The effect of whisker length on the mechanical properties of alumina-SiC whisker composites

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Silicon carbide whisker (20v/o)-reinforced alumina composites with various whisker lengths were prepared by hot pressing, then the dependences of whisker length on flexural strength and fracture toughness of the composite were examined. Using the modified Fukuda model, the strength of each composite was calculated. It was compared with experimentally measured strength. They coincided well in longer whisker-reinforced aluminas. Toughness of the composite was improved with whisker length via increasing of the pullout length of whisker.

1. Introduction

Alumina-SiC whisker ceramic composites have recently come into prominence for structural applications because of their attractive mechanical and thermal properties [1-4]. This material is a good candidate for advanced heat engines, cutting tool, and for other applications [3, 4].

When SiC whiskers are added to an alumina matrix, the fracture toughness and the strength are significantly improved compared to monolithic alumina. Researchers achieved fracture toughness value approaching 9 MPa $m^{1/2}$ and fracture strength 800 MPa for SiC whisker-reinforced alumina composites [1, 2]. The basic mechanism of strengthening in the composite is the load transfer to the whisker as pointed by Rice [5, 6]. This load transfer takes place at whisker ends within the range of a few whisker diameters. On the other hand, the stress concentration at the whisker ends could result in lowering the strength of composites. The amount of load that is transferred to the whisker changes depending on the length of the whisker and the mechanical properties of matrix and reinforcing whiskers.

In this study, the strength changes of alumina-20v/o SiC whisker composites fabricated by hot pressing were investigated as a function of the average whisker length of the composites and then compared with those calculated by modified Fukuda Model. The dependence of the fracture toughness on the whisker length was also measured. The major toughening mechanism of SiC whisker-reinforced alumina was proposed based on the microstructural changes of fracture surface.

2. Experimental procedures

The SiC whiskers (SCW-1, Tateho Chemical, Japan) used in the present study were mainly single crystals of β-SiC. The diameter varied from 0.1 to 0.5 μm and the length from 10 to 40 μm. The reported Youngs modulus and tensile strength of these whiskers are 581 and 20.685 GPa, respectively. The alumina powder (AES-11, Sumitomo Chem. Co., Japan) used in this study had a mean particle size of 0.3 μm and a purity above 99.8%.

The alumina-20 vol % SiC whisker composites with different length of whiskers were prepared by the following procedure. First 20 g SiC whisker were mixed with 500 cm^3 ethyl alcohol and the mixture was blended for 0, 18, 36 and 60 min, respectively, in a mechanical blender. During this procedure, the average length of whisker was changed. The average lengths of whiskers and standard deviations are listed in Table I. The whisker length was measured from well dispersed electron microphotographs. Secondly, the SiC whisker (20 vol %) pretreated according to the above procedure and alumina powder were added to ethyl alcohol. The slurry was blended for 8 min and ultrasonically dispersed for an additional 60 min. The additional size reduction of the SiC whiskers was not detected. The resulting slurry was dried and granulated.

Specimens (30 mm in diameter by 8 mm thick) were hot pressed in a graphite resistance furnace (Astro Industries, Inc., Santa Barbara, CA) with graphite dies lined BN. Hot pressing was done at 1800° C and 34.5 MPa for 1 h in an argon atmosphere.

The densities of the hot pressed composites were obtained by the liquid displacement method. Microstructures of polished specimen were examined by reflected light microscope and scanning electron microscope (SEM). SEM fractography was also used to examine the interaction between crack and whiskers. Transmission electron microscopy (TEM) was used to examine the internal defects of alumina matrix.

The fracture strength, σ_f was measured in four-point bending (6.0 mm inner span and 18.25 mm outer span) on rectangular bars (2 mm by 1.5 mm by 25 mm) machined from the hot pressed composites. In σ_f specimens, the tensile axis and the tensile face were

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perpendicular to the hot pressing axis. The tensile surfaces of bars were surface ground (up to $6\,\mu$m diamond disc). A minimum of six specimens were tested for each composite containing a different length of whiskers.

