

Microstructure and electric properties of Si_p/Al composites for electronic packaging applications

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Abstract: Si_p/1199, Si_p/4032 and Si_p/4019 environment-friendly composites for electronic packaging applications with high volume fraction of Si particles were fabricated by squeeze-casting technology. Effects of microstructure, particle volume fraction, particle size, matrix alloy and heat treatment on the electrical properties of composites were discussed, and the electrical conductivity was calculated by theoretical models. It is shown that the Si/Al interfaces are clean and do not have interface reaction products. For the same matrix alloy, the electrical conductivity of composites decreases with increasing the reinforcement volume fraction. As for the same particle content, the electrical conductivity of composites decreases with increasing the alloying element content of matrix. Particle size has little effects on the electrical conductivity. Electrical conductivity of composites increases slightly after annealing treatment. The electrical conductivity of composites calculated by P.G model is consistent with the experimental results.

Key words: Si/Al composite; microstructure; electric conductivity; electronic packaging

1 Introduction

For W/C[1–2], Mo/Cu[3] and SiC_p/Al[4–6] electronic packaging composites, poor machining properties hindered their extensive applications. The Si_p/Al composites developed recently have been adopted due to their low expansion coefficient ($(7.4\text{--}9.0)\times 10^{-6}/^{\circ}\text{C}$), high thermal conductivity ($100\text{--}180\text{ W}/(\text{m}\cdot^{\circ}\text{C})$), low density ($2.4\text{--}2.6\text{ g}/\text{cm}^3$), and excellent machining property after melting, which attracts more attention in the development of metal matrix composites[7–12].

Si_p/1199, Si_p/4032 and Si_p/4019 environment friendly composites for electronic packaging applications with large content of Si particles were fabricated by squeeze-casting technology. Effects of microstructure, particle content, particle size, matrix alloy and heat treatment on the electric properties of composites were discussed, and the electrical conductivity of composites was also calculated by theoretical models.

2 Experimental

The specimens were divided into as-cast and as-annealed states. Matrix 1199 was annealed at 340 °C for 3 h and furnace cooled, and for 4032 and 4019 alloy matrix, the process was 410 °C, 3 h and furnace cooling. The volume fraction of reinforcement Si particles was 55%–65%.

The microstructure was observed using a JEOL 200CX transmission electron microscope (TEM). The specimens were thinned using a Gattan-600 ion mill at 5 kV and 1 mA. The electrical conductivity was measured on digital eddy-current conduct meter SIGMATEST 2.068 made in Germany. The specimens with a size of 20 mm×20 mm×2 mm were abraded with sand paper. The testing frequency was 60 kHz.

3 Results and discussion

3.1 Microstructures

Fig.1 shows the TEM and HREM (high resolution

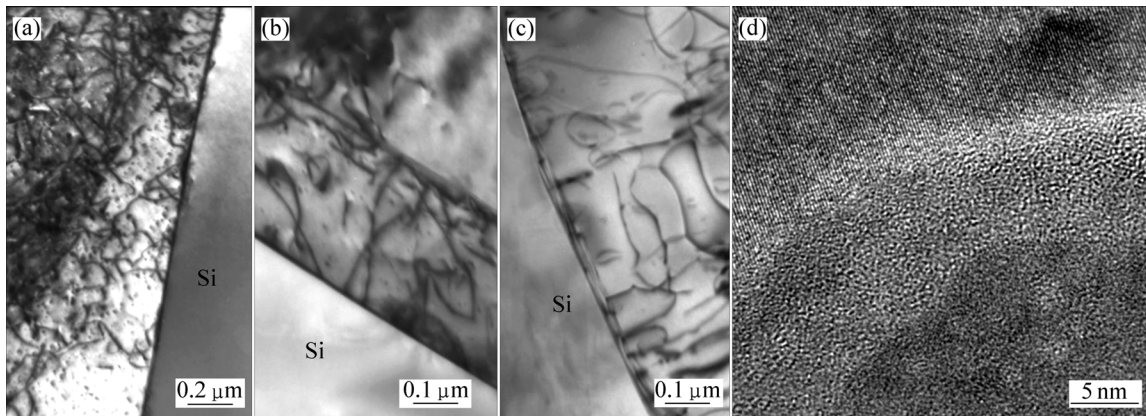


Fig. 1 TEM micrographs of interfaces in Si_p/Al composites: (a) 10 μm, 65%Si_p/1199; (b) 10 μm, 65%Si_p/4032; (c) 10 μm, 65%Si_p/4019

