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Review paper

Trend of the development of metal-based heat dissipative materials

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ABSTRACT

Fabrication of high-performance thermal management materials with ultra-high thermal conductivities and low CTEs is important in electronics fields. Recently we have initiated a series of investigations to fabricate such materials and found that metal-matrix composites (MMCs) uniquely fabricated are effective in improving their thermal and strength properties. In our study, to avoid the damage of filler particle surfaces, spark plasma sintering (SPS) processing was used as a processing technique. In this review article, various kinds of filler particle dispersed MMCs are introduced and their thermal properties of composites fabricated by using various methods, such as metal infiltration and vacuum hot pressing, are shown and well documented. This review article leads to strong indications regarding fabrication techniques for making better thermal management composites. Our SPS method is compared in terms of materials qualities to those fabricated by other fabrication techniques.

1. Introduction

High-performance thermal management materials should have high thermal conductivities and low coefficients of thermal expansion (CTE) for maximizing heat dissipation and minimizing thermal stress and warping, which are critical issues in packaging of power semiconductors, light-emitting diodes and micro electro mechanical systems. Thermal stress and warping arise from CTE differences, which become significant in advanced electronic devices because of high heat generated, for example, when high-power laser diodes or high integration level of IC are in use. To ensure ideal or desired performance and adequate life of these electronic devices, Halasz [1] shows that it is necessary to decrease the junction temperature between two components to temperatures lower than 398 K for military and automobile logic devices and 343 K for some commercial logic devices. In the case of high-power density devices, the allowable temperature range is limited in the package base and die-attach thermal resistances. In any cases, the development of thermal management materials is significant in electronics fields.

In order to fabricate high-performance thermal management materials with high thermal conductivities and low CTEs, many research groups carried out fabrication of composites using various materials made by different fabrication techniques. Composites fabricated includes metal-matrix composites (MMCs) that contain both diamond particles and mixtures of various metals and alloys powders, and fabrication methods employed were vacuum hot pressing, metal infiltration, belt-type high pressure apparatus and spark plasma sintering (SPS). We have recently initiated a series of investigations, where MMCs containing uniquely-designed high thermal conductive fillers were fabricated. For fabricating composites with high thermal conductivity, it is clear that the damage of filler particle surfaces, such as diamond particles, should be avoided or minimized as much as possible through fabrication processes of composites. It is also clear that the boundary conductance (hc) should be increased between filler particles and matrix. In these aspects, SPS processing [2–12] was proved to be very good as a processing technique. In the present review article, thermal properties of particle dispersed MMCs fabricated using SPS process in our recent works are introduced and the results are compared in comparison with thermal properties reported by using various fabrication techniques by other researchers.

2. Fabrication methods of metal-based heat dissipative materials

Four kinds of fabrication methods are mainly used for the processing of metal-based heat dissipative materials. Features of each method are described below.

2.1. Metal infiltration

Filler particles are poured and tapped in a preheated casting mold, and then molten metal is poured into the mold. Within a few minutes, this molten metal infiltrates between the filler particles. A metal matrix

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composite (MMC) containing filler particles can then be obtained after the solidification of the molten metal infiltrated. In this infiltration process, pore free MMCs can basically be obtained. When processing temperature is, however, higher than the melting point of metal matrix, such an infiltration technique is considered to have drawbacks. Such drawbacks include reductions in thermal conductivity which is caused by structural alterations of filler particles by direct contact with molten metal. In addition, it is practically difficult to uniformly disperse filler particles in the composite. This is especially true when composite contains a lower volume fraction of filler, say, < 50 vol% because of big differences in mass density between filler and matrix.

2.2. A belt-type high pressure apparatus

A belt-type high pressure apparatus [13] was originally used for the fabrication of synthetic diamonds, and Yoshida et al. utilized this apparatus to fabricate diamond particle dispersed copper (Cu) matrix composites. With this apparatus, MMC materials can be fabricated at temperatures higher than the melting point of metal matrix when applying ultra-high pressures, say, of about 5 GPa. Through such a condition, fully dense and pore less composites can be fabricated. Similar to a metal infiltration technique, however, composite fabrication using this apparatus has some drawbacks, including reductions in thermal conductivity. Such reductions are caused by structural alterations of filler particles due to direct contact with molten metal.