Fracture toughness, K_{IC}, of the composites was measured by single-edge notched beam (SENB) and chevron-notched four-point bend specimens at room temperature. The dimensions of SENB and chevron-notched specimens for K_{IC} measurements was 3.0 by 4.5 by $25\,mm^3$.

3. Results and discussion

3.1. Strengthening of SiC whisker–alumina composites

The understanding of strength of whisker reinforced composites and their fracture behaviour are very complicated because of the non-uniformity in whisker length and orientation. For unidirectional continuous fibre-reinforced composites, under the assumption of isostrain in the fibres and matrix, the rule of mixture is used to predict the strength [7]

$$\sigma_{cu} = \sigma_{fu} V_f + \sigma'_m (1 - V_f) \qquad (1)$$

where σ_{cu} is the ultimate strength of the composite, V_f, fibre volume fraction, σ'_m, the matrix stress at the fracture of composite, however, there are variations not only in whisker length but in orientation. Therefore, the rule of mixture had to be modified to [8, 9]

$$\sigma_{cu} = \sigma_{fu} V_f F(l_c/\bar{l})\, C_0 + \sigma'_m (1 - V_f) \qquad (2)$$

where $F(l_c/\bar{l})$ is the fibre length factor, l_c, critical fibre length, $\bar{l}$, average fibre length, and C_0 is the fibre orientation factor.

In order to deal with the distributions of fibre length and orientation, Fukuda and Chou [10] introduced two kinds of probability density function, and predicted the strength of composites using the concept of critical zone proposed by Bader *et al.* [11]. Their result was as follows

$$\begin{aligned}\sigma_{cu} = {} & \sigma_{fu} V_f \int_0^{\pi/2} g(\theta)\cos\theta\, d\theta \int_0^{\theta_0} g(\theta)\cos^3\theta\, d\theta \\ & \times \int_{\beta\bar{l}}^{\infty}\left[\int_0^{\theta_0}\left(1 - \frac{\beta\bar{l}}{\bar{l}\cos\theta}\right) g(\theta)\, d\theta\right] h(l)\, dl \\ & \times \left[\int_{\beta\bar{l}}^{l_c}\frac{l}{2l_c} h(l)\, dl + \int_{l_c}^{\infty}\left(1 - \frac{l_c}{2l}\right) h(l)\, dl\right] \\ & + \sigma'_m (1 - V_f)\end{aligned} \qquad (3)$$

where $g(\theta)$ and $h(l)$ are the probability density function of fibre length distribution and orientation distribution, respectively, and $\beta\bar{l}$ is the critical zone width.

The assumption that the distribution functions of whisker length and orientation are independent of each other in deriving Equation 3, makes it impossible to integrate the equation except some limited cases. In this study, under the assumption that there exist interrelationships between two distribution functions, the Equation 3 was modified as follows [12]

$$\begin{aligned}\sigma_{cu} = {} & \sigma_{fu} V_f \int_0^{\pi/2} g(\theta)\cos\theta\, d\theta \\ & \times \int_{\beta\bar{l}}^{\infty}\int_0^{\theta_0}\left(1 - \frac{\beta\bar{l}}{l\cos\theta}\right) g(\theta)\, d\theta\, h(l)\, dl \\ & \left[\int_{\beta l}^{l_c}\frac{\bar{l}}{2l_c} h(l)\int_0^{\theta_0} g(\theta)\cos^3\theta\, d\theta\, dl \right. \\ & \left. + \int_{l_c}^{\infty}\left(1 - \frac{l_c}{2\bar{l}}\right) h(l)\int_0^{\theta_0} g(\theta)\cos^3\theta\, d\theta\, dl\right] \\ & + \sigma'_m (1 - V_f)\end{aligned} \qquad (4)$$

The strength of composites is greatly decreased with increasing β and decreasing θ_0. It may be due to the fact that β is largely dependent upon the interaction distance between microcracks, which are inhibited by stress concentrations in matrix around the tips of whisker, and θ_0 is related with the degree of whisker alignment.

