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Thermo-physical and mechanical properties of high volume fraction SiC_p/Cu composites prepared by pressureless infiltration

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Abstract

SiC_p/Cu composites with high reinforcement content were fabricated by pressureless infiltration of copper alloy into porous SiC preform obtained by powder injection molding. The microstructure, thermo-physical and mechanical properties were investigated. The relative density of the SiC_p/Cu composite reached 98.1%. The reinforcement volume fraction achieved 57–68% by using bimodal or trimodal particle distributions. The coefficients of thermal expansion in the range of 20–500 °C were found to be between 7.9 and $10.5 \times 10^{-6}\,K^{-1}$. The CTEs agree well with estimated value based on Kerner's model. The composites exhibit negligible hysteresis loop and small residual plastic strain, implying that it has high thermal stability. The thermal conductivity was in the range of 125–153 $W m^{-1} K^{-1}$. The bending strength ranged from 176 to 259 MPa, depending on the particle size. The elastic modulus reached 250 GPa, which is close to the prediction by H–S model.

Keywords: Metal matrix composites; Pressureless infiltration; Thermo-physical properties; Microstructure

1. Introduction

SiC_p/Cu composite with 55–70 vol.% reinforcement becomes an interesting metal matrix composites, which is recognized as one of the best candidates for electronic packaging and thermal management application. Theoretically, SiC_p/Cu composite should have excellent thermo-physical properties such as high thermal conductivity (TC) (250–25 $W m^{-1} K^{-1}$), low coefficient of thermal expansion (CTE) ($8.0–12.5 \times 10^{-6}\,K^{-1}$) and superior mechanical properties [1].

Two critical problems standing in the way of fabricating SiC_p/Cu composites are poor wettability and strong reaction between SiC and Cu [2]. Rado et al. [3] observed that the contact angle was 137° for pure Cu on sintered α-SiC. Interfacial reaction ($Cu + SiC = Cu_3Si + C$) can easily occur, which is detrimental to the thermo-physical properties due to the solid solution of Si in the Cu matrix and the formation of graphite.

The main techniques available for fabricating SiC_p/Cu composites are powder metallurgy (PM) and pressure infiltration. In PM route, surface coating of SiC had to be used in order to improve the compatibility between SiC and Cu [4]. Yih and Chung [5] made vast research on hot-pressing of coated powder. The maximum SiC content reached 54 vol.%. Unfortunately, the TC was only 60 $W m^{-1} K^{-1}$. Sundberg et al. [6] obtained SiC_p/Cu composites with 99% of theoretical density and high thermal conductivity of 322.9 $W m^{-1} K^{-1}$ by the method that TiN was coated on SiC as a barrier to Cu diffusion. In liquid infiltration route, the poor wettability brought about the problem that molten Cu cannot infiltrate into the porous SiC preform spontaneously. Narciso et al. [7] made a study on pressure infiltration of SiC_p/Cu composite using preoxidized SiC particles, but the TC still ranged between 40–70 $W m^{-1} K^{-1}$. The generated SiO_2 layer was not very effective to improve the TC because of the intrinsically low TC of the matrix.

Pressureless infiltration has become the favored technique for producing metal matrix composites with high reinforcement content [8]. However, realization of pressureless infiltration is very difficult in this system. Little investigation has been reported on pressureless infiltration of SiC_p/Cu composite. Krauβ et al. [9] used 16 wt.% Ti to improve the wettability between SiC and Cu, which makes copper alloys infiltrate into the SiC preform spontaneously at 1100 °C. However, thick TiC layer formed near SiC particles would impair the thermo-physical properties.

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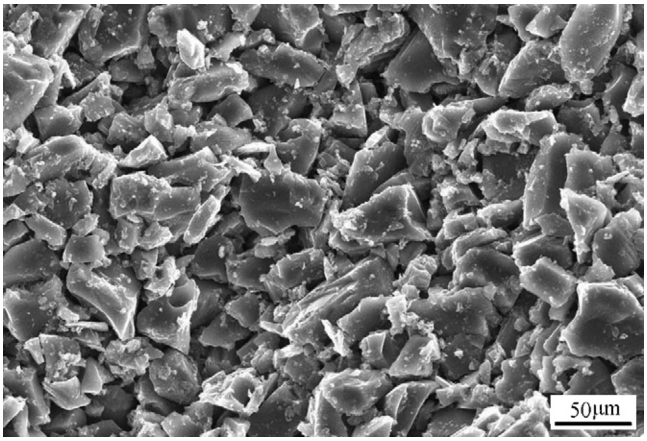

Fig. 1. The microstructure of porous SiC preform.

