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Microstructure and thermal conduction properties of an Al-12Si matrix composite reinforced with dual sized SiC particles

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Aluminum matrix composites with a large reinforcement content have drawn much attention in electronic packaging and thermal management applications [1–4]. In these applications, a high thermal conductivity is necessary to remove excess heat and keep the operating temperature low since the reliability of electronic components decreases sharply as temperature increases. During fabrication of a high reinforcement content composite, a mixture of different sized particles is often used [2, 5], but its effect on the thermal properties of the composite is seldom considered.

The present work deals with the microstructural characterization and thermal conduction properties of an Al-12Si matrix composite reinforced with 70 vol% SiC particles of two sizes, with an emphasis on the effect of dual sized particles on thermal conductivity. The microstructural features associated with heat conduction are also discussed.

The packing density of particles is of great importance to the fabrication of a high reinforcement content composite. If different sized particles are mixed together, an increased packaging density can be achieved because smaller particles can pack more efficiently around larger ones. Accordingly, SiC particles of 20 μm and 60 μm with a weight ratio of 4:1 were used in this work in order to obtain a volume fraction of 0.7. The matrix was an Al-12Si alloy, for which the nominal composition is listed in Table I. This alloy was chosen for its good casting fluidity and balance of thermal and mechanical properties. The composite was fabricated by squeeze casting technology [6], including the infiltration of molten alloy into a SiC perform and the solidification of the composite under pressure.

The microstructural observations were performed using a S-570 scanning electron microscope and a Jeol 200CX transmission electron microscope (TEM) operated at 200 kV. The samples for TEM observation were pre-thinned to 50 μm by mechanical polishing, followed by final ion thinning using a Gatan-600 ion beam thinning machine. The thermal conductivity measurement was carried out using a TCT 416 (Netzsch Corp.). Fig. 1 shows a schematic diagram of the instrumentation. A rod shaped sample, 6 mm in diameter and 35 mm long, is surrounded by a constant temperature ($T_U = 25\,^\circ$C), and heat is fed via the heater block ($T_H = 60\,^\circ$C) to the lower face of the sample. When the temperature T_2 of the lower surface of the sample and the temperature T_1 of the upper surface equilibrate, the thermal conductivity can be calculated. To reduce systematic errors, the equipment was calibrated by measuring a pure aluminum sample under identical conditions.

TABLE I Chemical composition of aluminum-silicon matrix (wt%)

Element	Si	Cu	Mg	Fe	Ni	Zn	Al
Matrix	12	0.5–1.3	0.8–1.3	1.0	0.5–1.3	0.25	Bal.

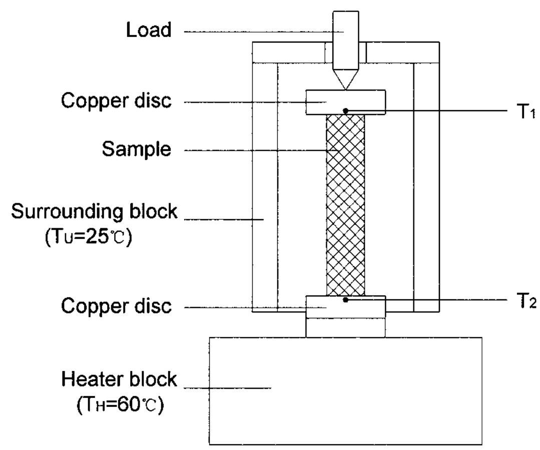

Figure 1 Schematic diagram of thermal conductivity instrumentation.

The microstructure of the as-fabricated SiCp/Al composite is shown in Fig. 2. It was found that fine SiC particles occupied the interstitial positions between larger ones and that the particles were distributed uniformly, without any particle clustering. As a result of the high pressure during the solidification process, a dense microstructure was obtained. This was helpful for the improvement of heat conduction.

