Mechanical Properties of Uni-Directionally Oriented SiC-Whisker/ Al_2O_3 Composite

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一方向に配向した SiC ウィスカー/ Al_2O_3 複合材料の力学的性質

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Uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 composite (UD-comp) was fabricated by the sol-gel method from $\text{Al}(\text{OC}_3\text{H}_7)_3$ and by its extrusion. Mechanical properties of UD-comp were compared with those of 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 composite (2DR-comp) made by conventional hot-press sintering. Fracture toughness K_{IC} value of UD-comp was measured to be $7.1 \text{ MPa}\cdot\text{m}^{1/2}$ which was larger than that of 2DR-comp ($5.6 \text{ MPa}\cdot\text{m}^{1/2}$). Improvement in fracture toughness by 2.3 times was realized over the fracture toughness K_{IC} $3.1 \text{ MPa}\cdot\text{m}^{1/2}$ of monolithic Al_2O_3 fabricated by the same sol-gel method. The same tendency was observed in effective fracture energy. These results indicate that whiskers aligned vertically to a crack were more effective than inclined whiskers for toughening by whisker bridging and pull-out. No increment in bending strength was obtained in UD-comp and its value was smaller than that of 2DR-comp. This result is attributable to the aligned direction of residual thermal stress.

Key-words : SiC whisker, Al_2O_3 , Composite, Fracture toughness, Effective fracture energy, Bending strength, Orientation

1. Introduction

Because whisker-reinforcement has some advantages mentioned below, it is expected to be one of the most effective method to toughen ceramics.

(1) It is possible to utilize many toughening mechanisms such as crack bowing, crack deflection, whisker bridging and whisker pull-out in the composite.

(2) It is able to fabricate whisker reinforced composites easier than continuous fiber reinforced ones.

(3) Whiskers and their composites seem to have high performance at high temperature.

We guess that whisker bridging and pull-out mechanisms might contribute much to toughening of SiC-whisker/ Al_2O_3 composites.¹⁾⁻³⁾ Here, we call bridging mechanism as stress shielding at the crack tip bridged by whiskers and pull-out mechanism as energy consumption by interfacial friction. Tensile stress acts on the whiskers and frictional stress acts on their interfaces during pulling-out whiskers

whose longitude oriented parallel to the direction of external uniaxial stress. On the contrary, when whiskers whose longitude inclined against the direction of external uniaxial stress are pulled-out, complicated multi-axial stress containing shear and bending modes acts on the whiskers.⁴⁾ Thus, the multi-axial stress makes inclined whiskers be broken easier than parallel whiskers. In practice, almost all whiskers exist at random in planes in composites fabricated by hot-press method⁵⁾ and are inclined against the direction of external uniaxial stress. We estimated that if mechanisms such as bridging and pull-out contribute much to toughening of SiC-whisker/ Al_2O_3 composites, fracture toughness of these composites will be influenced by whisker-orientation. Also we estimated that uni-directionally oriented SiC-whisker/ Al_2O_3 composite (UD-comp) seems to realize higher toughness than that of 2-dimensional randomly oriented SiC-whisker/ Al_2O_3 composite (2DR-comp). There are some reports mentioned on uni-directionally oriented whisker reinforced ceramic composites whose matrices are ZrO_2 ⁶⁾ and Si_3N_4 .⁷⁾⁻⁹⁾ In these papers, no remarkable differences have been reported in spite of uni-directional whisker-orientation. However, it is quite likely that in ceramics toughened by whiskers, the fracture toughness of the UD-comp should be higher than randomly oriented one.

In this study, UD-comp with 20 vol%-SiC-whisker was fabricated by sol-gel method from $\text{Al}(\text{OC}_3\text{H}_7)_3$ and followed by its extrusion. Mechanical properties of UD-comp were compared with those of 2DR-comp which was also fabricated by sol-gel method to investigate bridging and pull-out effects on toughening of SiC-whisker/ Al_2O_3 .

2. Fiber pull-out model

To analyze the behavior of fiber fracture during pulling-out, we introduce a simple model in which a fiber with radius r inserted into a matrix by length l_i is pulled-out by external uniaxial force F inclined against fiber longitude by angle θ . We call this angle θ as misorientation angle. It is assumed that external

Fig. 1. A schematic illustration of fiber pull-out model.

uniaxial force F directly acts on the edge of a fiber, which is perfectly fastened by a stiff matrix. A schematic illustration of this simple model is shown in Fig. 1.

