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The Influence of Whisker Dimensions on the Mechanical Properties of Cordierite/SiC Whisker Composites

I. Wadsworth & R. Stevens

School of Materials, University of Leeds, Leeds LS2 9JT, UK

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Abstract

Three batches of silicon carbide whiskers of different, but known, dimensions have been incorporated into a cordierite matrix. It was found that the aspect ratio of the whiskers and their physical size had a significant effect on the mechanical properties of the composites they constituted. Fracture toughness was governed by the relative contributions of the mechanisms of crack deflection, crack bridging and load transfer (pullout was not observed to occur in this system under the conditions used). Fracture strength was determined by the net, opposing, effects of an increase in fracture toughness and an increase in critical flaw size of the composites.

Auf der Basis einer Cordierit-Matrix wurden durch Zugabe von SiC-Whiskern mit definierten aber unterschiedlichen Abmessungen dreier verschiedener Chargen Verbundwerkstoffe hergestellt. Die mechanischen Eigenschaften der resultierenden Werkstoffe zeigten eine deutliche Abhängigkeit vom Länge/Durchmesser-Verhältnis der Whisker und ihrer Größe. Die Bruchzähigkeit wurde vor allem durch entsprechende Anteile der Rißablenkung, der Rißüberbrückung und der Lastübertragung beeinflußt. Unter den vorherrschenden Bedingungen ergaben sich keine Anzeichen von Whisker-pullout. Auf die Festigkeit der Verbundwerkstoffe wirkten sich die gegenläufigen Effekte einer erhöhten Bruchzähigkeit und einer vergrößerten kritischen Rißlänge aus.

Trois lots de whiskers SiC, de dimensions différentes mais connues, ont été incorporés à une matrice de cordiérite. Il apparaît que le facteur de forme et la taille des whiskers ont un effet significatif sur les propriétés mécaniques du composite. La ténacité est imposée par les contributions relatives des mécanismes de déviation de fissure, de pontage de fissure et de transfert de charge (dans les conditions d'expérience, on n'a pas observé de pullout dans ce système). La résistance mécanique est déterminée par les effets nets et opposés d'une augmentation de la ténacité et d'une augmentation de la taille de défaut critique des composites.

1 Introduction

During the last decade considerable research effort has been directed towards fabricating and evaluating the mechanical properties of SiC whisker-reinforced ceramics. The driving force behind such widespread activity has been the potential for significantly improving fracture toughness.

However, it is apparent from the literature that, in order to fully exploit the potential of whiskers, a knowledge is required of their morphology, surface chemistry and dimensions. Silicon carbide whiskers (SCW) are now available from many different sources and with many different designations, each of which may differ markedly from the next.[1–3] These differences are believed to be related to the process used to manufacture the whiskers, in particular the critical dependence of whisker characteristics on such variables as catalyst type and size, and process gas partial pressure.[4,5]

In order to tailor whisker-reinforced ceramics to produce the desired properties, an understanding is required of the effect of whisker characteristics on the composite properties. Only by adjusting one variable whilst ensuring consistency of the remainder can any conclusions be drawn.

Braue *et al.*[1] and Tiegs and Becher[6] have illustrated how whiskers from different sources affect the mechanical properties of silicon nitride and

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alumina. Braue *et al.*[1] characterised a number of different SCW in terms of their surface chemistry and dimensions. Clear differences were established which were manifest in the range of fracture strengths that were recorded. However, since both the surface chemistry and dimensions differed from batch to batch, it was not possible to determine the relative contributions of each. Similarly, Tiegs and Becher[6] demonstrated that a range of mechanical properties may be developed in Al_2O_3–SCW composites by simply using whiskers of different origins. Again these differences could not be interpreted in terms of one variable alone.

The aim of this study was to unambiguously determine the effect of whisker dimensions on the mechanical properties of SCW-reinforced cordierite by using whiskers of different mean aspect ratios and unit volumes with chemically cleaned surfaces.

2 Materials and Methods

Throughout the study Baikowski SAM194 CR cordierite powder was used. SCW from two sources, namely Nikkei Co. Ltd, Japan, and American Matrix Ltd, TN, USA, were utilised to reinforce the cordierite matrix.

In order to remove any surface impurities which may have been present on the whiskers, each batch was treated with an aqueous solution of 10% HCl and 10% HF for 24 h. The constituents were then homogenised in the appropriate proportions by means of a three-stage process. The matrix powder and whiskers were dispersed in distilled water in separate containers by means of an ultrasonic probe. The slurries were then combined and subjected to a further ultrasonic treatment. Following this the mixture was tumble mixed for 24 h. Removal of the dispersing medium was accomplished by freeze drying.

The aspect ratio of one batch of whiskers was reduced by ball milling for 24 h using zirconia media. In order to relate the mechanical properties of the composites to the different batches of SCW, it was necessary to accurately determine their dimensions. This was accomplished by depositing low concentrations of whiskers onto stubs and photographing using an SEM. Nine micrographs of each batch were produced such that a square grid covering an appropriate area was made. Each negative was enlarged by a factor of four and the grids assembled. The dimensions of the whiskers were measured using a steel rule and a calibrated eye-piece. On average about 400 whiskers from each batch were measured. The data was then processed to produce frequency distributions of length, diameter and aspect ratio for each batch.

Densification of the composites was achieved by hot pressing in an RF heated graphite die. In order to obtain acceptable densities of the consolidated material, a range of conditions were required. For the composites containing 10 vol.% SCW a pressure of 25 MPa at 1400°C for 20 min was used. As the whisker content was increased to 30 vol.%, it was necessary to raise the temperature to 1425°C and extend the dwell time to 45 min.

Fracture strengths were evaluated using a four-point bend test jig having an outer span of 18 mm and an inner span of 6 mm. Bars having dimensions of 22 × 4 × 3 mm were diamond machined from the hot-pressed discs. The tensile faces and edges of each specimen were polished to a 15-μm finish prior to fracture. Eight specimens of each composition were tested such that the direction of the applied load was parallel to the hot pressing axis. Fracture toughness was determined by the indentation crack length method as detailed by Anstis *et al.*[7]

3 Results and Discussions

3.1 Whisker dimensions

Measurement of distributions in the length, diameter and aspect ratio of the various SCW are illustrated in Figs 1–3. Statistical data is presented in Table 1. Figure 1 indicates that the majority of whiskers have lengths in the range 10–15 μm.

