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Studies on machinability of Al/Si$_p$ + SiC$_p$ composite materials

**Qiguo Zhang · Jianxun Qiu · Yi Wang ·
Mingyuan Gu**

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Abstract This paper presents the experimental results on the machinability of silicon and silicon carbide particles (SiC$_p$) reinforced aluminium matrix composites (Al/Si$_p$ + SiC$_p$) during milling process using a carbide tool. The total volume fraction of the reinforcements is 65 vol%. The milling forces, flank wear of the tool and the machined surface quality of composites with different volume fraction of SiC$_p$ were measured during experiments. The machined surfaces of composites were examined through SEM. The results showed that the flexural strength and Vickers hardness are improved when certain volume fraction of silicon particles are replaced by silicon carbide particles with the same volume fraction and particle size and the effect of SiC$_p$ on machinability is optimal when 9 vol% silicon particles in Al/Si$_p$ was replaced by silicon carbide particles with the same volume fraction and the same particle size. Cracks and pits were found on the machined surfaces of composites due to the intrinsic brittleness of silicon particles.

Introduction

With component size reduction and computing capability increase, current chip performance is largely limited by packaging materials. Thus, more and more attention has been paid to electronic packaging materials. The aluminum matrix composite reinforced with high volume fraction silicon particles (Al/Si$_p$) has been identified as a potentially suitable material system because it has high thermal conductivity, low coefficient of thermal expansion and low density [1–3]. In addition, Al/Si$_p$ is more machinable using conventional tooling, in contrast with aluminium matrix composite reinforced with silicon carbide particles [4]. According to our previous results, properties of Al/Si$_p$ were improved when certain volume fractions of silicon particles were replaced by silicon carbide particles with the same amount and the same particle size [5]. However, the hardness of silicon carbide is higher than that of silicon. Thus, it is necessary to study the effect of SiC$_p$ on the machinability of Al/Si$_p$.

As is well known, milling process can produce more accurate parts as well as remove the greatest possible quantity of material from the workpiece. It has become one of the most promising advanced manufacturing technologies in the last 20 years [6]. Milling of aluminium silicon alloy has been studied using carbide tools [7–9]. The coolant was believed to accelerate the wear of tools during the milling of both aluminum silicon alloy and aluminum based composites reinforced with SiC and Al$_2$O$_3$ [10–12]. Thus, the investigation in this work was done in dry milling process to avoid the interference of coolants.

Experimental procedures

Silicon particles, manufactured by Chemical Reagent Plant, Shanghai China. β-SiC$_p$, manufactured by Grinding

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Q. Zhang (✉) · J. Qiu · M. Gu
State Key Laboratory of MMCs, Shanghai Jiaotong University, Shanghai 200030, China
e-mail: zhangqiguo@sjtu.edu.cn

Y. Wang
Nanjing Research Institute of Electronics Technology, Nanjing 210013, China

Wheel Plant, Shenyang, China, were used in this work. Two different size groups of silicon particles: Large silicon particles (60 μm) and small silicon particles (10 μm) (the weight ratio of large particles to the small particles is 8:2) were used to make porous preforms with 65 vol% particles. In order to study the effect of SiC_p on machinability of the composite, 4 vol%, 9 vol% and 13 vol% (the volume fractions are all relative to the volume of the composite) Si_p (10 μm) were replaced by SiC_p with the same volume fraction and particle size. The corresponding composite was designated as M_4, M_9 and M_{13}, respectively. The composite without SiC_p was designated as M_0. The preforms were fabricated with gelcasting method that can ensure the uniform distribution of reinforcements and no un-cracking of reinforcements in the fabricated composite [13]. Then the preforms were infiltrated with molten pure aluminum with a vacuum pressure infiltration technique. The distribution of reinforcements in composites was observed with an optical microscope (LEICA MEF4M OM). Vickers hardness was measured by a hardness tester (HV-50) equipped with a Vickers indenter under 196N load and 15 s dwell time on the polished surface of the composites at room temperature. Each hardness value represents the average value of five such measurements and is reported in GPa. For four-point flexural strength tests, six specimens were performed on a AG-100KNA test machine with a specimen size of $3 \times 4 \times 36$ mm^3 and a loading rate of 0.5 mm/min. The average flexural strength value and their standard error were also calculated.

