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Development of Al_2O_3–SiC composite tool for machining application

Young Mok Ko [a], Won Tae Kwon [a,*], Young-Wook Kim [b]

[a] Department of Mechanical and Information Engineering, University of Seoul, Seoul 130-743, South Korea
[b] Department of Materials Science and Engineering, University of Seoul, Seoul 130-743, South Korea

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Abstract

Al_2O_3–SiC composites containing up to 30 wt.% of dispersed SiC particles (∼280 nm) were fabricated via hot-pressing and machined as cutting tools. The Al_2O_3–SiC particulate composites exhibit higher hardness than their unreinforced matrix because of the inhibited grain growth by adding SiC and the presence of hard secondary phase (SiC). The fracture toughness of the composites remains constant up to 10 wt.% loading of SiC. For machining heat-treated AISI 4144140 steel, the Al_2O_3–10 wt.% SiC composite tool showed the longest tool life, seven times longer than a commercial tool made of Al_2O_3–TiC composite, while the composite tool with 5 wt.% SiC showed the longest tool life for machining gray cast iron. The improved performance of the Al_2O_3–SiC composite tools attributes to the transformation of fracture mode from intergranular fracture for Al_2O_3 to intragranular fracture for Al_2O_3–SiC composites.

Keywords: C. Hardness; C. Fracture; C. Toughness; D. Al_2O_3; D. SiC; E. Cutting tools

1. Introduction

The need for cutting tool materials with improved mechanical properties and chemical inertness capable of operating at high cutting speeds is becoming critical. Ceramic materials are the prime candidates to fulfill these requirements because of their excellent physical properties such as thermal stability, high hardness, and good corrosion resistance. One of most widely used material for the ceramic cutting tool is alumina (Al_2O_3). The addition of hard secondary phases such as TiC, TiB_2, Ti(C,N), ZrO_2 particles, and SiC whiskers to alumina matrix provides great improvement in mechanical properties [1–8]. For example, the additions of TiC and TiB_2 particles to Al_2O_3 matrix improves the fracture toughness, the hardness, and the strength over those of monolithic Al_2O_3 and offers advantages to wear and fracture behavior when used as cutting tool materials [9,10]. The addition of SiC whisker to Al_2O_3 matrix improves the fracture toughness and the thermal shock resistance of Al_2O_3 [1,2,4] and offers advantages with respect to fracture behavior.

Al_2O_3–SiC particulate composites exhibit higher strength and slightly better hardness than their unreinforced matrix, whereas the fracture toughness remains practically constant [11–13]. The improvement in strength is mainly due to a reduction in the size of the surface defects [13], which sometimes may be favored by compressive residual stresses that are induced during machining. If the composite strengthening is mainly a surface phenomenon, it also should modify the wear properties and cutting performance. However, very few investigations of the wear and cutting performance of Al_2O_3–SiC composites have been published, and those are focused on the erosive and sliding wear of the composites [14,15]. This paper presents the preliminary results of an investigation of the cutting performance of Al_2O_3–SiC particulate composites in machining a heat-treated AISI 4140 steel and a gray cast iron. In this study, we have particularly focused on studying the effect of SiC content on tool life of the composite tools.

* Corresponding author. Tel.: +82-2-2210-2403; fax: +82-2-2248-5110.
E-mail address: kwon@uos.ac.kr (W.T. Kwon).

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Table 1
Batch composition and sintering condition of ceramic tools

Designation	Batch composition (wt.%)		Sintering condition			
	α-Al_2O_3[a]	β-SiC[b]	Temperature (°C)	Time (h)	Pressure (MPa)	Atmosphere
AO	100[a]	0	1550	1		
AOS1	95[b]	5	1650	2		
AOS2	90[b]	10	1650	2	25	Ar
AOS3	80[b]	20	1650	2		
AOS4	70[b]	30	1700	2		

[a] ∼0.3 μm, AKP30, Sumitomo Chemical Co., Osaka, Japan.
[b] ∼280 nm, Ultrafine, Ibiden Co., Nagoya, Japan.

