Improvement of Mechanical Properties and Reliability of Structural Ceramics by Whisker Reinforcement

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Abstract

Silicon carbide whisker-reinforced Si_3N_4 matrix and Al_2O_3 matrix composites were fabricated. Homogeneous dispersion of the whisker in the starting powder mixture dominates both strength level and its reliability. Improvements both in strength and fracture toughness have been observed. Alumina matrix composite was applied as a cutting tool ,which exhibited good performances.

1. Introduction

Improvements in both toughness and reliability are indispensable to the application of ceramics as a structural material. For this purpose, fiber-reinforcement, especially whisker-reinforcement attracts much attention today.

Whiskers in the FRC(Fiber-reinforced Ceramics) make crack sensitivity lower and then the composite tend to be tolerable against flaws on its surface or in the body. Whisker-reinforcement has also a prominent effect for improving reliability of the composite. In this paper, influences of whisker-reinforcement on the mechanical properties of the Si_3N_4 and Al_2O_3 matrix-FRC and application as a cutting tool are described.

2. Experimental

On the fabrication of whisker-reinforced composite homogeneous dispersion of whiskers in the composite body is essential. If the mixing of the whisker and the matrix powder is not enough, it is often observed that fracture begins from a whisker entangle. Unless these defects are removed from the starting powder mixture, whisker-reinforcement cannot be expected; on the contrary, only strength degradation will be observed.

In our experiment silicon carbide whisker was first dispersed in water by a mechanical stirring and then the suspension was filtered through a mesh having ca. 500 - 60 micrometer opening [1]. By this filtration process almost all whisker lumps can be removed from the suspension.

The slurry of matrix powder with 10 - 40 wt% silicon carbide whisker , doped with some sintering additives such as Y_2O_3 for Si_3N_4 or MgO for Al_2O_3, was dried and hot-pressed.

3. SiC(w)-Si_3N_4

Figure 1 shows temperature dependence of the strength of monolithic Si_3N_4 and 10, 20 and 30 wt % SiC(w)-Si_3N_4 FRC [2]. Significant strength degradation at the temperature over 1000°C, observed for monolithic Si_3N_4, is known to be caused by grain boundary softening or sliding of grains at the grain boundary containing silicate glass.

Although ambient temperature strengths of the FRC is a little bit lower than that of monolithic Si_3N_4, FRC tends to retain its ambient strength at high temperature. At 1000° to 1300° C, the strength become higher as increasing the whisker content, exceeding over that of monolithic Si_3N_4. It is considered that the applied load has been transferred to the whisker under the condition that elastic modulus of the fiber exceeds over that of the matrix. Such condition can be realized only when the matrix becomes soft at high temperature.

To assure the whisker-reinforcement effect, the composites with various amounts of silicon carbide particles have been fabricated, but they didn't show such strength improvement at high temperatures.

Figure 2 shows the variation of fracture toughness with the whisker content [3]. Fracture toughness was measured by indentation microfracture method. Toughness is improved by the whisker incorporation. From observation of crack propagation figures in the composite, it is suggested that frequent deflection of crack during propagation due to , probably, preferential debonding at whisker/matrix interface contributes to the toughening.

Whisker-reinforcement is also effective to make a ceramic "crack sensitivity" lower [4]. For example, when the whisker content is over 40 %, it is rather hard to fabricate a full-dense composite, resulting the residual porosity over 10 %. For monolithic ceramic such higher amount of pore will cause fatal strength drop. Whisker-reinforced Si_3N_4 with over 10 % pore, on the other hand, maintains a strength level as the same as that of the full-dense composite.

Figure 3 shows the relations of strength and Weibull's modulus to filter openings [4,5]. The finer the size of filter opening becomes, the higher the strength does. Weibull's modulus becomes significantly higher as the filter opening becomes finer. The composite with the whisker refined through 105 μm filter shows the modulus of m=23, which is extremely larger than that of monolithic Si_3N_4. High reliability for the strengths of the whisker-reinforced composite can be attributed to lowered sensitivity to surface crack or inner defects of the material.

One of other influences of whisker-reinforcement on the material properties is an improvement in thermal-shock resistance [6]. By the quench with the temperature difference of 300°, monolithic Si_3N_4 exhibits a great drop in its strength, from 900 MPa to 150 MPa. On the other hand, the composite with 20 % whisker shows only slight strength degradation, from 700 MPa to 500 MPa, against the same temperature difference. Improved toughness will be effective for hindering crack extension during the thermal shock. Higher thermal conductivity of silicon carbide whisker should also be considered in explaining improved thermal-shock resistance, as the thermal stress due to the temperature difference between the surface and inner part of the sample will be surpressed by good conductivity.

