

Fabrication and properties of SiC_p/Al composites by pulsed electric current sintering

M. J. YANG, D. M. ZHANG*, X. F. GU, L. M. ZHANG

State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, People's Republic of China
E-mail: zhangdongming71@hotmail.com

SiC_p/Al composites have aroused considerable interest in many fields of industrial applications due to their tailorable mechanical properties and tailorable thermo-physical properties. SiC_p/Al composites have been developed mainly as structural materials application in automobile and aerospace industries. However, recent efforts have been focused on thermal management applications in electronic packaging, such as substrates, heat slugs, and heat spreads. Electronic components used in thermal management applications dissipate the heat generated by the semiconductor and reduce thermal stresses caused by the thermal expansion mismatch between electronic packaging components. If volume fractions of SiC particles as high as 70% can be achieved, it is expected that SiC_p/Al composites will have thermal conductivity in excess of 130 W/m·K, and a coefficient of thermal expansion similar to those of alumina substrate or semiconductor, necessary for thermal management materials in electronic packaging applications [1–8].

Generally, the fabrication methods for SiC_p/Al composites are mainly categorized into two kinds: powder metallurgy (PM) and liquid phase method (pressure infiltration, pressureless infiltration, squeeze casting, etc.) [9–11].

The aim of this work was to prepare SiC particles reinforced aluminum matrix composites (SiC_p/Al) by pulsed electric current sintering (PECS) or (Spark Plasma Sintering SPS) with α -SiC particles and pure Al powder without additional sintering aids.

The starting materials used were α -SiC_p with grain size of 30 μ m and purity of 99.5% [Weifang Huamei (China)], and aluminum powder with grain size of 50 μ m and purity of 99.9% [General Research Inst. Nonferrous Metals (China)]. The starting powders were homogeneous blended for 5–7 h [12].

A SPS-1050 system (Sumitomo, Japan) was used for sintering. The mixed powders of α -SiC_p and Aluminum were put into graphite dies of 10, 20 and 32 mm in diameters respectively and without prepressure on the compacts. Thus vacuum, level before sintering should be high enough to avoid residual gas oxidizing mixed powder, typically -5 Pa or lower. The temperature was measured by inserting a thermocouple into the graphite die.

Densities were measured by the Archimedes immersion method. Fracture surface structure was analyzed by a scanning electron microscope (SEM) (QUANTA 400, FEI). Thermal conductivities of the composites were examined by measuring the thermal diffusivity of cylindrical die specimens with 10 mm in diameter and 1–2 mm in thickness, by the laser flash method, with TC-7000H; the coefficient of thermal expansion was obtained by averaging the values measured between room temperature and 100 °C using a thermomechanical analyzer (NETZSCH DIL 402C) with the samples of 23 \times 3 \times 3 mm.

The influences of sintering parameters on relative densities of the compacts of 20 mm in diameter and 4 mm in height were investigated for 33 vol% SiC_p reinforced Al matrix composites (Table I). The mixed powder at 500 °C and 30 MPa could not be sintered; so, higher temperature of 550 °C and the pressure of 30 MPa was adopted, but part of aluminum was melted and sprayed out. The reason may be that the mixed powder in the graphite die was not pressed before sintering, when higher temperature and higher pressure acted on it simultaneously, heterogeneous microstructure may be formed in the compact. So part of Al was melted suddenly and sprayed out along the looser area and had no time to have contact with SiC particles. When lower pressure of 20 MPa, and sintering temperature of 550 °C was applied, the relative density was 96.9%; furthermore, sintered at 580 °C, and pressure of 20 MPa, the relative density of 99.9% was obtained. In order to probe the influence of the temperature and pressure, the sintering process at 600 °C/20 MPa and 600 °C/30 MPa were carried out, but Al sprayed out in both cases. So the best temperature, pressure as well as heating rate for the fabrication of 33 vol% SiC_p/Al composites was 580 °C, 20 MPa and 100 °C/min. The data indicated that although higher temperature and higher pressure usually can fabricate denser specimen, it is not suitable for metal matrix composites with lower melting point fabricated by PECS. Because the melting points of Al and SiC are 660 and 2600 °C, respectively, SiC can not be sintered while Al has already been melted. In this situation, the combination between SiC_p and Al in the composites only depends on the cohesion of Al to SiC particles. So, during the sintering, Al was required to be

* Author to whom all correspondence should be addressed.