All milling tests were performed on a DMU70V high speed machining center (DECKEL MAHO, Germany). In order to reveal the effect of SiC_p on the machinability of Al/Si_p clearly, a fixed milling conditions shown in Table 1 were applied for all the specimens. The tool used in the test was carbide end milling tool (YG6, Shanghai Tools Co., Ltd., China). The flank wear land width of the tool (VB) was measured by a Nikon microscope and its corresponding microphotograph system with a resolution of 0.001 mm (Japan). Milling forces were measured by a Kistler four-component piezoelectric platform dynamometer (Switzerland, KISTLER9272). The machined composite surface was observed with a scanning electron microscope (Philips S-520, SEM). The arithmetic mean roughness (Ra) of the machined composite surface was measured by a roughometer (JB-3C, China).

Results and discussion

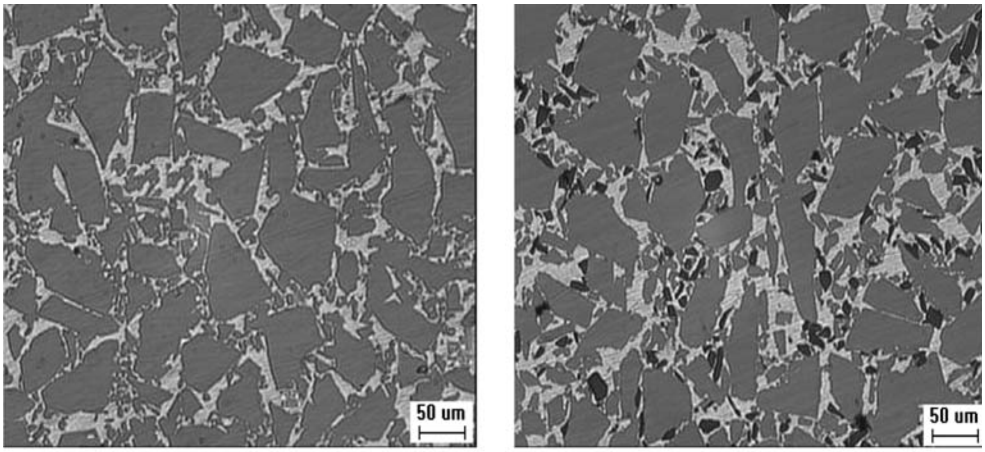
Tool wear

Figure 1 shows that the distribution of Si_p and SiC_p is uniform in the composite. Figure 2 shows that the flexural strength and Vickers hardness of Al/Si_p+SiC_p versus volume fraction of SiC_p. The standard errors of the average flexural strength and the average Vickers hardness of $Al/Si_p + SiC_p$ range from 2.3 MPa to 4.2 MPa and 0.033 GPa to 0.052 GPa, respectively. From Fig. 2, it can be observed that $Al/Si_p + SiC_p$ has higher flexural strength and Vickers hardness than Al/Si_p does. When 13 vol% silicon particles are replaced by SiC_p with the same volume fraction and particle size, the flexural strength and Vickers hardness of the composite are improved by 20.1% and 23.1%, respectively.

