Aluminum Composite Materials for Multichip Modules

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In the intensive materials development activities for electronic packaging and thermal management applications, the subclass of materials in which SiC particles reinforce aluminum alloy matrices has emerged as one with an especially attractive combination of physical properties, manufacturing flexibility, and cost. One benefit of these materials is the ability to tailor the physical properties through the selection of both reinforcement and alloy variables to match the thermal expansion coefficient of other electronic materials. In addition, the manufacturing flexibility of the various processes allows for shape complexity as well as selective reinforcement placement in the component to optimize system producibility. Finally, because raw materials are inherently inexpensive and low-cost production routes have been identified, aluminum composites may offer a range of cost-effective solutions to emerging problems in electronic packaging and thermal-management applications.

INTRODUCTION

As a result of continued advances in microelectronics, packaging technologies have become vital to the success of advanced designs. Progress in this field has been driven by advances in active device technologies that have resulted in significant miniaturization, increased functional density, and higher operating frequencies. These developments have produced ever-increasing power densities requiring improved thermal-management schemes. In particular, multichip modules (MCMs) present challenges because they contain several devices in close proximity. The alternatives to improved cooling schemes—higher junction temperatures and decreased reliability—are clearly unacceptable. Requirements for improved cooling are complicated further in avionics systems by the need to minimize system weight and in automotive systems by the need to provide protection from a more hostile environment while maintaining low cost.

These needs are driving materials developments along a number of fronts, as reviewed in Carl Zweben's article in this issue. Unfortunately, no current-generation material can meet all of these challenges. The use of aluminum or copper results in unacceptable expansion stresses on silicon- or gallium arsenide-based devices. Kovar® is costly to manufacture in complex configurations and is inherently poor in thermal conductivity. The Cu/W and Cu/Mo blends, either in the form of metallurgical or macroscopic composites, offer good thermal conductivity but are inherently heavy and are manufactured from expensive raw materials.

In contrast, aluminum/ceramic composites have shown the potential for good coefficient of thermal expansion (CTE) match, high thermal conductivity, and low density; further, they are manufactured from inexpensive raw materials. In addition, some processes are capable of producing net-shape products with high degrees of complexity. Especially significant is the ability to tailor the physical and mechanical properties of these materials for specific application needs via changes in both reinforcement volume and matrix composition. As an example, the CTEs can be precisely matched with those of the typical electronics substrates such as alumina, beryllia, and aluminum nitride, as well as of the device materials such as silicon and gallium arsenide themselves. This compatibility minimizes or eliminates thermally induced stresses on the devices, joints, and substrates, significantly increasing the reliability of the entire system. As a result of these benefits, aluminum composite materials are poised to revolutionize thermal management in electronic components.

Among the different reinforcement phases for aluminum-matrix materials (e.g., fibers, whiskers, and particulates), the particulate form is the more attractive in many cases. This is primarily due to the fact that properties of particulate-reinforced aluminum are relatively isotropic, allowing for complex shapes with uniform physical and mechanical properties. In addition, particulate-reinforced components are easier to fabricate in a cost-effective manner.

PROPERTY OPTIONS

The range of properties available in SiC/Al composites is determined primarily by the properties of the individual phases, as well as the details of the microstructure when they are combined into a composite.

Silicon carbide is the reinforcement of choice in aluminum composites primarily due to its excellent combination of physical properties, availability, and cost. The particulate form is available in both the alpha and beta crystal structures, with the typical value for CTE reported as 4.7 × 10⁻⁶/K. Thermal conductivity varies significantly with the purity of the silicon carbide, ranging from 80 W/(m·K) for commercial products to 170 W/(m·K) for “high-purity” polycrystalline products and over 200 W/(m·K) for single crystals. Silicon carbide is also a stiff...
material, with reported elastic modulus values as high as 430 GPa. In addition, the relatively low density of SiC of 3.2 g/cm³ makes it an efficient reinforcement on a weight basis as well.

The widespread use of SiC particulates in large-scale industrial applications means that it is both available in a number of grades and is relatively inexpensive. Abrasive-grade SiC is available in large quantities from several sources, in a range of mean-particle sizes from 3 μm to greater than 50 μm. Higher purity particulates are also available. Figure 1 illustrates the appearance of the SiC particulate materials.

