JOURNAL OF MATERIALS SCIENCE **35** (2000) 6231 – 6236

Fabrication process and thermal properties of SiC_p/Al metal matrix composites for electronic packaging applications

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The fabrication process and thermal properties of 50–71 vol% SiC_p/Al metal matrix composites (MMCs) for electronic packaging applications have been investigated. The preforms consisted with 50–71 vol% SiC particles were fabricated by the ball milling and pressing method. The SiC particles were mixed with SiO_2 as an inorganic binder, and cationic starch as a organic binder in distilled water. The mixtures were consolidated in a mold by pressing and dried in two step process, followed by calcination at 1100 °C. The SiC_p/Al composites were fabricated by the infiltration of Al melt into SiC preforms using squeeze casting process. The thermal conductivity ranged 120–177 W/mK and coefficient of thermal expansion ranged $6–10 \times 10^{-6}$/K were obtained in 50–71 vol% SiC_p/Al MMCs. The thermal conductivity of SiC_p/Al composite decreased with increasing volume fraction of SiC_p and with increasing the amount of inorganic binder. The coefficient of thermal expansion of SiC_p/Al composite decreased with increasing volume fraction of SiC_p, while thermal conductivity was insensitive to the amount of inorganic binder. The experimental values of the coefficient of thermal expansion and thermal conductivity were in good agreement with the calculated coefficient of thermal expansion based on Turner's model and the calculated thermal conductivity based on Maxwell's model. © *2000 Kluwer Academic Publishers*

1. Introduction

Metal matrix composites have been recently developed for electronic packaging application due to their attractive combination of physical properties, manufacturing flexibility and relatively inexpensive cost. One advantage of metal matrix composites is the ability to tailor the thermal properties, such as thermal conductivity and coefficient of thermal expansion, through the proper control of reinforcement and matrix. In addition, the manufacturing flexibility of the metal matrix composite by various processes allows the fabrication of complicated shaped parts [1–5].

The metal matrix composites for electronic packaging application have been actively investigated since late 1980's and several electronic packaging components have been commercialized using metal matrix composites. The SiC/Al, diamond/Cu, and silver/nickel-iron are the important candidate materials for electronic packaging applications [6]. Lanxide Electronic Component Inc. developed the microwave housing with SiC_p/Al metal matrix composite, which is only one third in weight and has 6 times higher thermal conductivity compared to conventional microwave housing [7]. Textron Special Material Inc. developed the heat sink in printed circuit board using the B/Al metal matrix composites [8], and PCast Co. developed the multichip module using SiC_p/Al metal matrix composites [9].

In order to use the metal matrix composite for electronic packaging application, it is very important to increase the volume fraction of ceramic reinforcement to over 50 vol% to reduce the coefficient of thermal expansion comparable to that of alumina substrate or semiconductor such as silicon and gallium arsenide, which coefficient of thermal expansion is ranged 6–7 ppm/K. The fabrication of metal matrix composites with high volume fraction of ceramic reinforcement above 50 vol% is not easy due to the agglomeration of reinforcements and the pore formation in agglomerated reinforcements.

In this study, the fabrication process of 50–71 vol% SiC_p/Al metal matrix composites for electronic packaging applications was investigated. The thermal properties, coefficient of thermal expansion and thermal conductivity, and microstructures of high volume fraction SiC_p/Al composites were characterized.

2. Experimental procedures

SiC_p preforms consisting of a high volume fraction of SiC particles above 50% were fabricated by the ball milling and pressing process. Two different sizes of

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SiC particles, 48 μm and 8 μm, were wet mixed with 0.5–3% of SiO_2 as inorganic binder, 1% of cationic starch as organic binder and distilled water in a ball mill. The mixtures were ball milled using Al_2O_3 ball of 5 mm in diameter at 50 rpm for 12 h. The ball milled mixtures were consolidated into preforms using a cylindrical mold of 30 mm in diameter by pressing with 1.2 MPa at room temperature. The consolidated SiC$_p$ preforms were dried in a two step process and followed by calcination at 1100 °C for 2–6 h. The strengths of calcined SiC$_p$ preforms were evaluated by compression tests at room temperature. The distribution of SiC particles and residual inorganic binders in preform were observed by scanning electron microscope.