2.1 Tensile fracture of a fiber

When a fiber is pulled-out by length l with maintaining the force balance in this system, external uniaxial force F_P given by the following equation is necessary to pull-out a fiber. Here it is assumed that interfacial shear stress τ_i is constant.

$$F_P = 2 \pi r (l_i - l) \tau_i / \cos \theta \quad (1)$$

On the other hand, external uniaxial force F_{Tmax} which makes a fiber be broken in pure tensile mode is given as follows:

$$F_{Tmax} = \pi r^2 \sigma_F / \cos \theta \quad (2)$$

σ_F : tensile strength of a fiber

If the maximum value of F_P ($=F_{Pmax}$) is larger than F_{Tmax} , namely the following inequality is satisfied,

$$(l_i - l) / r > \sigma_F / 2 \tau_i \quad (3)$$

then a fiber will be broken by tensile stress without pulling-out (at $l=0$).

2.2 Shear fracture of a fiber

Shear stress τ in Eq. (4) acts on the cross section of a fiber at the fastened edge regardless of pulled-out length l .

$$\tau = F \sin \theta / \pi r^2 \quad (4)$$

The external uniaxial force F_{Smax} to brake a fiber by shear stress is given as follows:

$$F_{Smax} = \pi r^2 \tau_F / \sin \theta \quad (5)$$

τ_F : shear strength of a fiber in radial in radial direction

Since SiC-whiskers used in this study are single crystals with a few stacking faults and are typical brittle materials, they seem to have high tensile strength σ_F in their longitudinal direction and high shear strength τ_F in their radial direction, and both of them are approximately comparable to the theoretical strength. It is reported that τ_F is nearly equal to σ_F ¹⁰ neglecting anisotropy of a SiC-whisker. Then, τ_F in Eq. (5) can be replaced by σ_F as follows.

$$F_{Smax} = \pi r^2 \sigma_F / \sin \theta \quad (6)$$

If F_{Pmax} is larger than F_{Smax} , a fiber will be broken by shear stress without pulling-out. The condition of shear fracture is obtained as follows:

$$l_i / r > \sigma_F / 2 \tau_i \tan \theta \quad (7)$$

2.3 Bending fracture of a fiber

When a fiber is pulled-out, stress on bending mode σ_B acts on a fiber responding to pulled-out length l . Shaw and Faber⁴) showed that the maximum bending stress σ'_{Bmax} acting on a fiber is given by Eq. (8) with beam theory.

$$\sigma'_{Bmax} = 4 Fl \sin \theta / \pi r^3 \quad (8)$$

However, the effect of fiber edge fastening was ignored in Eq. (8). Then, we considered edge fastening of a fiber based on beam theory and replace Eq. (8) by Eq. (9).

$$\sigma_{Bmax} = 2 Fl \sin \theta / \pi r^3 \quad (9)$$

On the other hand, tensile stress σ_T uniformly acts on a fiber in its longitudinal direction as follows:

$$\sigma_T = F \cos \theta / \pi r^2 \quad (10)$$

As a result, the maximum tensile stress σ_{max} on a fiber is expressed by Eq. (11).

$$\sigma_{max} = \sigma_T + \sigma_{Bmax} = F(2 l \sin \theta / r + \cos \theta) / \pi r^2 \quad (11)$$

External uniaxial force F_{Bmax} to brake a fiber with bending mode, can be given by the following equation.

$$F_{Bmax} = (\pi r^2 \sigma_F) / (2 l \sin \theta / r + \cos \theta) \quad (12)$$

If F_{Pmax} is larger than F_{Bmax} , a fiber will be broken by bending stress after pulling-out by length l . The condition of bending fracture is obtained as follows:

$$l^2 + (r/2 \tan \theta + l_i) l + (r^2 \sigma_F / 4 \tau_i - r l_i / 2) / \tan \theta < 0 \quad (13)$$

