New Heat Sink for Railroad Vehicle Power Modules

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As countermeasures against global warming and fossil fuel depletion, electric railways have been increasingly installed for their excellent energy efficiency. Sumitomo Electric Industries, Ltd. and its group company A.L.M.T. Corp. have developed a new heat sink that is made of a magnesium silicon carbide composite (MgSiC) to be used for the power modules of railroad vehicles. The MgSiC heat sinks are superior in thermal conductivity and easy to process compared with the conventional heat sink made of aluminum silicon carbide composite (AlSiC). The new heat sink is expected to contribute to the development of advanced power modules.

Keywords: heat sink, power modules, MgSiC, composite, thermal conductivity

1. Introduction

Electric railways are attracting attention as a means of energy-efficient land transportation to solve the problems of global warming and fossil fuel depletion, and the development of railway networks is currently in progress the world over.

To use energy efficiently, electric railway vehicles use power devices[*1]. In particular, devices driving the main power motors generate a great deal of heat, and to prevent them from breaking, a composite material of silicon carbide (SiC) and aluminum (Al) (referred to as AlSiC in the following) that provides a controlled linear thermal expansion and high thermal conductivity is used in heat sinks.

Sumitomo Electric Industries, Ltd. and A.L.M.T. Corp. have jointly developed new heat sinks consisting of a composite material (referred to as MgSiC in the following) composed of magnesium (Mg) and silicon carbide (SiC) destined for power modules installed on electric railway vehicles. This material has a linear thermal expansion equivalent to that of AlSiC and a higher thermal conductivity; in addition, this material can be manufactured with simple processes.

2. Heat Sink Products of A.L.M.T. Corp.

Semiconductor elements, such as microprocessors and power devices, produce heat, and to remove it, heat sink materials are used. Copper and aluminum alloys, which are inexpensive yet good heat conductors, are often used as heat sink materials. In devices that produce a great amount of heat and that require high reliability, however, advanced functional materials whose linear thermal expansion matches that of the element and surrounding members are used to prevent the devices from breaking due to thermal stress under high loads.

A.L.M.T. Corp is a comprehensive manufacturer of such advanced function heat sink materials. A.L.M.T. Corp responds to the various requirements of users for a wide range of linear thermal expansions and higher thermal conductivities with its core technology of composite materials technology. **Figure 1** shows linear thermal expansions of typical materials forming various devices in contrast with the linear thermal expansions and thermal conductivities of advanced function heat sink materials of A.L.M.T. Corp. The optimum thermal characteristics of a heat sink material, such as the thermal conductivity and linear thermal expansion, are selected in consideration of structure of the entire device.

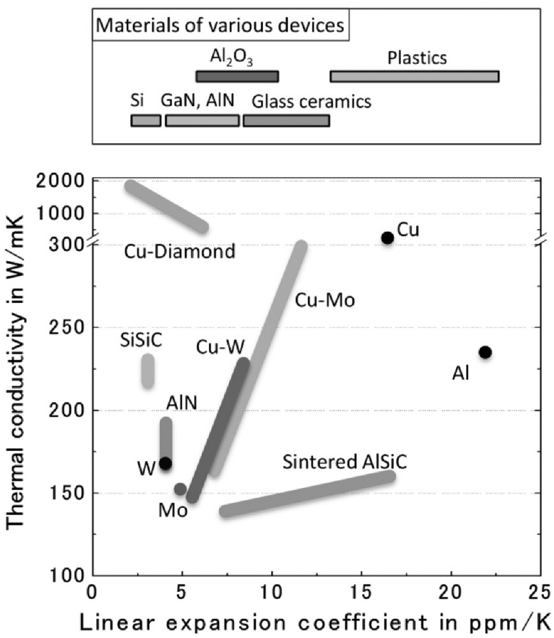

Fig. 1. Characteristics of heat sink materials from A.L.M.T. Corp

3. Features of an Electric Railway Vehicle Power Module and a Heat Sink

Figure 2 shows a pattern diagram of a power module for the main power control for electric railway vehicles. With the power devices joined to an AlSiC heat sink, the electric and electronic circuits necessary for control are packaged and integrated inside a casing. This power module has a size in common to the world over, generally providing compatibility between products of different makes.

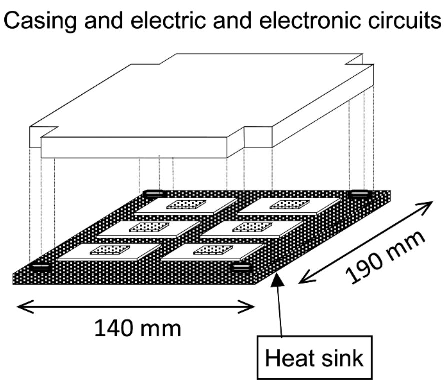

Fig. 2. Pattern diagram of a power module

Figure 3 shows a cross-section of a heat sink for electric railway vehicles attached to a cooling unit. The power device and the heat sink are on either side of a ceramic insulating substrate with a metal layer on both sides, and they are soldered to the ceramic insulating substrate. The power module is bolted to the cooling unit via heat conducting grease.