The Al melt was infiltrated into SiC$_p$ preforms to fabricate SiC$_p$/Al metal matrix composites by squeeze casting process. The squeeze casting was performed by infiltration of Al melt at 800 °C into SiC$_p$ preforms preheated to 750 °C with pressure of 50 MPa for 30 seconds. Densities of squeeze cast SiC$_p$/Al composites were measured by the Archimedes water immersion method. Thermal conductivities of squeeze cast SiC$_p$/Al composites were measured by laser flash method and coefficients of thermal expansion (CTE) were measured by thermomechanical analysis (TMA). The distribution of SiC particles and residual binders in squeeze cast SiC$_p$/Al composite were observed by the scanning electron microscope.

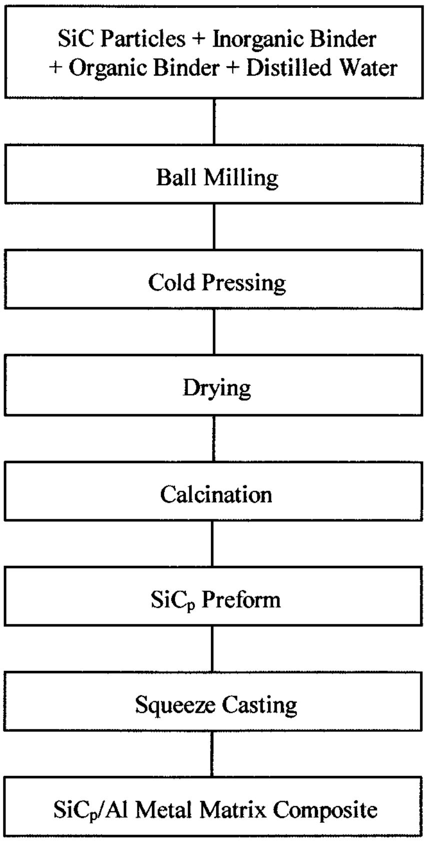


Figure 1 Flowchart on the fabrication process of SiC$_p$/Al metal matrix composite.