All curves are skewed to the lower end of the distribution, with that of the American matrix (AM)

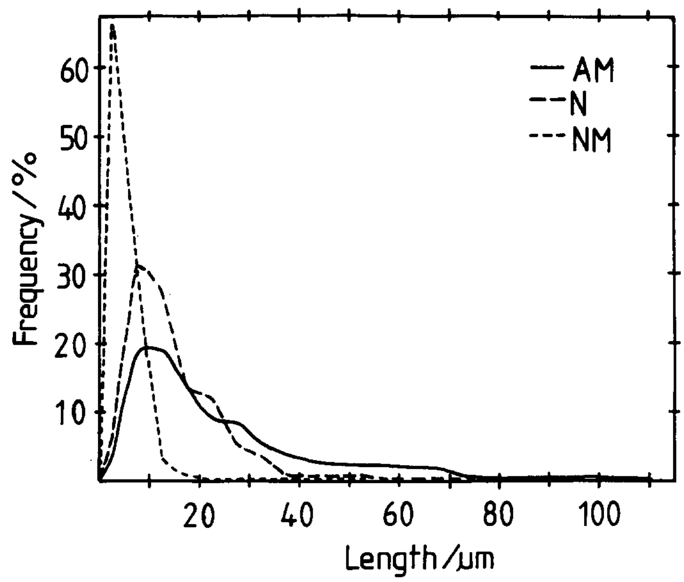


Fig. 1. Length distribution curves for the whiskers used.

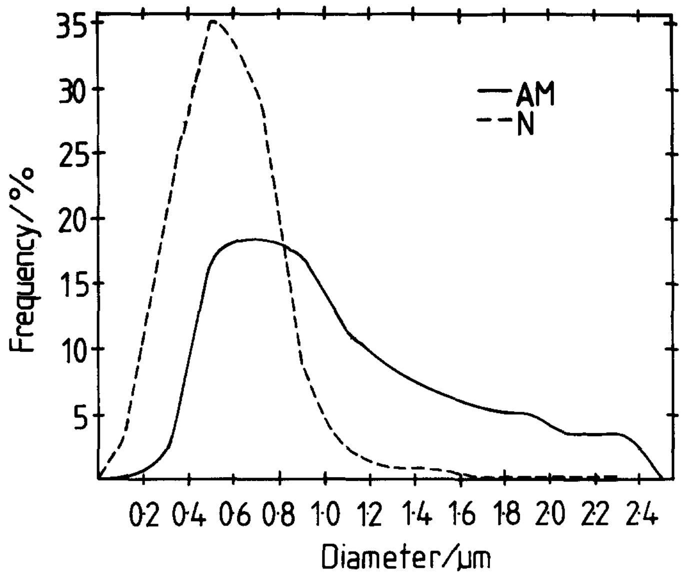


Fig. 2. Diameter distribution curves for the whiskers used.

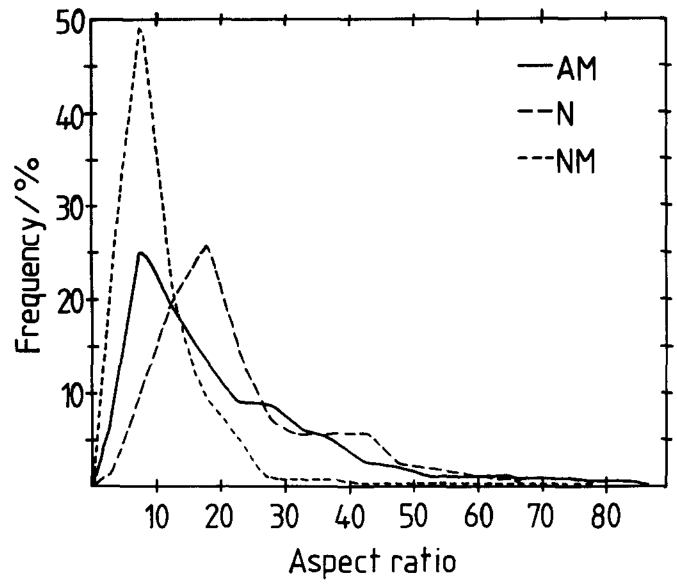


Fig. 3. Aspect ratio distribution curves for the whiskers used.

whiskers being the most significant. The AM whiskers also exhibited the greatest variation in length, indicated by the high standard deviation presented in Table 1. Over 15% of the population have lengths greater than 40 µm compared to less than 1% for the other two.

The variations in whisker diameter are illustrated in Fig. 2. The curves are only slightly skewed from the normal distribution. The Nikkei whiskers have, on average, a diameter which is 55% of that of the AM whiskers.

Table 1. Dimensional data for the SCW used

Whisker type	*Mean length (µm)*	*Mean diameter (µm)*	*Mean aspect ratio (S)*
Nikkei (N)	16·8 (8·5)[a]	0·67 (0·22)	24·2 (11·9)
Nikkei milled (24 h) (NM)	7·9 (2·9)	0·67 (0·22)	12·3 (6·2)
American matrix (AM)	26·3 (19·5)	1·17 (0·51)	22·3 (14·8)

[a] The standard deviations are in parentheses.

Figure 3 illustrates the variations in aspect ratio of the respective whiskers. In all cases there is a significant skew in the frequency distribution curves, particularly for the AM whiskers. The maximum frequency in aspect ratio for the Nikkei whiskers occurs at a value of 20, but due to the large deviation from the mean at the higher end of the frequency distribution the average value is somewhat higher (Table 1). It is of significance that the mean aspect ratios of the unmilled Nikkei whiskers and the AM whiskers are ostensibly the same.

There are two possible explanations for the variations in whisker dimensions. First, variations in manufacturing processing parameters will affect both the length and diameter of the whiskers. The diameter of the whiskers is controlled by the diameter of the catalyst spheres;[4,5] that is to say, the mass of the metal deposited and the surface tension that exists between the molten metal and the silicon carbide. It may therefore be inferred that the diameter of the metal spheres used in the production of Nikkei SCW are, on average, half that of those used to produce the AM SCW. The length of the SCW is controlled by the kinetics of the reaction process and the time over which the process is allowed to run. However, degradation in length is inevitable during harvesting and packaging. Therefore careless handling will tend to have a detrimental effect on the average whisker length.

3.2 Fracture toughness

The indentation-derived fracture toughness values of the cordierite composites containing whiskers of different dimensions is presented, as a function of whisker loading, in Table 2 and Fig. 4. Comparisons will be made in ensuing sections, but initially a discussion of the general trends of the curves will be made. In all cases an increase in whisker content resulted in enhancement of the fracture toughness.