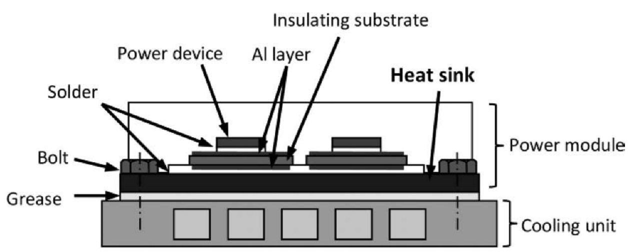

Fig. 3. Schematic diagram of a cross-section of a power module

Table 1 shows typical specifications of a power module used in this field.

The heat sink is provided with warping that is rendered convex on the cooling unit side with the aim of ensuring close contact between the cooling unit and the heat sink, which are fastened together with a bolt, with the warping being finished in suitable dimensions depending on the kind, and other properties of the insulating substrate.

Table 1. Specifications of a heat sink for power modules destined for electric railway vehicles

Charact eristics	Thermal conductivity	180 W/mk or more
	Linear thermal expansion	7.5 ppm/K
Shape and others	Size	140 × 70 × 5mm 140 × 130 × 5mm 140 × 190 × 5mm
	Warping	To be specified depending on the material of the insulating substrate
	Surface finish	Ni plating

4. Development of a New Heat Sink (in MgSiC)

4-1 MgSiC manufacturing method

Figure 4 shows the method of manufacturing MgSiC in contrast with the high pressure casting process[*2], the typical method of manufacturing AlSiC. Both are composite materials made of SiC particles and metal, and are made by allowing metal to permeate into the gaps between SiC particles.

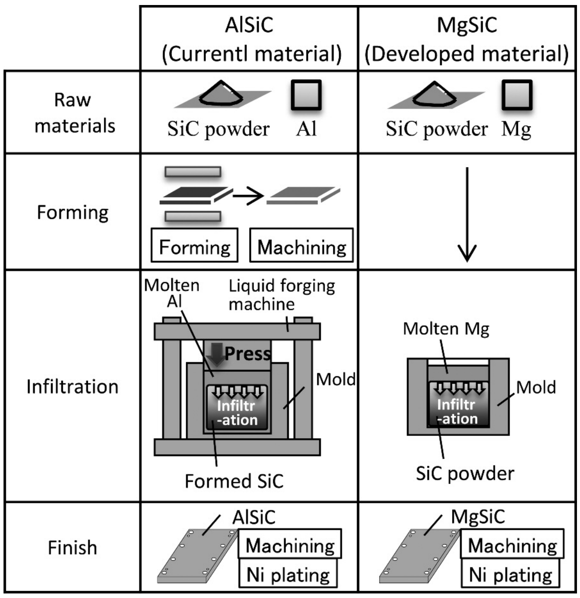

Fig. 4. Methods of manufacturing heat sinks

AlSiC requires formed SiC before molten metal is infiltrated between the SiC particles.

Having been processed as required, the formed SiC are placed into a mold, and high-pressure molten aluminum alloy is allowed to infiltrate. Following this, the structures are processed and plated to become products.

MgSiC does not require formed SiC; filling a mold with SiC particles sufficiently. In addition, the infiltration of fused magnesium does not need external pressure. Following solidification, the structures are processed and plated to become products.

As described above, the manufacturing process for MgSiC is simpler than that for AlSiC, and may be able to reduce costs. Furthermore, MgSiC is able to be formed into complex-shaped products if the shape allows SiC powder to be charged, and to be large-sized products because MgSiC does not need pressure. In addition, MgSiC allows the linear thermal expansion to vary depending on the percentage of SiC.

Photo 1 shows the appearance of an MgSiC heat sink, with **Photo 2** showing an optical microscope image of its cross section. The photo shows that Mg is tightly charged between SiC particles.