2. Experimental procedure

2.1. Materials

Commercially available α-Al_2O_3 (∼0.3 μm, AKP30, Sumitomo Chemical Co., Osaka, Japan) and β-SiC (280 nm, Ultrafine, Ibiden Co., Nagoya, Japan) were used as starting powders. Batch composition and sintering conditions of each homemade ceramic tool were given in Table 1. AO was fabricated from pure α-Al_2O_3 for comparison. For investigating the effect of SiC addition on mechanical properties and cutting performance of the composites, 5–30 wt.% of SiC were added to Al_2O_3. Each batch was ball-milled in ethanol for 24 h using SiC balls and 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 h for pure Al_2O_3 and 2 h for the Al_2O_3–SiC composites. Sintered density was measured using the Archimedes method. The sintered specimens were cut and polished up to 1 μm finish, then etched thermally. The microstructure was observed by inspecting both thermally etched and fractured surfaces of the manufactured tool using scanning electron microscopy (SEM). The hardness was measured using a Vickers indenter with a load of 500 g. The fracture toughness was measured by indentation method with a load of 49 N [16].

2.2. Cutting performance

All experiments were carried out on a computer numerical control (CNC) lathe (Hyundai HiT-15, Ulsan, Korea) under dry cutting condition. The sintered composites were cut and ground to make SNGN120408 (12.7 mm × 12.7 mm, 4.76 mm thickness, 0.8 mm nose radius and 0.2 mm × 20° chamfer). A tool holder of CSRNR 2525 M 12CEA type (offset shank with 15° [75°] side cutting edge angle, 0° insert normal clearance and 25 mm × 25 mm × 150 mm) was used for the cutting experiments. The cutting performance of the composite tools was tested by machining heat-treated AISI 4140 (HRC: 58) and gray cast iron. Chemical composition and mechanical properties of the AISI 4140 steel and gray cast iron were given in Table 2. The AISI 4140 was heat treated again to keep the hardness of the material constant after cutting 3 mm in the depth of cut direction.

Table 2
Chemical composition and mechanical properties of gray cast iron and AISI 4140 steel used for cutting test

Element	Gray cast iron	AISI 4140
Chemical composition (wt.%)		
Fe	93.0–94.0	96.78–97.84
C	3.25–3.5	0.38–0.43
Cr	0.05–0.45	0.8–1.1
Cu	0.15–0.4	–
Mn	0.5–0.9	0.7–1.0
Mo	0.05–0.1	0.15–0.25
Ni	0.05–0.2	–
P	Max. 0.12	Max. 0.035
S	Max. 0.15	Max. 0.04
Si	1.8–1.3	0.15–0.3
Mechanical property		
Hardness	HB 183–234	HB 285–352
	HRC 20	HRC 30–38
Ultimate tensile strength	Min. 276 MPa	Min. 655 MPa

The cutting tests for machining of heat-treated AISI 4140 were performed at a cutting speed of 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm. The tests for 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 dimension of work material was 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 Engineering, Micro Vision System SV-2000, Ulsan, Korea) at more than four points of 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, three kinds

Table 3
Typical composition of commercial tools

Tool material	Typical composition
C1	Al_2O_3
C2	Al_2O_3 + TiC
C3	Al_2O_3 + SiC whisker

of commercial ceramic tools, made of Al_2O_3, Al_2O_3–TiC composites, and Al_2O_3–SiC whisker composites (Table 3), were selected and tested under the same cutting conditions with the homemade cutting tools.

3. Results and discussion

3.1. Materials

The sintered densities of the materials are given in Table 4. The density of the materials decreased with increasing SiC content because of 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.

Fig. 1 shows the SEM micrographs of the monolithic Al_2O_3 (designated as AO) and the composites of Al_2O_3 and SiC (designated as AOS) after thermal etching at 1500 °C for 1 h in an argon atmosphere. As shown in Fig. 1, the addition of SiC particles inhibited the grain growth of Al_2O_3 and resulted with the smaller grain size. Generally, small SiC particles are distributed throughout the Al_2O_3 matrices, and large SiC particles are located on the boundaries or junctions of Al_2O_3 grains. Fig. 2 shows the SEM micrographs of the fracture surfaces of monolithic Al_2O_3 and the composites of Al_2O_3 and SiC. The facture mode of AO was mainly intergranular whereas that of AOS1 and AOS2 was intragranular. The addition of SiC particles made the fracture mode changed from intergranular to intragranular fracture. Thermal expansion coefficient mismatch between Al_2O_3 and SiC generates large tensile residual stresses in the matrix grains around intragranular SiC particles [6,17]. 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 [18].

