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METALLIC COMPOSITE MATERIALS FOR AFFORDABLE & RELIABLE THERMAL MANAGEMENT OF HIGH POWER DEVICES

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ABSTRACT

Lower cost aluminum silicon carbide (Al-SiC) metal matrix composite (MMC) produced by stir-casting is emerging as an important material in cost effectively improving the reliability of high power electronic devices; e.g. electronic (IGBT) baseplates, thermal spreaders & stiffeners for flip-chip microelectronics, and heat slugs or MCPCB base layers for high brightness LEDs. This paper will review the properties and competitive cost of these new Al-SiC materials as well as the ability to tailor the coefficient of thermal expansion (CTE) of the Al-SiC to minimize thermal fatigue on solder joints and reduce component distortion. The impact on the final component cost through the use of conventional forming techniques such as (a) rolling sheet followed by stamping, and, (b) die casting, will be described, as will be the opportunity of eliminating a thermal interface material (TIM) layer by integrating the thermal spreader with the heat sink for high power microelectronic packages.

INTRODUCTION

Size and performance of electronic equipment, devices and components continues to evolve at breakneck speeds. Smaller and smaller designs dictate more complex thermal solutions with customers demanding higher reliability and at the same time lower cost. High power devices continue to rely on a mix of metals, ceramics, and polymers. Metals have the highest thermal conductivity and tend to be scattered throughout the electronic design (silicon chip, copper circuitry & DBC, aluminum heat sink) while ceramics and polymers are used for electrical isolation and thermal interfaces, respectively[1]. The number of possible combinations and permutations for combining these layers are staggering and often lead to compromises in performance. Whether designing Insulated Gate Bipolar Transistors (IGBTs), High Brightness Light Emitting Diodes (HB LEDs), or the latest Flip Chip (FC) semiconductor packages, designers utilize these materials, balancing performance, reliability and cost. Aluminum and copper tend to be default metal selections in heat spreader and heat sink applications, with aluminum silicon carbide (AlSiC) metal matrix composites (MMCs) and copper-tungsten or copper-molybdenum options only being explored in niche applications because of perceived cost penalties. Stir-cast AlSiC MMC introduces a significant new level in cost-performance for high power reliability.

STIR-CAST AlSiC PROCESS

Stir-casting is a unique method for making aluminum metal matrix composite. Silicon carbide (SiC) particles are added to molten aluminum and then cast using equipment and techniques similar to the aluminum industry, allowing for high volume manufacturing and low production costs. A proprietary mixing technology disperses the SiC particles uniformly throughout the aluminum matrix, fully wetting each particle for excellent interface properties (Figure 1). SiC particle additions can range from 0 – 45% by volume (0 – 50% by weight).

Once the molten metal composite is fully mixed, the AlSiC can be cast into ingots or into rolling slabs for further processing. Ingots can be re-melted and cast using traditional aluminum foundry techniques like die casting, squeeze casting or investment casting. These casting techniques allow for varying speeds of production and complexity of part manufacturing. Die casting is the fastest with a high number of parts being produced per minute while investment casting is the slowest but allows for much more intricate parts to be made.

Rolling slabs can be rolled into plates and sheet ranging from as thin as 0.5mm to as thick as 1-inch (25.4mm). AlSiC formulations containing up to 30 volume percent (30 v/o) SiC can be rolled and stamped or coined into final parts.

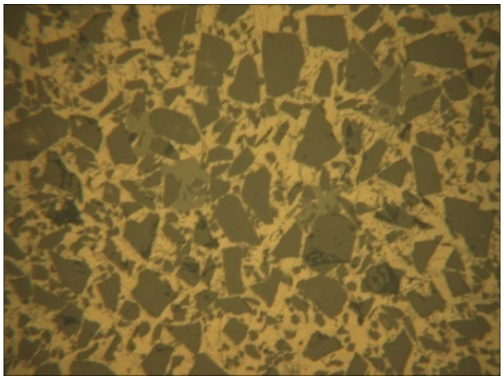


Figure 1: *45 v/o SiC MMC produced using Stir-Cast method*

STIR-CAST AlSiC MMC PROPERTIES

Thermal Properties

For thermal management applications, one of the key attributes of AlSiC is the ability to tailor the coefficient of thermal expansion (CTE). In using the stir-cast method, varying the aluminum alloy and the amount of SiC in the aluminum matrix can produce CTE values that range from over 16.5 ppm / ˚C to as low as 10.5 ppm / ˚C (Figure 2). The reduction in CTE allows for changes in TIM layer composition as well as DBC selection (alumina to aluminum nitride).