Equation 4 was calculated numerically using the distribution functions proposed by Fukuda and Chou [10] which are shown in Fig. 1. To calculate the strength of the composite, σ_{fu} was assumed to be 10 342.5 MPa which is the half value of reported whisker strength, and the values of σ'_m and the interfacial shear strength, τ_m, were both assumed to be identical with the flexural strength of hot pressed monolithic alumina, 287 MPa, which was measured in this study. The average whisker diameter was assumed to be $0.3\,\mu$m.

Fig. 2 shows the effect of average length of SiC whiskers on the strength of alumina–20v/o SiC whisker composites when the whiskers are arrayed two-dimensionally. The experimental results were compared with the calculated values in the same figure. Longer SiC

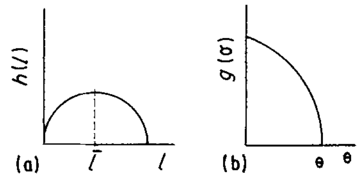

Figure 1 (a) Whisker length and (b) orientation distribution function assumed in modified Fukuda Model.

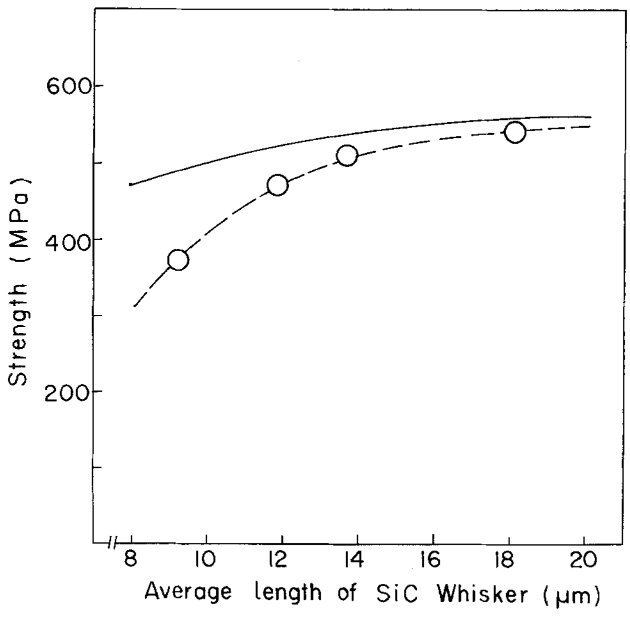

Figure 2 The affect of whisker length on the strength of alumina –20v/o SiC whisker composites. The theoretical value (——) was calculated from the modified Fukuda Model.

whiskers are more effective on the strengthening of the composite, but as the average whisker length is increased, the increment of the strength is reduced and the strength of the composite shows the asymptotic limit. When composites contain long whiskers, calculated strength values are well coincided with the experimentally measured strength. This shows that modified Fukuda Model can predict the strength of SiC whisker-reinforced alumina composite. However, there is some discrepancy in strength values between calculated and measured one in short whisker composites. Since the shorter whiskers have undergone longer pretreating time, it is considered that the pretreatment damages the whisker and lowers the strength of the whisker. It is concluded that assuming the same strength value without considering the whisker length causes the discrepancy between calculated and measured strength of the SiC whisker–alumina composite.

3.2. Toughening of SiC whisker–alumina composites

The polished surfaces (perpendicular to the hot pressing direction) of specimens were examined in order to observe the distribution of whiskers. It was revealed that the process altering the whisker length does not affect the distribution of whisker. As shown in Fig. 3, whiskers in composites are not interconnected with each other even though in the AR–0 specimen which contains the longest whisker (SC–0). They are mainly located in the grain boundaries of the alumina matrix.