Fig. 3 is a representative TEM micrograph of the SiCp/Al composite. The silicon in the matrix has adhered to a SiC particle, suggesting that SiC acted as a preferential nucleation site for silicon. Heavy twinning was also observed in the upper part of the silicon phase. In SiCp/Al-Si composites, the possibility of Si nucleating on SiC particles was confirmed through thermodynamic and crystal structural analysis [7, 8].

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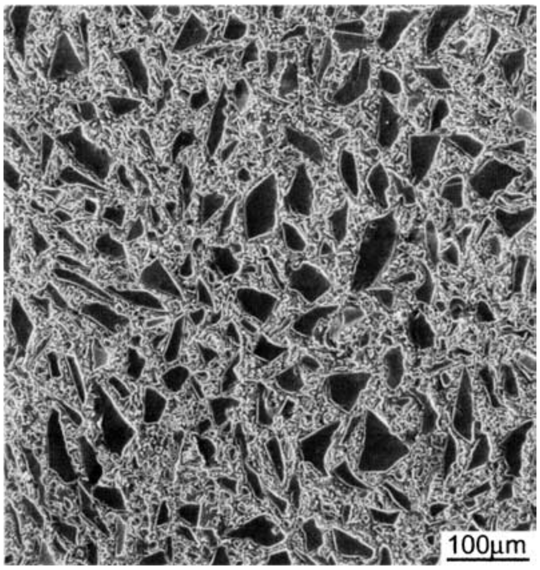

Figure 2 SEM micrograph of as-fabricated SiCp/Al composite.

Furthermore, previous calculations indicated that the work of adhesion of Si-SiC was larger than that of Si-Al and Al-SiC in SiC/Al-Si systems [7]. Thus, the nucleation of silicon on SiC particles could create a better bonded interface. An interface between SiC-Al is shown in Fig. 4. The interface is clean and free from any interfacial reaction products.

The measured thermal conductivity of the SiCp/Al composite was 151 W/(m·K) ($T_1 = 52.0\,^{\circ}$C and $T_2 = 54.9\,^{\circ}$C). Compared with that, the thermal conductivity of the unreinforced matrix was only 140 W/(m·K) ($T_1 = 51.8\,^{\circ}$C and $T_2 = 54.8\,^{\circ}$C). In general, the thermal conductivity of a composite varies with the thermal conduction properties, type, content, and distribution of different constituent components [1, 4, 9–12]. However, an interfacial resistance would be generated as a result of a poor mechanical or chemical bond and a thermal expansion mismatch between components [4, 10, 12–14]. Hasselman *et al.* derived an effective medium approximation (EMA) to solve this problem [10, 12]. For spherical dispersions, the effective thermal

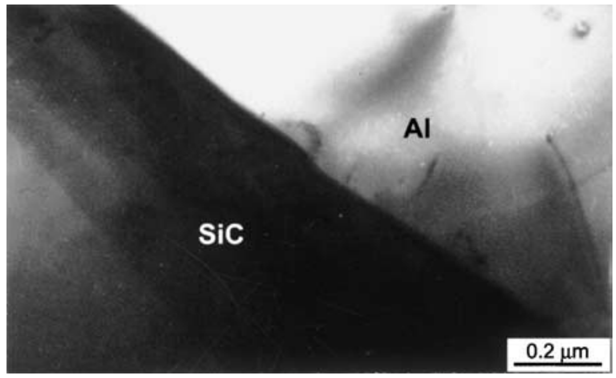

Figure 4 TEM micrograph of interface between SiC and Al.

