J Mater Sci (2008) 43:6495–6499
DOI 10.1007/s10853-008-2974-6

# Study of machinable SiC/Gr/Al composites

**Jinfeng Leng · Longtao Jiang · Qiang Zhang · Gaohui Wu · Dongli Sun · Qingbo Zhou**

Received: 15 May 2008 / Accepted: 26 August 2008 / Published online: 20 September 2008


**Abstract** The effect of flaky graphite particles [with volume fraction (vf) 3–7%] on machinability and mechanical properties of SiC/Al composites were investigated. Results showed that the machinability was improved greatly with the increasing vf of graphite particles. When the vf of graphite particles was 7%, the tool life was prolonged by 130%, and the tensile strength and elastic modulus of SiC/Gr/Al composite were 365 MPa and 144 GPa, respectively. The presence of flake graphite particle acted as solid lubrication and promoted chip formation during cutting, resulting in an improved machinability.

## Introduction

SiC/Al composites are a unique class of advanced engineering materials, which have been developed and qualified for application in aerospace structures, lightweight optical assemblies, and inertial guidance systems in the past 20 years [1, 2]. Those materials are as light as aluminum, but exhibit significantly greater specific strength and specific stiffness. Moreover, these isotropic materials show an improved compressive microcreep resistance than beryllium. However, the presence of hard, brittle, and abrasive SiC reinforcement makes the materials difficult to form or machine using traditional manufacturing processes [3–6]. Therefore, the flaky graphite particles were added in SiC/Al composites to improve its machinability [7]. Meanwhile, their damping [8, 9] and wear resistance [10–12] properties were also improved. Yet, unfortunately,the mechanical properties of SiC/Al composites were usually degraded, limiting their large-scale industrial applications.

The purpose of this study is to investigate the machinability of SiC/Gr/Al composites, and discuss the role of graphite particles on their machinability. The effect of graphite particles on mechanical properties of SiC/Al composites is also investigated, in order to find a way to design SiC/Gr/Al composites with good machinability and high mechanical properties.

J. Leng (✉) · L. Jiang · Q. Zhang · G. Wu · D. Sun
Center for Metal Matrix Composites Engineering Technology, Harbin Institute of Technology, Harbin, Heilongjiang 150001, China
e-mail: jfleng@126.com

Q. Zhou
Northeast Light Alloys Company Ltd., Harbin, Heilongjiang 150060, China

## Experiments

The matrix alloy is 2024Al whose chemical compositions (wt.%) are 4.79% Cu, 1.49% Mg, 0.611% Mn, 0.245% Fe, 0.168% Si, 0.068% Zn, 0.046% Ti, 0.013% Ni, 0.049% Cr, and the Al balance. SiC particles, with an average size of 3 μm and volume fraction (vf) of 40%, and flaky graphite particles, with an average size of 6 μm and vf of 3,5, and 7%, were used as the reinforcements. The composites were fabricated by squeeze casting technology [13]. The tensile specimens were T6 treated including being solution treated at 495 °C for 1 h, quenched into water, and then aged at 160 °C for 10 h. For comparison, the 40% SiC/Al composite specimens were prepared by the same process.

The as cast bars were machined with K10 inserts (positive rake angle 14°, clearance angle 6°, and nose radius 0.3 mm). Preliminary experiments were conducted to determine the machining parameters. The cutting speed, the feed rate, and cutting depth were fixed at 30 m/min, 0.1 mm/rev, and 0.15 mm, respectively. The maximum flank wear on the tool tip was measured by a SZX12-type Olympus toolmaker's microscope with measuring grids on the eye-piece. The maximum flank wear of 0.6 mm was chosen as the tool life limit. The morphology of flank wear was observed by Hitachi S-4700 scanning electron microscopy (SEM). Tensile tests were conducted on an Instron5569 testing machine at ambient temperature with the crosshead moving rate of 0.5 mm/min. The Brinell hardness test was measured on an HBV-30 sclerometer.