Fracture behaviour was examined by observing the fracture surface of the chevron-notched specimen. Fracture modes of monolithic alumina and SiC-reinforced alumina were different from each other. Fracture occurred intergranularly in monolithic alumina, but transgranularly in SiC-reinforced alumina as shown in Fig. 4. Since the thermal expansion coefficient of the SiC whisker is half that of alumina, cooling from the hot pressing temperature causes the tensile stress in the alumina matrix. The value of the tensile stress is about 800 MPa in Al_2O_3–20v/o SiC whisker composite, which is calculated from Selsing's equation [13]. It is considered that this stress degrades the alumina matrix and the degradation causes the transgranular fracture of the composite. In transmission electron micrographs, Fig. 5, dislocations are observed in the alumina matrix around the SiC whisker in composites. This observation is thought to be evidence of the weakening of the alumina matrix and the resulting transgranular fracture.

Fig. 6 shows the dependence of the fracture behaviour for 20v/o SiC whisker-reinforced alumina on the whisker length. Each composite containing short and

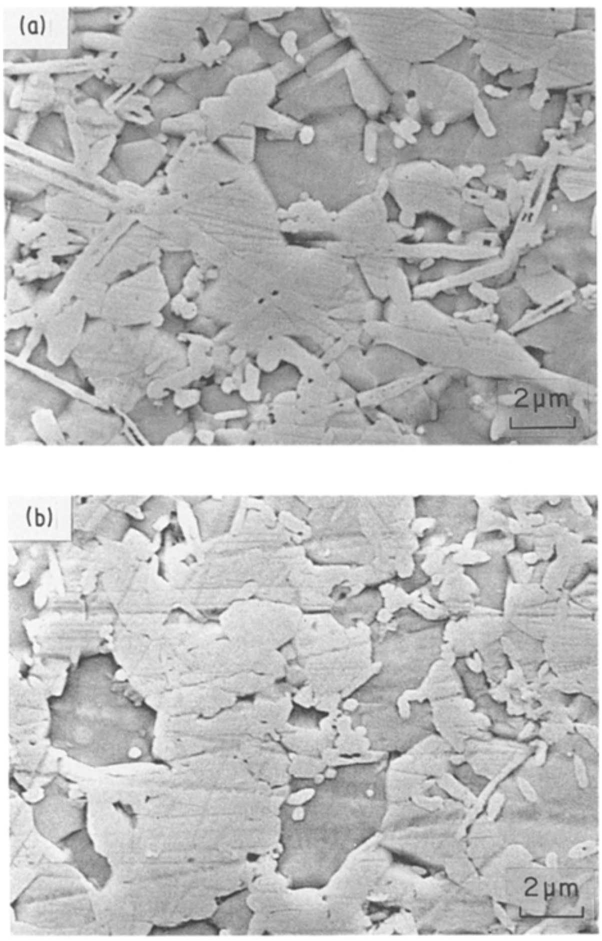

Figure 3 Distributions of whisker for alumina–20v/o SiC whisker composite containing (a) long whisker (SC-0) and (b) short whisker (SC-60).

