Cutting performance of Al_2O_3-SiC nanocomposite tools

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Since the initial work of Niihara [1], the superior properties of ceramic nanocomposites have been extensively investigated. A system of particular interest is the Al_2O_3-SiC system because it has been reported to have the most improved properties; Al_2O_3 ceramics containing 5% SiC particles of size 300 nm showing strengths of more than 1 GPa [1]. Compared to monolithic Al_2O_3 ceramics, an increase in strength accompanied by a modest toughness increase has been reported [2, 3]. The effects of varying the volume fraction and the particle size of the SiC on mechanical properties have been studied elsewhere [4–6]. However, very few investigations of the wear and cutting performance of Al_2O_3-SiC composites have been published, and those were focused on the erosive and sliding wear of the composites [7, 8].

This paper presents the preliminary results of an investigation on the cutting performance of Al_2O_3-SiC nanocomposites in machining a gray cast iron. Particular attention has been given to the study of the effect of SiC particle size on tool life of the composite tools.

Commercially available α-Al_2O_3 powder (~200 nm, AKP50, Sumitomo Chemical Co., Osaka, Japan) and two different β-SiC powders were used as starting powders; SiC with an average particle size of 280 nm (Ultrafine, Ibiden Co., Nagoya, Japan) and 30 nm (Material Institute Tech. Inc., Richmond, CA, USA). Batch composition and sintering conditions of each homemade ceramic tool are given in Table I. Monolithic Al_2O_3 tools were fabricated from α-Al_2O_3 for comparison purposes. Each batch was ball-milled in ethanol for 24 hrs using SiC balls in a polyethylene jar. The mixed slurry was dried, subsequently sieved through a 60-mesh screen and hot-pressed at 1550–1700 °C under a pressure of 25 MPa in an argon atmosphere. Sintering time was 1 hr for monolithic Al_2O_3 and 2 hrs for the Al_2O_3-SiC nanocomposites. Sintered density was measured using the Archimedes method. The sintered specimens were cut and polished to a 1 μm finish, then etched thermally. The microstructures were observed by inspecting both thermally etched and fractured surfaces of the manufactured tools using scanning electron microscopy (SEM). SEM micrographs of the polished and etched surfaces were quantitatively analyzed by image analysis (Image-Pro Plus, Media Cybernetics, Maryland, U.S.A.), using the procedure introduced in the previous studies [9, 10]. The hardness was measured using a Vickers indenter with a load of 500 g. The fracture toughness was measured by the indentation method with a load of 49 N [11].

Turning experiments were carried out on a CNC lathe (Hyundai HiT-15, Ulsan, Korea) under dry cutting conditions. The sintered nanocomposites were cut and ground to make SNGN120408 ($12.7 \times 12.7 \times 4.76$ mm, 0.8 mm nose radius and 0.2 mm $\times$ 20° chamfer). A CSRNR tool holder (offset shank with 75° side cutting edge angle, 0° insert normal clearance and $25 \times 25 \times 150$ mm) was used for the cutting experiments. Cutting performance of the composite tools was tested by machining gray cast iron. The cutting tests for machining the gray cast iron were performed at a cutting speed of 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm. The dimensions of the work piece were 110 mm in diameter and 350 mm in length. The wear of the tools was determined by measuring the wear depth on the flank face. The wear depth was measured by using a tool microscope (Hanra Precision Engineering, Micro Vision System SV-2000, Seoul, Korea) at more than four points on the flank face and the average of them was taken as a nominal flank wear depth. The tool life was considered to be finished when the wear depth on the flank face reached 0.3 mm. For comparison, two kinds of commercial ceramic composite tools, made of Al_2O_3-TiC composites, and Al_2O_3-SiC whisker composites (Table II), were selected and tested under the same cutting conditions with the homemade cutting tools.

The grain size, sintered density, hardness, and fracture toughness of the materials are given in Table III. The grain size of Al_2O_3 matrix decreased on adding the SiC particles and the addition of smaller SiC particles led to a smaller grain size in the composites. The density of the materials decreased on adding SiC particles because the theoretical density (3.218 g/cm^3) of β-SiC is lower than that (3.987 g/cm^3) of α-Al_2O_3. Almost full density ($\geq$99% of theoretical) was achieved in all materials.