conductivity of a composite is given by:

$$K_{\mathrm{com}} = K_{\mathrm{m}} \frac{\left[K_{\mathrm{P}}\left(1 + 2\frac{2R_{\mathrm{Bd}}K_{\mathrm{m}}}{d}\right) + 2K_{\mathrm{m}}\right] + 2V_{\mathrm{P}}\left[K_{\mathrm{P}}\left(1 - \frac{2R_{\mathrm{Bd}}K_{\mathrm{m}}}{d}\right) - K_{\mathrm{m}}\right]}{\left[K_{\mathrm{P}}\left(1 + 2\frac{2R_{\mathrm{Bd}}K_{\mathrm{m}}}{d}\right) + 2K_{\mathrm{m}}\right] - V_{\mathrm{P}}\left[K_{\mathrm{P}}\left(1 - \frac{2R_{\mathrm{Bd}}K_{\mathrm{m}}}{d}\right) - K_{\mathrm{m}}\right]} \quad (1)$$

where K is thermal conductivity, R_{Bd} is interfacial resistance, V is volume fraction, d is the diameter of the reinforcement, and subscripts com, P and m are composite, reinforcement particle and matrix, respectively.

It was demonstrated that EMA theory was applicable to composites with single sized reinforcements [4, 10, 12]. However, dual sized particles were used in this work. Hence, based on equal specific interfacial areas, an equivalent particle size (d_e) was introduced in this paper.

On the assumption that the particle is a sphere, the specific interfacial area (I) in a particle reinforced composite is expressed as:

$$I = \frac{6V}{d} \quad (2)$$

In the case of mixed particles with dual sizes of d_1 and d_2, the specific interfacial area of the composite is

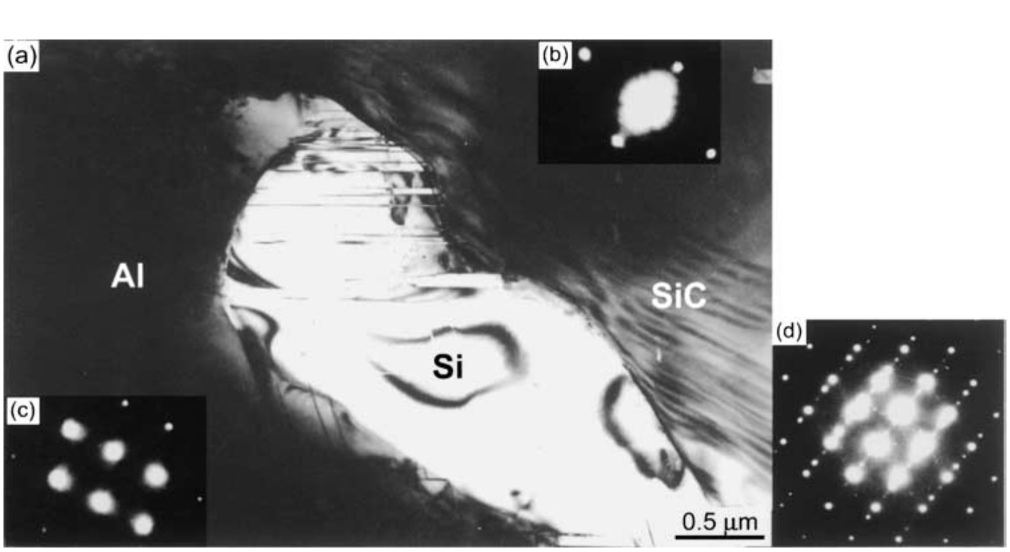

Figure 3 (a) TEM micrograph of SiCp/Al composite, (b) diffraction pattern of SiC [112], (c) diffraction pattern of Al [110], and (d) diffraction pattern of Si [110] obtained from the upper part of the silicon region.