Table 4
Properties of monolithic Al_2O_3 and Al_2O_3–SiC composites

Designation	Density (g/cm^3)	Hardness (GPa)	Fracture toughness (MPa m$^{1/2}$)
AO	3.96	19.6 ± 2.3	3.8 ± 0.5
AOS1	3.90	22.5 ± 0.8	3.8 ± 0.1
AOS2	3.85	23.0 ± 0.3	3.7 ± 0.4
AOS3	3.71	22.2 ± 0.6	5.2 ± 0.4
AOS4	3.66	23.4 ± 1.3	4.5 ± 0.3

As shown in Table 4, the addition of SiC increased the hardness of the composites, but the hardness value of the composites was not dependent on the content of SiC added.

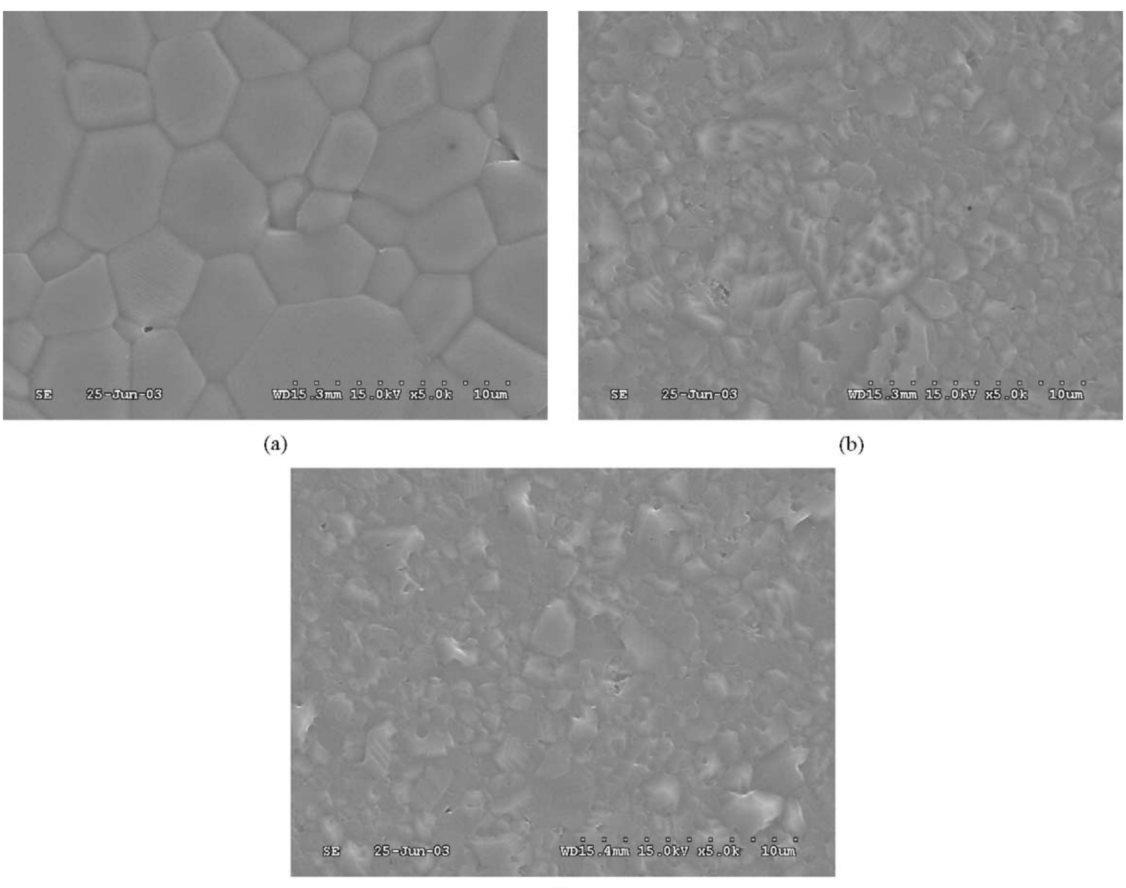

Fig. 1. SEM micrographs of thermally etched surfaces of monolithic Al_2O_3 and Al_2O_3–SiC composites: (a) AO, (b) AOS1, and (c) AOS2 (refer to Table 1).

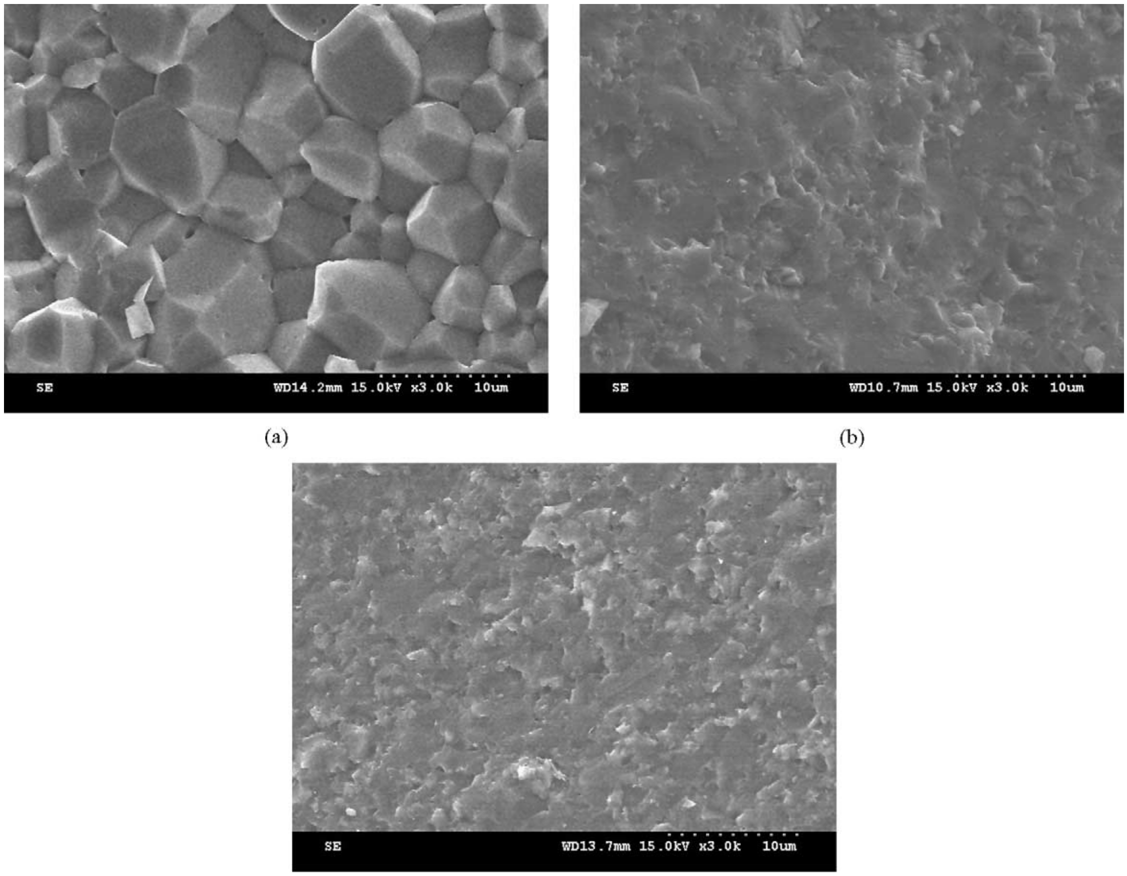

Fig. 2. Fracture surfaces of monolithic Al_2O_3 and Al_2O_3–SiC composites: (a) AO, (b) AOS1, and (c) AOS2 (refer to Table 1).