Fractographic studies revealed marked differences between the monolithic cordierite and the whisker-containing composites (Fig. 5). The fracture surface of the composites exhibited a much higher degree of crack perturbation than the monolithic material, due to the crack tip being constrained to follow a much more tortuous path during fracture. As may be seen from the micrograph, this was due to significant interaction of the crack front with the whiskers. Furthermore, detailed studies of fracture surfaces and indentor-derived cracks revealed that

Table 2. Fracture toughness of cordierite–SCW composites for SCW of differing dimensions

Specimen/Vol.% SCW	*Mean fracture toughness ($MPa\,m^{0.5}$)*
Cordierite/0	1·9 (0·1)[a]
Nikkei milled	
10	2·3 (0·1)
20	2·5 (0·1)
30	2·8 (0·2)
Nikkei	
10	2·4 (0·1)
20	2·7 (0·1)
30	3·4 (0·1)
AM	
10	2·6 (0·2)
20	3·0 (0·1)
30	3·6 (0·1)

[a] The standard deviations are in parentheses.

crack deflection made a significant contribution to the improved fracture toughness (Fig. 6). The analyses of Faber and Evans[8,9] indicate that toughening due to crack deflection will become insignificant as second phase contents approach and exceed 20 vol.%. However, with reference to Fig. 4, it may be seen that the fracture toughness of the composites continues to increase beyond a SCW content of 20 vol.%, which suggests that other toughening mechanisms were also operative.

Whiskers were frequently observed to protrude

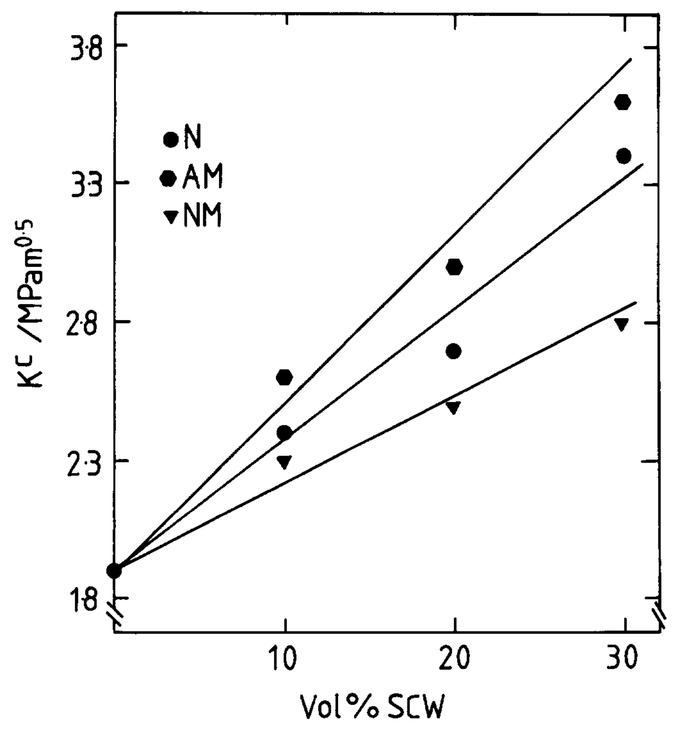


Fig. 4. The fracture toughness of cordierite–SCW composites as a function of whisker content.

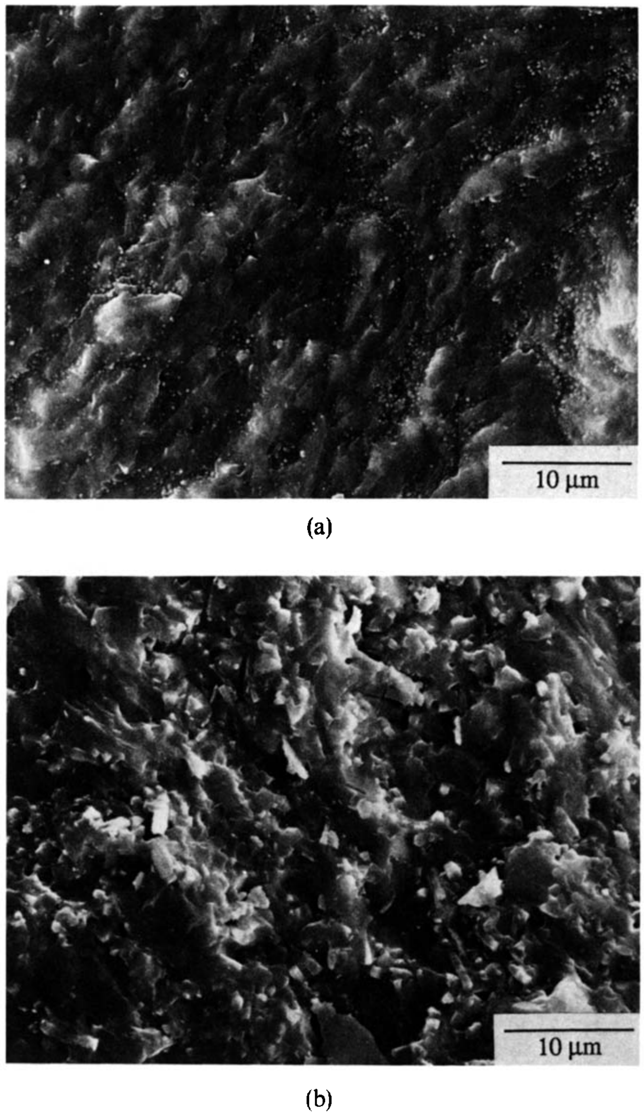
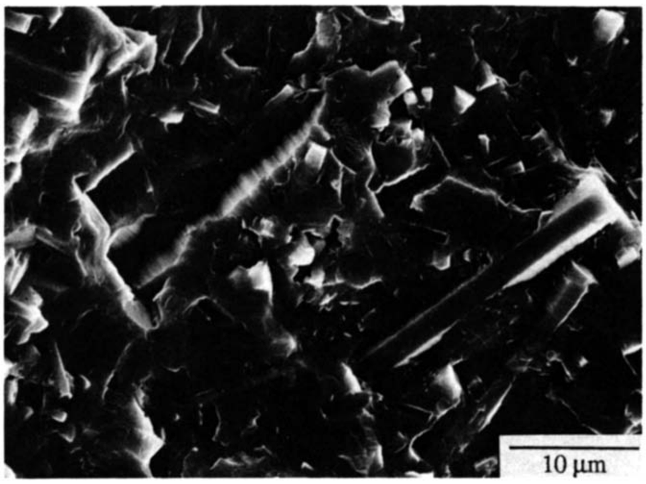