electron microscope) micrographs of the interfaces in Si_p/Al composites. As shown in Fig.1, the interfaces were straight, clean and without any reactant. It can also be seen that no particles dissolved. The dislocations were formed at the interfaces and the density of them was higher than other zones. One end of the dislocations connected with the interface, and the other was the free end and extended perpendicular to the interfaces. It can also be confirmed by the EDS line scanning of the Si/Al interfaces in Fig.2. The Si and Al content curve was very steep at the interfaces, and the peak-valley transformation was achieved in very short distance. Electrical conductivity of metal matrix composites was realized by free electron. And the directional transferring of electron was weakened by the interface, which led to the decrease of the electrical conductivity. But this kind of interface was clean, straight and combined compactly. Compared with other composites, clean and straight interfaces decreased the interface reactant, which hindered the movement of electron. Therefore, the interfaces effectively reduced the hindrance to the current, which was an important reason why the electrical conductivity of Al-Si composites was excellent.

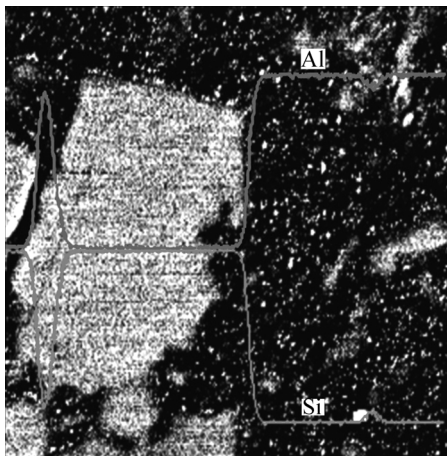


Fig.2 EDS pattern of Si_p/1199 composite

3.2 Effect of Si content on electrical conductivity

Metal matrix composites can be regarded as the materials which were reinforced with insulations, so the electrical conductivity of interfaces can be ignored. Fig.3 shows the electrical conductivity of Si_p/Al composites related to silicon content. It can be seen that when the matrix was the same, the electrical conductivity of Si_p/Al composites decreased with the increase of silicon content.

Within the Si_p/Al composites, the addition of lots of weak electrical conductivity Si particles would cause the electrical conductivity of the whole Si_p/Al composites to decrease (the electrical conductivity of Si was 3.3×10^{-10} MS/m and the electrical conductivity of pure Al was 36 MS/m). Meanwhile, the addition of silicon also degrades the integrality of matrix alloy lattice, which boosted the scattering of electron and electrical resistance formed. And lots of interfaces introduced will hinder the directional movement of electron, which led to the decrease of composite electrical conductivity.

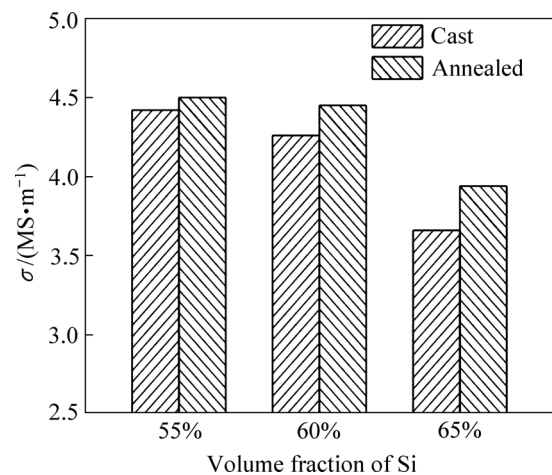


Fig.3 Effect of volume fraction of Si particle on electric conductivity of Si_p/LD11 composites

3.3 Effect of Si particle size on electrical conductivity

Fig.4 shows the electrical conductivity of Si_p/Al composites related to silicon particle size. It can be seen that the electrical conductivity of Si_p/Al composites decreased slightly with the increase of silicon size, but the decreasing was not very obvious, generally within 5%. The electrical conductivity of materials was related to its microstructure[13]. When the silicon particle content was the same, the larger the particle size, the smaller the effect of scattering on electron was, and the higher the electrical conductivity should be. But the particles in this study were fabricated by mechanical crushing method, and the geometrical shape was not regular, therefore, the microstructure of fabricated composites can not be uniform absolutely; on the other hand, the experimental conditions were limited, and all these led to the results in the Fig.4.