4. $SiC(w)-Al_2O_3$ [7)]

The fabrication process for $SiC(w)-Al_2O_3$ composite is the same as that for Si_3N_4 matrix composite principally. As described above, dispersion method for untangling whisker lumps is a determinant for strength and its reliability.

For comparison, three kinds of alumina matrix FRC have been fabricated. One with as-received whisker, one with the whisker which was untangled by ultrasonic for 10 minutes under a mechanical stirring, and one with the whisker refined through a filter with 50 μm opening after the ultrasonic treatment.

Figure 4 shows Weibull's plot of the strength values for FRC with as-received, ultrasonic-treated, and filtered whisker of 30 %. The average strength, ca. 470 MPa, and Weibull modulus of the FRC with as-received whisker is lower than even that for monolithic alumina. On the other hand, the whisker treatment improves both strength level and reliability. The composite with filtered-whisker has an average strength of 1 GPa, which would be one of the highest values reported for alumina-based ceramics.

Fracture toughness is also improved as shown in Fig. 5. Toughness increases as increasing with the whisker content. Toughening mechanism is assumed to be crack deflection and/or crack bridging of whisker in the crack wake region. Fiber pull-out has not been observed so much on the fracture surface.

This alumina matrix FRC was applied to a cutting tool. Important characteristic for cutting tool material is high wear resistance and mechanical-shock resistance. Improved strength and crack resistance by whisker incorporatinon seem to make the composite a promising candidate for the application.

Figure 6 shows wear curves on continuous cutting of heat-resistant alloy Inconel 718 for SiC(w)-Al_2O_3, Si_3N_4 and super-hard alloy K10. Alumina FRC exhibits a superior wear-resistance than other materials.

Figure 7 shows spalling-resistance on the intermittent cutting of cast iron for alumina-SiC(w), Si_3N_4, and alumina-TiC. The whisker composite has a longer life for repeated mechanical shock than the particulate reinforced composite.

Figure 8 shows cutting performance for the intermittent milling of cast iron for SiC(w)-Al_2O_3, TiC-Al_2O_3 and Si_3N_4. Under such severe cutting condition with complex stress-state at the tip, whisker-reinforced alumina shows excellent behavior than other materials.

5. Conclusion

SiC whisker reinforced Si_3N_4 and Al_2O_3 were fabricated. By the reinforcement, various mechanical properties were improved, such as bending strength, especially high temperature strength for SiC(w)-Si_3N_4 composite, hardness, or fracture toughness.

It was found that reinforcement of the whisker produced composites with high reliability. By field tests as a cutting tool, SiC(w)-Al_2O_3 composite exhibited to be a high wear-resistant and shock-tolerable material in comparios with conventional ceramic cutting tool.

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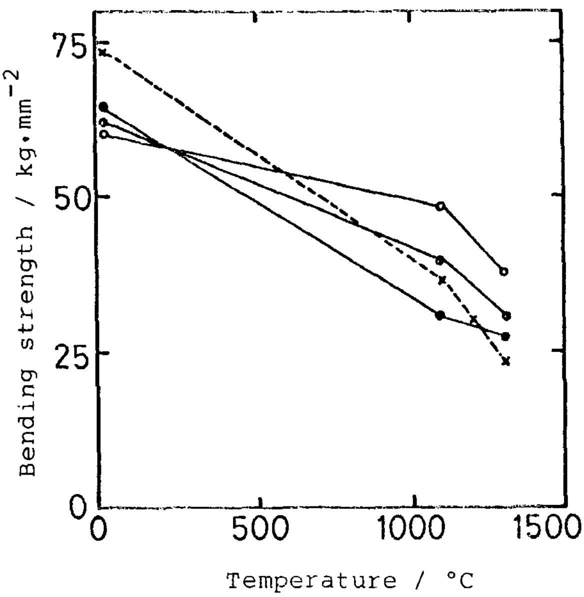

Fig. 1 Temperature dependence of the strength of monolithic Si_3N_4 (×) and 10 (●), 20 (◑) and 30 (○) wt% SiC whisker-Si_3N_4 FRC.

