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Wear Behaviors of Unidirectionally Oriented Si_3N_{4w}/Si_3N_4 Composites

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Wear behaviors of unidirectionally oriented Si_3N_{4w}/Si_3N_4 composites, sintered at different temperatures with different alignments of whiskers, have been studied in parallel and perpendicular sliding directions with respect to the orientation of the whiskers by using a ball-on-disk reciprocating sliding apparatus. The results show that wear rate in parallel direction is much greater than that in perpendicular direction. With decreasing alignment of the whiskers, the wear rate decreases in parallel sliding direction and increases in perpendicular direction. With increasing sintering temperature, the wear rate increases obviously in both parallel and perpendicular directions.

Key words : Si_3N_4, Whisker, Wear, Sliding direction

I. Introduction

Numerous studies on wear of SiC-whiskers reinforced Si_3N_4 composites have showed that the composites presented better wear properties compared with monolithic Si_3N_4 in both dry and lubricated conditions. The lower wear rate was generally related to improved fracture toughness or pull-out of the whiskers.[1-4] Studies on wear of β-Si_3N_4-whisker reinforced Si_3N_4 composites have, however, seldom been reported in literatures. Since β-Si_3N_4-whiskers develop an inherent lattice interface with the matrix and grow rapidly during sintering, they might behave in a different way from the SiC whiskers in wear.

It is well known that the advantage of β-Si_3N_4 whiskers over the seed particles in reinforcing Si_3N_4 ceramics is its larger aspect ratio. During a sintering process, these whiskers grow rapidly with an increase in sintering temperature and time. A question should then be answered clearly that what effects the growth of the whiskers have on the wear behaviors.

Another problem may be that in practical production, whisker-alignment of these unidirectionally oriented composites often varies due to using different alignment methods such as injection molding, tape-casting and extrusion,[5-7] or by adjusting sintering conditions for different applications. That has a great effect on mechanical properties[7] and should, therefore, have on the wear behaviors.

In this study wear behaviors of unidirectionally-oriented Si_3N_4 whisker reinforced Si_3N_4 composites were studied in different sliding directions with respect to the orientation of the whiskers by using a ball-on-disk reciprocating sliding apparatus. Where the composites were sintered at different temperatures and the whiskers were controlled to have a unidirectional orientation with different alignments. The aim of this study is to investigate the effect of alignments of unidirectionally-oriented whiskers and sintering temperature on friction and wear.

II. Experimental Procedures

The powder of α-Si_3N_4 (SN-E10, Ube Co., Japan.) and 3 wt% β-Si_3N_4 whisker (SN-WB, 0.1~1.5 μm in diameter, 10~50 μm in length and aspect ratio of 20~100, Ube Co., Japan.) were mixed with additives of 2 wt% Al_2O_3 (AKP-30, Sumitomo Chem. Co., Japan.) and 6 wt% Y_2O_3 (Fine, H.C. Stark Co., Germany). The slurry was formed by tape-casting, and the green sheets were, then, stacked and sintered by GPS at 1875°C and 2000°C respectively for 4 hours in 2.4 MPa of N_2 gas. By adjusting the casting rate and sintering temperature, three types of samples were prepared, as shown in Table 1.

Wear tests were carried out on a reciprocating ball-on-disk tester (Carmeron Plint Tribometer, TE77) at room temperature in air. The composites samples were used as the lower disks with the dimension of $20\times12\times3$ mm^3. The upper ball was a monolithic Si_3N_4 ceramic ball (NBD 100, Φ12.7 mm, Hv=2000 Kg/mm^2, K_{IC}=5.4 MPam$^{1/2}$). The testing parameters were set at a normal load from 5 N to 20 N with constant frequency of 5 Hz (sliding speed was about 0.07 m/s) and sliding time of 60 min (sliding distance was about 247 m). A stroke length of 6.85 mm was set in all the tests. The sliding directions were respectively parallel and perpendicular with respect to the whisker orientation.

The cross-sectional area of wear tracks of the composites was measured by a profilometer (Rank Taylor Hobson Co). Wear rate, defined as volume loss divided by normal load and sliding distance, was used as measure of wear. Two to five tests were carried out for each wear condition.

Table 1. Test Samples and Their Properties

Sample	Sintering temperature (°C)	Alignment of unidirectional whisker	Relative density (%)	Hv (Kg/mm^2)	K_{IC} (MPam$^{1/2}$)	
					//	⊥
A	1875	Well aligned	97.9	1473	5.46	7.98
B	1875	Poorly aligned	97.2	1385	5.08	7.11
C	2000	Well aligned	98.2	1225	3.92	7.79

// and ⊥: in parallel and perpendicular directions with respect to orientation of the whisker grains.