3. Results and discussion

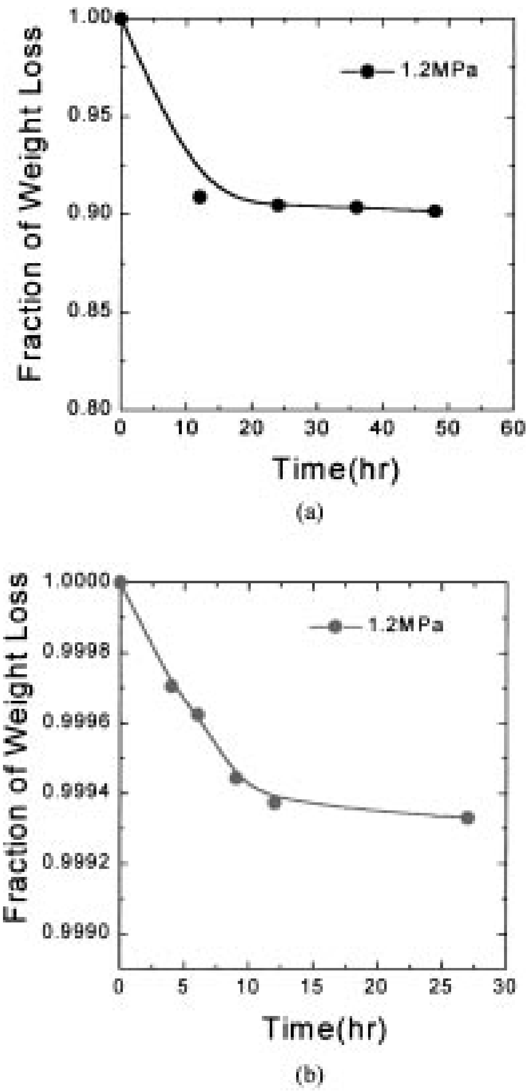
3.1. Fabrication process

The fabrication process of SiC$_p$/Al metal matrix composites consisted with the fabrication of SiC$_p$ preform and the squeeze casting of Al melt into SiC$_p$ preform. Fig. 1 shows the flow chart on the fabrication process of SiC$_p$/Al metal matrix composites. The SiC$_p$ preforms consisted with high volume fraction of SiC particles above 50% were fabricated by the ball milling and pressing process. The 50 vol% and 58 vol% SiC$_p$ preforms were fabricated with of 48 μm SiC particles. The 71 vol% SiC$_p$ preform was fabricated with two different sizes of 8 μm and 48 μm SiC particles mixed with weight ratio of 1 : 2 in order to improve the volume fraction of SiC in preform.

The consolidated SiC$_p$ preforms were dried in two step process of natural drying and forced drying. Two step drying process consisted with natural drying at 25°C followed by forced drying at 100°C was performed in order to prevent the micro-cracking in SiC$_p$ preform due to the thermal shock during the drying process. In addition, when the residual water is present in preform, the SiC$_p$ preform is oxidized due to vaporization of water and results in an incomplete infiltration of Al melt into preform during the squeeze casting process. The weight of SiC$_p$ preform was measured with increasing drying time as shown in Fig. 2 in order to establish proper drying condition. Fig. 2 shows the weight loss of SiC$_p$ preform with increasing drying time during the natural drying at 25°C and the forced drying at 100 °C. The weight of preform was nearly constant after 24 h during natural drying as shown in Fig. 2a, and was nearly constant after 12 h during forced drying shown in Fig. 2b.

The dried SiC$_p$ preforms were calcined at 1100 °C to give the strength of preforms. The compressive strength of SiC$_p$ need to be high enough to avoid the microcracking of SiC$_p$ preform during the pressure infiltration of Al melt into SiC$_p$ preform. The microcracks in SiC$_p$ preform influence on the thermal properties of SiC$_p$/Al composite [10]. Fig. 3 shows the increase in compressive strength of SiC$_p$ preform with increasing the calcination time at 1100 °C. In order to investigate the reason for increase of compressive strength of preform, the surface of SiC$_p$ preforms was analyzed by XRD after calcination for 4 h at 1100 °C. Fig. 4 shows the XRD analysis of SiC$_p$ preform after calcination for 4 h at 1100 °C and the arrow mark indicates the (101) peak of cristobalite SiO_2 located at the interface of SiC particles. It is known that the formation of cristobalite SiO_2 allows bonding between SiC particles, thus increases the compressive strength of SiC$_p$ preforms [11–13]. Fig. 5 show the increase of compressive strength of preform increased from 50 MPa to 121 MPa with increasing the addition of inorganic binder from 0.5% to 3%. Therefore, it is concluded that the SiC$_p$ preforms were strengthened due to the formation of cristobalite SiO_2 agglomerated at the contact interfaces of SiC/SiC particles during high temperature calcination at 1100°C.

The squeeze casting was performed by infiltration of Al melt at 800 °C into SiC$_p$ preforms preheated to 750 °C, and at 50 MPa for 30 seconds.



(a)

(b)

Figure 2 The variation of weight of 71 vol% SiC_p preform with increasing the drying time. (a) Natural drying at 25°C, (b) forced drying at 100 °C.

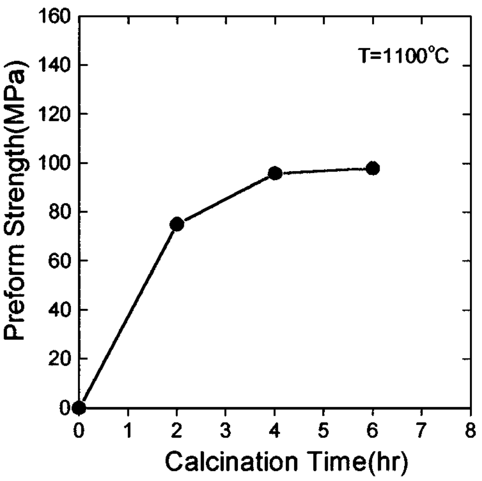


Figure 3 The variation of compressive strength of 71 vol% SiC_p preform with increasing the calcination time at calcination temperature of 1100°C.