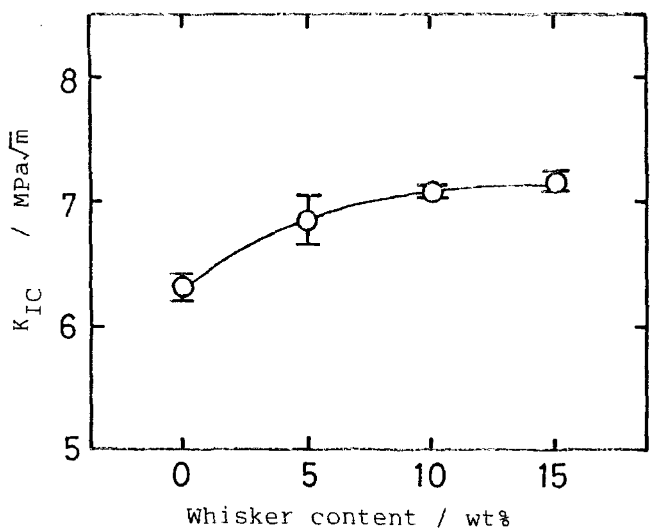

Fig. 2 variation of K_{IC} with the whisker content.

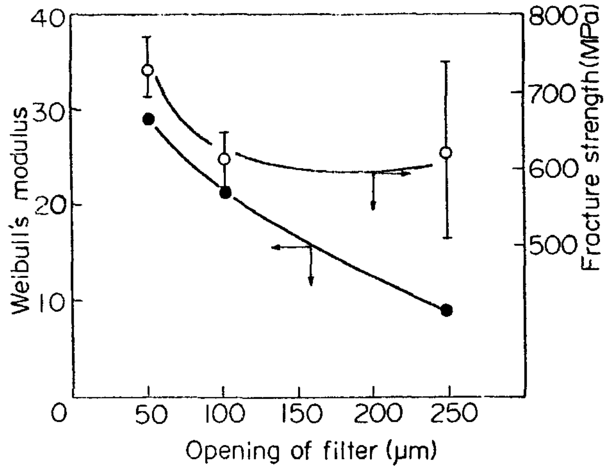

Fig. 3 Relation of strength and Weibull's modulus to filter opening.

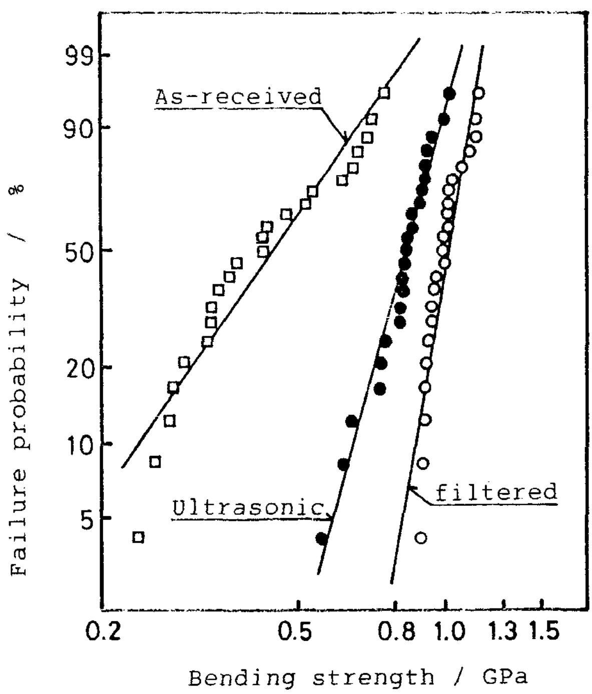

Fig. 4 Weibull's plots of bending strength for 30 wt% SiC(w)-Al_2O_3 composites with as-received, ultrasonic-treated and filered whisker.

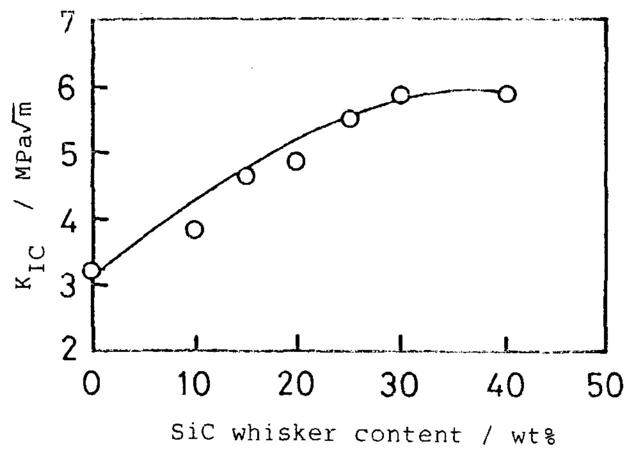

Fig. 5 Effect of SiC whisker content on fracture toughness of Al_2O_3-SiC(w) composite.