Fig. 1 shows the SEM micrographs of the fracture surfaces of monolithic Al_2O_3 (designated as AO) and Al_2O_3-SiC nanocomposites (designated as AOS and

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TABLE I Batch composition and sintering condition of ceramic tools

	Batch composition (wt%)			Sintering condition		
Designation	α-Al_2O_3*	β-SiC	Temperature (°)	Time (hr)	Pressure (MPa)	Atmosphere
AO	100	0	1550	1		
AOS	95	5**	1650	2	25	Ar
AOnS	95	5***	1700	2		

*∼200 nm, AKP50, Sumitomo Chemical Co., Osaka, Japan.
**∼280 nm, Ultrafine, Ibiden Co., Nagoya, Japan.
***∼30 nm, Material Institute Tech. Inc., Richmond, CA, USA.

TABLE II Typical composition of commercial tools

Tool material	Batch composition (wt%)
C1	Al_2O_3 + TiC
C2	Al_2O_3 + SiC whisker

TABLE III Properties of monolithic Al_2O_3 and Al_2O_3-SiC composites

Designation	Grain size (μm)	Density (g/cm^3)	Hardness (GPa)	Fracture toughness (MPa·m$^{1/2}$)
AO	5.67	3.95	20.4 ± 1.6	3.7 ± 0.5
AOS	1.38	3.90	22.5 ± 0.8	3.8 ± 0.1
AOnS	0.85	3.90	22.2 ± 0.6	3.1 ± 0.2

AOnS, see Table I). As shown in Fig. 1, the addition of SiC particles inhibited the grain growth of Al_2O_3 and resulted in a smaller grain size. The fracture mode of AO was mainly intergranular whereas that of AOS and AOnS was intragranular. The addition of SiC particles changed the fracture mode from intergranular to intragranular fracture. Thermal expansion mismatch between Al_2O_3 and SiC generates large tensile residual stresses in the matrix grains around intragranular SiC particles [12, 13]. An intergranular crack that encounters an intergranular particle may deflect into the matrix, because of the high interfacial fracture energy of the Al_2O_3/SiC interface, promoting intragranular fracture [14].

As shown in Table III, the addition of SiC increased the hardness of the composites slightly, but the hardness of the composites was not related to the particle size of the SiC added. The improvement of hardness of Al_2O_3-SiC nanocomposites is attributed to both the smaller grain size of the composites and the presence of hard secondary phase (SiC). The toughness remained constant for AOS and decreased slightly for AOnS. The decreased grain size and the transformation of the fracture mode from intergranular to intragranular may lead to the reduction of the fracture toughness, whereas crack deflection by SiC particles may contribute to the increase of the toughness. Thus, these two competing effects seemed to result in the small change of the fracture toughness in the composites.