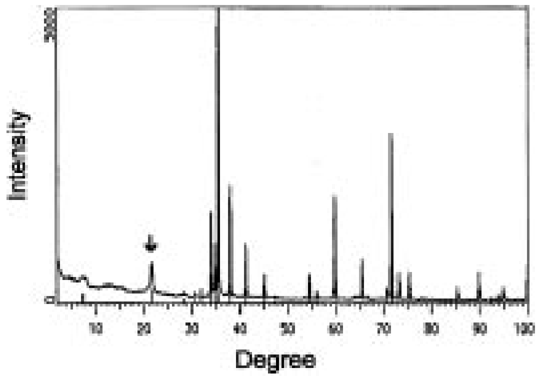


Figure 4 XRD analyses of 71 vol% SiC_p preform after calcination at 1100 °C for 4 hours. The arrow indicates the (101) peak from SiO_2, cristobalite having tetragonal structure.

3.2. Thermal properties and microstructures

The microstructures of SiC_p/Al composite with varying the volume fraction of SiC particles are shown in Fig. 6. Fig. 6 shows the homogeneous distribution of SiC particles in Al matrix. The 50 vol% SiC_p/Al (Fig. 6a) and 58 vol% SiC_p/Al (Fig. 6b) composites are consisted with SiC particles with unimodal size of 48 μm. The 71 vol% SiC_p/Al (Fig. 6c) composite consists of bimodal sizes of SiC particles with 8 μm and 48 μm. In 71 vol% SiC_p/Al composite, the smaller SiC particles of 8 μm were agglomerated between the larger SiC particles of 48 μm as shown in Fig. 6c. The relative densities were measured as 98.9%, 99.3% and 97.8% for 50 vol%, 58 vol% and 71 vol% SiC_p/Al composite, respectively. The relative density, coefficient of thermal expansion and thermal conductivity with varying volume fraction of SiC and fabrication condition is listed in Table I.

The coefficient of thermal expansion and thermal conductivity can be estimated with varying the volume fraction of reinforcement by Turner's model [14] and Maxwell's model [15], respectively. Considering the

TABLE I The coefficient of thermal expansion, thermal conductivity and relative density of SiC_p/Al composites calcined at 1100°C for 4 hours with varying the volume fraction of SiC_p preform and fabrication condition

	Fabrication Condition				
Volume Fraction of SiC_p (%)	SiC Particle Size (μm)	Content of Inorganic Binder (%)	Coefficient of Thermal Expansion (ppm/K)	Thermal Conductivity (W/mK)	Relative Density (%)
50	48	3	9.50	177	98.9
58	48	3	7.89	172	99.3
71	8 + 48	1	7.74	138	97.5
		2	6.33	125	97.8
		3	6.54	123	97.1

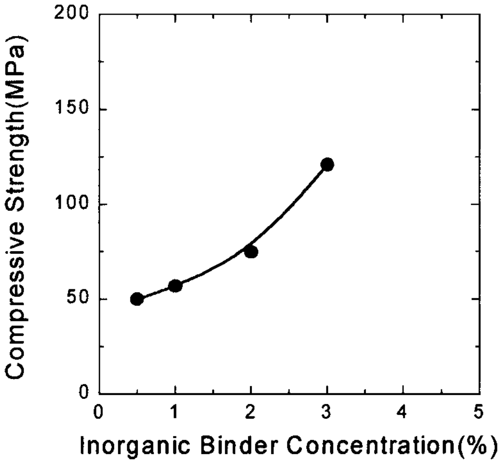


Figure 5 The variation of compressive strength of 71 vol% SiC_p preform with increasing the concentration of SiO_2 inorganic binder after calcination at 1100°C for 4 hours.