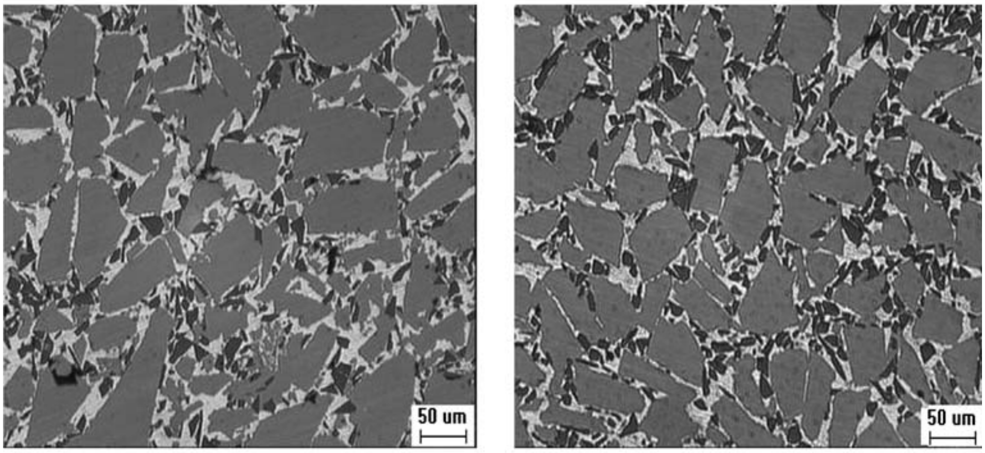
Figure 3 shows the influence of SiC_p on the flank wear under the milling process. From the figure, it can be observed that VB is only 0.012 mm when M_0 was milled for 40 seconds whereas it is respectively 0.016, 0.021 and 0.037 mm when M_4, M_9 and M_{13} were milled for the same time. Experimental results reveal that VB increases with increasing volume fraction of SiC_p. When volume fraction of SiC_p increases up to 13 vol%, VB goes up three times. This is understandable because the hardness of silicon carbide is 27~32 GPa [14], whereas it is 10~12 GPa for silicon and is 16~18 GPa for the carbide milling tool [15]. SiC_p wears the flank face of the tool more heavily than Si_p does. Those particles were exposed on the composite surface and collided directly with the flank face of the carbide tool. Particles grind the flank face of the milling tool on similar way of a grinding wheel during machining the composite. From Fig. 3, it also can be observed that VB increases from 0.021 mm to 0.037 mm when the volume fraction of SiC_p in $Al/Si_p + SiC_p$ increases from 9 vol% to 13 vol%. It indicates that 9 vol% is a turning point after which the wear of the tool flank face

Table 1 Parameters of the milling test

Milling speed (m/min)	The spindle speed (rev/min)	Feed per tooth (mm/z)	Feed (mm/min)	Milling depth (mm)	The end milling tool
25	2000	0.015	60	0.5	YG6



(a) 0vol% SiC_p and 65vol% Si_p **(b)** 4vol% SiC_p and 61vol% Si_p



(c) 9vol% SiC_p and 56vol% Si_p **(d)** 13vol% SiC_p and 52vol% Si_p

Fig. 1 OM micrographs of $Al/Si_p + SiC_p$ with different volume fractions of SiC_p and Si_p

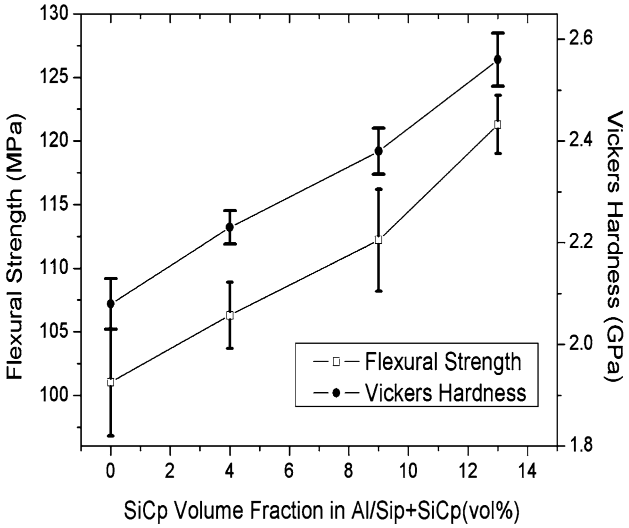


Fig. 2 The average flexural strength and Vickers hardness (with their standard errors) of $Al/Si_p + SiC_p$ versus SiC_p volume fraction