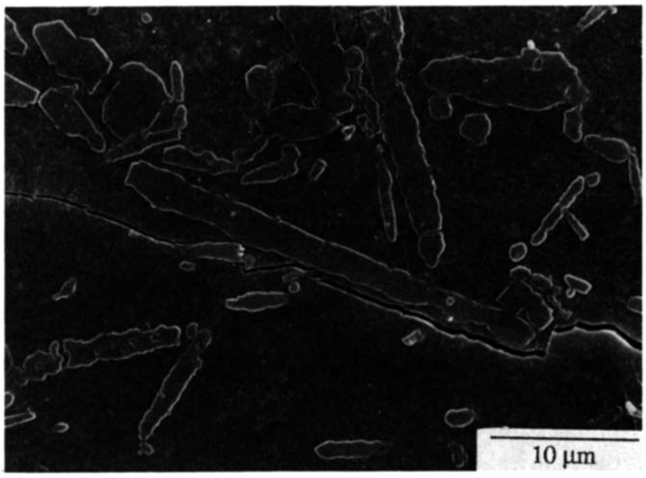
Fig. 5. Fracture surfaces of (a) monolithic cordierite and (b) cordierite–30 vol.% Nikkei SCW.

above the plane of fracture of the composites. Similarly, cavities in the form of hexagonal and circular sockets were also commonplace (Fig. 7). Initially it might be assumed that such features are a direct consequence of whisker pullout. However, it is suggested here that whisker pullout is unlikely. Three reasons supporting this view are as follows:

1. During fracture of the composites by the application of a bending moment those whiskers lying normal to the crack plane will experience a stress which is greatest in the plane of the crack.
2. The lengths of the protruding ends and the depths of the sockets were only of the order of twice the whisker diameter, which is small when compared with their mean lengths (Table 1).
3. In order for pullout to occur the whiskers must be debonded from the matrix and drawn out



(a)



(b)

Fig. 6. Crack deflection occurring in cordierite–20 vol.% SCW. (a) Fracture surface and (b) an indentor-derived crack.

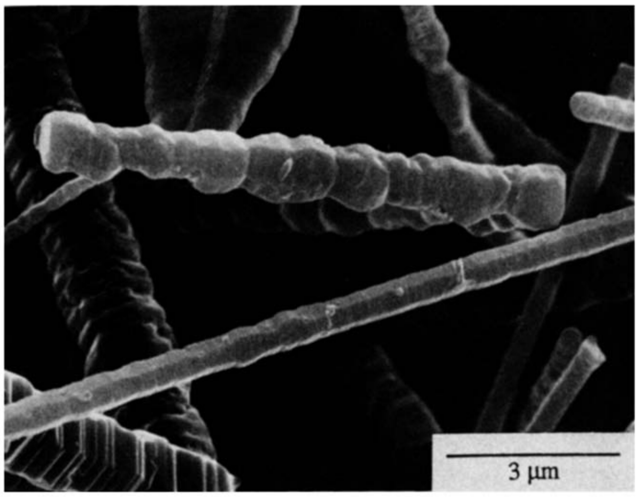


Fig. 8. A group of typical silicon carbide whiskers with uneven surfaces.

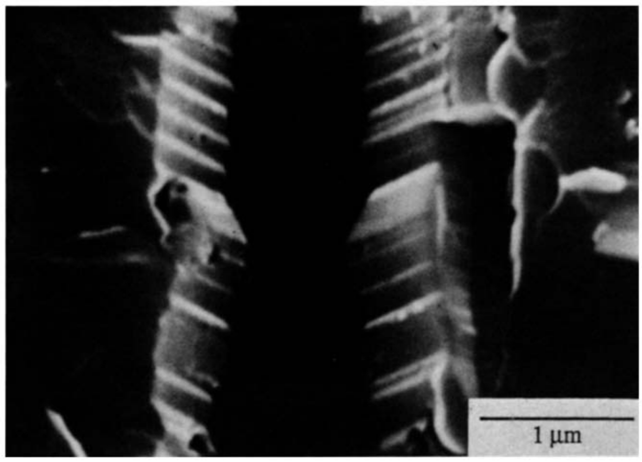


Fig. 9. A SEM micrograph illustrating an impression left by a SCW on a fracture surface. Note how effectively the matrix had adapted to all the surface irregularities.

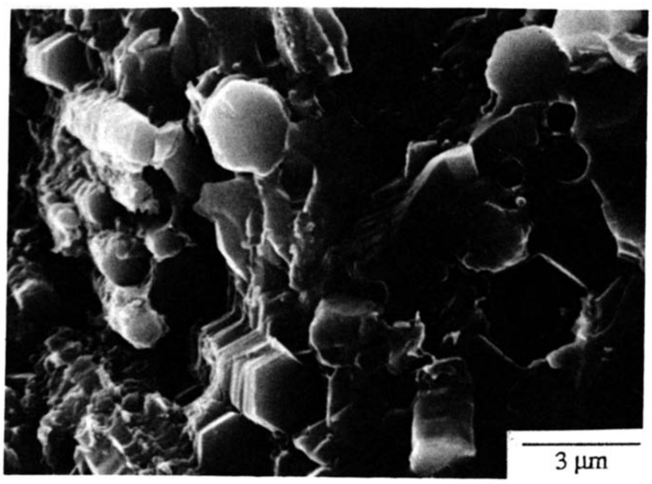


Fig. 7. A SEM micrograph of a fracture surface of cordierite–20 vol.% SCW illustrating the presence of whisker ends protruding above the fracture plane and impressions in the matrix phase similar in cross-section to the whiskers used.

from their sockets. The surfaces of the majority of the whiskers studied were uneven (Fig. 8), which have been shown to generate an effective mechanical key between themselves and the matrix (Fig. 9), making the process of pullout highly unlikely.

It is proposed that the mechanisms responsible for the features illustrated in Fig. 7 are, in fact, crack bridging by whiskers situated at angles near normal to the crack plane, followed by debonding of the whisker–matrix interface and finally fracture of the whisker at a point of weakness, such as a neck or a recess. In this case there is no requirement for sliding displacements between the whiskers and matrix.[10] Evidence of the occurrence of crack bridging is presented in Fig. 10. This evidence was further corroborated by the elemental analysis, using an EDX point analysis facility on the SEM, of the bases of some of the larger whisker-derived sockets in