From Eq. (13), the condition in which a fiber is fully pulled-out is given as follows:

in the case of $0^\circ < \theta < \tan^{-1}(\tau_i / \sigma_F)$

$$l_i / r < \sigma_F / 2 \tau_i \quad (14)$$

in the case of $\tan^{-1}(\tau_i / \sigma_F) < \theta < 90^\circ$

$$l_i / r < (\sigma_F / \tau_i \tan \theta)^{1/2} - 1/2 \tan \theta \quad (15)$$

2.4 Effect of misorientation angle on fiber fracture

It is reported that the strength of a SiC-whisker is about 10 GPa.^{11),12)} In addition, it is also reported that residual thermal stress exists in SiC-whisker/Al₂O₃ composites and the residual stress in radial direction of a whisker is about 1 GPa¹³⁾ in compression. In very rough approximation, interfacial shear stress caused by friction is deduced as 0.3 GPa from radial compressive stress multiplied by frictional factor of 0.3. Thus, l_i / r are plotted as a function of misorientation angle θ give by Eqs. (3), (7), (14) and (15) in the case of $\sigma_F / \tau_i = 30$ (Fig. 2). θ_A and θ_B are expressed in Eqs. (16) and (17), respectively:

$$\theta_A = \tan^{-1}(\tau_i / \sigma_F) \quad (16)$$

$$\theta_B = \tan^{-1}\{(\sigma_F / \tau_i + 1)^{1/2} \tau_i / 4 \sigma_F\} \quad (17)$$

In the case of $\sigma_F / \tau_i = 30$, θ_A is calculated to be 1.9° and θ_B is also calculated to be 83° . In Fig. 2, fracture behaviors of a fiber with some misorientation angle are divided into 5 modes as follows:

Region 1: A fiber is not broken and is fully pulled-

Fig. 2. A fiber fracture map in the case of $\sigma_F/\tau_i = 30$ as a function of misorientation angle.

σ_F : tensile strength of a fiber, τ_i : interfacial shear stress

$\theta_A = 1.9^\circ$, $\theta_B = 83^\circ$

Region 1: A fiber is not broken and is fully pulled-out.

Region 2: A fiber is broken by bending stress after some pulling-out.

Region 3: A fiber is broken by shear stress without pulling-out.

Region 4: A fiber is broken by tensile stress without pulling-out.

Region 5: A fiber is broken by shear or tensile stress without pulling-out.

out.

Region 2: A fiber is broken by bending stress after some pulling-out.

Region 3: A fiber is broken by shear stress without pulling-out.

Region 4: A fiber is broken by tensile stress without pulling-out.

Region 5: A fiber is broken by shear or tensile stress without pulling-out.

Figure 2 indicates that the larger the misorientation angle of a fiber is, the smaller the l_i/r value of Region 1 results. This means that it is easy for inclined fibers to be broken. Thus, the number of fibers which contribute to toughening by bridging or pull-out mechanism decrease in randomly oriented fiber reinforced composite. Fibers in Region 2 can be pulled-out before their fracture, but their pull-out length l expressed in Eq. (18) are much shorter than their insert length l_i . In Fig. 3, ratio of pull-out length/radius (l_i/r) are plotted as a function of misorientation angle θ in the case of $\sigma_F/\tau_i = 30$.

Fig. 3. Pull-out length/radius ratio of a fiber in the case of $\sigma_F/\tau_i = 30$ as a function of misorientation angle.

σ_F : tensile strength of a fiber, τ_i : interfacial shear stress.

Solid lines are drawn by Eq. (18).

$$l/r = l_i/2r - 1/4 \tan \theta - \{ (l_i/r + 1/2 \tan \theta)^2 - \sigma_F/\tau_i \tan \theta \}^{1/2}/2 \quad (18)$$

Figure 3 also indicates that the larger the misorientation angle of a fiber is, the much harder the pull-out of the fiber. If pull-out length l of a fiber in Region 2 is neglected, calculated ratio of {area in Region 1}/{area in (Region 1+2+3)} corresponds to estimation of the effectiveness of randomly oriented fibers for toughening by bridging or pull-out mechanism.

when $\theta < \sigma_F/\tau_i < 1$

$$\begin{aligned} \text{Ratio} &= (4\tau_i/\pi\sigma_F) \left\{ \pi\sigma_F/8\tau_i \right. \\ &\quad \left. + \int_{45^\circ}^{90^\circ} (\sigma_F/2\tau_i \tan \theta) d\theta \right\} \\ &= 0.5 + (\ln 2)/\pi = 0.72 \end{aligned} \quad (19)$$