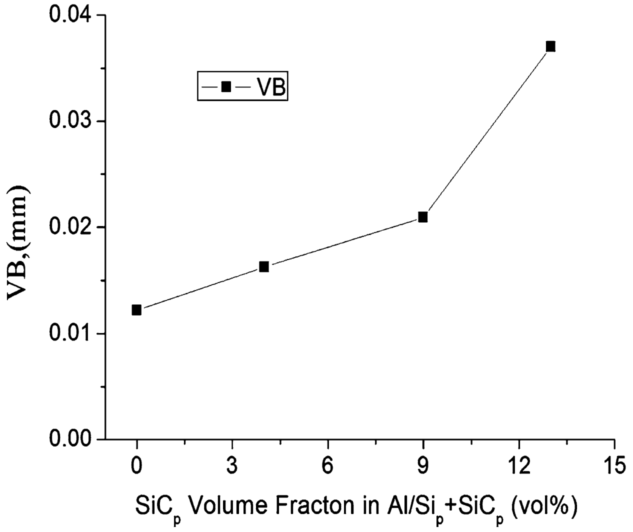


Fig. 3 VB versus volume fraction of SiC_p in $Al/Si_p + SiC_p$

worsens more quickly. Considering both the effect of SiC_p on improving the flexural strength of the composite and VB of the tool, it is suitable that the volume fraction of SiC_p in Al/Si_p doesn't exceed 9 vol%.

Milling forces

The milling force was also an important criterion to evaluate the machinability of the composite. The measured milling forces during milling process include F_x: milling force in the feeding direction, F_y: the milling force that is perpendicular to F_x on the milled surface and F_z: the milling force that is perpendicular to the milled surface. Figure 4 shows the influence of SiC_p volume fraction on F_x, F_y and F_z during the milling process. The figure shows that the milling forces, F_x, F_y and F_z verified with a similar tendency with the volume fraction of SiC_p. All of the milling forces reach the lowest point when 9 vol% Si_p was replaced by SiC_p. It has been mentioned that silicon carbide particles wear the tool more heavily than silicon particles and the abrasive action would become more serious when more Si_p were replaced by SiC_p. The serious abrasive action results in thermal softening of the composite matrix and that would decrease the milling forces. However, the effect of thermal softening of the composite matrix on the decrease of milling forces can not compensate the improvement in the milling forces when the content of SiC_p exceeds 9 vol%. Thus, the milling forces for M_{13} are higher than those for M_9.

Surface integrality

Figure 5 shows the influence of SiC_p on the surface roughness under the milling process. The figure shows that the value of Ra reaches the lowest for M_9. The main reason is that more heavily abrasive action can soften the matrix of the workpiece and tool flank face can iron the surface of composites easier. Figure 6 shows the SEM micrographs of the milled composite surface edge. Comparing Fig. 6(c) with the others, it can be found that the amount of cracks and pits are less and there are no broken parts on the machined composite surface edge. Thus, the surface integrity is the optimal for M_9. In addition, the broken parts enlarge with the increase of milling forces because higher milling forces break parts on the edge of the machined composite surfaces easier. Comparing Fig. 6 with Fig. 4, the surface integrality of the milled composite surface is corresponding to the milling forces well.

Cracks and pits were also observed on the machined surfaces of the composite. Pits and cracks on the machined surface are resulted form the intrinsic brittleness of silicon particles. Figure 7 shows the typical example of cracks and pits due to the fragile fracture of silicon particles on the milled composite surface. The main reason is that the yield strength and elastic modulus of silicon particles are very high. In addition, the total volume fraction of reinforcements in the composite is up to 65 vol% and the contact among particles restricts the distortion of reinforcements. Therefore, silicon particles may only deform elastically or fracture on the surface of the workpiece when the tool edge came in contact with them.

