ANISOTROPY EFFECTS IN THE FRACTURE BEHAVIOUR OF A UNIAXIAL HOT PRESSED SiC WHISKER REINFORCED CERAMIC COMPOSITE

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The room temperature fracture toughness and fracture behaviour of a hot pressed SiC whisker reinforced alumina have been studied. Special attention was paid to the influence of the direction of crack propagation in fracture surfaces formed parallel to the pressing direction. The fracture toughness associated with crack propagation parallel to the pressing direction was higher than that for a crack propagation perpendicular to that direction. It was shown that this difference could be explained in terms of differences in the degree of tilt of the crack path observed in the two cases. The results confirm that crack tip deflection is one of the main toughening mechanisms in this material.

INTRODUCTION

One of the principal factors limiting the exploitation of ceramics in structural applications is their poor reliability and poor fracture toughness. A way to manipulate the mechanical properties is to incorporate fibres in the structure. For example the addition of 20-30% SiC whiskers in Al_2O_3 has shown up to a twofold increase in fracture toughness compared to pure monolithic Al_2O_3 (Wei and Becher (1)). Examples of suggested toughening mechanisms are fibre pull out, crack bridging and crack deflection.

The material studied in the present investigation is a commercially available composite material intended primarily for machining applications. It consists of an Al_2O_3 matrix containing about 33 volume percent SiC whiskers and is densified by uniaxial hot pressing. This leads to a strong anisotropy of the whisker orientation. It is expected and has been confirmed experimentally that the fracture toughness for a crack plane parallel to the pressing direction is higher than that for a crack perpendicular to the pressing direction. However it is not immediately obvious whether or not the toughness should be influenced by the direction of crack growth in the former case, *i.e.* by whether the crack front is parallel or perpendicular to the pressing direction. The main aim of this work was to address this problem. In addition to fracture toughness measurements quantitative fractographic measurements of crack profiles were made to assess the degree of crack deflection.

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CRACK DEFLECTION THEORY

When a crack stressed under mode I condition approaches a second phase, *e.g.* a particle or a fibre, the crack front can be deflected in a tilt and a twist mode (Fig. 1). Instead of pure mode I loading the crack front is subjected to mode I and mode II loading for the tilted part and mode I and mode III loading for the twisted part. Faber and Evans (2) have developed a model for assessing contributions to toughening due to deflection. By calculating the local stress intensities k_1, k_2 and k_3 the strain energy release rate can be calculated using

$$G=1/E \cdot [k_1^2 \cdot (1-\nu^2)+k_2^2 \cdot (1-\nu^2)+k_3^2 \cdot (1+\nu)] \quad (1)$$

where E and ν are Young's modulus and Poisson's ratio respectively. The ratio between the average strain energy release rate at the deflected crack front G and the strain energy release rate for an undeflected crack G_m then gives the relative toughening

$$G_c/G_c^m=G_m/G \quad (2)$$

where c indicates critical values and m refers to matrix. A tilted crack tip subjected to mode I applied loading experiences local stress intensity components described by

$$k_1^t=K_{11}(\theta) \cdot K_I \quad (3\ a)$$
$$k_2^t=K_{21}(\theta) \cdot K_I \quad (3\ b)$$

where K_I is the applied mode I stress intensity, K_{11} and K_{21} are angular functions, θ is the tilt angle and subscript t refers to tilt. First order solutions are given by Cotterell and Rice (3) as

$$K_{11}=\cos^3(\theta/2) \quad (4\ a)$$
$$K_{21}=\sin(\theta/2) \cdot \cos^2(\theta/2) \quad (4\ b)$$

The local stress intensity factors at a twisted crack front can be written as

$$k_1^T=K_{11}(\phi) \cdot k_1^t+K_{12}(\phi) \cdot k_2^t \quad (5\ a)$$
$$k_3^T=K_{31}(\phi) \cdot k_1^t+K_{32}(\phi) \cdot k_2^t \quad (5\ b)$$

where K_{11}, K_{12}, K_{31} and K_{32} are angular functions associated with tilt and twist and ϕ is the twist angle. The angular functions have been suggested by Faber and Evans (2) as

$$K_{11}(\phi)=\cos^4(\theta/2) \cdot [2\nu\sin^2\phi+\cos^2(\theta/2)\cos^2\phi] \quad (6\ a)$$
$$K_{12}(\phi)=\sin^2(\theta/2)\cos^2(\theta/2) \cdot [2\nu\sin^2\phi+3\cos^2(\theta/2)\cos^2\phi] \quad (6\ b)$$
$$K_{31}(\phi)=\cos^4(\theta/2) \cdot [\sin\phi\cos\phi \cdot (\cos^2(\theta/2)-2\nu)] \quad (6\ c)$$
$$K_{32}(\phi)=\sin^2(\theta/2)\cos^2(\theta/2) \cdot [\sin\phi\cos\phi \cdot (3\cos^2(\theta/2)-2\nu)] \quad (6\ d)$$

To be able to superpose the two contributions from tilt and twist it is nessesary to estimate the proportions of tilt and twist. Faber and Evans (2) have given the fractions as

$$f_t=\sin\phi/(\sin\phi+\cot\phi) \quad (7\ a)$$
$$f_T=1-f_t \quad (7\ b)$$

where t refers to tilt and T refers to twist. Since an increase of the crack front length is accompanied by twist but not tilt, the contribution from twist must be reduced by a factor $\cos\phi$ (2). The relative strain energy release rate can then be written as

$$G/G^m = 1/K_I^2 \cdot [f_t \cdot (k^t)^2 + \cos(\phi) \cdot f_T \cdot (k^T)^2] \tag{8}$$

where

$$k^t = \surd[(k_1^t)^2 + (k_2^t)^2] \tag{9}$$

and

$$k^T = \surd[(k_1^T)^2 + (k_3^T)^2] \tag{10}$$

This relationship makes it possible to compare the theoretical model with experimental data.