III. Results

The wear rates of all the samples as a function of load and sliding directions are shown in Fig. 1. For sample A, the wear rate in parallel direction is much higher than that in perpendicular direction and it increases obviously with increasing load. The wear rate in perpendicular direction is very low at load of 5 N, and increases obviously as the load rises to 10 N and keeps a steady state as the load rises to 20 N. Sample B presents a similar wear behavior to A, except for that the wear rate is lower in parallel direction and a little higher in perpendicular direction. The wear rate of sample C is obviously higher than that of sample A in both parallel and perpendicular directions.

Figs. 2~4 show SEM micrographs of worn surfaces of the samples at load of 20 N. The worn surface of sample A in perpendicular sliding direction is shown in Fig. 2(a) with the evidences of pull-out and fracture of the whiskers as well as overall microfracture of the matrix grains (Fig. 2(b)). It suggests that the wear mechanism is microfracture including pull-out and fracture of the whiskers. An overall rough morphology can be seen on the worn surface in parallel sliding direction (Fig. 2(c)). This indicates that much more severe wear occurred in parallel sliding direction compared with that in perpendicular direction. For sample B, worn surface in perpendicular direction presents more evidences of pull-out and fracture of the surface whiskers and shows more severe wear (Fig. 3(a)) compared with that for sample A, with a quite random distribution of whiskers on the bottom. In parallel sliding direction (Fig. 3(b)), the worn surface is rough but not so severe as that of sample A. As for sample C, the worn surfaces in the two sliding directions present much severer evidences of pull-out and fracture of larger whiskers (Fig. 4).

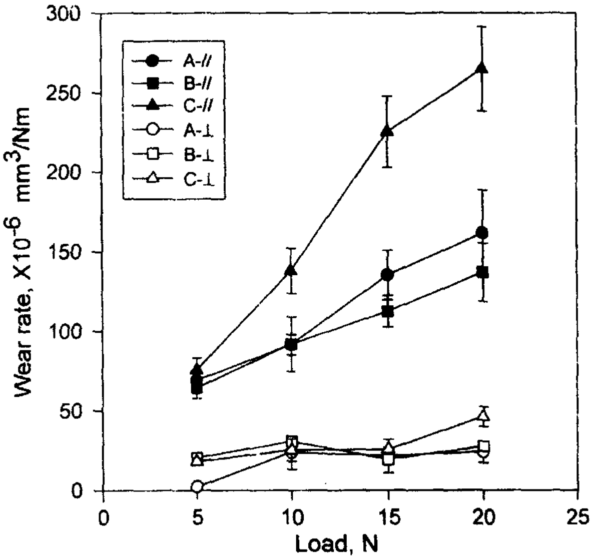


Fig. 1. Variation of wear rate with load (//-paralled direction; ⊥-perpendicular direction).

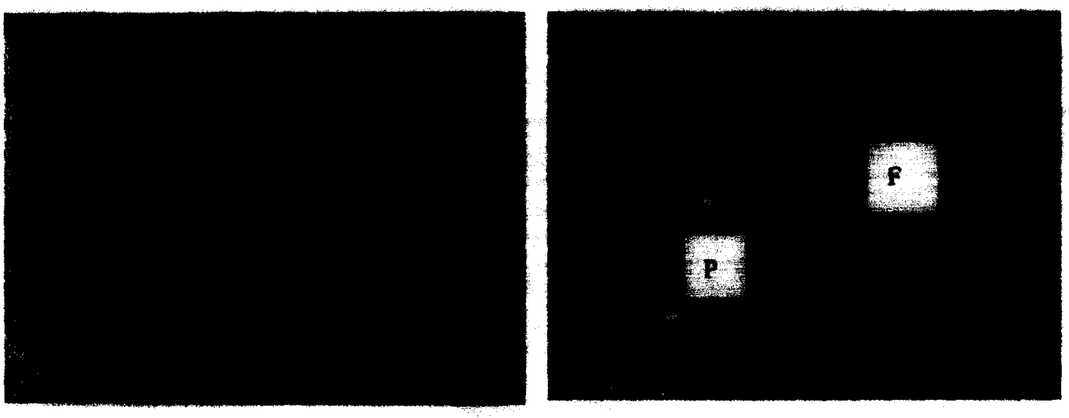
IV. Discussion

1. *Effects of alignments of the whiskers and structures on wear behaviors*

From the results it is seen that for sample A with well unidirectionally aligned whiskers, the wear rate in parallel direction is much greater than that in perpendicular direction. While for sample B with less aligned whiskers, the wear rate is lower in parallel direction and higher in perpendicular direction compared with that of sample A. It might be attributed to the different ways for the whiskers to be acted by the upper ball in different directions during sliding.