when $1 < \sigma_F/\tau_i$

$$\begin{aligned} \text{Ratio} &= (4\tau_i/\pi\sigma_F) \left[(\sigma_F/2\tau_i) \tan^{-1} (\tau_i/\sigma_F) \right. \\ &\quad \left. + \int_{\tan^{-1}(\tau_i/\sigma_F)}^{\tan^{-1}\{(\sigma_F/\tau_i+1)^2\tau_i/4\sigma_F\}} \{ (\sigma_F/\tau_i \tan \theta)^{1/2} - 1/2 \tan \theta \} d\theta \right. \\ &\quad \left. + \int_{\tan^{-1}\{(\sigma_F/\tau_i+1)^2\tau_i/4\sigma_F\}}^{90^\circ} \sigma_F/2\tau_i \tan \theta d\theta \right] \\ &= (2/\pi) \tan^{-1} (1/X) \\ &\quad + \{ (2/X)^{1/2}/\pi \} \ln \{ (X+1)^3 \\ &\quad + (X-1)^2(2X)^{1/2} \} / \{ (X+1)^3 \\ &\quad - (X-1)^2(2X)^{1/2} \} \\ &\quad - (2/\pi) (2/X)^{1/2} [\tan^{-1} \{ 2(X+1) \\ &\quad \times (2X)^{1/2}/(X-1)^2 \} + \tan^{-1} \{ (2X)^{1/2}/ \\ &\quad (X-1) \}] \\ &\quad - (2/\pi X) \ln [(X+1)^2 \\ &\quad \times (X^2+1)^{1/2} / \{ 16X^2 + (X+1)^4 \}^{1/2}] \\ &\quad - (2/\pi) \ln [(X+1)^2 / \{ 16X^2 \\ &\quad + (X+1)^4 \}^{1/2}] \end{aligned} \quad (20)$$

$$X = \sigma_F/\tau_i$$

Effectiveness of fibers in bridging and pull-out mechanism is shown in Fig. 4 according to the Eqs. (19) and (20). Figure 4 indicates that the larger the σ_F/τ_i value, the smaller the effectiveness of fibers on bridging and pull-out. Since large value of σ_F/τ_i me-

Fig. 4. Effective pull-out ratio of a composite reinforced by random oriented fibers as a function of σ_F/τ_i .

σ_F : tensile strength of a fiber, τ_i : interfacial shear stress.

A solid line is drawn by Eqs. (19) and (20).

ans easiness of fiber pull-out, behavior of fiber pulling-out in a composite in which fibers can be pulled-out easily are sensitively affected by orientation of fibers. In the case of $\sigma_F/\tau_i=30$ and random orientation of fibers, effective pull-out ratio is obtained to be 0.38 from Eq. (20). The volume fraction of fibers will be multiplied by effective pull-out ratio to offset random orientation of fibers.

3. Experimental procedure

3.1 Fabrication of materials

SiC-whiskers (Toka whisker TWS400; average diameter: $1.1\ \mu\text{m}$, average length: $45\ \mu\text{m}$, β -SiC) supplied by Tokai Carbon Co., Ltd. was used in this study. For well alignment of whiskers and easy processing, extrusion process was adopted. It is important to adjust the viscosity of matrix precursor. As a starting material of matrix, we used sol-gel method from $\text{Al}(\text{OC}_3\text{H}_7)_3$ supplied by Mitsubishi Materials Co., Ltd. with extrusion process, because it is easy to control the viscosity of $\text{Al}(\text{OH})_3$ gel. After extrusion, $\text{Al}(\text{OH})_3$ dry gel was heat-treated in vacuum to make Al_2O_3 matrix. The operations of sol-gel method are shown in detail as follows.

(1) $\text{Al}(\text{OC}_3\text{H}_7)_3$ was put into hot water above 80°C and they were stirred for 30 min. The amount of water was enough for the reaction with $\text{Al}(\text{OC}_3\text{H}_7)_3$.

(2) Two weight percent of α - Al_2O_3 powder corresponding to Al_2O_3 matrix were added to a $\text{Al}(\text{OH})_3$ sol as nuclei of Al_2O_3 grain growth. α - Al_2O_3 powder used in this process was manufactured by Showa Denko Co., Ltd. (AL16059-1).

(3) pH of the solution with $\text{Al}(\text{OH})_3$ sol was arranged to about 3 by HCl.

(4) The solution was stirred keeping its temperature above 80°C for 3–4 h and then it was peptized and condensed.

