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Sliding Wear of Alumina - silicon Carbide Nanocomposites

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ABSTRACT

Alumina-based nanocomposites have improved mechanical properties such as hardness, fracture toughness and fracture strength compared to monolithic ceramics. In this study, alumina with 5 vol% of nanosized SiC was sintered by a hot pressing technique at 1600°C, 30 MPa for 1 h in an argon gas atmosphere. Microstructures and mechanical properties in alumina-SiC nanocomposite were investigated. Moreover, tribological properties in air and water were compared each other. Relationships of wear properties with mechanical properties such as hardness, strength, and fracture toughness as well as microstructures were studied. Based on experimental results it was found that nanosized SiC retarded grain growth of matrix alumina. Mechanical properties such as hardness, fracture toughness and strength were improved by the addition of nanosized SiC in alumina. Improved mechanical properties resulted in increased sliding wear resistance. Tribological behavior of nanocomposites in water seemed to be governed by abrasive wear.

Key words : Nanocomposite, Trobological behavior, Sliding wear, Microcracking

1. Introduction

Advanced ceramics such as alumina, silicon nitride, and zirconia have been utilized in the various high technologies due to their excellent mechanical properties. Among the advanced ceramics alumina has excellent properties such as high thermal resistance, wear resistance, and chemical stability. However, it has relatively lower values of fracture toughness and strength than other structural ceramics. Ceramic-reinforced ceramic composites represent one of the best developments so far in the race to produce tough and mechanically reliable ceramic materials for advanced structural applications at elevated temperatures.1) Specially, nanosized SiC particle reinforced alumina composites had improved mechanical properties compared to monolithic alumina.2-3) Niihara2) demonstrated that 300 nm SiC particles improved not only the toughness from 3.0 to 4.7 MPa · $m^{1/2}$ but also improved the strength from 300 to 1000 MPa. It had been proposed that the intragranular and intergranular location of the reinforcement nano-phase impacts the mechanical properties by affecting the local tensile and compressive stresses at the boundary between the two phases.4) High strength of these materials has been widely obtained and reported by other researchers.5)

The wear problem of mechanical components has been raised as an important issue in the application of structural ceramics although the following parameters such as the coefficient of thermal expansion, fracture toughness, thermal shock resistance, and density have been considered to define the characteristic properties of the mechanical components.6) The wear resistance of alumina has been studied widely and those investigations were focused on the effects of lubricant. In the humidity condition, several researchers investigated the effects of formation of the lubricant film.7,8) Recently, a few investigations of the wear resistance of nanocomposites have been studied, and they are focused on the erosive wear that is induced by a slurry of alumina grit in water.9,10) Also, other researchers investigated the wear behavior of Al_2O_3-SiC nanocomposites in the air sliding conditions.11) Intergranular fracture also was dominant in the nanocomposites of equivalent grain size at contact loads higher than 100 N. At lower contact loads, these nanocomposites exhibited a mixture of intergranular and transgranular fracture.11)

In this paper, the sliding wear resistance of monolithic alumina and alumina-5 vol% silicon carbide nanocomposites in air and water was investigated.

2. Experimental Procedure

A high purity Al_2O_3 (AKP-50, 100-300 nm, Sumitomo Chemical Co., Japan) and nanosize SiC (Betarundum, 270 nm, Ibiden Co., Japan) powders were used in this study. Nanosized SiC of 5 vol% was mixed with Al_2O_3 in ethanol, and ball-milled in a plastic pot for 24 h at 250 rpm. A rotary evaporator was used to dry the slurry. The compacted powder mixtures were hot pressed in a graphite mold coated with BN at 1600°C for 1 h with an applied pressure of 30 MPa in a flowing Ar atmosphere.

Density of the hot pressed samples was measured by the Archimedes method in toluene, and the relative density was

