. Micro-cracking occurs in $Al_2O_3$-$SiC_w$ having a large grain matrix (Angelini et al. 1986). Since the grain size of the matrix as discussed herein small, the occurence microcracking also is ruled out. However, crack deflection can take place synergistically with any crack shielding phenomenon, which includes microcracking, transformation toughening and crack bridging. Therefore, in the present case, the two most important mechanisms are crack bridging and crack deflection in that order of importance. Secondly, since several mechanisms are operating together in the present case, the future direction of modelling should be directed towards defining regions where a predominant mechanism prevails. This should lead to 'toughening mechanism maps'.

Finally, the model assumes that whiskers are aligned uniaxially, which truely speaking, is not the case here. A better approach to experimental method would be to extrude or injection mould the composite powder and sinter the as-received product (Claussen and Petzow, 1986).

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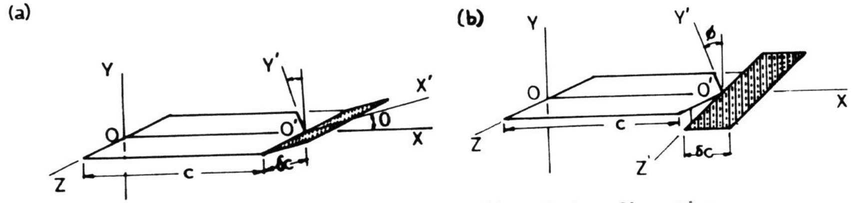
**Fig.1 : Modelling of crack deflection**




(a) 'tilt' cofiguration

(b) 'twist' configuration

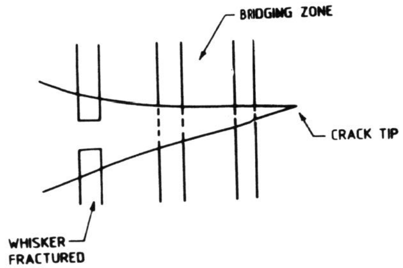



**Fig.2 : Crack bridging model**

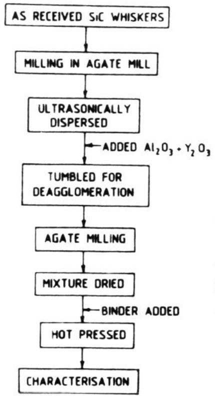



Fig. 3: Typical Flow chart for fabricating $Al_2O_3$-$SiC_w$ Composite

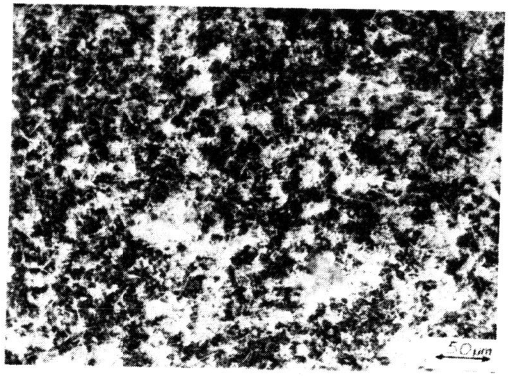



Fig.4: Optical micrograph (200x) showing the uniform dispersion of the SiC Whiskers in the green $Al_2O_3$-$SiC_w$ mixture


Fig.5 : Scanning Electron Micrograph (1000x) of polished and etched surface showing uniform distribution of SiC whiskers throughout the alumina matrix



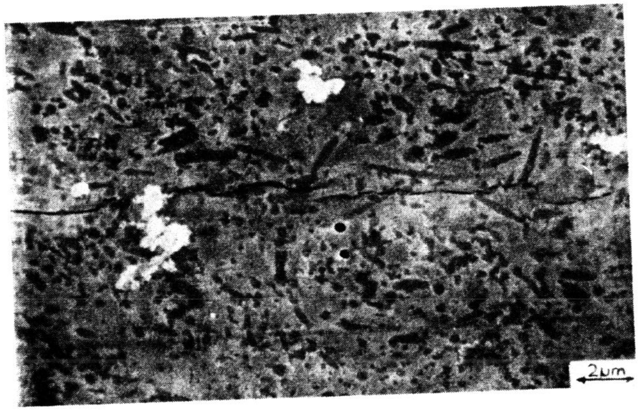



Fig.6 : SEM photograph (2000x) showing both deflection and bridging

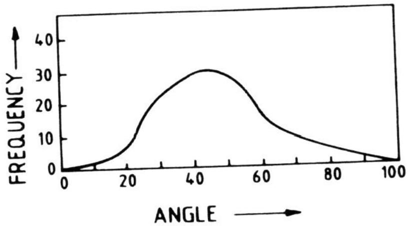



Fig.7 : Frequency vs Deflection angle curve based on the crack path