Diamond & Related Materials 70 (2016) 52–58

Contents lists available at ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Elasto-plastic deformation within diamond reinforced metals for thermal management

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ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form 20 September 2016
Accepted 28 September 2016
Available online 29 September 2016

Keywords:
Diamond reinforced metals
Thermal management
Neutron diffraction
Acoustic emission
Interface bonding strength
Tensile testing

ABSTRACT

Diamond reinforced metals are being developed for use as highly sophisticated heat spreading material in power electronics or satellite laser optics. These particle reinforced composites combine the excellent thermal properties of diamond with a metal matrix, which enables shaping and joining onto the components. The mismatch in thermal expansion and Young's moduli of matrix metal and diamond reinforcement is responsible for high micro stresses under operational conditions of thermal cycling. These stresses may lead to interface delamination and/or matrix damage degrading the initially good thermal properties. Therefore, the interface bonding strength and the deformability of the matrix determine the quality of such metal matrix composites. Aluminum is favored as matrix metal due to its high ductility and carbide forming ability on diamond surfaces, which significantly improves the interface bonding strength. Silver offers high thermal conductivity and alloying with silicon produces reactivity with diamond, giving strong bonding strength. The tensile behavior of both composites was investigated by non-destructive in-situ neutron diffraction and acoustic emission (AE) measurements. Post mortem scanning electron microscopy reveal the bonding quality of the composites correlated to the reinforcement architecture and the plasticity of the matrices. Conclusions on the elasto-plastic deformation behavior of the investigated composites for thermal management application are drawn.

1. Introduction

In power electronic modules (insulated gate bipolar transistor units, IGBT), laptop processors and laser diodes (slab crystal housings), the increasing demand on thermal management requires appropriate heat sink materials [1,2]. Particle reinforced composites are promising candidates, combining the thermal properties of a highly conductive metal matrix with ceramic particles exhibiting low coefficients of thermal expansion (CTE) [3]. A high thermal conductivity (TC) is realized in SiC particle reinforced aluminum (Al-SiC), which are used to replace Cu heat sinks [4]. In such particle reinforced metals (PRM) the Al matrix combines its thermal properties of TC_{Al} ~ 240 W/mK and CTE_{Al} ~ 25 ppm/K with those of SiC with TC_{SiC} ~ 140 W/mK and CTE_{SiC} ~ 4 ppm/K resulting thermal properties of TC_{AlSiC} ~ 180 W/mK and CTE_{AlSiC} ~ 9 ppm/K for composites containing 70 vol.% bimodal SiC particles [5,6]. These properties provide sufficient heat dissipation through the metal matrix and concomitantly reduce the thermal mismatch stresses with the adjacent ceramic substrate, thereby increasing the long term stability of the system loaded with thermal cycles [3].

Metal matrices reinforced with up to 60 vol.% monomodal diamond particles are developed to replace Al-SiC as heat sink material [7]. Carbon diamond (CD) offers the highest thermal conductivity TC_{CD} > 2000 W/mK combined with almost no thermal expansion of CTE_{CD} ~ 1 ppm/K [8,9] achieving thermal properties of AlCD composites of TC_{AlCD} ~ 500 W/mK and CTE_{AlCD} ~ 6 ppm/K [10–13], both improved with respect to Al-SiC [14]. The best performance has been achieved by a silver matrix reinforced by CD particles [13,15,16] exhibiting TC_{AgCD} > 800 W/mK [7,13]. Such PRM are developed for satellite laser optics, where the economic limitations are less restrictive.

The major problem with diamond particles is their poor wettability by liquid metals during infiltration and the resulting low interface bonding strength [9,17,18]. Liquid metal infiltration of densely packed particle preforms comprising up to 60 vol.% CD-particles may produce infiltration voids, which may be harmful to the structural stability as well as to the thermal properties of the PRM [19–21]. However, the shrinking of the solidifying metal matrix in between the particles causes

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http://dx.doi.org/10.1016/j.diamond.2016.09.027
0925-9635/

mandatorily initial voids, which will grow during cooling owing to the CTE mismatch of the composite's components [22]. Such shrinkage voids in a composite with sufficient particle-matrix interface bonding strength can be useful to reduce thermal mismatch stresses by elasto-plastic matrix deformation during temperature changes [23]. Therefore, infiltration quality and interface bonding strength are the key issues of CD reinforced MMC to achieve high thermal conductivity and low thermal expansion for long term operation conditions under cycling thermal loads [7,16,25,27].

The high CTE mismatch between matrix and reinforcement (ΔCTE ~ 24 ppm/K in AlCD, ΔCTE ~ 18 ppm/K in AgCD) will lead to high micro stresses and severe matrix deformation near the particle interfaces [26]. Interface delamination initiates thermal fatigue damage in such heat sink materials [24,25]. The interface bonding strength [17] and matrix deformability [27] is the key to successful material selection for demanding thermal management with sufficient long term stability.

The AlCD composites benefit from the low cost of aluminum as matrix material, its castability and interface reactivity [8,11]. In order to support carbide formation to increase the bonding strength of the plane crystallographic diamond surfaces, the particle filled preforms are heat treated prior to the liquid metal infiltration. In case of the AgCD composites a high interface reactivity and bonding strength can be achieved by alloying the matrix with Si, as shown in previous investigations [15,16].