From above review, SiC_p/Cu composites have not yet achieved their full potential. In this paper, we investigate the possibility of attaining 57–68 vol.% SiC_p/Cu composites by pressureless infiltration of copper alloy into porous SiC preform for electronic packaging application. The microstructure, thermo-physical properties and mechanical properties were characterized.

2. Experimental procedures

2.1. Preparation of composite

Green and abrasive grade α-SiC particles with a purity of 98.5% were used in this study. Particle size was in the range of 13–100 μm. In order to achieve high SiC volume fraction, SiC particle with bimodal and trimodal size distribution were designed. The SiC preforms were prepared by powder injection molding (PIM) using wax based binder. Firstly, the feedstocks for PIM were produced by mixing SiC powder and the binder in the double planetary mixer at the temperature of 150 °C. Then the preforms were injected under the pressure of 80 MPa. Subsequently, the molded specimens were firstly subjected to solvent debinding, and then moved into a vacuum furnace for further thermal debinding. Fig. 1 shows the microstructure of the porous SiC preform.

Pressureless infiltration was carried out in vacuum (1×10^{-3} Pa) using two kinds of copper alloys prepared by induction melting in nitrogen atmosphere. The chemical compositions of the alloys are presented in Table 1. The SiC preform with a plate of copper alloy on the top was heated to 1430 °C and held for 40 min.

Table 1
Chemical composition of the copper alloy

Alloying elements (wt.%)	Cu	Al	Fe	Mn	Ni	Si	Ti
Cu(1)	90	5	2	1	2	–	–
Cu(2)	94	2	–	–	–	3	1

2.2. Property testing

The densities of the composites were measured by Archimedes' principle. Reinforcement content and the distance between particles were measured using an image analyzer (Image Pro-Plus 4). The microstructure and the fractural surfaces were observed on the LEO1450 scanning electron microscopy (SEM). TEM study of the interface was carried out on a JEM 200 electron microscopy. XRD analysis was performed on Siemens D 5000 X-ray diffraction meter using Cu radiation. The CTE measurement and thermal cycling test were both carried out on a Dilatometer 402C (NETZSCH). The specimens with a diameter of 5 mm and a length of 25 mm were used. TC was determined by first measuring the thermal diffusivity by laser flash technique, and then calculated by the equation: $K = \alpha\rho C_p$, where α, ρ and C_p are the thermal diffusivity, density and specific heat, respectively. Bending strength and elastic modulus was determined using three-point-bending tests with a span of 30 mm on an Instron 5569 universal testing system.

3. Results and discussion

3.1. Microstructure

High volume fraction SiC_p/Cu composites were fabricated by pressureless infiltration of copper alloy into porous SiC preforms. Fig. 2 shows the photograph of the preform and the infiltrated parts for electronic packing application.

Fig. 3(a)–(e) shows the microstructures of SiC_p/Cu composites with five kinds of single particles sizes (100, 40, 32, 24, 18 μm). All images reveal that the SiC particles are homogeneously distributed in the microstructure. The SiC particles remain the original irregular shape. No separated interface is observed. There is still some space to accommodate small particles between large particles. Small amount of residue pores can be observed in the microstructure. Pores may arise from the poor wettability of the ceramic by the metals or the evaporation of copper under high temperature. Shrinkage of the residual metal

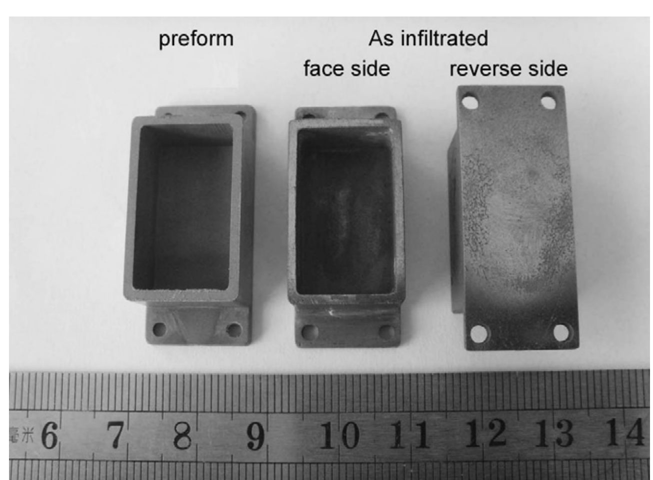

Fig. 2. Photograph of the preform and the infiltrated parts for electronic packing application.