## Results and discussion

### Tool wear

Figure 1 shows variations in flank wear with cutting time when machining SiC/Gr/Al composites. The tool wear rate decreases with increasing vf of graphite particles in SiC/Gr/Al composites. SiC/Gr(7%)/Al composite shows the lowest wear rate compared to all other composites. A tool life criterion of 0.6 mm is chosen. The tool life is obtained from wear curves such as the present in Fig. 1. The effect of vf of graphite particles on tool life is shown in Fig. 2. For SiC/Al composites, by adding 3–7% graphite particles, the tool life is prolonged by 10–130%. The tool life can reflect the machinability of composite. Therefore, SiC/Gr/Al composites possess good machinability when the volume fracture of graphite is 5–7%.

Figure 3 shows worn surfaces of tool in machining SiC/Al and SiC/Gr(7%)/Al composite (cutting time, 104 s). The scratched grooves are parallel to the direction of cutting on the worn flank surface and such grooves are formed by the interaction between two-body abrasive wear and three-

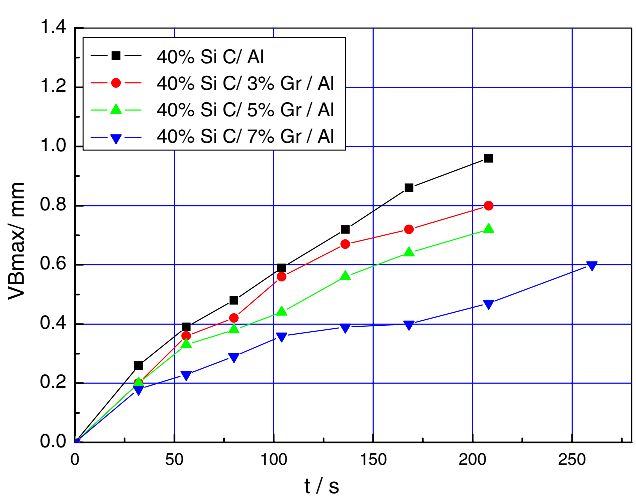


**Fig. 1** Variations in flank wear with cutting time when machining SiC/Gr/Al composites

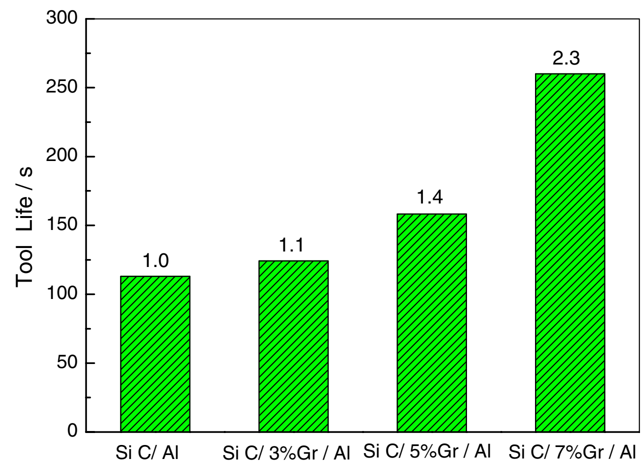


**Fig. 2** Effect of the vf of graphite particles on tool life

body abrasive wear [14]. Moreover, workpiece materials are adhered to the edges of the tool, indicating the tool wear is caused by the co-existence of abrasive wear and adhesive wear. From Fig. 3, we can see that when machining the SiC/Gr(7%)/Al composite, the flank wear of the tool is less severe than that of SiC/Al composite. This confirms that the addition of flake graphite improves the machinability of SiC/Al composites. The results can be explained as following: (1) The hardness and strength of SiC/Gr/Al composites are HB198–HB163 and 295–230 MPa (shown in Table 1), respectively, lower than those of SiC/Al (HB209, 368 MPa). For materials with poor ductility, the decrease in hardness and strength are favorable for machinability. (2) The presence of flake graphite can act as solid lubrication, leading to a decrease in the friction coefficient of rake tool surface/chip and flank tool surface/workpiece material during cutting. This results in low rates of tool wear, relatively low tool forces, and power consumption. Since the power consumed during cutting is largely converted into heat near the cutting edge of the tool, which induces softening of tool materials and leads to the increasing of adhesive wear. (3) The flaky graphite in SiC/Gr/Al composites promotes chip formation and the SiC particle in matrix also act as chip breaker [15]. During the plastic deformation of chips, lots of dislocations form on shear plane, and when they meet reinforcement particles, the dislocations pile up on the interfaces between reinforcement and matrix. When the applied stress further increase, the cracks are initiated in the zones with stress concentration near interface. Hence, both the SiC particle and flaky graphite particle may act as chip breakers and are favorable for the continuous chips. When compared with SiC particle, graphite flake is relatively weak so that the crack is easier to initiate on the interfaces between graphite and matrix and may propagate rapidly along the interface between Al matrix and graphite particle.