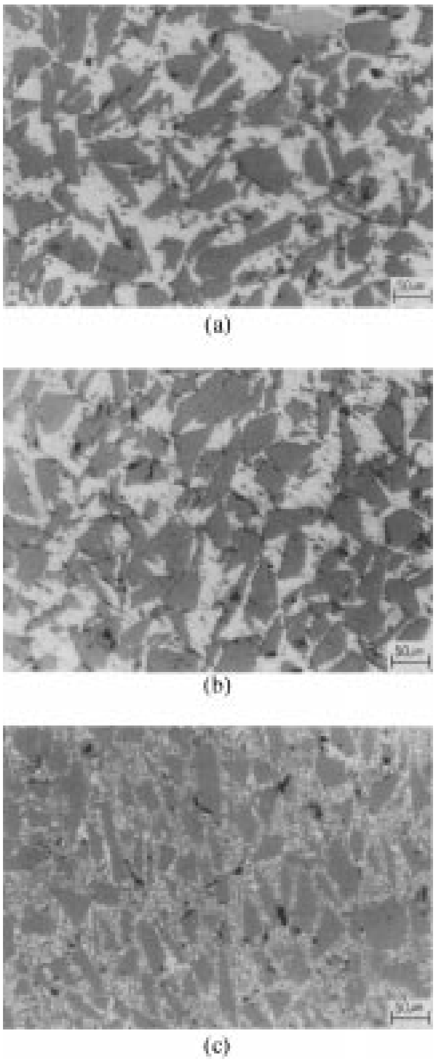


Figure 6 Microstructures of SiC_p/Al metal matrix composite with varying the volume fraction of SiC_p. (a) 50 vol% SiC_p/Al (b) 58 vol% SiC_p/Al and (c) 71 vol% SiC_p/Al composites.

constraint due to dimensional change of each component, the coefficient of thermal expansion is represented by Turner's model as following Equation 1;

$$\alpha_c = \frac{V_r K_r \alpha_r + (1 - V_r) K_m \alpha_m}{V_r K_r + (1 - V_r) K_m} \tag{1}$$

where α_c, α_r, and α_m are coefficients of thermal expansion of composite, reinforcement and matrix, respectively, V_r is volume fraction of reinforcement and K_r and K_m are bulk moduli of reinforcement and matrix, respectively. Maxwell's model predicts the overall thermal conductivity of the mixture by considering the random distribution of spherical reinforcement in matrix as shown in Equation 2;

$$\frac{k_c}{k_m} = \frac{2 - 2V_r + (1 + 2V_r)\frac{k_r}{k_m}}{2 + 2V_r + (1 - V_r)\frac{k_r}{k_m}} \tag{2}$$

where k_c, k_r and k_m are thermal conductivities of composite, reinforcement and matrix, respectively, V_r is volume fraction of reinforcement.

Fig. 7 shows the variation of thermal properties of SiC_p composites with increasing the volume fraction of SiC_p reinforcement. The sold line and the dotted line in Fig. 7a are the theoretically calculated values of the coefficient of thermal expansion with varying the volume fraction of SiC_p based on the rule-of-mixture and Turner's model, respectively. The experimental values