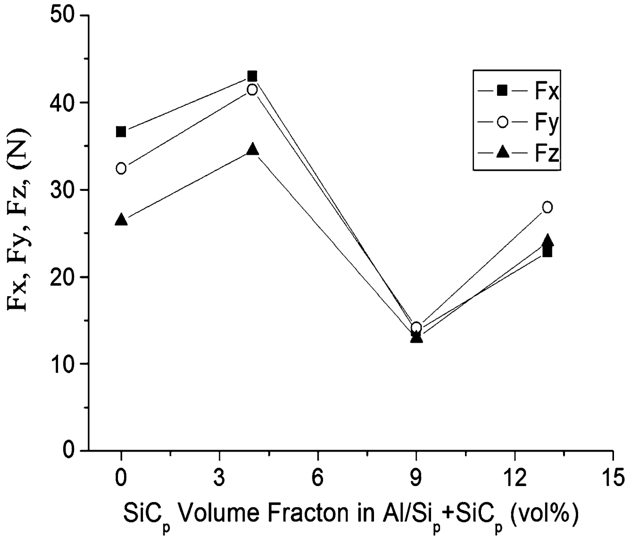


Fig. 4 The milling forces versus volume fraction of SiC_p in $Al/Si_p + SiC_p$

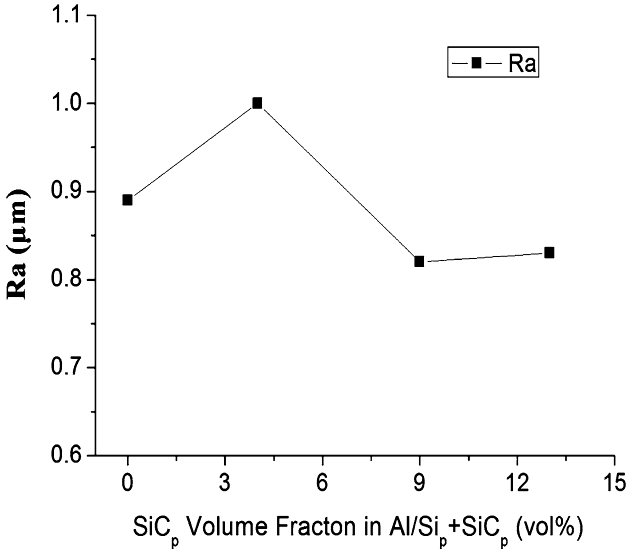
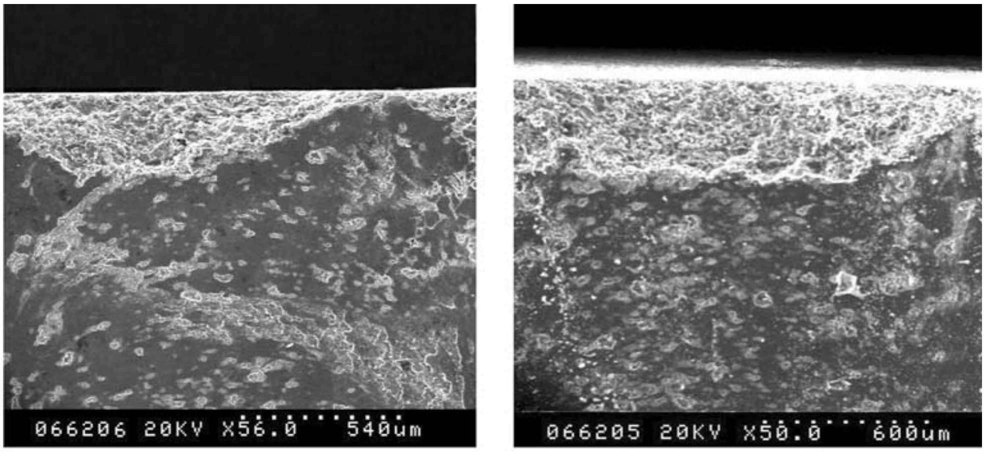