SiC-whiskers dispersed in a water were added to the solution in the process (3). After the process (4), condensed gel was extruded into rods (about 1 mm in diameter and 50 mm in length) by extrusion equipment shown in Fig. 5. They were dried at room temperature for about 24 h in air. After that, the rods were heat-treated at 1000°C for 30 min in a vacuum ($<10^{-1}$ Torr). In this heat treatment, $\text{Al}(\text{OH})_3$ dry gel changed to α - Al_2O_3 by dehydration.

A billet of UD-comp was fabricated by hot-pressing of bundled heat-treated rods. The hot-pressing was carried out in a condition of 1750°C under 33 MPa during 1 h in an Ar gas atmosphere.

A billet of 2DR-comp was also fabricated by hot-pressing of heat-treated gel without extrusion. The hot-pressing condition was the same as that of UD-comp. To check the mechanical properties of composites would change by molding or not, then, monolithic Al_2O_3 specimens were also fabricated by hot-pressing of 2 kinds of heat-treated gel without SiC-whiskers. One heat-treated gel is fabricated by

Fig. 5. A. schematic illustration of extruder.

extrusion and the other one is fabricated without extrusion. The hot-pressing of monolithic Al_2O_3 was carried out at 1500°C under 33 MPa during 1 h in an Ar gas atmosphere. All specimens fabricated in this study showed high apparent density (more than 99% of theoretical density).

3.2 Estimations of mechanical properties

Bending strength of materials was measured by 4-point bending test (inner span: 10 mm, outer span: 30 mm) based on Japanese Industrial Standard JIS R 1601. All fracture tests were carried out by a testing machine made by Shimadzu Co., Ltd. (DSS-25T). Specimens for strength test were polished by #600 diamond wheel in the longitudinal direction on their tensile surface. All specimens were designed for their tensile surface to be perpendicular to the direction of hot-pressing.

Fracture toughness K_{IC} was estimated by 3-point bending test (span : 30 mm) of chevron notched beam specimen. Crosshead speed of the testing machine was 0.005 mm/min. All specimens were designed for their notches to be parallel to the direction of hot-pressing. Fracture toughness K_{IC} was calculated based on straight through crack assumption¹⁴ using Wakai's equation¹⁵ constructed for a beam with straight through crack. This estimation was done only for the specimens which realized "stable" fracture. The details of this analysis were reported in Ref. 1).

The values of effective fracture energy γ_{eff} were determined from the work done by testing machine and from projected area of fractured surfaces using the following equation:¹⁶⁾

$$\gamma_{\text{eff}} = U/2A \quad (21)$$

γ_{eff} : effective fracture energy, U : work done by testing machine, A : projected area of fractured surfaces. This estimation was carried out only for the specimens whose main cracks propagated quasi-statically until their final fracture.

Fractured surfaces and the paths of crack propagation induced by Vickers indenter were observed by scanning electron microscope (SEM) to investigate toughening behavior of composites.

4. Results and discussion

4.1 Texture of composites

Polished surfaces of composites were observed by optical microscope as shown in Fig. 6. In the case of UD-comp, almost all whiskers aligned parallel to the direction of extrusion. On the other hand, whiskers in 2DR-comp were oriented at random in planes which are transverse to the hot-pressed direction in 2DR-comp.

4.2 Fracture toughness K_{IC} and effective fracture energy γ_{eff}

Obtained fracture toughness K_{IC} and effective fracture energy γ_{eff} are shown in Figs. 7 and 8, respectively. In the case of monolithic Al_2O_3 , there were no changes in both K_{IC} ($3.1 \text{ MPa} \cdot \text{m}^{1/2}$) and γ_{eff} ($16\text{--}22 \text{ J/m}^2$) by different processes. In the case of UD-

Fig. 6. Surfaces of UD-comp and 2DR-comp observed by optical microscope.

Fig. 7. Fracture toughness K_{IC} of monolithic Al_2O_3 , UD-comp and 2DR-comp.

UD-comp: uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 . 2DR-comp: 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 .

Fig. 8. Effective fracture energy γ_{eff} of monolithic Al_2O_3 , UD-comp and 2DR-comp.