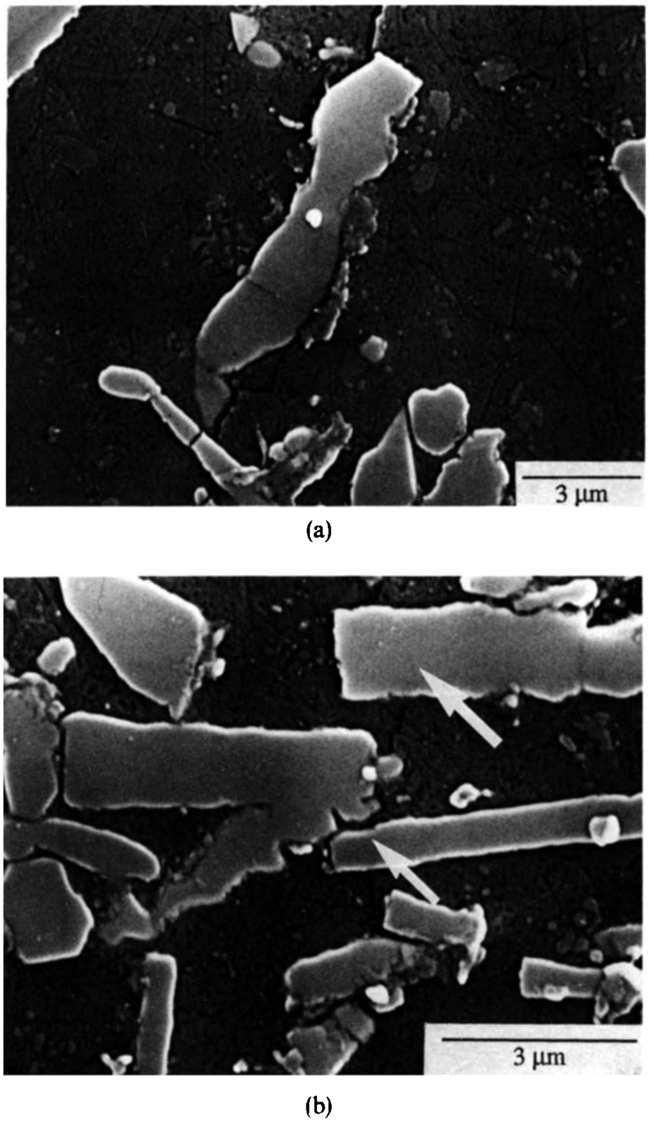


Fig. 10. Crack bridging by SCW in the near crack tip region of an indentor-derived crack in cordierite–20 vol.% SCW.

which, in many cases, only silicon was detected. In those where cordierite was detected it is believed that the crack plane intersected the whisker close to an end and was deflected around it.

It may also be considered that load transfer contributed to the enhanced fracture toughness of the composites. On the assumption that, when loaded, the strain in the whiskers is equivalent to that in the matrix and since stress intensities scale with stresses, the fracture toughness due to load transfer may be written

$$K_{\rm l}^{\rm c} = \frac{K_{\rm m}^{\rm c} E_{\rm c}}{E_{\rm m}} \tag{1}$$

where the super- and subscripts m and c refer to the matrix and composite, and l refers to the load transfer mechanism.

Although it is difficult to assess the contribution from this mechanism on the overall fracture toughness of the composites, the large differences in elastic moduli between the two phases would indicate that it may have a contributory effect.

3.2.1 Effect of whisker aspect ratio

Figure 4 illustrates that reducing the aspect ratio of the whiskers adversely affects their ability to inhibit crack propagation. The improved fracture toughness of the composites has been discussed in terms of crack deflection, crack bridging and load transfer. In order to explain the lower fracture toughness of the Nikkei milled composites when compared with the Nikkei composites, the effect of whisker aspect ratio on the contribution of each of the above must be considered. A reduction in the contribution by crack bridging may be dismissed as this mechanism has been shown to be independent of aspect ratio.[10]

The elastic moduli of the composites were measured using the resonant frequency technique.[11] For a given composition they were found to be independent of the dimensions of the whiskers used. However, this method of measurement generates very low stress amplitudes, insufficient to give any indication of the load-carrying capacities of the whiskers. Although E_c/E_m appeared to be independent of whisker type, it would be anticipated that the toughening increment due to load transfer in the Nikkei Milled composites was less than in the Nikkei composites.

Crack deflection has been shown to be highly dependent on aspect ratio[7] in the region of $S = 1$–10. At higher aspect ratios the toughening increment diminishes. Although the ball milling process reduced the average aspect ratio by 50%, it was still approximately 12 (Table 1). However, the values quoted in Table 1 were determined prior to mixing and consolidating the whiskers with the cordierite. It would be expected that some degradation of the whiskers would take place during these processes. Figure 11 illustrates the occurrence of such a phenomenon. Similar observations have been made by Braue *et al.*[1] and Buljan *et al.*[12] Thus a possible diminution in crack tip perturbations, due to the lower whisker aspect ratio, may have also been a causal factor in the reduced fracture toughness when compared to the Nikkei composites. Examination of fracture surfaces of the Nikkei Milled and Nikkei composites (Fig. 12) did not indicate any fundamental differences between the crack trajectories of the two materials. However, such simple fractographic observations are unlikely to detect small differences in crack deflection profiles and tilt and twist angles. In order to achieve this it would be

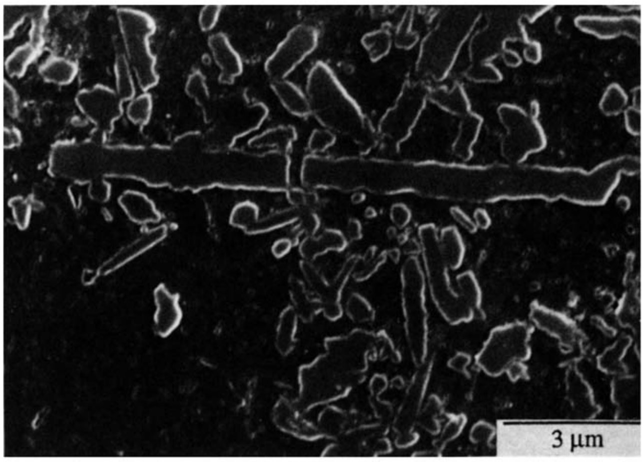
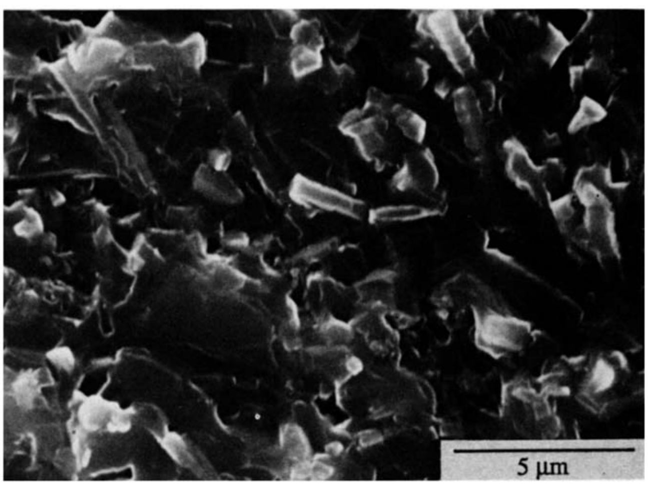


Fig. 11. Whisker fracture during hot pressing.

(a)



(b)

Fig. 12. Comparison of the fracture surfaces of (a) a Nikkei composite and (b) a Nikkei milled composite, each containing 20 vol.% Nikkei SCW.

necessary to perform quantitative studies on crack trajectories on numerous fracture surfaces.