2.3. Vacuum hot pressing (VHP)

Vacuum hot pressing is one powder consolidation technique in solid state and known to be a limited field of applications for such materials, where a pore-free state is required. With this process powder particles are inserted into a mold and pressed at high temperatures in vacuum. The consolidation of powder particles occurs at the necking of contact points between particles. The heating of powder particles is indirectly carried out by heating elements placed outside the mold. Although the speed of necking formation of powder particles is higher than conventional pressure-less sintering, it takes relatively a long time to heating the mold uniformly because of indirect heating. This long time heating may cause the damage of MMC.

2.4. Spark plasma sintering (SPS)

Spark plasma sintering (SPS) is a sintering method where a direct heating of powder particles is made under pressures which are created using an electric conductive die set. Powder particles are inserted into an electric conductive die set such as a graphite die set. DC on-off pulsed currents of several thousand amperes (A) are given into powder particles, which are stacked in the die through upper and lower punches under pressure. A local high temperature state is generated momentarily at the contact points between particles. This causes evaporation, cleaning and melting on the surface of powder particles and then necks are formed around the contact points between particles for a short time. SPS enables consolidation of powders at about two third of the melting points of the powders and enables the powder consolidation for a shorter time. This short time consolidation is considered to be advantages as compared to conventional consolidation methods such as sintering, vacuum hot pressing (VHP) and hot isostatic pressing (HIP).

3. Measurement methods of thermal conductivity

There are a number of possible ways to measure thermal conductivity, and each of them are suitable for a limited range of materials, depending on the thermal properties and the medium temperature [14]. Among them, three kinds of measurement methods are mainly used to measure the thermal conductivity of electronic materials. According to the report by Akoshima et al. [14] for the thermal conductivity of materials, most appropriate measurement methods should be chosen. Features of each method are described below.

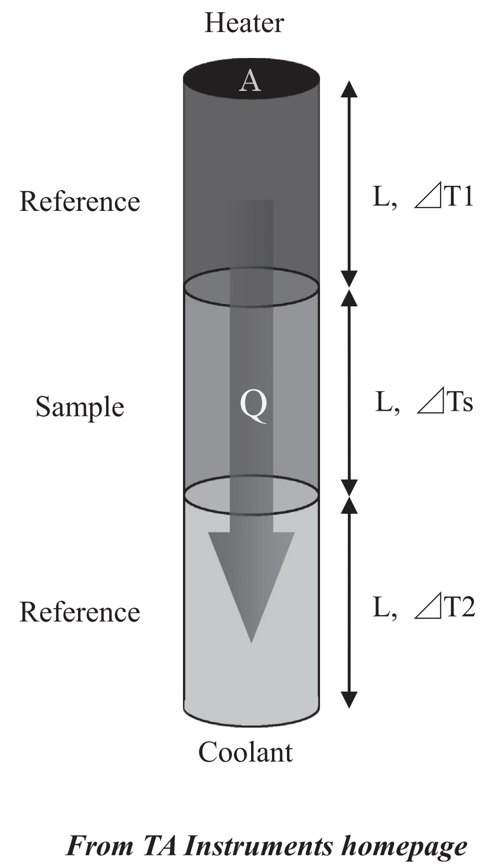

Fig. 1. Thermal conductivity measurement by comparative-guarded-axial heat flow method in steady state.

3.1. Measurement in steady-state

A comparative-guarded-axial heat flow method is perhaps the most widely used for axial thermal conductivity testing in steady-state. In this method, a test sample of unknown thermal conductivity is sandwiched between two reference samples of known thermal conductivity, which forms what will be referred to as a sample column as shown in Fig. 1. A temperature gradient is set up and measured through the samples using a heater on one end of the sample column and a coolant on the other end. A guarding system is used to prevent or reduce radial heat losses from the sample column, where K_r is the thermal conductivity of reference. From this, the thermal conductivity of the unknown sample (K_s) can be obtained from the following Eq. (1).

$$\frac{Q}{A} = K_s \times \frac{\Delta T_s}{L} = K_r \times \frac{\Delta T_1 + \Delta T_2}{2} \times \frac{1}{L} \tag{1}$$

where Q is the heat flow in sandwiched samples, “A” the base area of cylindrical sample and reference samples, ΔT_s, ΔT_1 and ΔT_2 the temperature differences between the upper and lower part of each sample, L the length of each sample. Suffixes s, 1, and 2, indicate test sample, reference [1,2], as shown in Fig. 1.

This measurement technique is considered to be suitable for materials having relatively low thermal conductivity, say lower than 125 W/mK, such as thermal insulation materials [14]. The technique is also difficult to estimate the thermal resistivity at the contact areas between the test sample and references for high thermal conductive materials, such as metals and diamond composites.