UD-comp: uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 . 2DR-comp: 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 .

comp, values of K_{IC} and γ_{eff} were obtained as $7.1 \text{ MPa} \cdot \text{m}^{1/2}$ and 101 J/m^2 , respectively, while those in 2DR-comp were $5.6 \text{ MPa} \cdot \text{m}^{1/2}$ and 52 J/m^2 , respectively. It was reported that in bridging¹⁾ and pull-out²⁾ mechanism both square of increment of fracture toughness (ΔK_{IC})² and increment of effective fracture energy $\Delta \gamma_{eff}$ of whisker-reinforced composites have linear relationships with volume fraction of whiskers. On the other hand, the effective pull-out ratio was calculated from the theory given in Section 2.4 and the value of 0.38 was obtained for SiC-whisker reinforced Al_2O_3 with rough approximation. The value of 0.38 means that 38% of whiskers in random orientation contributes for toughening by bridging and by pulling-out. To compare with the effective pull-out ratio of 0.38, we calculated the following toughening ratios.

$$\frac{\{K_{IC}(2\text{DR-comp}) - K_{IC}(Al_2O_3)\}^2}{\{K_{IC}(\text{UD-comp}) - K_{IC}(Al_2O_3)\}^2} = 0.38$$

$$\frac{\{\gamma_{eff}(2\text{DR-comp}) - \gamma_{eff}(Al_2O_3)\}}{\{\gamma_{eff}(\text{UD-comp}) - \gamma_{eff}(Al_2O_3)\}} = 0.35$$

It is found that both toughening ratios were close to the calculated effective pull-out ratio. This result indicates that almost all whiskers should be broken with bending stress and that whiskers with some misorientation angle can not devote themselves to toughening of composites. If it is assumed that a main crack in a composite deflects by internal stress such as residual thermal stress, randomly oriented whiskers seems to be more effective for toughening than uni-directionally oriented ones. However, the fact that UD-comp showed higher toughness than 2DR-comp suggests that toughening of whisker-reinforced composites is actually due to bridging or pull-out mechanism. In SiC-whisker/ Al_2O_3 composites, making interface bonding adequately weak seems to bring high fracture toughness by whisker bridging and pull-out. Furthermore, being suggested from Figs. 3 and 4, it is concluded that orientation of whiskers must be also controlled at the same time.

4.3 Observation of fractured surfaces

Fractured surfaces of monolithic Al_2O_3 , UD-comp and 2DR-comp were observed by SEM as shown in Fig. 9. In addition, a crack on polished surface of 2DR-comp was observed by optical microscope as shown in Fig. 10. In the case of monolithic Al_2O_3 , there are both intergranular fracture and transgranular fracture on their fractured surfaces regardless of molding methods. In the case of composites, some pulled-out whiskers can be observed and almost all pulled-out whiskers are vertical to the fractured surfaces which showed transgranular fracture. In addition, there were more pulled-out whiskers on the fractured surface of UD-comp than that of 2DR-comp. However, pulled-out length of whiskers (less than $5\text{--}6\text{ }\mu\text{m}$) is very short compared with half length of whiskers (about $23\text{ }\mu\text{m}$). This short pull-out length of whiskers seems to be attributed to small value of σ_F/τ_i (roughly estimated as 30), which suggests the difficulty of pulling-out of whiskers. In Fig. 10, pulled-out whiskers and inclined broken whiskers after some pulling-out can be observed.

Fig. 9. Fractured surfaces of monolithic Al_2O_3 , UD-comp and 2DR-comp observed by scanning electron microscope. UD-comp: uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 . 2DR-comp: 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 .

Fig. 10. Crack propagation induced by Vickers indenter on the surface of 2DR-comp observed by scanning electron microscope. 2DR-comp: 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 .

Fig. 11. Four-point bending strength of monolithic Al_2O_3 , UD-comp and 2DR-comp.

UD-comp: uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 . 2DR-comp: 2-dimensional randomly oriented 20 vol%-SiC-whisker/ Al_2O_3 .

4.4 Bending strength of composites

Bending strength of monolithic Al_2O_3 , UD-comp and 2DR-comp were shown in Fig. 11. In the case of monolithic Al_2O_3 , there was no change in bending strength (340–350 MPa) by molding. 2DR-comp showed higher bending strength (460 MPa) than monolithic Al_2O_3 . On the contrary, no increase of bending strength was obtained in UD-comp (330 MPa).

According to linear fracture mechanics, high fracture toughness leads to high strength assuming that there is no change in flaw size. On the other hand, tensile residual thermal stress in matrices of SiC-whisker/ Al_2O_3 composites¹³⁾ has a possibility to decrease strength of composites. This residual thermal stress is originated from thermal expansion mismatch between SiC-whiskers and Al_2O_3 matrix, and exists around whiskers. As a result, both UD-comp and 2DR-comp show higher fracture toughness than monolithic Al_2O_3 , while increase of strength was realized only in 2DR-comp. This difference might be due to aligned residual thermal stress in a matrix of UD-comp caused by uni-directional orientation of whiskers. However, for discussion about their strengths in detail, *R*-curve behaviors of UD-comp and 2DR-comp must be investigated. This is because the slope of rising *R*-curve is closely related with fracture strength of materials.