3.2.2 Effect of whisker size

Table 1 indicates that although the AM whiskers are, on average, larger than their Nikkei counterparts, their aspect ratios are similar. It may be seen in Fig. 4 that the higher average unit volumes of the AM whiskers resulted in composites whose fracture toughness was superior to those containing Nikkei whiskers. It is expected that a difference in whisker size will result in changes in their mean spacing within the matrix. Bansal and Ardell[13] attempted to calculate the mean spacing of second phase cylinders as a function of diameter, aspect ratio and volume fraction. However, in order to make their analysis mathematically tractable, a simplified model was constructed, based on uniformly spaced rods, orientated in two dimensions. Such assumptions severely restricted the applicability of their analysis. In order to obtain a comparison between the spacing of whiskers in this study, a simple calculation proved informative. For a given volume fraction of whiskers

$$\frac{N_1 d_1^2 l_1 \pi}{4} = \frac{N_2 d_2^2 l_2 \pi}{4} \quad (2)$$

where N is the number of whiskers per unit volume, d is the whisker diameter, and l is the whisker length.

Substituting the values of mean dimensions of the Nikkei and AM whiskers from Table 1 indicated that the average spacing of the latter was approximately five times that of the former. This result should be treated with a certain degree of caution as it is only a crude calculation based on the centre to centre spacing of particles, which is very difficult to interpret in terms of the spacing of three-dimensionally orientated whiskers. However, observations of polished sections of the composites (Fig. 13) indicated that the calculation did generate a solution of the correct order of magnitude.

It would be expected that the increased size of the regions of matrix devoid of whiskers in the AM composites compared to those in the Nikkei composites would encourage fracture and reduce toughness. The stress intensity at a crack tip increases approximately in proportion to the square root of the crack length. The fracture energy of a particle is dependent upon its fracture toughness and its cross-sectional area. The mean cross-sectional area of the AM whiskers is more than three times that of the Nikkei whiskers. It may therefore be concluded that the toughness decrement caused by an increase in whisker separation was compen-

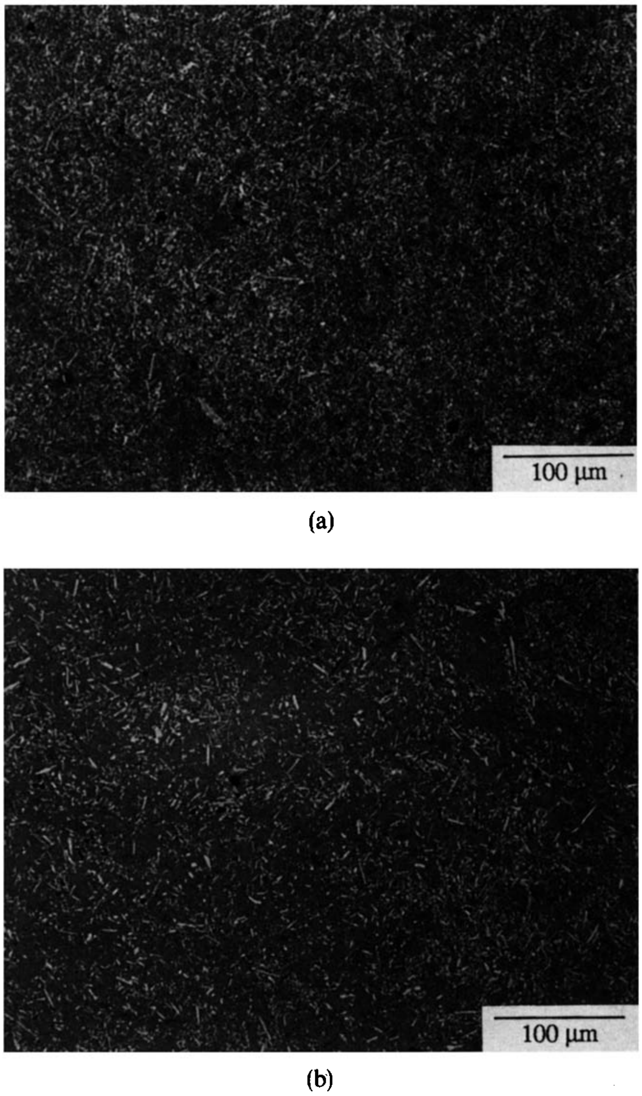


Fig. 13. Optical micrographs of polished sections of (a) cordierite–30 vol.% Nikkei SCW and (b) cordierite–30 vol.% AM SCW illustrating the effect of whisker dimensions on their spacing within the matrix.

sated by the increase in the fracture energy of the whiskers.

The superior fracture toughness of the AM composites may be explained in terms of the contribution by the crack bridging mechanism. The analysis and experimental studies of Becher *et al.*[10] revealed that the contribution of crack bridging is proportional to the square root of the whisker radius. For this reason the toughening increment, due to the AM whiskers, would be expected to be greater than for the Nikkei whiskers.

3.3 Fracture strength

The fracture strength data for the composites are presented in Table 3 and graphically in Fig. 14. No deviation from Hookean behaviour was observed and all composites fractured in a brittle manner.

The fracture strength of the composites exhibited

Table 3. Fracture strength data for cordierite–SCW composites as a function of whisker content

Specimen/Vol.% SCW	*Mean fracture strength (MPa)*
Cordierite/0	170 (24·9)[a]
Nikkei milled	
10	185 (16·3)
20	192 (21·4)
30	203 (27·8)
Nikkei	
10	190 (20·1)
20	220 (25·4)
30	241 (26·8)
AM	
10	192 (18·0)
20	204 (18·4)
30	225 (10·3)

[a] The standard deviations are in parentheses.

a linear relationship with whisker content, despite the associated increase in critical flaw size (Table 4). This increase may be explained in terms of the improvement in fracture toughness and by the load transfer mechanism in which the stronger whiskers support a high proportion of the stress when the composites are loaded. The degree of strengthening by load transfer depends on a number of factors, including the nature of the matrix–whisker interface, the strength of the whiskers and their orientation within the matrix. The fracture strength of a brittle

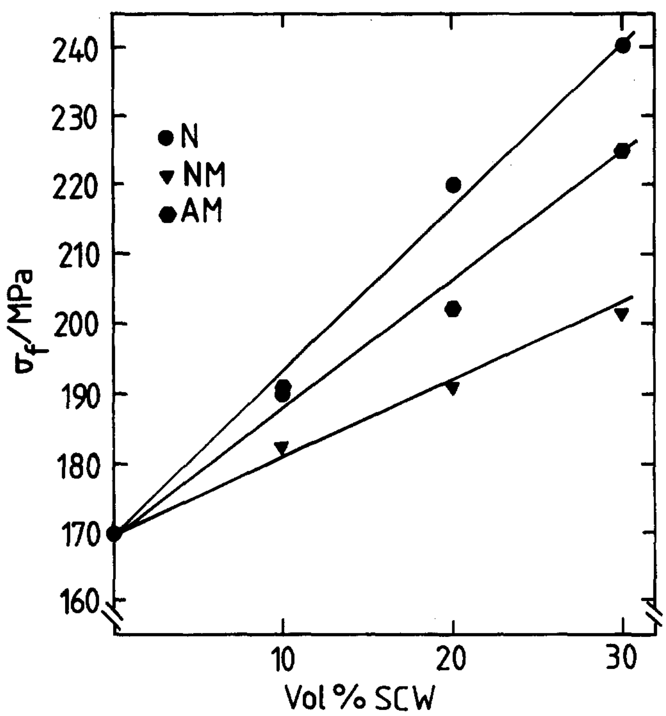


Fig. 14. The fracture strength of cordierite–SCW composites as a function of whisker content.