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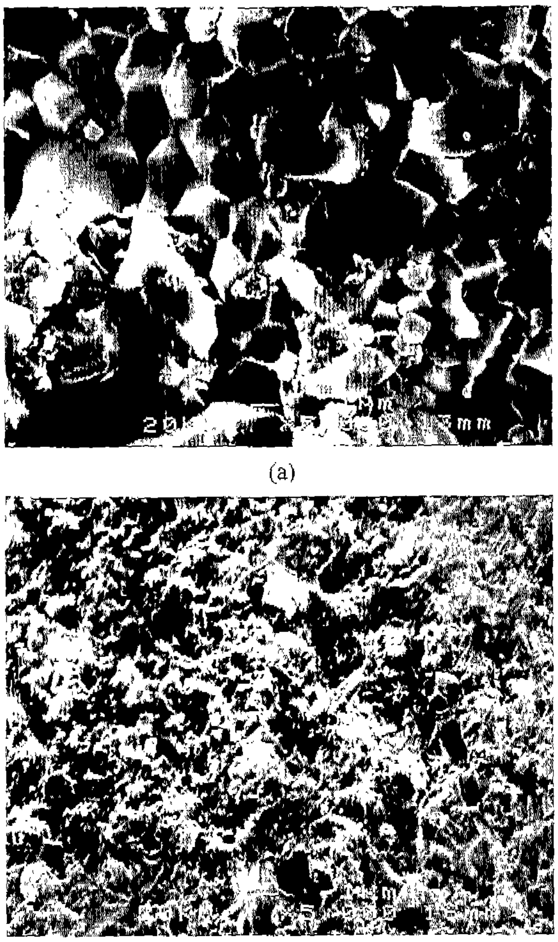
calculated from the theoretical density of each powder by the mixing rule. Hardness and fracture toughness of sintered samples were measured by an indentation method using Zwick 3212 hardness tester, and indentation was performed for 15 second at a 98 N load. The value of fracture toughness was calculated from the Lawn and Fuller equation.[12] Flexural strength specimens of $3 \times 4 \times 35$ mm in dimension were cut and ground from the sintered body and the polished using a 0.5 mm diamond slurry. The strength was measured at room temperature using the three point bending test at the conditions of crosshead speed of 0.5 mm/min with spans of 30 mm.

Friction and wear tests were performed using Plint Tribometer (TE77, Carmeron Plint Co., UK) on a reciprocating ball-on-plate tester. Before the wear and friction test, the specimen surface was fininshed with a 0.5 μm diamond slurry. Used balls for the friction and wear test were commercial silicon nitride balls (NBD200, Norton Co., USA). The test was performed either in air or in water at room temperature. The applied load was 10 N at 0.068 m/sec. The sliding time was 60 min. After completing the wear test, the wear volume was measured using a profilometer (Form Talysurf Plus, Rank Taylor Hobson Co., UK). The profilometer was utilized to measure a wear track, and planimeter was used to calculate the wear area. SEM was employed to examine the worn area on the surface of monolithic Al_2O_3 and Al_2O_3-5 vol% SiC nanocomposite.

3. Results and Discussion

Table 1 shows mechanical properties of monolithic alumina and nanocomposites. Relative density was close to the theoretical density of both specimens. As SiC particles were added to alumina, mechanical properties such as hardness, fracture toughness and flexural strength were increased. According to the early works of Niihara *et al.*[13-15] SiC nanosized particle suppressed the grain growth of alumina. Therefore, it has commonly been accepted that hardness generally increases with decreasing grain size, due to the Hall-Petch type effect on the associated plastic flow. It can be suggested that hardness and flexural strength were increased with increasing amount of hard nano-sized SiC into Al_2O_3 that is associated with the reduction of grain size as shown in Fig. 1. Fig. 1 shows the difference in the grain size of alumina matrix between the monolithic alumina and the nanocomposite. As nano-sized SiC particles were added into alumina, both fracture toughness and strength were improved. The enhanced toughness might be owing to the crack deflection toward the SiC particles, due to the residual tensile strain field associated with thermo-elastic mismatch between alumina and SiC.[16] The retardation of Al_2O_3 grain growth improved the fracture strength because of the fracture stress decreases with an increase in grain size.[17]



(a)

(b)

Fig. 1. SEM micrographs of the fracture surface of (a) Al_2O_3 and (b) Al_2O_3-5 vol% SiC nanocomposite.