The improvement of hardness of Al_2O_3–SiC particulate composites attributes to both the smaller grain size of the composites and the presence of hard secondary phase (SiC). The toughness remained constant up to 10 wt.% loading of SiC and increased slightly for 20 and 30 wt.% additions (Table 4). The large SiC particles on the grain boundary is believed to contribute to the increment of the toughness at high (≥20 wt.%) SiC loadings. The reduced grain size and the transformation of the fracture mode from intergranular to intragranular of the composites may lead to the reduction of the fracture toughness whereas crack deflection by SiC particles is expected to contribute the increase in toughness. Thus, these two competing effects seemed to result in the small change of the fracture toughness in the composites.

3.2. Cutting performance

The variation of the flank wear of the homemade and commercial tools during machining heat-treated AISI 4140 as a function of the machining time is shown in Fig. 3. The cutting tests were performed at a cutting speed of 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm. In the monolithic Al_2O_3 tool (AO), the flank wear was rapidly developed right after the interaction of the tool to the work-material. Microfracture was observed in the material and seemed to attribute to the rapid development of the flank wear. Almost similar fast tool wear was observed in com-

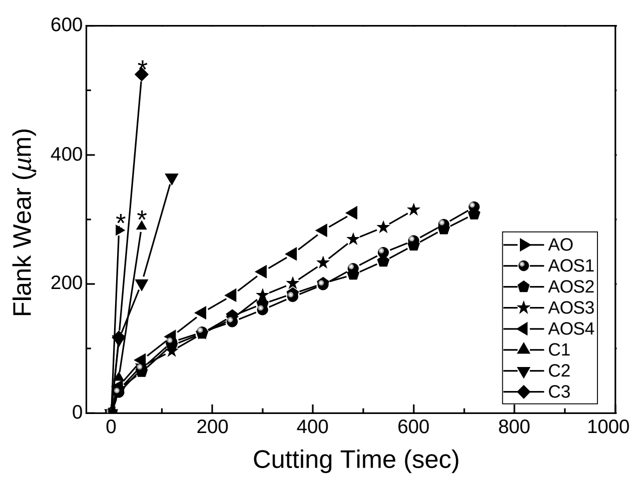

Fig. 3. Flank wear of various cutting tools as a function of cutting time during machining heat-treated AISI 4140 at a cutting speed of 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm (asterisk (∗) denotes tools broken during machining).

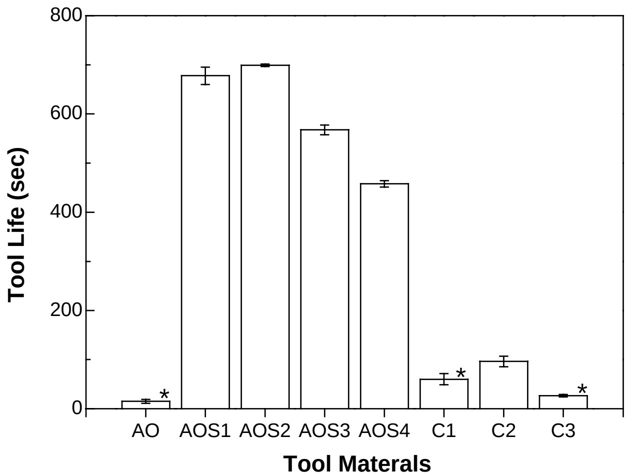

Fig. 4. Tool life of various cutting tools during machining heat-treated AISI 4140 at a cutting speed of 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm (asterisk (∗) denotes tools broken during machining).

mercially tools (C1–C3). In contrast, the composite tools (AOS1–AOS4) have very good wear resistance, as shown in Fig. 3. AOS2 showed the longest tool life among the tools tested for machining heat-treated AISI 4140. The tool life of AOS2 was seven times longer than that of a commercial tool (C2) (see Fig. 4). As shown in Fig. 2, the addition of SiC made the transformation of fracture mode from intergranular fracture for Al_2O_3 to intragranular fracture for Al_2O_3–SiC composites. The improved cutting performance of the Al_2O_3–SiC composite tools attributed to the intragranular fracture mode of the composites. Generally, the tool life shortened with increasing the SiC content in the composites. The microfracture was also observed in AOS4 and it was considered to be the reason for the shorting of tool life in AOS4.