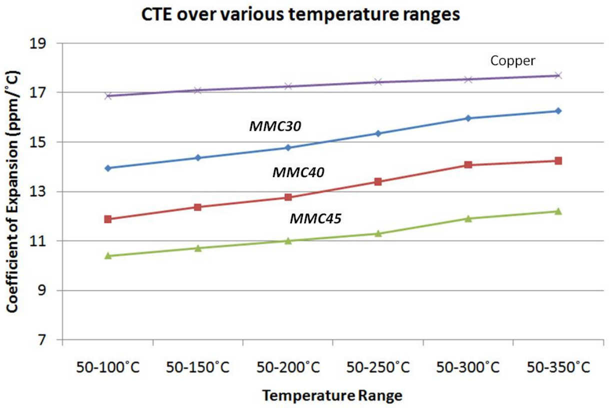


Figure 2: *CTE comparison of copper versus three stir cast AlSiC formulations over various temperature ranges.*

Thermal conductivity typically measures between 160 W/mK and 180 W/mK for stir-cast AlSiC products depending on the alloy and particle combination. Table 1 compares thermal properties of common metals used in thermal management of electronic components. AlSiC's combination of good thermal conductivity and low thermal expansion allows for more creative uses of Thermal Interface Materials (TIMs) and possibly the elimination of a TIM layer altogether. TIMs have the lowest thermal conductivity of any layer in an electronic package.

Material	Thermal Conductivity	Coefficient of Thermal Expansion
6061aluminum	~180 W/mK	~23.6 ppm / ˚C
C10100 copper	~ 390 W/mK	~ 17.5 ppm / ˚C
30 v/o SiC MMC	~ 160 W/mK	~ 14.5 ppm / ˚C
45 v/o SiC MMC	~ 180 W/mK	~ 10.5 ppm / ˚C

Table 1: Thermal properties of thermal spreaders and heat sinks

Mechanical Properties

The addition of SiC ceramic particles to aluminum significantly improves strength, wear resistance and elastic modulus over basic aluminum. Rolled copper has good strength but with significant penalty on weight (copper density is 8.9 g/cc versus 2.8 g/cc for 30 v/o SiC MMC). Elastic modulus (stiffness) of AlSiC is another key parameter often overlooked in electronic components (see Table 2). The high stiffness and low density of AlSiC provides a material with high specific modulus, creating a damping effect, which dissipates vibration energy. Minimizing vibration improves reliability of components like metal clad printed circuit boards (MCPCBs) and IGBTs going into harsh environments (e.g. military vehicles automotive)[2].

Material	Yield Strength	Elastic Modulus
6061aluminum*	Up to 55 MPa	69 GPa
C10100 copper**	Up to 365 MPa	115 GPa
30 v/o SiC MMC**	Up to 275 MPa	115 GPa
45 v/o SiC MMC*	Up to 180 MPa	175 GPa

* as-cast condition
** rolled and heat treated

Table 2: *Mechanical properties of thermal spreaders and heat sinks*

ALSIC MMC APPLICATIONS IN ELECTRONICS

Use of AlSiC MMC in thermal management has been limited to primarily IGBT base plates[3] in traction applications and Flip Chip lids in semiconductor packaging. Low usage of preform infiltrated AlSiC is not because of performance or availability, but because of cost or difficulty in determining the cost benefit over copper[4]. IGBT baseplates and cold plates in hybrid or electric vehicle power modules is a prime area for stir cast AlSiC to upgrade reliability and lifetime of critical components at a very light weight and similar cost when compared to copper. High volumes of baseplates can be blanked from stir-cast AlSiC sheet while pin-fin designs can be manufactured quickly and efficiently using traditional die casting equipment used in producing aluminum parts. Casting can also allow for insert designs for effective active-coolant systems. Whether used in very large IGBT modules for wind turbines or power modules in the upcoming HEV fleets, stir-cast AlSiC can keep all of the essential properties to a minimum: i.e. weight, failure rates and cost.

Another emerging application for stir-cast AlSiC is in the use as the base layer in metal clad printed circuit boards (MCPCB) which require high thermal conductivity and low CTE. While aluminum and copper effectively move heat away from the die, the high CTE of these metals reduce the reliability of high power devices like High Brightness Light Emitting Diodes (HBLED). Solder joint failure is the primary cause of reduced life of LEDs. Utilizing rolled sheets of stir-cast AlSiC improves the reliability by reducing the CTE mismatch between the LED and the board[5]. Furthermore, direct bonded copper (DBC) packaged LED components can be soldered directly to an exposed section of the AlSiC board, reducing the thermal resistance (Rth) created by the boards dielectric layer.

Preform infiltrated AlSiC has been used in microelectronic packaging for more than 15 years. Traditionally, the AlSiC is used as the thermal spreader or lid in the Flip Chip (FC) design. With the advent of low cost stir-cast AlSiC sheet, lids can be rapidly stamped or coined from the sheet to provide higher reliability solder joints for FC packages. In addition, the low cost process of die casting stir-cast AlSiC can be used to eliminate the TIM layer between the lid and the heat sink, integrating the lid and heat sink into one thermally optimized design (see Figure 3)[6].

