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Cutting Performance of Si_3N_4 Based SiC Ceramic Cutting Tools

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Composites of Si_3N_4-SiC containing up to 30 wt% of dispersed SiC particles were fabricated via hot-pressing with an oxynitride glass. To determine the effect of sintering time and SiC content on the mechanical properties and the cutting performance, the composites with fixed 8 hr-sintering time and 20 wt% SiC content were fabricated and tested. Fracture toughness of the composites increased with increasing sintering time, while the hardness increased as the SiC content increased up to 20 wt%. The hardness of the composites was relatively independent of the grain size and the sintered density. For machining heat-treated AISI4140, the insert with 20 wt% SiC sintered for 8 hr showed the longest tool life while the insert with 20 wt% SiC sintered for 12 hr showed the longest tool life for machining gray cast iron. An effort was made to relate the mechanical properties, such as hardness, fracture toughness and wear resistance coefficient with the tool life. However, no apparent relationship was found between them. It may be stated that tool life is affected by not only the mechanical properties but also other properties such as surface roughness, density, grian size and the number of the inherent defects in the inserts.

Key Words : Si_3N_4, SiC, cutting Tool, Mechanical Properties

1. Introduction

Silicon nitride ceramics have been increasingly used as cutting tools because of their excellent intrinsic mechanical, thermal and chemical properties (Tajima, 1993 ; Hirosaki et al., 1994 ; Kim et al., 1995). They are applied successfully in machining cast irons (Szafran et al., 2000), however, their performance for cutting steels is less than satisfactory. The wear rate of a silicon nitride cutting tool is two orders of magnitude higher when machining AISI 1045 steel than machining gray cast iron (Zhao et al., 1999). Improvement in the cutting performance and material development for machining steels have been strongly emphasized in the literature (Hirosaki et al., 1994 ; Kim et al., 1995 ; Szafran et al., 2000 ; Zhao et al., 1999) and industries.

One approach for improving properties is to combine the properties of different materials. Examples are SiC-TiC composites for improved fracture toughness (Cho et al., 1996 ; Kim et al., 2000) and Si_3N_4-SiC composites for improved strength (Kim et al., 1999 ; Kim and Mitomo, 2000). A new approach that has received much less attention for developing advanced ceramic cutting tools is the incorporation of SiC in Si_3N_4 with oxynitride additives. SiC has higher hardness and oxidation resistance, whereas Si_3N_4 has

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better strength and thermal-shock behavior.

In the present study, Si_3N_4-SiC ceramic composites that contained up to 30 wt% of dispersed SiC particles were fabricated via hot-pressing with an oxynitride glass. The mechanical properties and cutting performance of the resulting ceramics were investigated.

2. Materials

Commercially available β-SiC (0.27 μm, Ultrafine, Ibiden Co., Ltd., Nagoya, Japan), α-Si_3N_4 (0.30 μm, E10, Ube Industries, Tokyo, Japan), β-Si_3N_4 (0.56 μm, SN-P21, Denkikagaku, Tokyo, Japan), were used as the starting powders. A mixture of SiO_2 (reagent grade, Kanto Chemical Co., Tokyo, Japan), MgO (high purity grade, Wako Pure Chemical Industries Ltd., Osaka, Japan), Y_2O_3 (99.9% pure, Shin-Etsu Chemical Co., Tokyo, Japan), Al_2O_3 (99.9% pure, Sumitomo, Chemical Co., Tokyo, Japan), and AlN (Grade F, Tokuyama Soda, Co., Tokyo, Japan) powders was prepared by ball milling in ethanol for 24 hr to form an oxynitride composition of $Y_{0.124}Mg_{0.160}Si_{0.302}O_{1.400}N_{0.151}$ (Kim et al., 1999). Each batch was mixed using SiC balls and a polyethylene jar, each of which contained 8 wt% of the oxynitride glass powder. The mixed slurry was dried, subsequently sieved through a 60 mesh screen, and hot-pressed at 1760℃ under a pressure of 25 MPa in N_2 atmosphere. The composition and sintering conditions are given in Table 1. The hot-pressed composites were cut and ground to make SNGN120416. The cutting performance of home-made ceramic inserts was compared with a commercial Si_3N_4 inserts (designated as A, Taegue TEC, Taegue, Korea).