When an asperity slides on a solid surface, the stress field near the contact presents compressive and tensile states, respectively.[8] During the reciprocating sliding, the surface asperities of the upper ball slide on the worn surface of the composites, and make the surface whiskers suffer an action of compressive and then tensile stress repeatedly. This promotes debonding of the whiskers with the matrix and induces formation and propagation of cracks in the matrix. It should be pointed that the acting length for an asperity to slide on a surface whisker in each sliding pass is different with respect to the orientation of whiskers, resulting in different time for a surface whisker to be acted by an asperity during sliding.

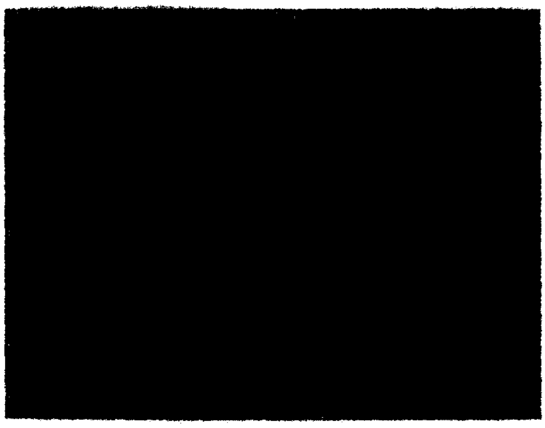
For sample A with well unidirectionally-aligned whiskers, when an asperity slides parallel to the whiskers, the acting length ($x_{//}$) is the length of the whisker; for sliding in perpendicular direction, the acting length ($x_{\perp}$) is the diameter of the grain. Since the aspect ratio of the whiskers is about 20~100 (as stated in section 2), the ratio of $x_{//}/x_{\perp}$ is about 20~100. Moreover, fracture toughness measured in parallel direction is much lower than that in



Sliding direction ↔

(a) In perpendicular sliding direction

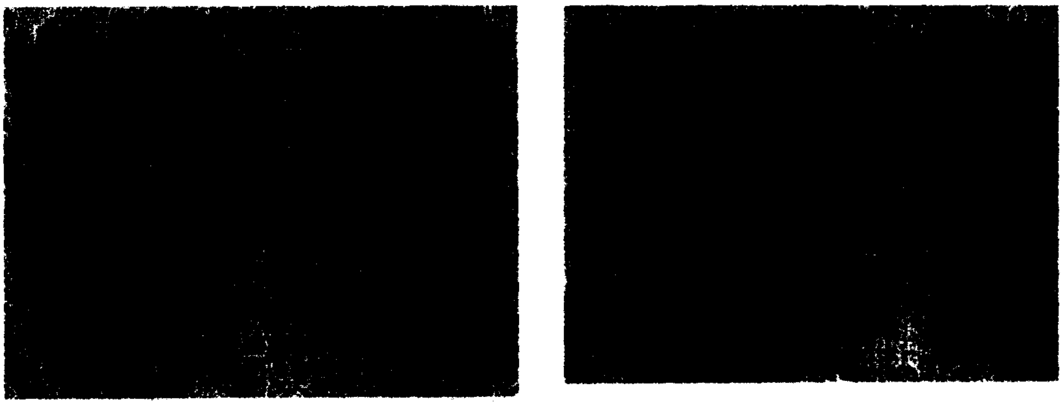
(b) High magnification of (a) (P: pull-out and F: fracture of whiskers)



Sliding direction ↔

(c) In parallel sliding direction

Fig. 2. Worn surfaces of sample A at load of 20 N in different sliding directions.