Table 4. Calculated critical flaw size in the composites

Whisker loading (vol.%)	Critical flaw size (μm)		
	Nikkei	Nikkei Milled	AM
10	40	39	47
20	38	43	56
30	51	48	65

matrix reinforced by non-aligned whiskers may be given as modification of the rule of mixtures.

$$\sigma_f = \sigma_w V_w C C_a + \sigma_m V_m \quad (3)$$

C is a length correction factor which takes into account the fact that the whiskers are discontinuous; it is a function of l/l^c (where l^c is the critical transfer length). C_a is a coefficient of alignment which takes into account the effect of misalignment of the whiskers from the stress axis on their load-carrying ability. Estimates of the value of C_a for various systems have been made by several researchers. Bowyer and Bader[14] and Curtis *et al.*[15] determined C_a by experimental means, whereas Fukuda and Chou[16] and Baek and Kim[17] used a theoretical approach involving probability density functions.

In order to compare the strengthening effects of discontinuous, randomly orientated whiskers with continuous, uniaxially aligned fibres, eqn (3) may be rearranged in terms of the product CC_a. The products CC_a for the Nikkei composites as a function of whisker loading are presented in Table 5.

Although the precise value of fracture strength of the Nikkei SCW was not known, an estimate of 10 GPa was used. This figure was based on the average value reported in the literature for a range of SCW.[18–22] Table 5 indicates that the product CC_a was independent of whisker loading. The length correction factor was expected to be independent of whisker loading, since the processing used was identical and no differences in the degree of whisker damage were expected. It may therefore be inferred that whisker loading had no effect on their dispersion within the matrix. The mean value of the parameter CC_a in the Nikkei composites was 0·04, whereas for continuous uniaxial fibre composites it has the theoretical value of unity. Hence, by using short, randomly orientated whiskers, it was only possible to achieve fracture strengths approaching 8% of the theoretical value, as predicted by the rule of mixtures.

Table 5. CC_a for the Nikkei whisker-reinforced cordierite

Whisker loading (vol.%)	CC_a
10	0·037
20	0·042
30	0·041

3.3.1 Effect of whisker aspect ratio

Figure 14 indicates that the shorter whiskers used in the Nikkei Milled composites are less effective in strengthening the cordierite than the as-received whiskers used in the Nikkei composites. Evaluation of the product CC_a for the Nikkei Milled composites (Table 6) reveals two important points. First, since the homogeneity and critical flaw size of the Nikkei Milled composites was comparable to the Nikkei composites,[23] it may be confirmed that the reduction in the length correction factor (C) contributed to limiting the strength of the Nikkei Milled composites. Secondly, as with the Nikkei composites, the coefficient of alignment was independent of whisker content. Substitution of experimental data from the Nikkei Milled and Nikkei composites containing 30 vol.% SCW into eqn (3) provided a means by which a comparison of the length correction factors could be made. The result was that

$$\frac{C^{NM}}{C^{N}} = 0{\cdot}69$$

Hence a 50% reduction in whisker aspect ratio resulted in a 30% reduction in the load-carrying capabilities of the whiskers. This result is supported by the theoretical approach developed by Fukuda and Chou,[16] which predicted a reduction in fracture strength of a composite with decreasing fibre aspect ratio. Baek and Kim[17] incorporated SCW of differing mean aspect ratios into alumina. They observed that a reduction in whisker length resulted in a reduction in fracture strength. Their experimentally-derived results compared well with the theoretical predictions of Fukuda and Chou[16] for long whiskers but deviated from the predicted curve when short whiskers were incorporated. Their belief was that milling, used to reduce the length of the whiskers, was responsible for weakening them also. It may be surmised that the lower fracture strength of the Nikkei Milled composites was due to a

Table 6. The product of coefficient of alignment and length correction factor for the Nikkei Milled composites

Whisker loading (vol.%)	CC_a
10	0·032
20	0·028
30	0·028

reduction of the load-carrying capabilities of the whiskers, coupled with a reduction in fracture toughness. The reduction in whisker aspect ratio was responsible for both.

3.3.2 Effect of whisker size

The results in Fig. 14 indicate that the reinforcing efficiency of the AM SCW was not as high as that of the Nikkei SCW. In order to interpret this observation, consideration should be made of the dimensions of the whiskers and their surface roughness. Differences in interfacial chemistry may be assumed to be insignificant, as both batches of whiskers were pre-treated in a solution of hydrofluoric and hydrochloric acids, in order to remove any surface impurities.

Reference to Table 2 indicates that although the AM SCW were, on average, longer and had larger diameters than the Nikkei SCW, they had similar aspect ratios. Whisker aspect ratio has a deterministic effect on strengthening due to load transfer, but in this case the contribution by the load transfer mechanism would be expected to be similar.

Account must be made of the surface texture of the whiskers because this will also affect the degree of load transfer from the matrix to the whiskers. Whiskers with undulating surfaces are more likely to be effective at strengthening than perfectly smooth whiskers. Observations using the SEM did not reveal any fundamental differences between the surface characteristics of the Nikkei and AM SCW. In both cases whiskers with larger diameters tended to have rough or undulating surfaces and those with smaller diameters tended to be smooth and needle-like. It was therefore expected that the loading characteristics of each type of whisker was similar.

Differences in fracture strength may not be explained in terms of differences in fracture toughness (Fig. 4), since the fracture toughness of the AM composites was greater than that of the Nikkei composites. Other potential causes of the observed behaviour were, therefore, related to the dimensions of the whiskers and will be discussed in such terms. In the Nikkei and Nikkei Milled composites a correlation existed between the spacing of the whiskers and the critical flaw size of the material.[23] Calculations of the critical flaw sizes in the AM composites (Table 4) indicated that, for a given whisker loading, the AM SCW generated larger apparent flaws than the Nikkei SCW.