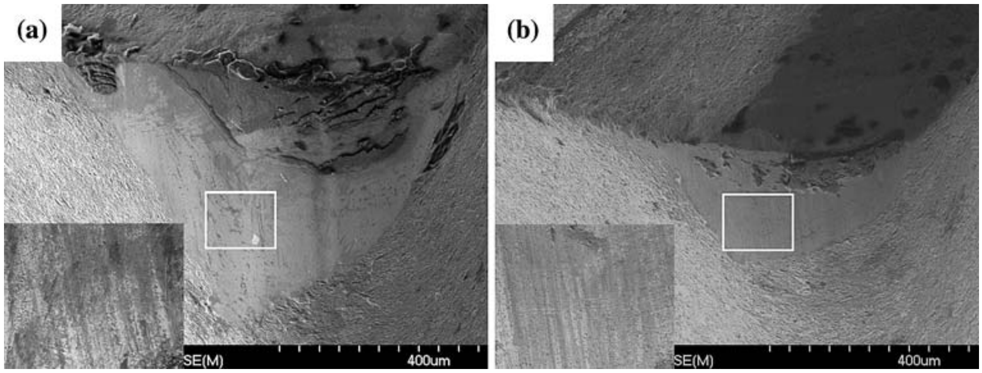


**Fig. 3** Worn surface of tool in machining (**a**) SiC/Al composite and (**b**) SiC/Gr(7%)/Al composite (cutting time, 104 s)

**Table 1** Mechanical properties of SiC/Gr/Al and SiC/Al composites at room temperature

| Materials | Tensile strength $\sigma$b (MPa) | | Elastic modulus *E* (GPa) | | HB (MPa) |
|---|---|---|---|---|---|
| | As-cast | T6 | As-cast | T6 | As-cast |
| 40%SiC/Al | 368 | 510 | 132 | 172 | 209 |
| 40%SiC/3%Gr/Al | 295 | 412 | 130 | 152 | 198 |
| 40%SiC/5%Gr/Al | 286 | 405 | 130 | 150 | 186 |
| 40%SiC/7%Gr/Al | 230 | 365 | 128 | 144 | 163 |

## Mechanical properties

Mechanical properties of SiC/Gr/Al and SiC/Al composites (T6) are shown in Table 1. As shown in Table 1, the tensile strength of SiC/Gr/Al composites are decreased with the addition of graphite particles, and this is mainly attributed to the poor strength of graphite (20–30 MPa). When adding 3–7% graphite particles, the tensile strength of SiC/Al composites is decreased by 19–28%. But for SiC/Gr(7%)/Al composite, the tensile strength is 365 MPa, which is relatively high and suitable for most engineering applications.

Assuming the graphite particles to be equiaxed, particles spacing ($\lambda$) is calculated using the following relationship [16]:

$$\lambda = 0.77dV_{\mathrm{p}}^{-1/2}, \tag{1}$$

where *V*p is the vf of graphite particles and *d* is the particles size. Based on formula (1), we can see that, with increasing volume content of graphite particles, the particle spacing decreased at an exponent function,which results in the fact that the matrix was dramatically divided by graphite particles. The relationship between the tensile strength and particles spacing is shown in Fig. 4. It can be seen that with shortening the particles spacing, the tensile strength is significantly decreased.