5. Conclusions

(1) From fiber pull-out model proposed here, it could be expected that whiskers whose longitude inclined against the direction of external stress were easy to broken by bending stress and that random orientation of whiskers decreased the number of whiskers which contributed to toughening of composites by bridging and pull-out.

(2) Both uni-directionally oriented 20 vol%-SiC-whisker/ Al_2O_3 (UD-comp) and 2-dimensionally oriented 20 vol%-SiC-whisker/ Al_2O_3 (2DR-comp) showed higher fracture toughness K_{IC} as 7.1 MPa·

$\text{m}^{1/2}$ and $5.6 \text{ MPa} \cdot \text{m}^{1/2}$, respectively and effective fracture energy γ_{eff} as 101 J/m^2 and 52 J/m^2 , respectively than monolithic Al_2O_3 ($3.1 \text{ MPa} \cdot \text{m}^{1/2}$ and $16\text{--}22 \text{ J/m}^2$).

(3) Differences between UD-comp and 2DR-comp in K_{IC} and γ_{eff} corresponded to the result of model calculation as the ratio of tensile strength of a whisker and interfacial shear stress to be 30.

(4) Almost all whiskers pulled-out from fractured surface seemed to be vertical to fractured surface and their pull-out length was very short compared with the length of whiskers.

(5) Increase of bending strength was realized in 2DR-comp, while bending strength of UD-comp did not change.

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References

- 1) P. F. Becher, C. H. Hsueh, P. Angelini and T. N. Tiegs, *J. Am. Ceram. Soc.*, **71**, 1050–61 (1988).
- 2) E. Yasuda, T. Akatsu and Y. Tanabe, *Seramikkusu Ronbunshi (J. Ceram. Soc. Japan)*, **99**, 52–58 (1991).
- 3) T. Akatsu, Y. Tanabe, S. Matsuura, H. Ishii, M. Munakata, M. Yamada and E. Yasuda, *Seramikkusu Ronbunshi (J. Ceram. Soc. Japan)*, **99**, 431–33 (1991).
- 4) M. C. Shaw and K. T. Faber, *Ceramic Microstructures '86*, Vol. 21, Plenum Press (1987) pp. 929–38.
- 5) P. F. Becher and G. C. Wei, *J. Am. Ceram. Soc.*, **67**, C267–69 (1984).
- 6) N. Claussen and M. V. Swain, *Materials Forum*, **11**, 194–201 (1988).
- 7) Y. Goto, T. Yonezawa and A. Tsuge, Extended Abstract of the 8th Annual Meeting on Science of the High Temperature and Engineering Ceramics, The Ceram. Soc. Japan, (1988) pp. 95–99.
- 8) S. Kobayashi, T. Kandori and S. Wada, *Yogyo-Kyokai-Shi*, **94**, 903–05 (1986).
- 9) T. Matsui, O. Komura and M. Miyake, *Seramikkusu Ronbunshi (J. Ceram. Soc. Japan)*, **99**, 1103–09 (1991).
- 10) R. W. Davidge, "Mechanical Behaviour of Ceramics", Cambridge Univ. Press (1979) p. 28.
- 11) S. C. Samanta and S. Musikant, *Ceram. Eng. Sci. Proc.*, Vol. 6 (1985) pp. 663–72.
- 12) J. J. Petrovic, J. V. Milewski, D. L. Rohr and F. D. Gac, *J. Mater. Sci.*, **20**, 1167–77 (1985).
- 13) Z. Li and R. C. Bradt, *J. Am. Ceram. Soc.*, **72**, 70–77 (1989).
- 14) D. Munz, R. T. Bubsey and J. L. Shannon, Jr., *J. Am. Ceram. Soc.*, **63**, 300–05 (1980).
- 15) F. Wakai, S. Sakaguchi and H. Matsuno, *Yogyo-Kyokai-Shi*, **93**, 81–82 (1985).
- 16) J. Nakayama, *J. Am. Ceram. Soc.*, **48**, 583–87 (1965).