Table 1 List of composition and sintering condition

Sample	Batch (wt%)				Sintering Time
	SiC	α-Si_3N_4	β-Si_3N_4	Oxynitride glass	
SCN1-20	20	71	1	8	1 hr
SCN2-20	20	71	1	8	2 hr
SCN4-20	20	71	1	8	4 hr
SCN8-5	5	86	1	8	8 hr
SCN8-10	10	81	1	8	8 hr
SCN8-20	20	71	1	8	8 hr
SCN8-25	25	66.1	0.9	8	8 hr
SCN8-30	30	61.1	0.9	8	8 hr
SCN12-20	20	71	1	8	12 hr
SCN16-20	20	71	1	8	16 hr
SCN24-20	20	71	1	8	24 hr

3. Mechanical Properties

Indentation fracture method was used to determine the toughness and the Archimedes method to determine the density. The physical and mechanical properties of the home-made inserts and a commercial insert were measured and compared in Table 2. Home-made inserts have similar or a little bit lower fracture toughness, while they have higher hardness than the commercial insert. As the sintering time increases, the fracture toughness increases and the hardness remains relatively constant (Fig. 1). The increment of the toughness attributes to the growth of the Si_3N_4 grains during sintering (Kwon and Kim, 2001). The effect of SiC on the characteristic of the composite is investigated by adding 5~30 wt% of SiC to Si_3N_4

Table 2 Mechanical properties of ceramic cutting tool materials

Sample	Fracture Toughness ($MPa \cdot m^{1/2}$)	Hardness (GPa)	Bulk Density (g/cm^3)
A*	6.0	15.5	3.2
SCN1-20	4.5±0.2	16.4±0.1	3.15
SCN2-20	5.2±0.3	16.2±0.4	3.14
SCN4-20	4.7±0.1	16.6±0.3	3.18
SCN8-5	6.5±0.2	14.9±0.2	3.18
SCN8-10	5.7±0.6	15.5±0.3	3.18
SCN8-20	6.6±0.2	16.9±0.1	3.18
SCN8-25	6.1±0.1	17.0±0.3	3.19
SCN8-30	6.4±0.4	17.0±0.3	3.19
SCN12-20	5.5±0.1	16.2±0.3	3.19
SCN16-20	7.1±0.4	17.2±0.5	3.19
SCN24-20	6.5±0.4	17.3±0.2	3.19

*A commercial tool (Taegue Tec, Taegue, Korea) when sintering time is fixed at 8 hr. As shown in Fig. 2, hardness increases until the amount of SiC reaches 20 wt%. Hardness increment with less than 20 wt% SiC may attribute to the higher hardness of the SiC than Si_3N_4 and its effect is saturated when the SiC composition reaches 20 wt%. The amount of SiC gives little effect on the fracture toughness of the composite. It may be attributed to the fact that toughness increment caused from the growth of elongated Si_3N_4 grains is compensated by the increased contribution of SiC when the SiC content was higher than 10 wt%.

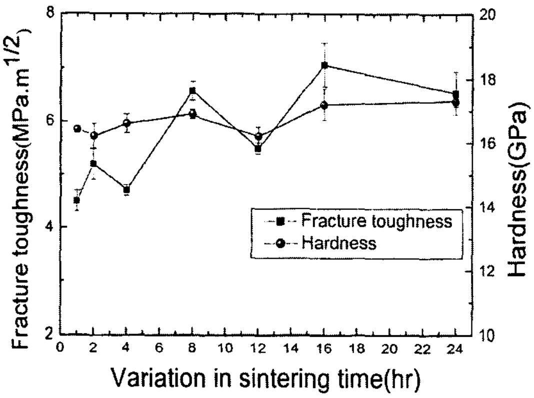

Fig. 1 Variation of fracture toughness and hardness of the compositions with 20 wt% SiC according to the variation of the sintering time (hr)

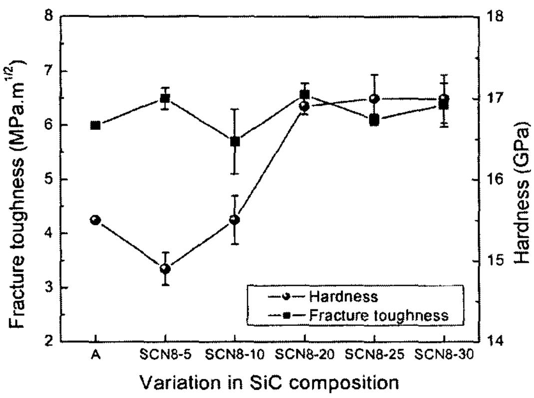

Fig. 2 Variation of fracture toughness and hardness with SiC content. (SCN8-m denotes 8 hr of sintering time and m wt% of SiC content in each composition. A is a commercial tool as a reference.)