The hybrid-reinforced composites may be divided into two parts as SiC + Al and graphite since there is a strong bond between SiC particles [17] and Al, while a weak bond

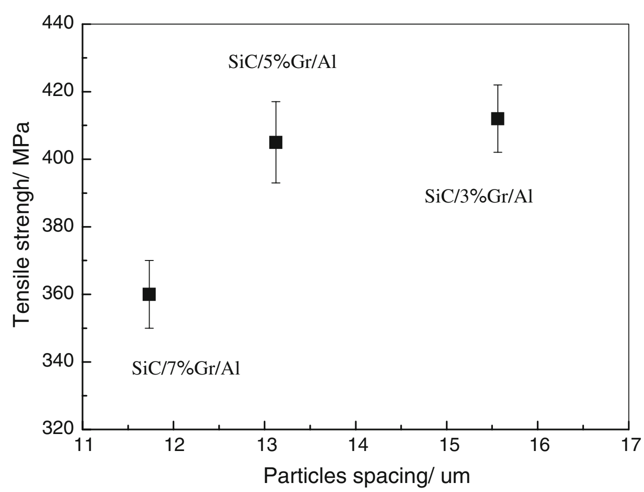


**Fig. 4** The relationship between tensile strength and particles spacing

between graphite and Al. The fracture surfaces of the composite were examined by SEM, and the fractography is shown in Fig. 5. It can be seen that SiC + Al matrix failed in a ductile manner, while graphite particles in a brittle manner. Cleavage fracture along the graphite basal plane of the graphite particles is found, as shown A and B in Fig. 5. Crack propagates between flakes and/or along the interface of Al/graphite. Graphite particles in composites tend to fracture brittly, which could be ascribed to two factors. On one hand, graphite particle layers parallel to the basal plane are held together by weak van der Waals forces. At the

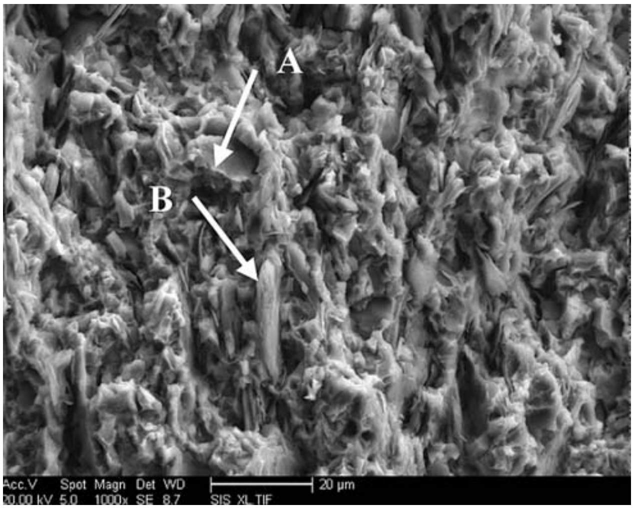


**Fig. 5** SEM tensiling fractographs of SiC/7%Gr/Al composites

same time, the weak-bonding interfaces exist between the graphite particles and Al. These would become crack source under applied stress and then crack propagated rapidly between flakes and/or along the interface of Al/graphite. With increasing the vf of graphite particles, the crack source would increase correspondingly, hence, the tensile strengths of composite are reduced.

According to Hashin–Shtrikman model [18], the elastic modulus of composite is mainly affected by the elastic modulus of reinforcement and the matrix alloy. When compared with SiC particle and Al matrix, the graphite particles have extremely lower elastic modulus (6 GPa). Therefore, the composite modulus must mainly come from SiC particle and Al matrix. When the vf of graphite particles increases from 0 to 7%, the values of elastic modulus decrease from 172 to 144 GPa with a reduction rate of 12–16%.

The densities of SiC/Gr/Al composites are about 2.90–2.93 kg/cm$^3$. Figure 6 illustrates the comparison of specific modulus among several conventional inertial guidance materials. As can be seen, beryllium possesses the highest specific modulus among these conventional inertial guidance materials, and was firstly used in an inertial guidance device in USA. However, the application of beryllium was restricted because of its toxicity, cost, and brittle performance. The specific moduli of 40%SiC/3%Gr/Al and 40%SiC/7%Gr/Al composites are approximately as twice as those of preferred inertial guidance materials—aluminum alloy (LY12) and bearing steel (GCr15) [19]. A high specific modulus would increase the dimensional stability of the materials used for the inertial instruments. Then an inertial guidance device could be made smaller and lighter.