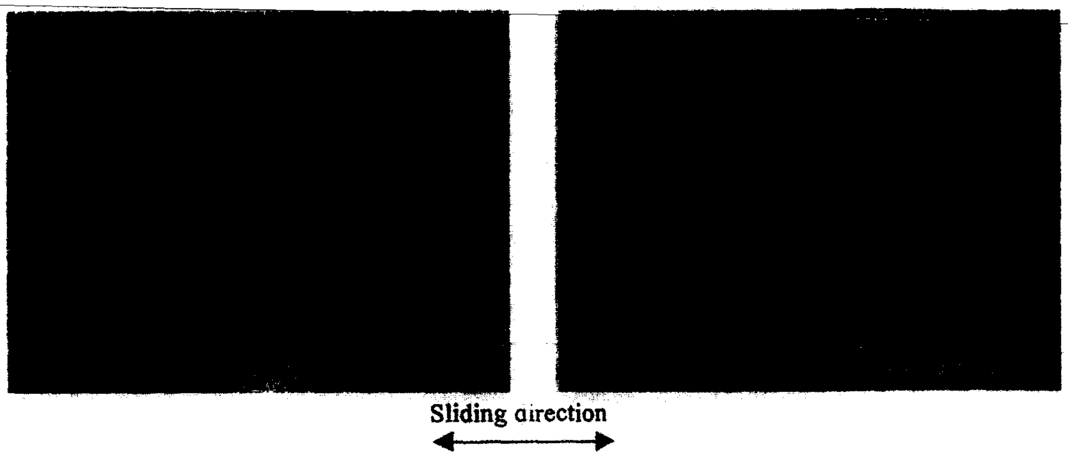
Sliding direction ↔

(a) In perpendicular sliding direction

(b) In parallel sliding direction

Fig. 3. Worn surfaces of sample B at load of 20 N in different sliding directions.

perpendicular direction, as shown in Table 1. The cracks in the surface layer are, therefore, much easier to form, propagate, and combine with each other to develop large cracks in parallel direction than those in perpendicular



(a) In perpendicular sliding direction (b) In parallel sliding direction

Fig. 4. Worn surfaces of sample C at load of 20 N in different sliding directions.

direction, leading to the different wear rates.

For sample B, the whisker orientation is not so well-aligned as sample A, and when an asperity slides on the surface whisker, the grain is generally not oriented in parallel or perpendicular direction to the sliding direction, but with a certain angle. The acting length is, therefore, smaller in parallel direction and larger in perpendicular direction compared with that of sample A, resulting in less wear rate in parallel direction and more wear rate in perpendicular.

Apart from the direct influence of the whisker alignment, as stated above, it affects density and hardness of the composites, and therefore, the wear properties. As shown in Table 1, since the alignment of sample B is not so good as A, its density is lower. This leads to a little decrease in hardness and thus, contributes the increase in wear rate to some extent.

2. *Effects of sintering temperature on wear behaviors*

From the results, it is seen that the unidirectionally oriented sample C sintered at a higher temperature of 2000°C present higher wear rates in both parallel and perpendicular directions. The difference in the wear rates between the two directions becomes larger, compared with sample A sintered at a lower temperature of 1875°C. It could be attributed to the change of microstructure and mechanical properties.

When the sintering temperature increases, the whiskers grow remarkably. Thus, the area of the interface of the whisker with the matrix increases, and a greater shear force is required for debonding of the whisker from the matrix. When elongated-grains cannot dissipate the strain energy by means of debonding, and therefore, by pull-out, deflection or bridging, the "load transfer" should be considered as the main mechanism for the elongated grains to transfer the load. Cho and Hayashi pointed in their recent study on SiC whisker/Si_3N_4 composites[9] that the enhancements of K_{IC} by the arrangement of SiC(w) cannot be explained by conventional theory, i.e., "crack deflection effect", but mainly by "load transfer effect". It is believed that for the sample C sintered at higher temperature, since the dimension and the interface area of the whiskers with the matrix increase, the tendency of "load transfer" increases, which leads relatively easy fracture of the whiskers. This easier fracture of the whiskers may be the main reason for little improvement in fracture toughness, and thus, the increase in wear rate compared with those of the samples sintered at lower temperature.

Another reason for increase in wear rate with increasing the sinter temperature may be the decrease in hardness (as shown in Table 1). Rice[10] indicated that "plastic deformation and cracking" are the two of the three basic factors affecting wear of ceramics. Decrease in hardness must result in increase in plastic deformation, and therefore, increases stress in the affected zone due to the constraint of the deformed grains by the surrounding undeformed materials This in turn can lead to cracking, especially accumulate formation of interval crack. It suggests that much grain growth due to increase of sintering temperature or holding time might not be beneficial for improvements of the mechanical properties as well as wear resistance.

V. Conclusions

1) The wear rate in parallel direction is much greater than that in perpendicular direction and increases with an increase in load; while that in perpendicular direction presents a steady state or a slow increase.

2) With decreasing alignment of the whiskers from sample A to B, wear rate decreases in parallel sliding direction and increases in perpendicular direction.

3) With increasing sintering temperature, wear rate increases in both parallel and perpendicular directions.

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