4. Cutting Performance

4.1 Experimental setup

All experiments were carried out on the CNC lathe (Hyundai HiT-15) under dry cutting condition. The type of the inserts and tool holder were SNGN 120416 and CSRNR with 75° inclination angle, respectively. The cutting performance of home-made ceramic inserts were tested by machining heat-treated AISI4140 (HRC : 58) and gray cast iron. AISI4140 was heat treated again to keep the hardness of the material constant after cutting 3 mm in the depth of cut direction. Hardness of the inserts and workmaterial was measured by Rockwell series 600 hardness measurement system of Instron. The cutting tests for machining of heat-treated AISI4140 were performed at 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm. The test for gray cast iron were performed at 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm. The workmaterial size was 110 mm in diameter and 350 mm in length. Due to the lengthy cutting time, one experiment for one insert was carried out except when extraordinary result was obtained. Additional tests were performed to confirm the result in that case. A commercial Si_3N_4 grade tool manufactured by TaegueTec (Taegue, Korea) was used as a reference. Tool life was considered to be finished when the flank wear reached 0.3 mm. Flank wear was measured by a tool microscope at more than 4 points of flank wear land and average of them was taken to use as a norminal flank wear land length.

4.2 Results and discussion

To determine the effect of the sintering time on the characteristics of the cutting tool, the inserts with 20 wt% SiC composition and various sintering time were manufactured and tested. The results are given in Fig. 3. Wear of SCN2 grew so fast as its life was finished in 30 sec. SCN4 and SCN8 showed the similar performance with commercial tool before cutting time reached 30 sec after which wear grew faster than commercial tool. SCN8-20 has the longest tool life among them.

Since SCN8-20 shows the best result, the sintering time for further development was set to 8 hr and the content of β-SiC was changed from 5 to 30 wt%. As shown in Fig. 4, the insert with 5 wt% SiC had the shortest tool life among home-made ceramic tools during machining. Generally, the more the amount of SiC, the longer the tool life, until the composition of SiC reaches 20 wt%, after that tool life is getting shorter.

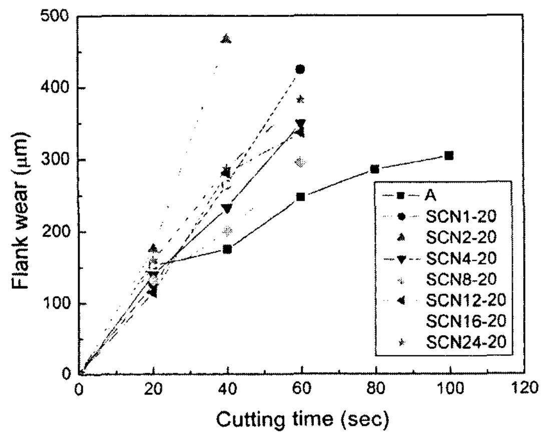

Fig. 3 Flank wear curves of SCN-series with different sintering time during machining heat-treated AISI4140 at 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm

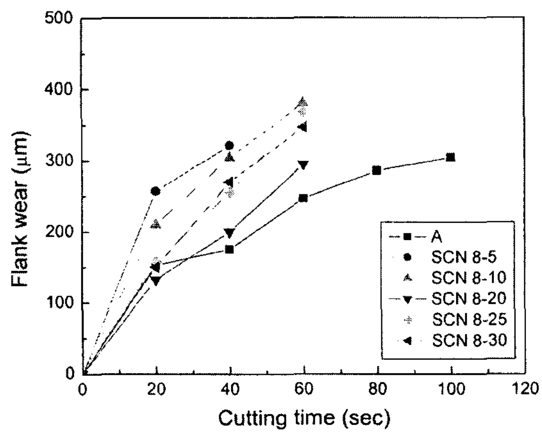

Fig. 4 Flank wear curve of SCN-series containing different SiC content during machining heat-treated AISI4140 at 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm

Next experiments were carried out to find the cutting performance of the developed ceramic inserts for machining gray cast iron. The cutting condition was set to one of the recommended condition whose cutting speed of 330 m/min, a feed rate of 0.2 mm/rev, and a depth of cut of 0.5 mm. The effect of the sintering time on the cutting performance was investigated and shown in Fig. 5. The composition of SiC was fixed as 20 wt%. For the inserts with relatively short sintering time (4 hr), the tool life was short. As the sintering time becomes longer, so is the tool life until the sintering time reaches 12 hr. The cutting performance of the inserts with 16 and 24 hr deteriorated severely. SCN12-20 showed better performance than the commercial tool.

The effect of the amount of SiC on the cutting performance was investigated and shown in Fig. 6. SCN8-20 showed the longest tool life during machining the heat-treated AISI4140. In this case, the tool life of the SCN8-20 was longer than that of the commercial insert. The inserts with the SiC composition over 25 wt% showed the poor cutting performance for machining gray

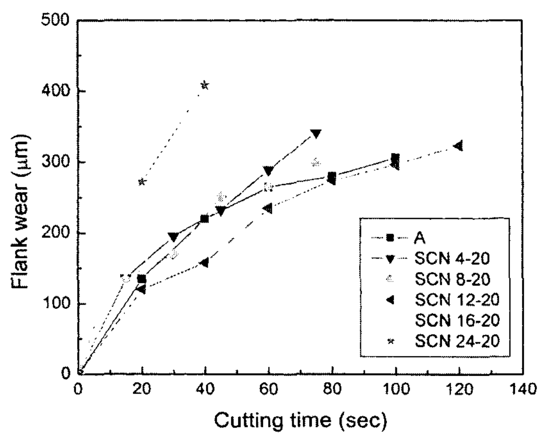

Fig. 5 Flank wear curves of SCN-series with different sintering time during machining gray cast iron at 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm

cast iron.

Efforts were made to determine the relation between the mechanical properties and tool life. In Fig. 7~8, hardness, toughness, and tool life are compared to see the relation among them. In Fig. 9~10, the wear resistance coefficient (WRC) declared to be proportional to the tool life (Baldon et al., 1985) was compared to the tool life. The condition for WRC to be proportional to the tool life was that the main wear mechanism between tool and work material should be abrasive. When the surface of the work material was examined by microscope after the machining, parallel ridges were observed. It means that the main removal mechanism was abrasive wear. Nevertheless, no apparent relationship between mechanical characteristics and cutting performance was revealed in this case. It

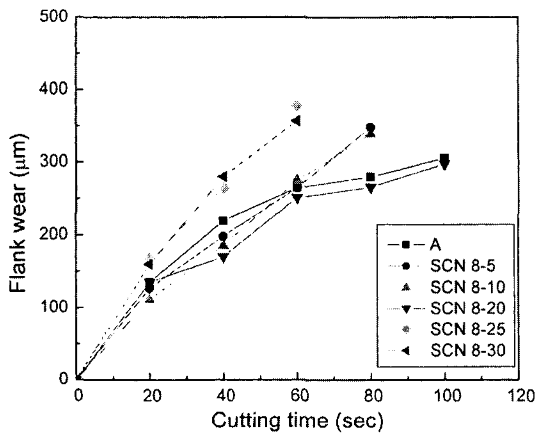

Fig. 6 Flank wear curve of SCN-series with different SiC content during machining gray cast iron at 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm

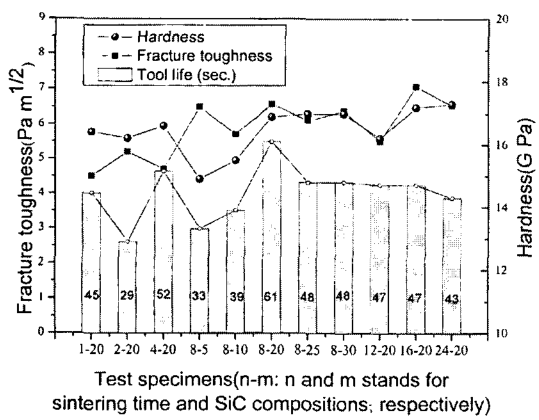

Fig. 7 Relation between mechanical properties (fracture toughness and hardness) and tool life during machining heat-treated AISI4140 at 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm

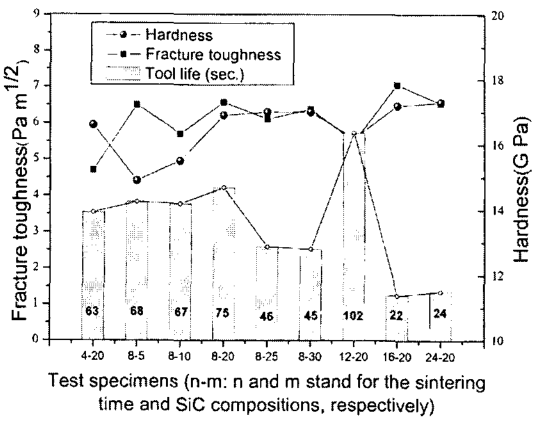

Fig. 8 Relation between mechanical properties (fracture toughness and hardness) and tool life during machining gray cast iron at 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm

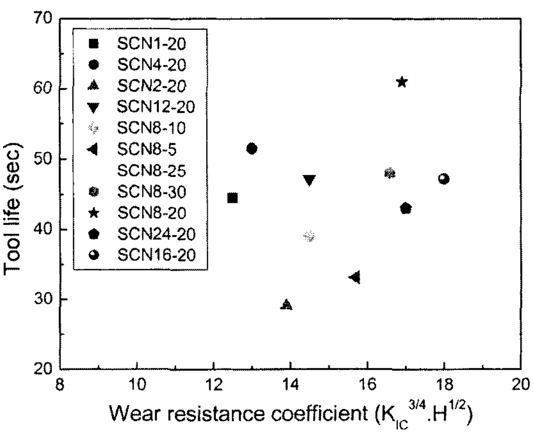

Fig. 9 Relation between wear resistance coefficient ($K_{IC}^{3/4}H^{1/2}$, K_{IC}=fracture toughness, H=hardness) and tool life during machining heat-treated AISI4140 at 160 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.25 mm

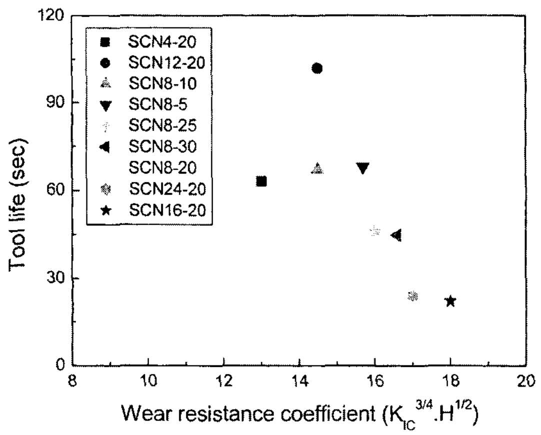

Fig. 10 Relation between wear resistance coefficient ($K_{IC}^{3/4}H^{1/2}$, K_{IC}=fracture toughness, H=hardness) and tool life during machining gray cast iron at 330 m/min with a feed rate of 0.2 mm/rev and a depth of cut of 0.5 mm

may attribute to the fact that tool life is also affected by the other properties such as surface roughness, density, grain size, chemical reaction between work and tool material, and the size and the number of the inherent defects in the insert.

5. Conclusions

SiC-Si_3N_4 ceramics were manufactured and the effect of the sintering time and the composition was investigated for machining heat-treated AISI4140 and gray cast iron. The effect of sintering time and SiC content both on the mechanical properties and cutting performance was invertigated by manufacturing and testing the inserts with fixed 20 wt% SiC and 8 hr sintering time, respectively. The 8-hr-sintered insert containing 20 wt% SiC showed the best cutting performance for machining AISI4140 and the 12-hr-sintered insert containing 20 wt% SiC for gray cast iron. Fracture toughness of the composite increased with increasing the sintering time, while the hardness increased as the SiC content increased up to 20 wt%. The hardness of the composite was relatively independent of the grain size and the sintered density. No apparent relationship between mechanical properties and cutting performance was revealed. It may attribute that the tool life is affected by not only mechanical properties but also other properties such as surface roughness, density, grain size and the numbers of the inherent defects in the inserts.

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