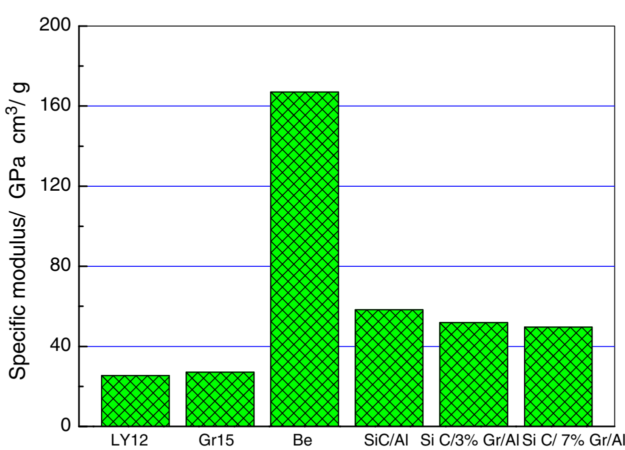


**Fig. 6** Specific moduli of several conventional inertial guidance materials, SiC/Al and SiC/Gr/Al composites

## Conclusions

With the addition of 3–7% flaky graphite particles, the machinability of SiC/Al composites improved greatly and the tool life is prolonged by 10–130%. Correspondingly, the tensile strength and elastic modulus are decreased by 19–28 and 12–16%, respectively, but still keep relatively high values of 365 MPa and 144 GPa for most engineering applications. The specific modulus of related SiC/Gr/Al composites are approximately as twice as those of preferred aerospace materials.

## References


1. Mohn WR, Vukobratorich D (1988) J Mater Des 10:225. doi:10.1007/BF02834166
2. Mohn WR (1988) SAMPE January–February 26
3. Bergman F, Jacobason S (1994) Wear 179:89. doi:10.1016/0043-1648(94)90224-0
4. Hung NP, Boey KA, Khor CA (1995) J Mater Process Technol 48:292. doi:10.1016/0924-0136(94)01661-J
5. Ei-Gallab M, Sklad M (1998) J Mater Process Technol 83:151. doi:10.1016/S0924-0136(98)00054-5
6. Deuis RL, Subramanian C, Yellup JM (1996) Wear 201:132. doi:10.1016/S0043-1648(96)07228-6
7. Songmene V (2000) Machinability of graphitic MMC consisting of an aluminium alloy matrix reinforced with both soft nickel-coated graphite particles and SiC [D] 78
8. Zhang J, Perez R, Lavernia EJ (1994) Acta Metall Mater 42:395. doi:10.1016/0956-7151(94)90495-2
9. Rohatgi PK, Nath D, Singh S, Keshavaram S (1989) J Mater Sci 29:5975. doi:10.1007/BF00366882
10. Ames W, Alpas AT (1995) Metall Mater Trans A 26A:85. doi:10.1007/BF02669796
11. Ted Guo L, Tsao CYA (2000) Compos Sci Technol 60:65. doi:10.1016/S0266-3538(99)00106-2
12. Gui MC, Kang SB (2001) Mater Lett 51:396. doi:10.1016/S0167-577X(01)00327-5
13. Leng JF, Wu GH (2006) Trans Nonferrous Soc China 16:1640
14. Rabinowicz E (1965) Friction and wear of material. Wiley, NY
15. Lin JT, Bhattacharyya D, Lane C (1995) Wear 181–183:883

16. Leroy G, Embury JD, Edward G, Ashby MF (1981) Acta Metall 29:1509. doi:10.1016/0001-6160(81)90185-1
17. Flom Y, Arsenault RJ (1986) Mater Sci Eng 77:191. doi: 10.1016/0025-5416(86)90368-X
18. Geiger L, Jackson M (1989) Adv Mater Process 136:23
19. Wu GH, Ma SL, Li RH, Jiang LT (1998) Chinese inertial instruments and component academic conference. Wenzhou, China