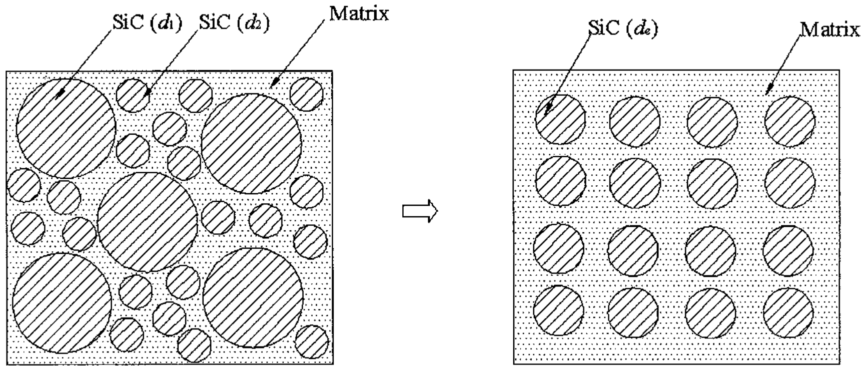

Figure 5 Schematic diagram illustrating the conversion from a dual size composite to one with spheres of the equivalent diameter, d_e.

denoted as I and given by:

$$I' = \frac{6V_1}{d_1} + \frac{6V_2}{d_2} \quad (3)$$

where V_1 and V_2 are the volume fraction of particle d_1 and particle d_2, respectively.

As shown in Fig. 5, equating the specific interfacial areas in the two cases, so that $I = I'$, gives the equivalent particle size (d_e) as:

$$d_e = \frac{(V_1 + V_2)d_1 d_2}{V_1 d_2 + V_2 d_1} \quad (4)$$

The d_e combines the effect of the two sizes. By replacing the d in Equation 1 with d_e, the effective thermal conductivity of the composite with dual sized reinforcements can be calculated.

In this work, the SiC particles were a mixture of 20 μm and 60 μm with a weight ratio of 4:1. This gives a d_e of 23 μm. The SiC particles had a thermal conductivity of 160–180 W/(m·K) [1, 4]. Thus, taking R_{Bd} as 0.685×10^{-8} m^2·K/W for Al-SiC systems [4, 10, 12], results in a calculated k_{com} of 144–156 W/(m·K) for the composite. The calculated value agrees well with the experimental value, suggesting that the modified EMA with an equivalent particle size was valid in the case of a dual sized particle reinforced composite.

According to EMA theory, the variation of k_{com} as a function of d_e is shown in Fig. 6. It is clear that an increase in d_e would improve the thermal conductivity of the composite because of the lessening effect of interfacial resistance.

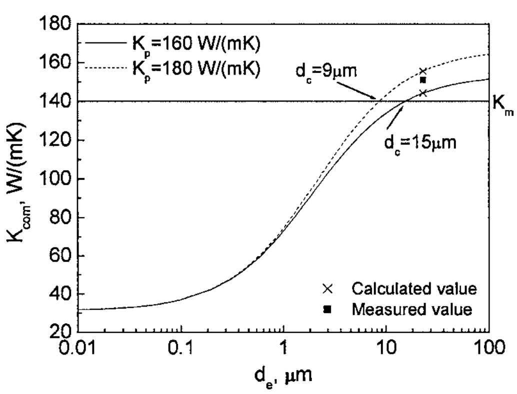

Figure 6 Variation of thermal conductivity of SiC/Al composite with d_e.

A critical diameter (d_c) at which K_{com} is equal to K_m can be determined according to Equation 5:

$$d_c = \frac{2R_{Bd}K_m}{1 - K_m/K_P} \quad (5)$$

Using this equation, a d_c of 9–15 μm was obtained. In this work, SiC particles had a d_e of 23 μm, suggesting that it was possible that k_{com} was larger than k_m.

In summary, an Al-Si matrix composite reinforced with 70 vol% SiC particles of two sizes was produced in this work. The composite was dense and porosity-free macroscopically. TEM observations indicated that the composite was free from interfacial reaction products and SiC acted as heterogeneous nucleation sites for Si phases in the matrix. The composite had a better thermal conductance than the unreinforced matrix. Based on equal specific interfacial areas, an equivalent particle size was introduced to the effective medium approximation and the thermal conductivity of the composites was calculated. The theoretical value agreed well with the experimental data.

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