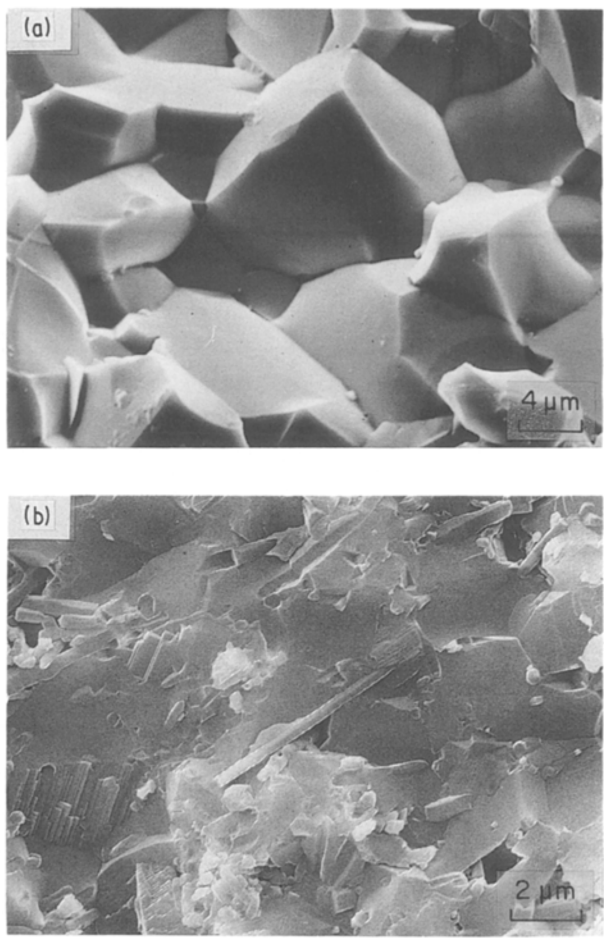

Figure 4 Fracture surfaces of (a) monolithic alumina and (b) the composite containing 20v/o SiC whisker. Monolithic alumina shows intergranular fracture; composite transgranular.

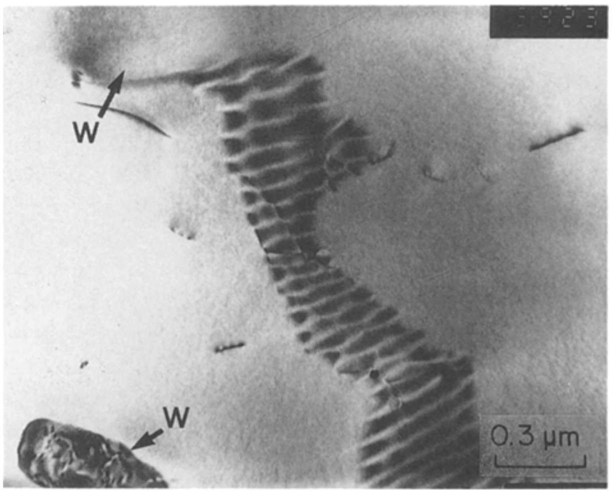

Figure 5 TEM micrograph of alumina–20v/o SiC whisker composite showing dislocations in the neighbourhood of SiC whiskers marked W.

long whiskers shows the same ragged fracture surface which arises from the crack deflection mechanism. Namely, the fracture behaviour is not affected by the change of the aspect ratio of the whisker. Faber and Evans calculated the toughness increment of composites containing various second phase shapes and considered the existence of crack deflection reaction between cracks and second phase [14, 15]. When rod-shaped particles exist in the composite, toughness increment shows the asymptotic limit at large aspect ratio. The contributions of the second phase to the toughening are almost the same in the region above the aspect ratio value of 12. The aspect ratios of whiskers used in this study are from 30 to 60. Therefore the contribution of crack deflection mechanisms is almost identical in composites reinforced by the four different types of whisker used in this study.

However, Fig. 7 shows that 20v/o SiC–alumina composite with long whiskers has a higher toughness than that with short whiskers. This increment of toughness can be explained by observing the microscopic difference of fracture surface. The protruding length of whiskers in composites containing long whiskers (SC-60) is longer than those containing short whiskers (SC-0). The composite AR-0 has a protruding length of 2.3 μm which is 7.7 times the whisker diameter and that of AR-60 is 1.1 μm which is 3.7 times the diameter. As the average whisker length of AR-0 is about 18 μm and that of AR-60 is about 9 μm, the length of reinforced whisker has an influence on the protruding length of fracture surface.

On the basis of the pullout mechanism, Cottrell pointed out that the work of fracture of composites is increased by a third power with the pullout length of short fibres [16]. Consequently, it is concluded that the higher fracture toughness of the AR-0 composite results from the longer pullout length of whiskers, and the longer pullout length is attributed to the initial longer whiskers (SC-0). It is considered that the whisker pullout mechanism contributes mainly to the toughening of whisker-reinforced hot-pressed alumina rather than the crack deflection mechanism.