It is expected that the increased critical flaw size in the AM composites was due to the presence of larger whisker networks, due to the greater dimensions of the AM SCW, compared to the Nikkei SCW. A further possible contribution to the inferior fracture strength of the AM composites may have been due to the greater variation in the lengths of the AM SCW (Fig. 1 and Table 1) as proposed by Fukuda and Chou.[16]

4 Conclusions

Improvements in fracture toughness were due to crack deflection, crack bridging and load transfer. Pullout was not observed to be a contributory mechanism.

Fracture strength exhibited a linear increase with whisker content, despite the fact that whisker additions increased the flaw size of the materials. The improvement in fracture strength is believed to have been due to the contribution from load transfer coupled with enhanced fracture toughness, which predominated over the detrimental effects of an increase in flaw size.

A reduction in whisker aspect ratio had a detrimental effect on both the fracture toughness and fracture strength of the composites. The inferior fracture toughness is believed to have been due to the restricted contribution by the load transfer mechanism coupled with a possible reduction in the contribution of crack deflection. Whiskers of lower aspect ratio were also less effective in strengthening the cordierite. The experimental results indicate that this was due to the reduced load-carrying capabilities of the shorter whiskers, along with the inferior fracture toughness, when compared to those composites containing whiskers of higher aspect ratio.

Composites containing whiskers with similar aspect ratio, but having larger dimensions, have been shown to have superior fracture toughness but inferior fracture strength to those with smaller dimensions. It has been established that a preponderance of crack bridging was responsible for the superior fracture toughness. Those composites containing the more voluminous whiskers had inferior fracture strengths as a result of the generation of larger flaws within the matrix. The net effect of a higher fracture toughness and a greater flaw size was a detrimental effect on fracture strength.

References

1. Braue, W., Holscher, A., Saruhan, B. & Ziegler, G., Effect of SiC-whisker characteristics on interface and mechanical

properties of silicon nitride matrix composites. In *Euroceramics*, ed. G. de With, R. A. Terpstra & R. A. Metselaar. Elsevier Applied Science, London, 1989, pp. 263–7.

2. Karasek, K. R., Bradley, S. A., Donner, J. T., Martin, M. R., Haynes, K. L. & Yeh, H. C., Composition and microstructure of silicon carbide whiskers. *J. Mater. Sci.*, **24** (1989) 1617–22.
3. Karasek, K. R., Bradley, S. A., Donner, J. T., Schienle, J. L. & Yeh, H. C., SiC whisker characterisation: an update. *Amer. Ceram. Soc. Bull.*, **70** (1991) 224–8.
4. Milewski, J. V., Gac, F. D., Petrovic, J. J. & Skaggs, S. R., Growth of beta-silicon carbide whiskers by the VLS process. *J. Mater. Sci.*, **20** (1985) 1160–6.
5. Shalek, P. D., Phillips, D. S., Christiansen, D. E., Katz, J. D., Parkinson, W. J. & Petrovic, J. J., Synthesis and characterisation of VLS-derived silicon carbide whiskers. In *Whisker and Fibre Toughened Ceramics, Proc. International Conference*, Oak Ridge, TN, USA, 7–9 June 1988, ed. R. A. Bradley, D. E. Clark, D. C. Larsen & J. O. Stiegler. ASM International, USA, pp. 53–62.
6. Tiegs, T. N. & Becher, P. F., Whisker reinforced ceramic composites. In *Tailoring of Multiphase Ceramics*, ed. R. Tressler, G. Messing, C. Pantano & R. Newnham. Plenum, New York, 1986, pp. 639–47.
7. Anstis, G. R., Chantikul, P., Lawn, B. R. & Marshall, D. B., A critical evaluation of indentation techniques for measuring fracture toughness. I: Direct crack measurements. *J. Amer. Ceram. Soc.*, **64** (1981) 533.
8. Faber, K. T. & Evans, A. G., Crack deflection processes. I: Theory. *Acta Metall.*, **31** (1983) 565–84.
9. Faber, K. T. & Evans, A. G., Crack deflection processes. II: Experiment. *Acta Metall.*, **31** (1983) 565–84.
10. Becher, P. F., Hseuh, C.-H., Angelini, P. & Tiegs, T. N., Toughening behaviour in whisker reinforced composites. *J. Amer. Ceram. Soc.*, **71** (1988) 1050–61.
11. Davis, K., Measurements of the elastic constants of ceramics by the resonant frequency method. Research Paper No. 607, British Ceramic Research Association, 1968.
12. Buljan, S. J., Baldoni, J. G. & Huckabee, M. L., Si_3N_4–SiC composites. *Amer. Ceram. Soc. Bull.*, **66** (1987) 347–52.
13. Bansal, P. P. & Ardell, A. J., Average nearest-neighbor distances between uniformly distributed finite particles. *Metallog.*, **5** (1972) 97–111.
14. Bowyer, W. H. & Bader, M. G., On the reinforcement of thermoplastics by imperfectly aligned discontinuous fibres. *J. Mater. Sci.*, **7** (1972) 1315–21.
15. Curtis, P. T., Bader, M. G. & Bailey, J. E., The stiffness and strength of a polyamide thermoplastic reinforced with carbon fibres. *J. Mater. Sci.*, **13** (1978) 377–90.
16. Fukuda, H. & Chou, T.-W., A probabilistic theory of the strength of short-fibre composites with variable fibre length and orientation. *J. Mater. Sci.*, **17** (1982) 1003–11.
17. Baek, Y. K. & Kim, C. H., The effect of whisker length on the mechanical properties of alumina–SiC whisker composites. *J. Mater. Sci.*, **24** (1989) 1589–93.
18. Petrovic, J. J. & Roof, R. B., Fracture toughness of a beta-SiC whisker. *J. Amer. Ceram. Soc.*, **67** (1984) C219–20.
19. Hyami, R., Veno, K., Kondou, I., Tamari, N. & Toibani, I., Si_3N_4–SiC whisker composite material. *Mater. Sci. Res.*, **20** (1986) 663–74.
20. Samanta, S. & Musikank, S., SiC whisker-reinforced ceramic matrix composites. *Ceram. Eng. Sci. Proc.*, **6** (1985) 663–72.
21. Gadkaree, K. P. & Chyung, K., SiC whisker reinforced glass and glass ceramics. *Amer. Ceram. Soc. Bull.*, **65** (1986) 370–6.
22. Petrovic, J. J. & Hoover, R. C., Tensile fracture behaviour of long SiC whiskers. *J. Mater. Sci.*, **22** (1987) 517–22.
23. Wadsworth, I., Fabrication and microstructure–property relationships in cordierite composites. PhD thesis, School of Materials, University of Leeds, UK, 1990.