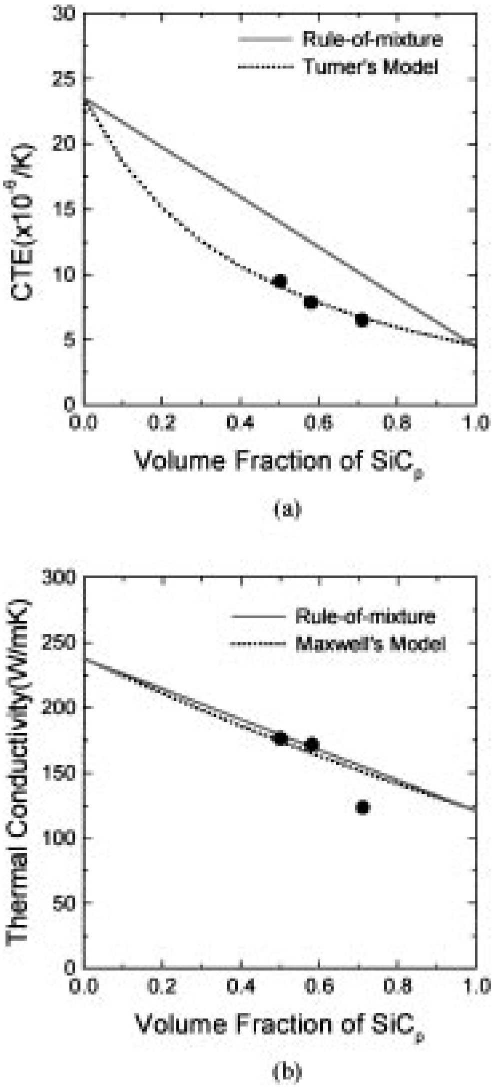


Figure 7 The variation of thermal properties of SiC_p/Al metal matrix composites with increasing the volume fraction of SiC_p reinforcement. (a) Coefficient of thermal expansion, (b) thermal conductivity.

of the coefficient of thermal expansion agreed well with the theoretical values based on Turner's model in Fig. 7a. The experimental values of the thermal conductivity agreed with the theoretical values based on the rule-of-mixture and Maxwell's model at 50 vol% and 58 vol% SiC_p/Al composites is shown in Fig. 7b. The thermal conductivity decreased from 177 W/mK to 172 W/mK with increasing the SiC_p volume fraction from 50 vol% to 58 vol%. However, the measured thermal conductivity of 71 vol% SiC_p/Al composite was much lower than the theoretical value.

It is suggested that the reasons for low thermal conductivity in 71 vol% SiC_p/Al composite is due to the agglomeration of smaller SiC particles and remaining SiO_2 inorganic binders. Fig. 6c shows the agglomeration of smaller SiC particles between the larger SiC particles. The agglomeration of SiC particles prevents the infiltration of Al melt into SiC preform. The incomplete infiltration results in a decrease in density due to the presence of pores. The relative density of 71 vol% SiC_p/Al composite was measured as 97.8%, which is lower than that of 50 vol% and 58 vol% SiC_p/Al composite measured as 98.9% and 99.3%, respectively, as shown in Table I.

The scanning electron microscopy in Fig. 8 shows the existence of SiO_2 inorganic binder between the interfaces of SiC particles. The SiO_2 inorganic binder also results in a decrease of thermal conductivity of SiC_p/Al composite because of lower conductivity of SiO_2, which is about 2.5 W/mK. Therefore, it is considered that the lower thermal conductivity of 71 vol% SiC_p/Al composite is due to the existence of significant amount of residual SiO_2 and micro-pores at the SiC/SiC interfaces due to the incomplete infiltration of Al melts into SiC preform.

Fig. 9 shows the variation of thermal properties of 71 vol/% SiC_p/Al composites with increasing concentration of inorganic binder. The coefficient of thermal expansion was a relatively constant value of about 7 ppm/K independent to the content of inorganic binder as shown in Fig. 9a. On the other hand, the thermal conductivity decreased from 140 W/mK to 120 W/mK with increasing content of inorganic binder from 1% to 3%. The decrease of the thermal conductivity with increasing content of inorganic binder is manly due to the increased amount of residual inorganic binder between the interfaces of SiC particles in SiC_p/Al composites.