TABLE I The sintering results of 33vol% SiC_p/Al composites with die diameter of 20mm

	T (°C)	P (MPa)	Heating-Rate (°C/min)	Relative-density
1	500	30	100	Unsintered
2	550	20	100	Al melting
3	550	20	100	96.9%
4	580	20	100	99.9%
5	600	20	100	Al melting
6	600	30	100	Al melting

TABLE II TC and R-D for different SiC_p/Al composites

SiC _p /Al composites	R-D (%)	TC(W/m·K)
33vol%SiC _p	87.5	120
33vol%SiC _p	99.7	220
46vol%SiC _p	88.0	123
46vol%SiC _p	97.5	201
63vol%SiC _p	94.0	199
63vol%SiC _p	94.6	217

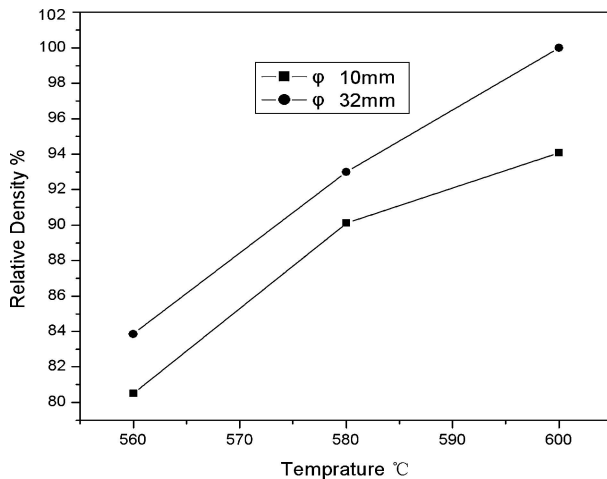


Figure 1 The relative densities of SiC_p/Al composite with die diameters of 10 and 32 mm at different temperatures.

in a state of half liquid and half solid, to adhere the SiC particles together. Thus, much more attention should be paid to the temperature and pressure in sintering process to ensure Al achieves this state.

PECS is an advanced technology different from other fabrication methods. The temperature in the graphite die varied according to the various die diameters, while other sintering conditions were the same. The same phenomena were observed during the sintering of 63 vol% SiC_p/Al composites.

Fig. 1. showed that in order to obtain the similar relative density (R-D), while the other sintering parameters

were the same, powder in Φ 10 mm needed higher temperature than that of in Φ 32mm. It is indicated that the temperature in the sintered body of Φ 32 mm is higher than that in Φ 10 mm, though the surface temperature of the graphite die is observed to be the same.

It has been found by D. M Zhang [13] in the study of the distance between cracks of ZnAl₂-O₄ that the die diameter has influence not only on the periodical temperature distribution but also on the sintering temperature in whole body, and the temperature in sintered body of Φ 20 mm was higher than that in Φ 10 mm, although the surface temperature of die were the same. Such results agreed well with our experiment.

TCs of SiC_p/Al composites were all higher than 190 W/m·K as long as the relative densities (R-D) were high enough (Table II). TCs are higher than those of samples prepared by other methods, Y. L. Wang [14] reported TCs of 110–160 W/m·K by powder metallurgy for 25–40 vol% SiC_p/Al composites; 110–180 W/m·K was reported by H. S. Lee [15] with pressure infiltration for 45–70 vol% SiC_p/Al, 120–130 W/m·K was reported by G.H.Wu [16] with squeeze casting for 60 vol% SiC_p/Al composites, etc. It is valuable for the electronic package application to effectively dissipate the residual heat to render the semiconductor system work longer. Moreover, TCs were nearly independent of various volumes of SiC particles and were similar to each other. Reasons may be that Al forms continuous phase in sintered composites, which dissipate heat energy faster, as shown in Fig. 2b. But for the composites with same components, TCs declined with the decrease in the relative density. The rapid decrease in TC of the corresponding composites is caused by the presence of residual pores. The residual pores disconnect the continuous