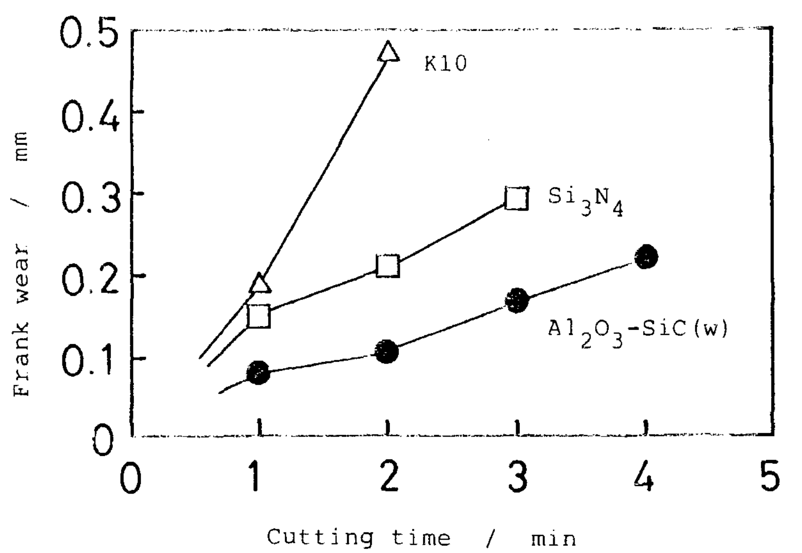

Fig.6 Wear curves on cutting of heat-resistant alloy for Al_2O_3-SiC(w), Si_3N_4 and hard metal.

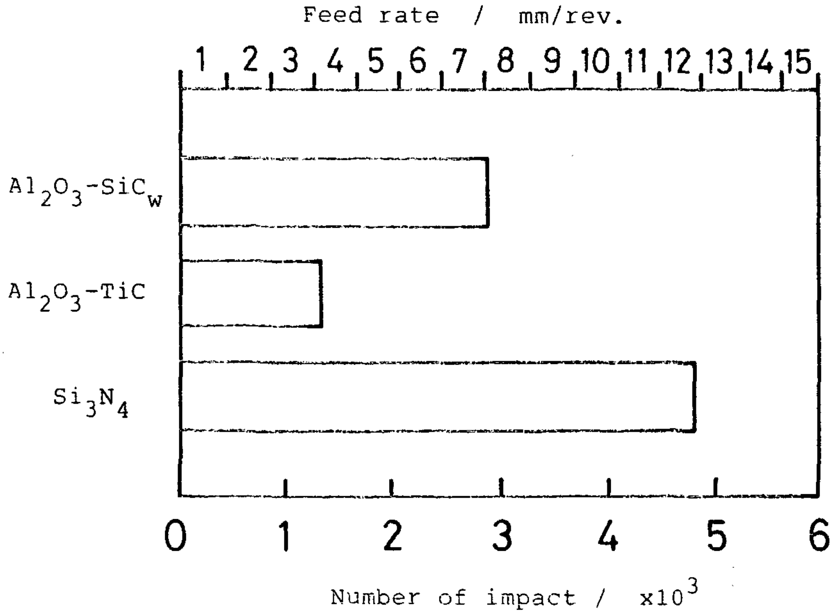

Fig. 7 Number of impact up to failure on intermittent cutting of cast iron for Al_2O_3-TiC , Al_2O_3-SiC(w) and Si_3N_4.

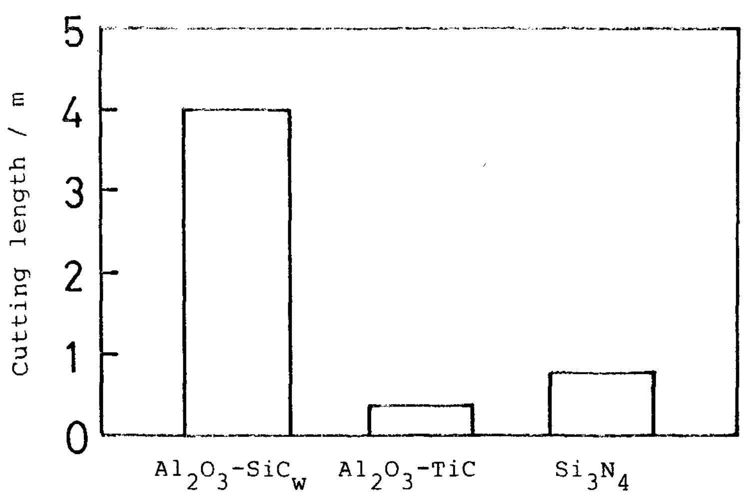

Fig. 8 Cutting length up to failure in milling for Al_2O_3-SiC(w), Al_2O_3-TiC and Si_3N_4.