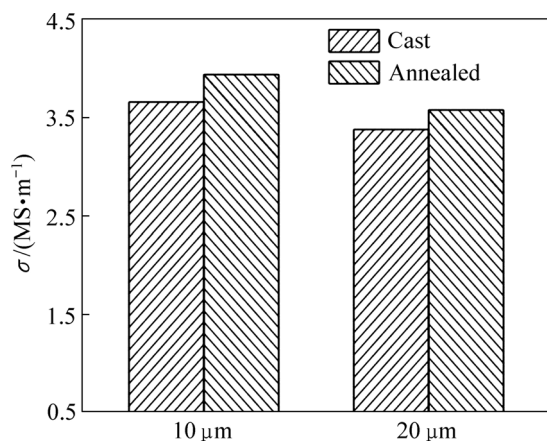


Fig.4 Effect of Si particle size on electrical conductivity of composites

3.4 Effect of matrix alloy on electrical conductivity

Different alloying elements in the matrix of composites generally had different the electrical conductivity. Fig.5 shows the electrical conductivity of composites with the silicon content of 65% after annealing. The electrical conductivity of composites was the lowest with matrix alloy of 4019, and the highest with 1199.

3.5 Effect of heat treatment on electrical conductivity

The electrical conductivity of metal matrix composites differed with the heat treatment methods, as shown in Fig.3. The electrical conductivity of Si_p/Al composite increased after annealing treatment. Among these, the electrical conductivity of Si_p/4032 composite after annealing with volume fraction of 55% increased by 1.8%, for volume fraction of 60%, increased by 4.6%, and for volume fraction of 65%, increased by 7.65%.

The electrical conductivity of materials was sensitive to the structure of material. Crystal defects and

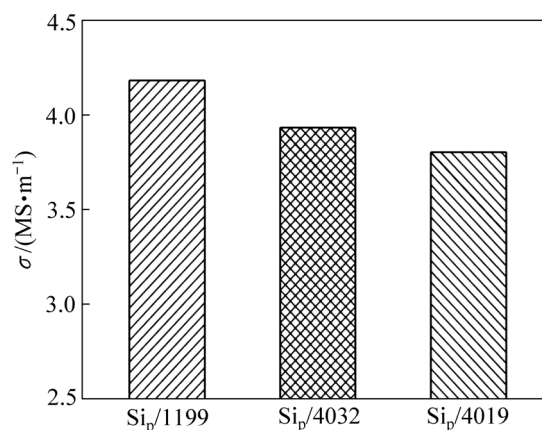


Fig.5 Effect of matrix alloy on electrical conductivity of Si_p/Al composites

lattice distortion in the matrix have an important effect on the electrical conductivity. The main objective of annealing treatment was to eliminate dislocations and lattice distortions maximally, which could lead to the mean free path of carriers motion in the electric field increased, as a result, increased the electrical conductivity. The ascension amplitude was different after annealing due to the different content of the reinforcement, which was related to disperse phase consolidation. The dislocations and lattice distortions in the matrix alloy increased with the reinforcement content, but the increasing of the defect was not linear; therefore, the increase of the electrical conductivity after defect elimination was not linear.

3.6 Theoretical calculation

The electrical conductivity of the matrix in the composites was transferred by free electron, whereas the reinforcement was by phonons and its carries[14–15]. There are following three classical electrical conductivity calculation equations:

1) Maxwell model: the expression of calculating the electrical conductivity of particulate reinforced metal matrix composite was given by

$$\sigma_{\text{com}} = \sigma_m \frac{1 + 2 \frac{\sigma_m}{\sigma_p} - 2\varphi_p \left(\frac{\sigma_m}{\sigma_p} - 1 \right)}{1 + 2 \frac{\sigma_m}{\sigma_p} + 2\varphi_p \left(\frac{\sigma_m}{\sigma_p} - 1 \right)} \quad (1)$$

where σ_{com} , σ_m and σ_p are electrical conductivities of composite, matrix and particles; φ_p is the volume fraction of particle.