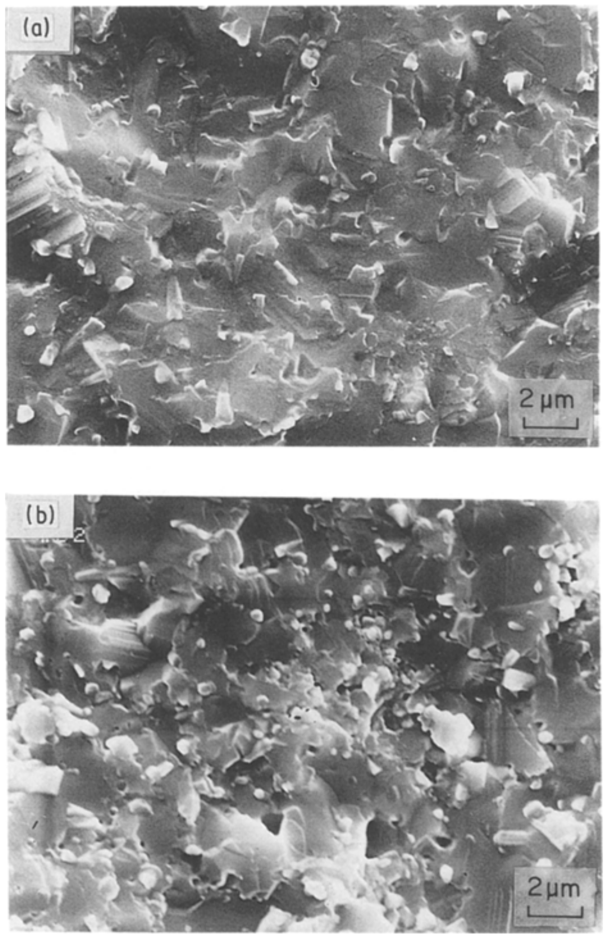

Figure 6 Fracture surfaces of alumina–20v/o SiC whisker composite containing (a) long whiskers (SC-0) and (b) short whiskers (SC-60).

4. Conclusion

Al_2O_3–20v/o SiC whisker composites with different lengths of whisker were prepared by hot pressing. The modified Fukuda model was used to calculate the strength of composite. The measured flexural strength

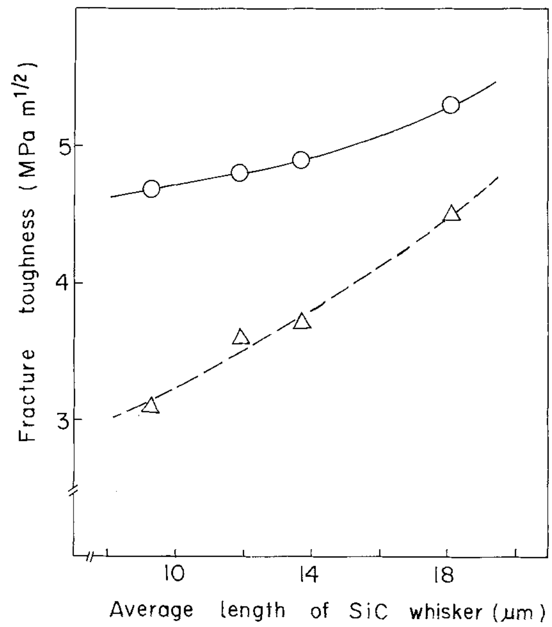

Figure 7 The effect of whisker length on the fracture toughness of alumina–20v/o SiC whisker composites. (—— single-edge notched beam, - - - chevron notched beam).

TABLE I Lengths of the treated SiC whiskers and classification of the alumina–20v/o whisker composite

Names of the SiC whiskers	Pretreating time (min)	Length of treated SiC whiskers		Names of composites
		Average (μm)	Deviation (μm)	
SC-0	0	18.12	10.49	AR-0
SC-18	18	13.70	8.54	AR-18
SC-36	36	11.91	7.05	AR-36
SC-60	60	9.34	4.06	AR-60

was compared with the calculated value. In long whisker-reinforced alumina, the calculated and measured strength nearly coincided. The toughness of 20v/o SiC–alumina composites increased with the length of whisker used. The toughness increment was related to the pullout length of the whiskers. The SiC whisker–alumina composite with the longer whiskers showed a longer pullout whisker length and higher fracture toughness.

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