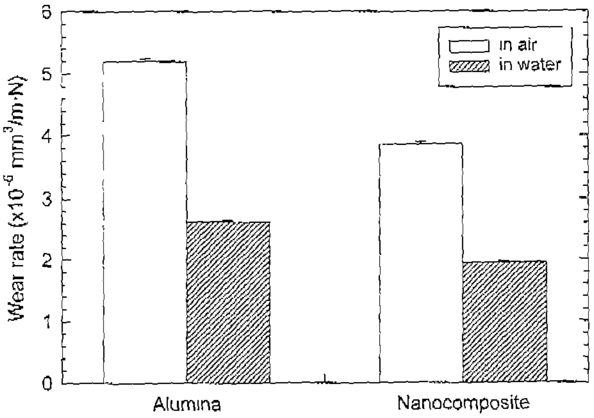
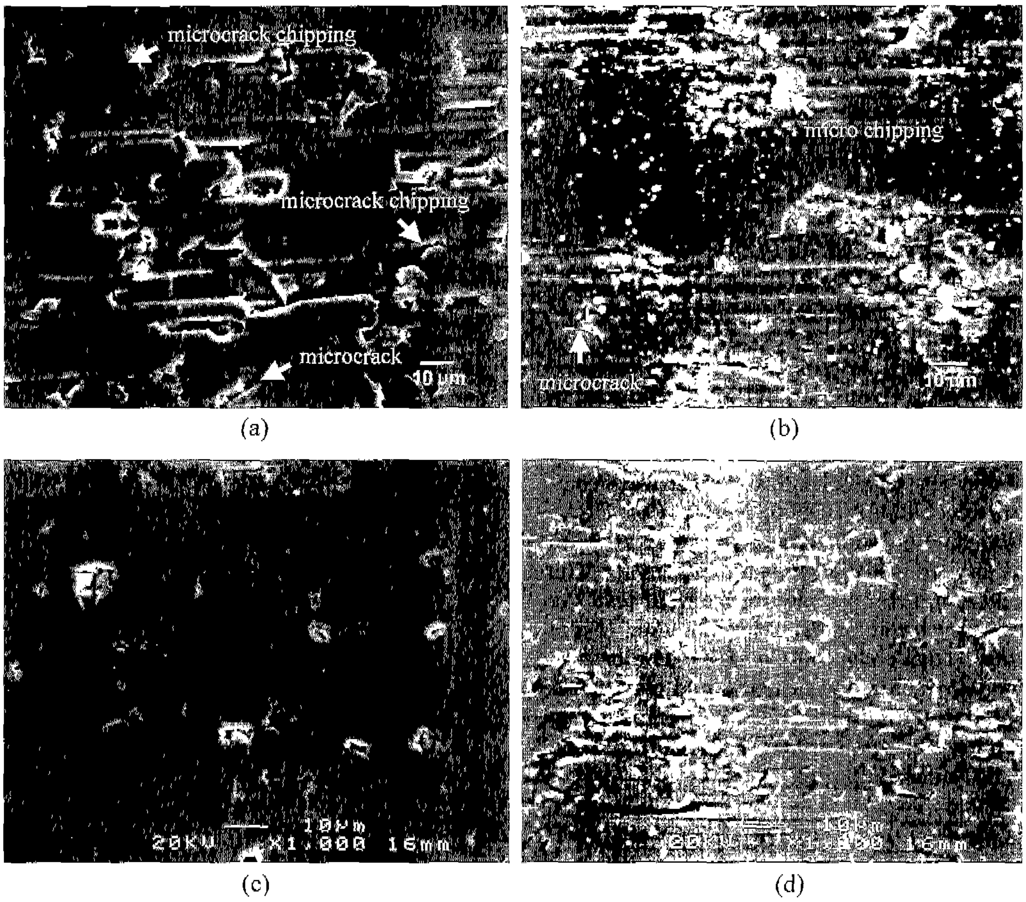


Fig. 2. Variations of wear rate in air and water condition with monolithic alumina and nanocomposite.

Table 1. Test Samples and their Mechanical Properties

Sample	SiC content (vol%)	Relative density (TD%)	Hardness (GPa)	Fracture toughness (MPa · m$^{1/2}$)	Flexural strength (MPa)
Alumina	0	100	16.32 ± 0.55	3.15 ± 0.24	442 ± 32
Nanocomposite	5	99.50	19.49 ± 0.20	4.03 ± 0.74	933 ± 98



(a) (b)

(c) (d)

Fig. 3. SEM micrographs of the worn surface in air (a, b) and in water (c, d) of alumina (a, c) and nanocomposite (b, d) at 10 N, 0.068 m/sec for 1 h.

Fig. 2 shows the wear rates of monolithic alumina and alumina-SiC nanocomposite tested in air and water. The wear rates of the nanocomposite in air and water were lower than those of monolithic alumina at 10 N, 0.068 m/sec for 1 h. In 5 vol% SiC in Al_2O_3, the improvement of wear resistance seemed to be caused by the improved mechanical properties. The worn surface of the composite in air revealed the abrasive wear morphology with scratches. As shown in Fig. 3, tribological behavior in alumina shows microcracking and mircometer chipping. In the nanocomposite, scratches on the worn surface was shallower than in alumina, and also microcracks and micrometer sized debris were observed on the worn surfaces.