EXPERIMENTAL

The material studied is a commercially available grade of alumina reinforced with 33 volume percent SiC whiskers. The composite is produced by Greenleaf Corp. under the tradename WG-300. After mixing the alumina powder and whiskers densification is achieved by uniaxial hot pressing. This processing technique yields a strongly anisotropic structure (Fig. 2). The whiskers have a diameter between 0.1 and 1 μm and the aspect ratio is 10 - 100. The grain size of the alumina matrix is between 1 and 5 μm.

Fracture toughness was measured in four point bending on single edge notched bend bars with dimensions 4x8x45 mm at room temperature in air. Straight-through precracks with a depth greater than 2 mm were produced by the bridge indentation technique described by Warren and Johannesson (4). At least three samples were tested for each experimental condition.

Tilt and twist angles were measured by digitizing crack profiles in two orthogonal directions. The crack paths on the side surface were digitized subsequent to precracking. The near tip twist angles were measured by preparing a section close to the tip of a precrack produced on one of the two pieces after fracture. The method for estimating the tilt and twist angles is described by Karlsson and Wasén (5). At least 1 mm profile lengths were measured in each case using scanning electron micrographs.

RESULTS AND DISCUSSION

As shown in Fig. 2 two different types of samples were tested. The two types, A and B, have exactly the same crack plane but their crack fronts in relation to the hot pressing direction are different. Table 1 shows the deflection angles and the fracture toughness. An estimation of expected fracture toughness can be made by using the tilt and twist angles in Eq. 8 together with the relation between the critical values of strain energy release rate and stress intensity.

$$G_c = K_c^2 \cdot (1-\nu^2)/E \tag{11}$$

The difference in fracture toughness between samples of type A and B is predicted by the model. As shown in Table 1 the mean twist angles are almost the same but the mean tilt angle of type A is twice that of type B. According to the deflection model, type A is expected to have 15% higher fracture toughness which is in excellent agreement with the experimentally observed 14%.

TABLE 1 - Fracture toughness and fractographic data.

Type	K_{Ic} ($MNm^{-3/2}$)	Mean tilt angle (deg.)	Mean twist angle (deg.)
A	6.35	30	24
B	5.55	16	26

A comparable grade of pure alumina has a K_{Ic}-value around 4.6 $MNm^{-3/2}$ (1). Assuming that pure polycrystalline alumina exhibits a relatively undeflected crack path, the deflection model used here predicts the fracture toughness values to be 6.3 and 5.5 $MNm^{-3/2}$ for A and B respectively, which are close to the measured values. Even if crack deflection may not be the only toughening mechanism present, it can obviously explain an extensive part of the toughening caused by the whisker reinforcement.

CONCLUSIONS

Not only the orientation of the crack plane normal but also the crack propagation direction play an important role in the fracture behaviour of the SiC whisker reinforced alumina studied.

The deflection model developed by Faber and Evans has shown to be in good agreement with experimental results and a major part of the toughening caused by whisker reinforcement of alumina can be explained by crack deflection.

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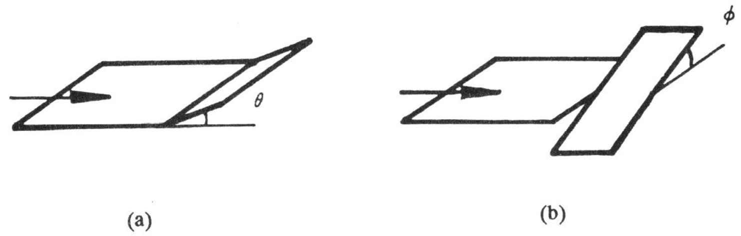

Figure 1 Definition of: (a) The tilt angle. (b) The twist angle. Arrows indicate crack growth direction.

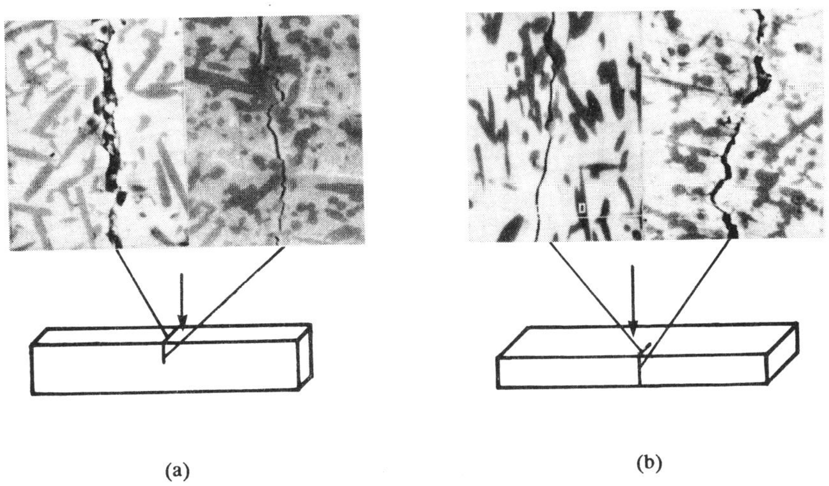

Figure 2 The microstructure and crack profiles from specimens of: (a) Type A. (b) Type B. Arrows indicate hot pressing direction.