Due to the low electrical conductivity of silicon, in a level of 10^{-10} magnitude (3.3×10^{-10} MS/m), we have $\sigma_p/\sigma_m = 0$, and the equation can be simplified as

$$\sigma_{\text{com}} = \sigma_m \frac{1 - \varphi_p}{1 + \varphi_p} \quad (2)$$

2) P.G model: the equation of calculating the effective electrical conductivity was expressed as

$$\sigma_{\text{com}} = \sigma_m (1 - \varphi_p) + \sigma_p \varphi_p - \frac{1}{3} (1 - \varphi_p) \varphi_p \frac{(\sigma_m - \sigma_p)^2}{\sigma_m (1 - \varphi_p) + \sigma_p \varphi_p} \quad (3)$$

For the same reason, $\sigma_p/\sigma_m=0$, and the expression above can be simplified as

$$\sigma_{\text{com}} = \sigma_m \left(1 - \frac{4}{3} \varphi_p \right) \quad (4)$$

3) Equivalent medium approximate model (EMA model): a theoretical expression of calculating electrical conductivity of composites was given by

$$\sigma_{\text{com}} = \sigma_m \frac{\left[2 \left(\frac{\sigma_p}{\sigma_m} - 2 \frac{\sigma_p R_{\text{Bd}}}{d} - 1 \right) \varphi_p + \frac{\sigma_p}{\sigma_m} + 2 \frac{\sigma_p R_{\text{Bd}}}{d} + 2 \right]}{\left[\left(1 - \frac{\sigma_p}{\sigma_m} + 2 \frac{\sigma_p R_{\text{Bd}}}{d} \right) \varphi_p + \frac{\sigma_p}{\sigma_m} + 2 \frac{\sigma_p R_{\text{Bd}}}{d} + 2 \right]} \quad (5)$$

where R_{Bd} is the electrical resistance at the interface; d is the particles diameter.

Since the matrix/reinforcement interfaces provide little contribution to the conductivity of metal matrix composites, the value of R_{Bd} can be considered infinite. Therefore, Eqn.(5) can be expressed as

$$\sigma_{\text{com}} = \sigma_m \frac{(2\varphi_p + 1) \frac{\sigma_p}{\sigma_m} + 2(1 - \varphi_p)}{(1 - \varphi_p) \frac{\sigma_p}{\sigma_m} + 2 + \varphi_p} \quad (6)$$

Also, $\sigma_p/\sigma_m = 0$, the expression above can be expressed as

$$\sigma_{\text{com}} = \sigma_m \frac{2(1 - \varphi_p)}{2 + \varphi_p} \quad (7)$$

The electrical conductivity of Si is 3.3×10^{-10} MS/m, while that of 1199 is 36 MS/m, and the electrical conductivities of 4032 and 4019 are 19.33 MS/m and 11.48 MS/m. The electrical conductivity calculated with Eqns.(3), (5) and (8) and the measured are shown in Table 1.

Table 1 Predicted and experimental electric conductivities of Si_p/Al composites (MS/m)

Material	Maxwell model	P.G model	EMA	Measurement
10 μm 65%Si _p /1199	7.64	4.80	9.51	4.19
10 μm 55%Si _p /4032	5.61	5.15	6.82	4.5
10 μm 60%Si _p /4032	4.83	3.87	5.95	4.45
10 μm 65%Si _p /4032	4.10	2.58	5.11	3.94
10 μm 65%Si _p /4019	2.44	1.53	3.03	3.58
20 μm 65%Si _p /4032	4.10	2.58	5.11	3.81

The results obtained were shown as follows:

1) The electrical conductivity calculated with EMA model was the highest, that with Maxwell model was the middle, while P.G model the lowest. For the three models, the trends were the same to three composites, that was, when matrix alloy was the same, the electrical conductivity of Si_p/Al composites decreased with the increase of alloying silicon content; and when the particle content was the same, the electrical conductivity decreased with the increase of element content of matrix, whereas the particle size had little effect on the conductivity.

2) Compared with the measured values, the results of P.G model was closer to the tests, especially for the 10 μm 65%Si_p/1199 and 10 μm 60%Si_p/4032. But, it can be seen that these models are either higher or lower than tests because they considered the particles as spherical approximately, whereas in fact the particle shape is irregular geometric polyhedrons. In addition, they ignored the effects of particle size and the stacking mode on the electrical conductivity.