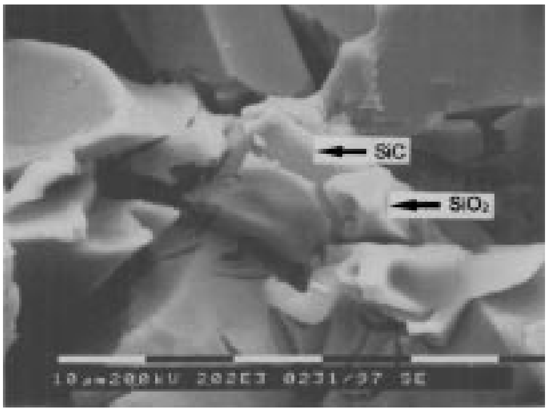


Figure 8 Microstructure showing the existence of SiO_2 residual binders between the interfaces of SiC particles in preform mixed with 3% SiO_2 after calcination at 1100°C for 4 hours.

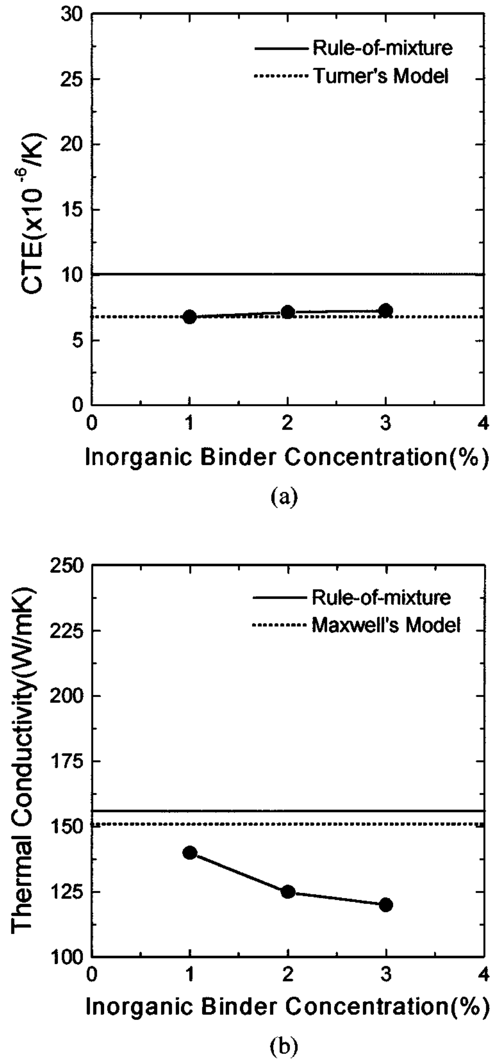


Figure 9 The variation of thermal properties of SiC_p/Al metal matrix composites with increasing the concentration of SiO_2 inorganic binder. (a) Coefficient of thermal expansion, (b) thermal conductivity.

4. Conclusions

The fabrication process and thermal properties of SiC_p/Al metal matrix composites for electronic packaging applications have been investigated and the major conclusions are summarized as follows.

1. The SiC_p preforms with high volume fraction of SiC particles up to 71% were successfully fabricated by the ball milling and pressing method. The compressive strength of calcined SiC_p preform increased from 50 MPa to 121 MPa with increasing SiO_2 inorganic binder from 0.5% to 3% due to the formation of SiO_2 cristobalite phase at the contact point of SiC particles during calcination at 1100°C.
2. The coefficient of thermal expansion and thermal conductivity of SiC_p/Al composite decreased with increasing volume fraction of SiC particles. The measured coefficient of thermal expansion and thermal

conductivity of 50 vol% and 58 vol% SiC_p/Al composites agreed well with the theoretical values with increasing SiC_p volume fraction. However, the thermal conductivity of 71 vol% SiC_p/Al composite was measured much lower than the theoretical value due to the residual SiO_2 inorganic binders, and the lower density resulted from incomplete infiltration of Al melt into preform.

3. The coefficient of thermal expansion of 71 vol% SiC_p/Al composites was measured relatively constant value of about 7 ppm/K with increasing amount of SiO_2 inorganic binder from 1% to 3%. However, the thermal conductivity decreased from 140 W/mK to 120 W/mK, which is mainly due to increased amount of residual SiO_2 inorganic binder located at the interfaces of SiC particles.

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Received 22 February 1999
and accepted 22 May 2000