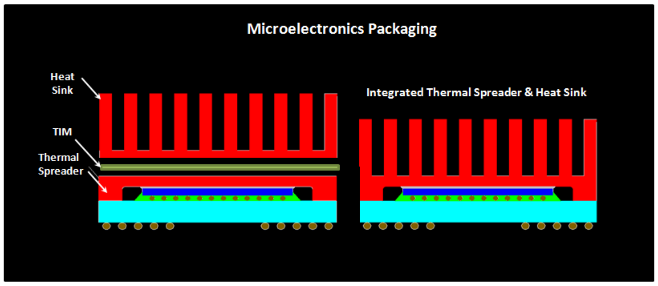


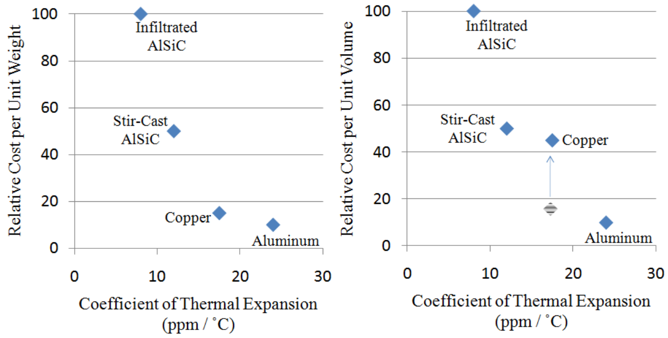
Figure 3: *Sketch representing typical Flip Chip microelectronics package design compared with an integrated spreader/heat sink option*

ALSIC MMC COST COMPARISON

Stir-casting AlSiC opens a new regime in thermal spreading and heat management in terms of cost performance. Traditionally, aluminum is selected due to its very low cost, straightforward manufacturability and relative ease in locating a vendor. Copper is also used in many applications due to its higher conductivity and lower CTE than aluminum. However, copper still has too high a CTE for many of the higher performing materials comprising the total package (AlN, high T_c TIM, etc). Couple this with copper's very heavy weight per until volume penalty, high reactivity to air and moisture, and difficulty in forming outside of rolled sheet, selecting copper has many drawbacks that offset the eye-catching thermal conductivity. The final option has been preform infiltrated AlSiC. With CTE's from 9 ppm/˚C down to less 6 ppm/˚C and thermal conductivity equivalent to aluminum, preform infiltrated AlSiC use has been used in niche applications because of its high reliability over numerous thermal cycles. The main reason it is not more widely used is the very high cost to manufacture.

Until recently, there has not been a material to fill the gap between copper (CTE ~17.5ppm/˚C) and high priced infiltrated AlSiC (CTE 10ppm/˚C to 6ppm/˚C). Now, AlSiC can be tailored to range from 16.5ppm/˚C down to 10.5ppm/˚C at a cost that can approach that of copper. Stir-cast AlSiC can provide the higher reliability of low CTE materials with a lower price because of its ability to be formed using traditional, high volume metal-forming techniques.

The most common mistake made when comparing costs of thermal spreading materials is not correcting for density (weight per unit volume). Copper's density is 3.0 – 3.3 times that of aluminum and AlSiC. So if you have an IGBT baseplate or sheet of MCPCB that weighs 1.0 kilogram, the same part made from AlSiC may only weigh 0.3 kilograms. By using copper, you are in effect paying for three times as much metal. Copper pricing is volatile and can be tracked on the London Metal Exchange (LME). Assuming that copper is priced at $7/kg, to try and compare that same 1 kg baseplate or MCPCB in AlSiC would mean starting at $21/kg worth of raw materials. Since stir-cast AlSiC can be processed using similar techniques as copper (rolling and stamping/coining), downstream manufacturing costs of copper versus stir-cast AlSiC are more or less equivalent, leading to AlSiC being a cost-effective alternative.



(a) (b)

Figure 4: *Graphs displaying relative costs of thermal management metals using (a) unit weight and (b) unit volume versus Coefficient of Thermal Expansion. Cost figures are approximate and very much part dependent. Normalized values in (a) and (b) are meant to display the 'value change' for copper when corrected for density.*

CONCLUSION

By selecting the appropriate CTE of the AlSiC and thermal conductivity of the TIM layer, power electronic devices can be engineered without compromise on performance or cost. In many applications, the TIM2 layer may even be engineered out of the design, further improving the Rth of the overall package. The low density and CTE of stir-cast AlSiC makes it cost effective against copper for IGBT modules, especially Hybrid Electric (HEV) and fully Electric Vehicles (EV). Furthermore, its ultra high stiffness to weight ratio provides IGBTs and MCPCBs with rugged vibration resistance in harsh conditions, preserving the solder joints and wire bonds for long life and reliability.

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