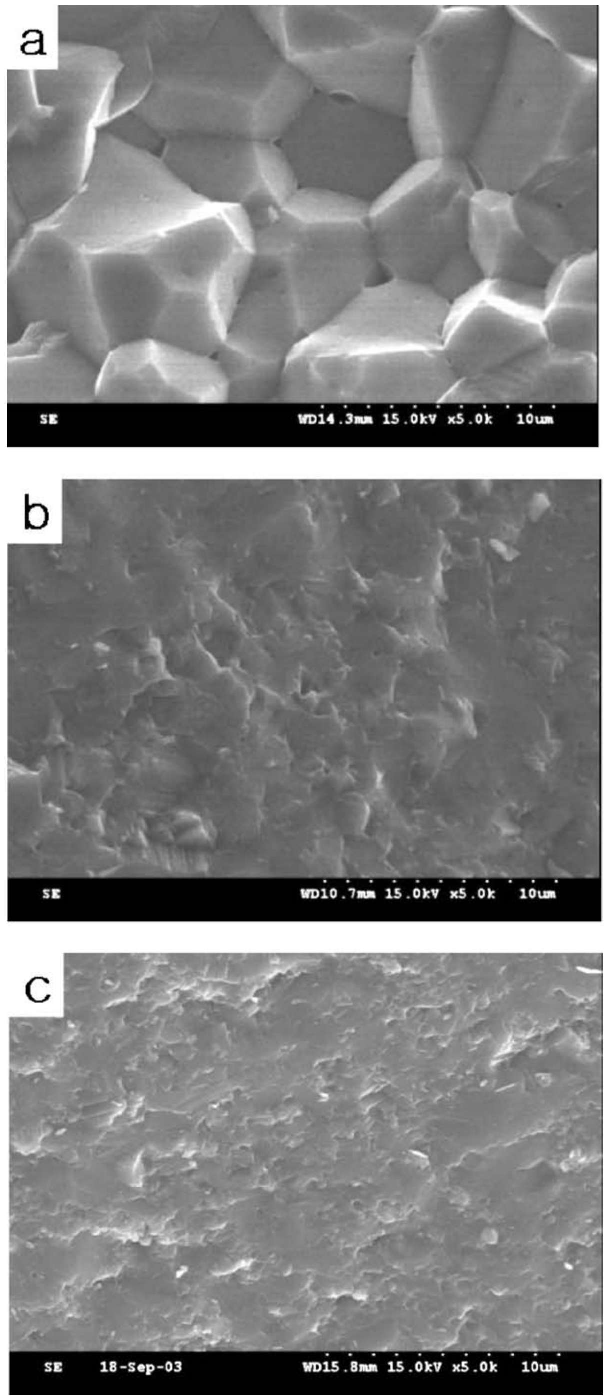

Figure 1 SEM micrographs of fracture surfaces of monolithic Al_2O_3 and Al_2O_3-SiC composites: (a) AO, (b) AOS and (c) AOnS (refer to Table I).

The flank wear curves of the home-made and commercial tools during machining gray cast iron as a function of the machining time are shown in Fig. 2. In the monolithic Al_2O_3 tool (AO), the flank wear was rapidly developed on interaction of the tool with the workmaterial. AOnS with 30-nm-SiC showed the longest tool life among the tools tested for machining gray cast iron. AOS showed a shorter tool life than AOnS, but it

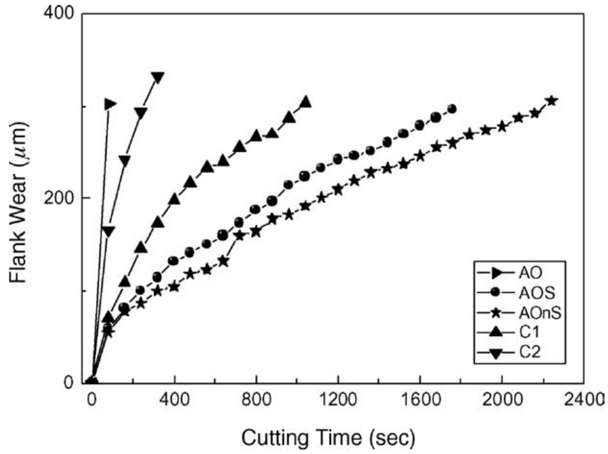

Figure 2 Flank wear of various cutting tools as a function of cutting time during machining gray cast iron at a cutting speed of 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm (refer to Table I).

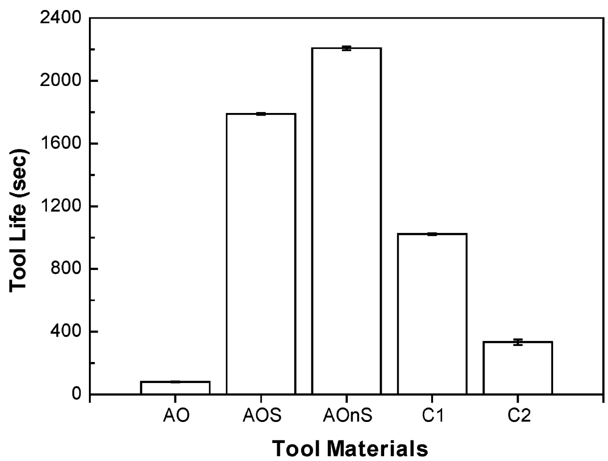

Figure 3 Tool life of various cutting tools during machining gray cast iron at a cutting speed of 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm (refer to Table I).

still showed a longer tool life than those of commercial tools. The tool life of AOnS was 2 times longer than the longest tool life of the selected commercial tool (C1) (Fig. 3). Generally, the tool life was improved more by adding smaller SiC particles to the composites.

Two effects of the addition of SiC on cutting performance of Al_2O_3-based composite tools can be seen. Firstly, the matrix grain size and, hence, the wear rate was reduced. Addition of 30-nm-SiC particles resulted in a smaller grain size of the composite, resulting in better wear resistance. Secondly, the addition of SiC into Al_2O_3 caused a transformation of the fracture mode from intergranular fracture for Al_2O_3 to intragranular fracture for Al_2O_3-SiC nanocomposites. Consequently, grain boundary fracture was inhibited during cutting just as it was during fast fracture. These combined effects resulted in much improved cutting performance of the Al_2O_3-SiC nanocomposite tools, compared to the commercial tools made of Al_2O_3-TiC composites and Al_2O_3-SiC whisker composites. The present results indicate that Al_2O_3-SiC nanocomposites are promising materials for machining applications.

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