In particle reinforced composites with a stiff ceramic reinforcement embedded in a ductile matrix metal, high micro stress gradients lead to partial plastification of the ductile phase [27]. The stress gradients by diamond reinforcements should be favorably accommodated by elasto-plastic matrix deformation [23] counteracting damage mechanisms such as cracking or delamination. Interconnectivity of a network-like reinforcement structure [26] may provoke crack formation in this network [27] under mechanical loads. In contrast to isolated particles embedded in a ductile matrix phase, which is able to deform and consequently, high interfacial micro stress gradients relax [14]. In the following, elasto-plastic deformation in Al/CD/60p composites in two different conditions is compared with AgSi11/CD/60p under externally applied stress. The deformation behavior of a carbon diamond particle reinforced ductile matrix is compared with that of a relatively brittle matrix by in-situ non-destructive testing techniques.

2. Experiment

2.1. Materials description

Three different diamond particle reinforced composites were investigated (Table 1). All composites were produced by gas pressure assisted liquid metal infiltration [28] at the Laboratory for Mechanical Metallurgy of EPF Lausanne in Switzerland.

The synthetic diamond powder was purchased from Luoyang High-Tech Qiming Superhard Materials Co. Ltd., China. A monomodal diamond powder of the grit mesh size 500/600 (average particle diameter of about 22 μm) was used to produce densely packed preforms of particle content of 60 vol.%. The preforms for the Al/CD/60p composites were heated to the infiltration temperature of 800 °C. Furthermore, the temperature was kept for 3 h or 10 h in vacuum to stimulate graphite formation at the diamond particle surfaces. Both conditions were infiltrated by pressing the liquid aluminum with 15 bar into the mold. The preforms are completely infiltrated after 3 min and the pressure was subsequently released during cooling. Although the thermal conductivity of the interfaces will be reduced by carbide formation on the diamond particles, long term integrity of the composites (i.e. reduced interface delamination) is improved. Therefore great emphasis is given to investigate the influence of carbides on interface bonding strength.

The AgSi11/CD/60p composites were produced by the same method with the preform initially heated to the infiltration temperature of 1050 °C held there for 30 min and then pressure infiltrated by the liquid alloy at 22.5 bar pressure. Again, the preform is supposed to be completely infiltrated after 3 min and the pressure subsequently released after solidification, while the mold is cooled. The materials were cast in the shape of tensile test specimens as used for previously performed mechanical tests [16]. The dimensions of the tensile test specimens' gauges are 25 × 6 × 2.5 mm. Two specimens for each composite type were used for the following neutron diffraction and acoustic emission measurements.

2.2. Neutron diffraction

Angle dispersive neutron diffraction (ND) was performed at E3 strain scanner at HZB Wannsee, Germany [29] using a monochromatic neutron beam with $\lambda = 1.486$ Å and flux ~5×10^6 n cm^{-2} s^{-1} through the sample. A 50 kN tensile test equipment was mounted on the x,y,z-table for the in-situ strain measurements [30]. The same sample dimensions have been used for previous investigations [16]. A primary aperture of 6 × 6 mm^2 and a secondary of 6 mm width ensured a complete flooding of the test specimens' cross section of 6 × 2.5 mm^2 within the neutron beam. The 2D^{3}He position sensitive detector (PSD) unit with 256 × 256 capillaries with a pixel size of 1.38 × 1.38 mm^2 was set to $2\theta = 42°$ for diamond (111) and $2\theta = 72°$ for diamond (220) for serial acquisition of the two most representative diamond lattice planes (according to CEN ISO/TS 21432:2005). The Ag (311) peak from AgSi11/CD/60p could be acquired additionally, due to the smaller grain size of the AgSi11alloy compared to the pure Al metal matrix, which could not be recorded.

The external tensile force was controlled by a calibrated load cell and stepwise increased (with 200 N/step for Al/CD/60p 10 h ht, 300 N/step for Al/CD/60p 3 h ht, 400 N/step for AgSi11/CD/60p and with 50 N/s load rate) in between the strain scans during tensile testing, starting from the initially unloaded condition. 5 min acquisition time was set to scan the CD (111) and CD (220) peak intensity (additionally, Ag (311) of AlSi11/CD/60p). The micro strains were evaluated in relation to the unloaded condition [27], neglecting the initial microstress state from casting (cooling after infiltration).

2.3. Acoustic emission

The acoustic emission (AE) was measured during tensile test experiments carried out like for neutron diffraction. The computer controlled DAKEL-IPL-4 AE data-streaming system was used for a continuous storage of emitted signals with 2 MHz sampling frequency. A miniaturized MST8S piezoelectric transducer (diameter of 3 mm, almost point AE detection, a frequency band from 100 to 600 kHz, sensitivity 55 dB at 1 V_{eff}) was attached to the specimens on the 6 mm wide side of their rectangular cross section. A good acoustic contact was ensured by using silicon grease and a small preloaded spring clamp. A preamplifier with a gain of 35 dB was used to reduce the AE noise-to-signal-ratio. The 12-

Table 1
Composition of diamond reinforced composites as used for the investigations.

Composite	Matrix 40 vol.%	Diamond 60 vol.%	Condition
Al/CD/60p 3 h ht	Al 99.99%	Ø ~ 22 μm	Particle preform heat treated for 3 h at 800 °C prior to infiltration
Al/CD/60p 10 h ht	Al 99.99%	Ø ~ 22 μm	Particle preform heat treated for 10 h at 800 °C prior to infiltration
AgSi11/CD/60p	Ag 89 at.%, Si 11 at.%	Ø ~ 22 μm	No additional particle heat treatment