As shown in Fig. 3 (c) and (d), the worn surface in water was smooth only in pure Al_2O_3 and reveals the typical abrasive wear morphology with shallow scratches in the nanocomposite. The wear debris came off from the wear track. Wear debris was smeared out even though some grains were chipped out. The worn surface tested in water exhibited relatively a smooth surface rather than in air. Cho *et al.*[18] suggested the wear transition of alumina in paraffin oil. The wear of alumina occurred by the brittle fracture and the subsurface damage resulted in dislocation pile up in the preferred orientation in single alumina grains. The shear stress generated a microcrack at the grain boundary and the crack propagated through several alumina grain boundaries. Finally the crack reached the surface and big flakes of wear debris of several grains were removed. Therefore the smaller grain size provided the higher wear resistance. In this study, it has been found that the grain growth of Al_2O_3 matrix is retarded by SiC nano-size particle, therefore the smaller grain size of Al_2O_3 enhanced the wear resistance. Even microcrackings are observed in both Al_2O_3 and Al_2O_3-SiC nanocomposite, the formation of dislocation due to plastic deformation can be observed on the wear tracks, which are produced in air as well as in water.

The relatively high friction coefficient was caused by high surface contact damage. In this reason, for the fine-grained specimen the entrapped wear debris increases the real contact area between the ball and the plate. In the case of the coarser grains on the other hand, fine debris was not almost generated that it has been reported that the threshold for crack propagation was much higher in coarse-grained alumina than in fine-grained alumina matrix.[19] As the friction coefficient increased, therefore, the wear rate was increased. Fig. 4 shows that the wear rate was similar to the trend of friction coefficient. The effect of the friction coefficient on the wear rate depended on the initial friction coefficient rather than the static state friction coefficient. In this study,

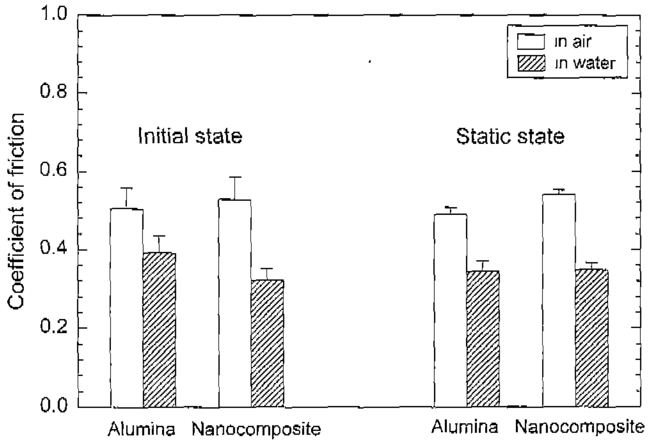


Fig. 4. Comparison of friction coefficients between alumina and nanocomposite at 10 N, 0.068 m/sec for 1 h.

the initial friction coefficient only in water showed that wear seems to be mostly affected at the initial sliding time. In initial sliding time, the wear rate was rapidly dropped and then it decreased gradually.[20] Also, the friction coefficient in water was lower than that in air because of the formation of the tribochemical films such as covered wear debris as well as hydroxide film.[7,8] However, the initial friction coefficient in air was not changed during the sliding time.

The improvement of mechanical properties such as fracture strength and toughness Al_2O_3-SiC nanocomposites due to the presence of SiC particles enhanced the tribological properties. Significant decrease in grain pullout of alumina matrix for the nanocomposites material compared to monolithic alumina might be associated with grain boundary strengthening.[16] As nanosized SiC were added to Al_2O_3, therefore, tribological properties is supposed to be improved mainly by the residual compressive stress around the nanosized SiC particle. In air, microcracks and micrometer chipping were produced as well as plastic deformation. In water, however, abrasive wear grooves were observed.

4. Conclusions

In this study, the sliding wear behaviors of alumina containing nanosized SiC were investigated with the following results; As nanosized SiC was added to alumina, mechanical properties such as hardness, fracture strength and fracture toughness were improved and the wear rate was lower than that of monolithic alumina. Transgranular fracture and the retardation of grain growth of alumina enhanced mechanical properties as well as tribological properties probably owing to the residual compressive stress around the nanosized SiC particles.

In air, wider abrasive grooves were observed for both Al_2O_3 and Al_2O_3-SiC nanocomposite. In water, the worn surface in monolithic alumina revealed to be polished. However, Al_2O_3-SiC nanocomposite showed more abrasive grooves.

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