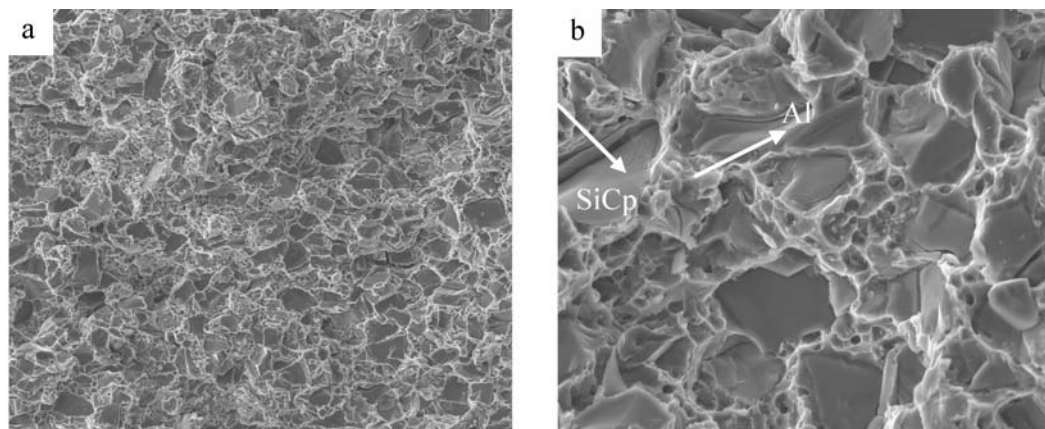


Figure 2 Microstructure of 46 vol% SiC_p/Al composite fabricated by PECS (SEM) indicate that SiC particles are distributed homogeneously in Al matrix (a): 200 \times , (b): 1000 \times).

channels of the Al matrix which are the major conducting paths in metal matrix composites, thus resulting in a rapid decrease in TC with increasing amount of porosity.

CTEs of SiC_p (33, 46, 63 vol%) reinforced Al composites were 15.2, 10.8 and $9.9 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$, respectively. They declined with increasing volume of SiC particles. It is known that in SiC_p/Al composites, the thermal expansion behavior is influenced by the thermal expansion of Al matrix as well as SiC particles. Since the thermal expansion of SiC particles is lower, the thermal expansion for the composites will decrease with increasing volume of SiC particles. The results indicated that CTEs of SiC_p/Al composites could be controlled by varying the volume of SiC particles. But the decreases were not obvious. The reason may be that in samples fabricated by PECS, SiC particles do not bind tightly and aluminum fills into the gaps of SiC particles (Fig. 2b); thermal expansion of composites is mainly dependent on thermal expansion behavior of Al matrix, and not on the SiC particles.

All the results show that the fabrication parameters (T, P) play an important role in the sintering of SiC_p/Al composites; temperature of sintered body with larger graphite dies is higher than that with smaller, though the surface temperature of dies are observed to be the same. Because of the synthesis mechanism, TCs of composites are high and CTEs decline with increasing volume fraction of SiC particles.

Acknowledgment

This work was financially supported by National Natural Science Foundation of China (50232020).

Reference

1. C. HEMAMBAR, B. S. RAO and V. JAYARAM, *Mater. Manuf. Processes* **16** (2001) 779.
2. R. F. JEFFRIES and D. J. BURROWS, *Geol. J. Res.* **3** (1994) 150.
3. K. HANADA, K. A. KHOR and M. J. TAN, *J. Mater. Process. Technol.* **67** (1997) 8.
4. G. TIMMERMANS and L. FROYEN, *Wear* **230** (1999) 105.
5. B. K. HWU, S. J. LIN and M. T. JAHN, *Mater. Sci. Eng. A* **207** (1996) 135.
6. Y. H. QING, *Light Metals* **7** (2003) 49.
7. Q. ZHANG, D. L. SUN and G. H. WU, *Mater. Sci. Technol.* **8** (2000) 66.
8. Q. ZHANG, *Microelec. Technol.* **27** (1999) 30.
9. Z. C. LIU, Z. F. WANG and G. S. JIANG, *Ordnance Mater. Sci. Eng.* **24** (2001) 51.
10. Q. HUANG and M. Y. GU, *Elec. Pack.* **10** (2003) 23.
11. H. S. LEE and S. H. HONG, *Mater. Sci. Technol.* **19** (2003) 1057.
12. J. Z. FAN, *Mater. Eng.* (1997) 42.
13. D. M. ZHANG, *J. Mater. Sci. Technol.* **19** (2003) 3.
14. Y. L. WANG, *Composites.* **30** (1997) 507.
15. H. S. LEE and S. H. HONG, *Mater. Sci. Technol.* **19** (2003) 1063.
16. G. H. WU and Q. ZHANG, *Elec. Mater.* **6** (2003) 28.
17. Q. HUANG, *J. Mater.* **9** (2000) 29.

Received 24 November 2004

and accepted 2 May 2005