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Mechanical properties of diamond/Al composites with Ti-coated diamond particles produced by gas-assisted pressure infiltration

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ABSTRACT

Diamond particles reinforced Al matrix (diamond/Al) composites were produced by a gas-assisted pressure infiltration method. Ti coating on diamond particles was carried out to bring interfacial TiC layer between diamond reinforcements and Al matrix. The TiC layer was found to play a critical role in enhancing mechanical properties of the composites, owing to strong connection between dissimilar phases. Three analytical models of Mori–Tanaka, generalized self-consistent, and Torquato identical hard spheres were used to correlate the monotonic uniaxial stress–strain curves of the diamond/Al composites. The results suggest that Ti coating on diamond particles is a feasible way to strengthening diamond/Al composites.

1. Introduction

The ever-increasing power density of electronic devices is appealing for new generation of packaging materials with excellent thermal conductivity (TC). As a promising candidate, diamond particles reinforced Al matrix (diamond/Al) composites are attracting much attention [1–5]. So far the TC as high as 700 W/mK has been reported in diamond/Al composites [5]. While this level of TC can meet the requirement of thermal conducting in highly powered devices, the mechanical reliability of packaging materials could be a technical obstacle to actual applications, because considerable stresses will be inevitably incurred during machining, assembly, and service of the packaging materials. Compared with extensive investigations of thermal conductivity of diamond/Al composites, the mechanical characterization has been rarely reported [6–8].

Diamond acts as an ideal rigid and Al matrix is rather soft compared to diamond reinforcements. The deformation and fracture of diamond/Al composites are unique among particulate-reinforced metal matrix composites (MMCs). Weidenmann et al. [7,8] reported that the ultimate tensile strength of diamond/Al composites is 124 MPa and the strain at failure is 0.12%. Although the strength is much higher than that of Al matrix, the plastic deformation is limited. This is owing to the restriction of Al matrix by the surrounding diamond particles embedded. The diamond/Al composites provide an interesting platform for theoretical study, where analytical models can be applied to correlate the deforming behavior of the materials.

Interface has a decisive effect on the properties of a composite. Many studies have shown that Ti coating on diamond particles can significantly enhance the thermal conductivity of diamond/Al composites [2–4]. To detect the influence of interfacial layer on the mechanical performance of diamond/Al composites, Ti coating is also used to modify the diamond/Al interface in this study. With Ti coating on diamond particles for various lengths of time, interfacial layers with varied thickness are developed, allowing us to survey the effect of interface thickness.

In this article, the molten salts route is firstly employed to coat metallic Ti onto diamond particles, and then the coated diamond particles are incorporated into Al matrix by using a gas-assisted infiltration method. The effect of interface thickness on the mechanical properties of the diamond/Al composites is clarified, and existing analytical models are applied to explore the underlying mechanism.

2. Experimental

2.1. Materials

The starting materials were single-crystalline diamond particles (MBD-4, particle size 159 μm, Luoyang Diamond, China), Al

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bulks (purity 99.99 wt%, Beijing Cuibolin Nonferrous, China), and Ti powders (purity >99.9 wt%, particle size 74 μm, Beijing Chemical Reagent, China). The as-received diamond powders were cleaned in acid to remove possible impurity. Some of the cleaned diamond powders were coated with Ti by a molten salts route [9]. At 850 °C, coating times of 15–180 min were used to get various thicknesses of Ti coating.

2.2. Infiltration

The diamond/Al composites were produced by a gas-assisted pressure infiltration (GPI) method. The pristine or coated diamond powders were installed into a graphite mold, and the Al bulks were covered on top of the diamond particles bed. The assembly was then moved to a chamber for infiltration. The chamber was firstly evacuated to a vacuum below 0.1 Pa and then heated to 800 °C with a ramp rate of 50 °C/min. At 800 °C, high purity argon gas was pumped into the chamber to maintain a gas pressure of 1.0 MPa. After the infiltration was kept for 20 min, the samples were furnace cooled down to room temperature. The samples produced with Ti-coated diamond particles are hereinafter shortened as Ti-diamond/Al composites.

2.3. Mechanical test

The mechanical test of the diamond/Al composites was conducted on a material testing platform (MTS 809, MTS Systems Corporation, USA). In order for various types of mechanical test, different dimensions of diamond/Al specimens were produced. As an example, Fig. 1 shows the dimensions of specimens for tensile loading. The tensile loading rate was 0.5 mm/min. The compressive strain rate was $1 \times 10^{-3}\ s^{-1}$, using specimens with dimensions of 3 mm × 3 mm × 8 mm. The bending loading rate was 0.3 mm/min, using specimens with dimensions of 3 mm × 5 mm × 30 mm. At least three specimens were used for each test. The derived mechanical strength was the average of the three tests, and the error was thus determined.