The use of aluminum as the matrix in the composite offers a number of advantages:

- High thermal conductivity, typically in the range of 180–230 W/(m·K).
- Low density of 2.7–2.8 g/cm³ depending on alloy content.
- Ease of processing, especially relative to other commonly used high-conductivity metals such as copper.
- Ability to tailor physical as well as mechanical properties by alloying and heat treatment.

Its primary disadvantage is the high CTE value (~23 x 10⁻⁶/°K) relative to other materials used in electronics packaging.

When the SiC and aluminum components are combined, a range of interesting and useful physical properties can be obtained. Of primary interest in electronic packaging and thermal management applications are coefficient of thermal expansion (CTE), thermal conductivity, density, and elastic modulus. These properties can be reasonably well modeled for a two-phase system such as SiC/Al, and one can tailor the aluminum alloy and SiC particulate parameters based on the requirements. As an example, Figure 2 shows the effect of SiC particulate volume fraction (Vₚ) on the CTE of a composite. The solid line represents the predicted trend of CTE with increasing SiC content using one of the commonly employed models developed by Turner, and assuming that the CTE of SiC is 4.5 x 10⁻⁶/°K and the CTE of aluminum is 23 x 10⁻⁶/°K. Experimentally observed data from many investigators are also plotted in this figure. The comparison indicates that the CTE can be relatively well predicted by existing models.

Also included in the figure are CTE values for key electronic substrate and device materials. By comparing the values for these latter materials with the SiC volume fraction vs. CTE data, it is apparent that SiC volume fractions of ≥0.65 are necessary for close CTE matching.

The thermal conductivity of these composite systems is not as easily understood. Conduction through a two-phase system such as a SiC/Al compos-

ite is affected by both the bulk conductivity of the phases as well as the interfaces between them. Unfortunately, the interfacial effects are dependent on the surface chemistry of the SiC and details of the fabricating operations. Uncertainty in bulk thermal conductivity of the SiC particulates in the composite also contributes to errors in the predictions. However, the composite thermal conductivity can still be estimated using models such as that of Maxwell. Such a prediction and the thermal conductivities of various SiC/Al composites are shown in Figure 3. The predicted curve for thermal conductivity of the composites was generated using thermal conductivity values of 80 W/(m·K) for SiC and 230 W/(m·K) for the aluminum matrix. Comparison of the thermal conductivity values of the SiC/Al composites with those of other packaging materials illustrates a substantial advantage over some of the baseline materials such as Kovar.

Another property of interest to designers for these applications is elastic modulus. A material with higher elastic modulus provides a more rigid base for the active components in a system, reducing chances of damage during handling and use. This factor is doubly important in MCMs due to their relatively large size. Figure 4 shows the influence of the SiC particulates on the elastic modulus of a SiC/Al composite. The elastic behavior of two-phase systems is well understood and the prediction of one of the models due to Hashin and Shtrikman is shown in the figure along with experimental values obtained in the different composite systems. The elastic modulus of these new packaging materials is comparable to that of steel.

The magnitude of the density advantage offered by the SiC/Al composites is revealed in Figure 5, which shows the specific thermal conductivity and CTE of these materials in comparison to the traditional packaging materials as well as other electronic materials and substrates. The composites offer a threefold improvement in specific thermal performance with similar expansion characteristics when compared to Kovar and W/10 vol.% Cu. This is a significant factor for avionics applications, where weight savings are highly valued.

**PROCESSING ROUTES**

Many different technologies for the production of SiC/Al composites have emerged over the years. A few of these evolved from methods originally developed for structural applications wherein the amount of SiC particulates was restricted to Vₚ of ~0.15–0.25, while some are more specifically suited for higher particulate volume fractions required for optimum CTE matching to electronic materials.

**Powder Metallurgy**

The powder metallurgy (P/M) process is based on well-established technology whereby the SiC particulates (SiCₐ) are blended with aluminum powder and then consolidated into a fully dense product by vacuum hot pressing. The hot-pressed billet can be further processed into forged and extruded stock for subsequent fabrication by machining into electronic packaging components. DWA Composites Specialties and Advanced Composite Materials Corporation manufacture products of this type. Product literature of DWA indicates an electronic-grade Al/SiCₐ metal-matrix composite with a Vₚ of 0.50–0.55 to have a CTE of 7.9–8.6 x 10⁻⁶/°K with a thermal