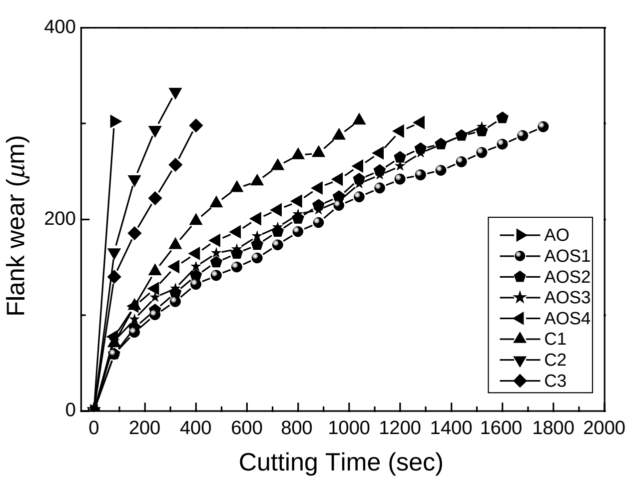

Fig. 5. Flank wear of various cutting tools as a function of cutting time during machining gray cast iron at a cutting speed of 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm.

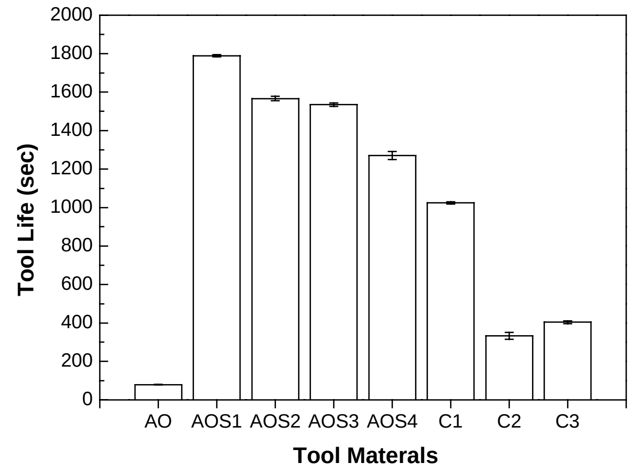

Fig. 6. Tool life of various cutting tools during machining gray cast iron at a cutting speed of 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm.

The variation of the flank wear of the homemade and commercial tools during machining gray cast iron as a function of the machining time is shown in Fig. 5. The cutting tests 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 monolithic Al_2O_3 tool (AO) was worn out rapidly as it did during machining heat-treated AISI 4140. AOS1 with 5 wt.% SiC showed the longest tool life among the tools tested for machining gray cast iron (Fig. 6). AOS4 showed the shortest tool life among the home-made composite tools, but it was still longer than those of commercial tools. The tool life of AOS1 was 1.5 times longer than the longest tool life of selected commercial tool (C1). Generally, the tool life shortened with increasing the SiC content in the composites. This may attribute to the chemical reactions between SiC and Fe in the work-material during machining [2,4].

4. Conclusions

The introduction of hard SiC grains into monolithic Al_2O_3 increased the hardness and decreased the grain size of the material, thereby greatly improving its cutting performance, compared to the commercial tools made of monolithic Al_2O_3, Al_2O_3–TiC composites, and Al_2O_3–SiC whisker composites. The Al_2O_3–5 wt.% SiC composites and the Al_2O_3–10 wt.% SiC composites showed the best cutting performance for machining gray cast iron and heat-treated AISI 4140 steel, respectively. The tool life of the Al_2O_3–5 wt.%SiC and Al_2O_3–10 wt.%SiC composite tools was 1.5 times and 7 times longer than those of commercial tools in machining gray cast iron and heat-treated AISI 4140, respectively. The present results indicate that the Al_2O_3–SiC composites are a promising material for machining applications.

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