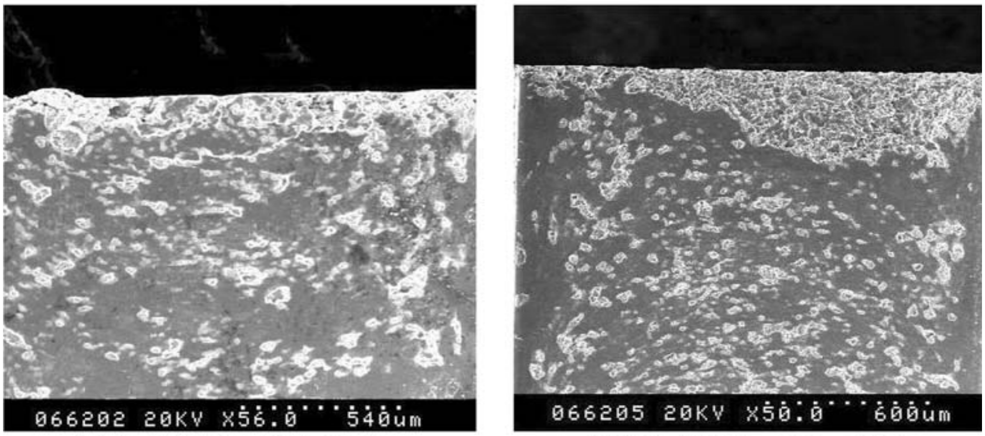
Fig. 5 Ra versus volume fraction of SiC_p in $Al/Si_p + SiC_p$

Fig. 6 SEM micrographs of the machined surfaces of Al/Si_p + SiC_p with different volume fractions of SiC_p and Si_p



(a) 0vol% SiC_p and 65vol% Si_p

(b) 4vol% SiC_p and 61vol% Si_p



(c) 9vol% SiC_p and 56vol% Si_p

(d) 13vol% SiC_p and 52vol% Si_p

Conclusions

(1) Flexural strength and Vickers hardness increase with the increasing volume fraction of SiC_p in Al/Si_p + SiC_p. When 13 vol% silicon particles are replaced by SiC_p with the same volume fraction and the same particle size, the flexural strength and Vickers hardness of the composite can be improved by 20.1% and 23.1%, respectively.

(2) VB increases with the volume fraction of SiC_p. The flank wear mode of the tool is the grain wearing. Taking the milling force, flank wear of the tool, the machined surface roughness and the milled surface integrity all round, the effect of SiC_p on machinability is optimal when 9 vol% Si_p in Al/Si_p was replaced by SiC_p.

(3) Cracks and pits were observed on the machined composite surfaces that were caused by the fragile fracture of silicon particles. This phenomenon

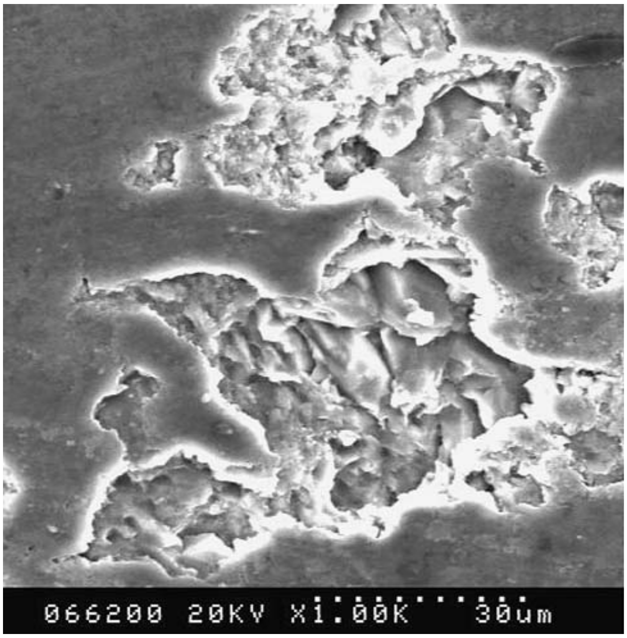


Fig. 7 Pits on machined composite surface

connects with the intrinsic brittleness of silicon particles closely.

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