4 Conclusions

1) Si_p/1199, Si_p/4032 and Si_p/4019 environmentally friendly composites for electronic packaging applications with high volume fraction of Si particles were fabricated by squeeze-casting technology.

2) Si/Al interfaces are straight and clean without any reaction products and dissolved particles, which is beneficial to the electrical conductivity.

3) The increased Si content with matrix alloying decreases the electrical conductivity of Si_p/Al composites; the increase of Si volume fraction decreases slightly the conductivity, generally within 5%; with increasing the volume fraction and particle size, the electrical conductivity decreases.

4) The electrical conductivity of composite increases after annealing treatment.

5) The results of P.G model calculated are in

agreement with the experimental data.

References

- [1] SABBAAH A, MARCUS K, ESSAM E M. Effects of the deformed volume and the volume fraction on the local deformation behavior of W/Cu composites[J]. Key Engineering Materials, 2006, 345/346: 1205–1208.
- [2] CHEN Wen-ge, KANG Zhan-ying, DING Bing-jun. Preparation and arc breakdown behavior of nanocrystalline W-Cu electrical contact materials[J]. Journal of Materials Science and Technology, 2005, 21: 875–878.
- [3] CHEN Guo-qin, JIANG Long-tao, WU Gao-hui, SUN Dong-li. Fabrication and thermal expansion properties of high dense Mo/Cu composites[J]. Journal of Harbin Institute of Technology 2005, 37: 195–197. (in Chinese)
- [4] PECH-CANUL M I, KATZ R N, MAKHLOUF M M. Optimum conditions for pressureless infiltration of SiC_p preforms by aluminum alloys[J]. Journal of Materials Processing Technology, 2000, 108: 68–77.
- [5] YAN Yi-wu, GENG Lin. Effects of particle size on the thermal expansion behavior of SiC_p/Al composites[J]. Journal of Materials Science, 2007, 42: 6433–6438.
- [6] LUO Z P, SONG Y G, ZHANG S Q. A TEM study of the microstructure of SiC_p/Al composite prepared by pressureless infiltration method[J]. Scripta Materialia, 2001, 45(10): 1183–1189.
- [7] CHIEN C W. Effects of Si_p size and volume fraction on properties of Al/Si_p composites[J]. Materials Letters, 2002, 12(2): 334–341.
- [8] HASSELMAN D P H, LLOYD F J. Effective thermal conductivity of composites with interfacial thermal barrier resistance[J]. Journal of Composites, 1987, 21(6): 508–515.
- [9] WU Gao-hui, XIU Zi-yang, SUN Dong-li, ZHANG Qiang, SONG Mei-hui. Study on properties of the environmental-friendly Si_p/Al composites for electronic packaging applications[J]. Material Science and Technology, 2006, 14: 244–246, 250. (in Chinese)
- [10] XIU Zi-yang, WU Gao-hui, ZHANG Qiang, SONG Mei-hui. Thermo-physical properties of Si_p/4032 composites for electronic packaging[J]. Trans Nonferrous Met Soc China, 2005, 15(2): 227–230.
- [11] WU Gao-hui, ZHANG Qiang, CHEN Guo-qin. Properties of high-reinforcement-content aluminum matrix composite for electronic packages[J]. Journal of Materials Science–Materials in Electronics, 2003, 14(1): 9–12.
- [12] ZHANG Qiang. Microstructure and properties of a 70vol.% SiC_p/Al-12Si composite for electronic packaging[J]. Materials Science Forum, 2005, 475: 881–884.
- [13] XIONG D S, PENG C Q, HUANG Q Z. Development of MoS₂-containing Ni-Cr based alloys and their high-temperature tribological properties[J]. Trans Nonferrous Met Soc China, 1998, 8(2): 226–229.
- [14] WU Gao-hui, XIU Zi-yang, ZHANG Qiang. Properties of the environmental-friendly Si/Al composite for electronic packages fabricated by squeeze casting technology[J]. Journal of Shanghai Jiaotong University, 2007, 41: 144–149.
- [15] WANG Y Q, ZHOU B Y. Mechanism of formation of TiB₂ particulates prepared by in situ reaction in molten aluminum[J]. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science, 1998, 29(3): 635–640.

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