2.4. Characterization

X-ray diffraction (XRD, Rigaku DMAX-RB, Japan) was used to characterize the phase structure of the produced diamond/Al composites. Before microstructural observations, the samples were polished by using a diamond-containing grinding machine. Scanning electron microscopy (SEM, Zeiss Supra 55, Germany) was applied to examine the polished surfaces. Elemental distribution with respect to diamond/Al interface was analyzed by using backscattered electron images. The fractured surfaces of the diamond/Al composites after mechanical test were examined by using secondary electron images. With the metallographic method, volume fraction of dispersed diamond particles was determined over several polished surfaces.

3. Results and discussion

3.1. Microstructure and fractography of the diamond/Al composites

The phase structure of the produced diamond/Al composites is given in Fig. 2. For the unmodified diamond/Al composite, only Al (PDF# 85–1327) and diamond (PDF# 79–1467) phases were identified. The Ti-diamond/Al composite showed XRD patterns similar to the unmodified diamond/Al composite, except for a small amount of TiC (PDF# 71–0298). This indicates that the coated Ti has reacted with diamond to form an interfacial layer TiC. It is noted that diamond (2 2 0) peak is rather weaker for the Ti-diamond/Al composite, compared with the unmodified diamond/Al composite. A reasonable interpretation is that diamond

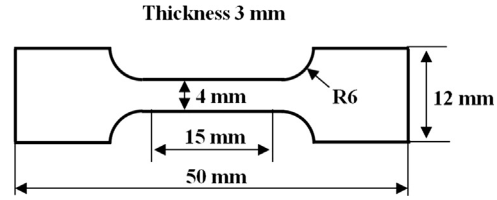

Fig. 1. Schematic illustration of the tensile test specimens.

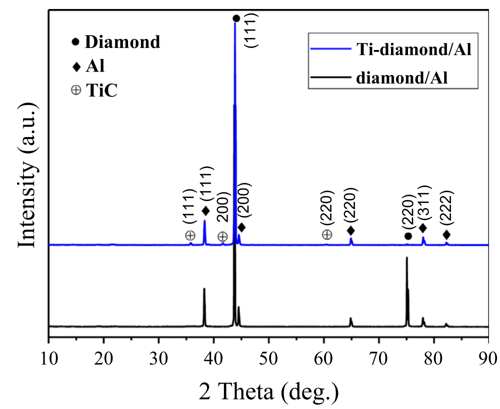

Fig. 2. XRD patterns of the produced diamond/Al composites.

faces could be exposed to sample surface in a random manner, because diamond particles with a large size of 159 μm was used in the experiment. The phenomenon is reported in other study [10]. No Al_4C_3 phase was detected in the XRD patterns, since the diamond/Al composites were produced at a low temperature of 800 °C [11].

Fig. 3 shows the microstructure of the produced diamond/Al composites. The diamond particles were found to be uniformly dispersed in the Al matrix, as shown in Figs. 3(a) and (b). The loading of diamond particles was about 65 vol% through the metallographic examination. As seen in Fig. 3(c), sharp interfaces were observed in the unmodified diamond/Al composite. However, some reactants were formed at interfaces in the Ti-diamond/Al composites (typically Fig. 3(e)). The comparison suggests that Ti coating on diamond particles is important to connect diamond reinforcements and Al matrix closely.

The EDS analysis was performed on the Ti-diamond/Al composites to examine the interfaces. Fig. 4(a) displays such an interface between diamond reinforcement and Al matrix. Fig. 4(b)–(d) shows that Ti element is predominantly detected in the transition region between diamond and Al. It is thus reasonable to deduce that some Ti has reacted with diamond to form TiC, which is verified by the XRD results in Fig. 2. As an example, a transition region about 5 μm wide was characterized in the Ti-diamond/Al composite produced with 120 min Ti coating on diamond particles, as shown in Fig. 4(e).

Fig. 5 shows the fractography of the diamond/Al composites after tensile testing. As shown in Fig. 5(a), some diamond particles were found to dispatch directly from Al matrix. This implies that the unmodified diamond/Al interface could be weak. It was found that the proportion of bare surfaces of diamond decreased dramatically in the Ti-diamond/Al composites, as shown in Fig. 5(b). The comparison suggests that the bonding between diamond and Al is promoted by the interfacial layer TiC.

3.2. Mechanical properties of the diamond/Al composites

3.2.1. Tensile strength

Fig. 6 shows the tensile stress–strain curves of the produced diamond/Al composites. As summarized in Table 1, the ultimate