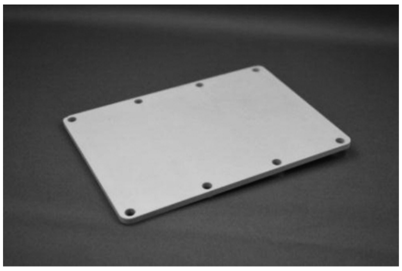

Photo 1. Appearance of MgSiC

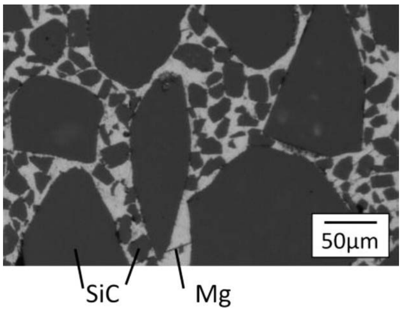

Photo 2. Cross section of an MgSiC sample

4-2 Characteristics of MgSiC

Table 2 shows the characteristics of pieces of MgSiC whose linear thermal expansion is adjusted to 7.5 ppm/K, the linear thermal expansion of AlSiC for heat sinks for railway vehicles, in comparison with the characteristics of AlSiC.

It was confirmed that MgSiC shows a thermal conductivity value as high as 210-230 W/mK, a better value than AlSiC by 10-20%. In regard to other physical properties, MgSiC shows a slightly smaller specific weight value but equal mechanical properties.

Table 2. Typical characteristics of MgSiC

	Thermal conductivity [W/mK]	Linear thermal expansion [ppm/K]	Specific weight [g/cm^3]	Bending modulus [Gpa]	Bending strength [MPa]
MgSiC	210～230	7.5	2.7	140	400
AlSiC	185	7.5	3	145	380

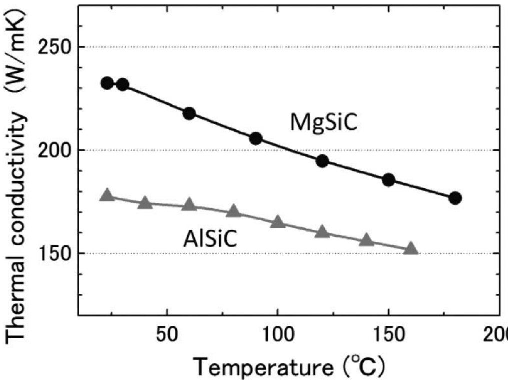

Fig. 5. Temperature dependency of the thermal conductivity of MgSiC

Figure 5 shows the temperature dependence of the thermal conductivity of MgSiC. MgSiC shows higher thermal conductivity values than AlSiC in the temperature range between room temperature and 200°C.

4-3 Consideration on the thermal conductivity of MgSiC

To investigate the reason for the high thermal conductivity of MgSiC, we observed the interface between Mg and SiC particles with a transmission electron microscope.

With AlSiC, it is known that growth of Al_4C_3 often occur in the interface between Al and SiC particles as shown in **Photo 3**[1].

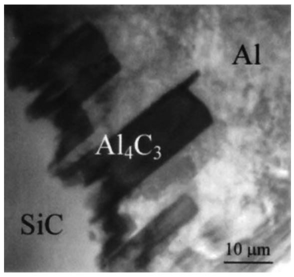

Photo 3. TEM image of carbonate produced in the interface between Al and SiC[1]

With MgSiC, on the other hand, the transmission electron microscope image of the interface between Mg and SiC particles in **Photo 4** shows no intermediate layers in the interface between Mg and SiC but a direct coupling in-

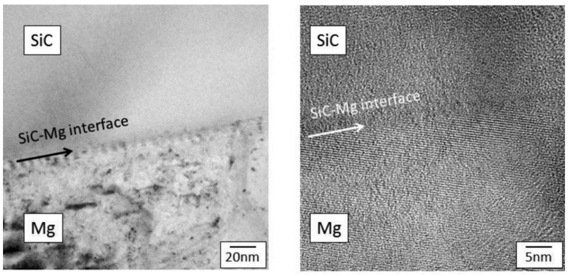

Photo 4. TEM image of the interface between SiC and Mg in MgSiC

stead. We consider that this structure accounts for good heat transmission and the appearance of high thermal transmission.

4-4 Confirmation of the reliability of MgSiC

We fabricated samples in which MgSiC and an insulating substrate (with a metal layer on both sides) are bonded with solder to assess their durability. Aluminum nitride (AlN) substrates with an Al layer on both sides were used as insulating substrates.

Table 3 shows the experiment conditions.

Table 3. Conditions for bonding and conditions for durability assessment

Insulating substrate	AlN insulating substrate with an Al layer on both sides Dimensions:70 × 40mm AlN section thickness:0.635mm Al layer thickness: 0.4mm
Solder type	Paste solder with a composition of Sn-3% Ag-0.5% Cu Model M705 (manufactured by Senju Metal Industries, Co. Ltd.)
Joining condition	Hot plate Heating temperature: 280˚C
Heating-cooling cycle	Liquid bath heating-cooling test Heating-cooling test between the conditions of −40˚C for 7 min and 125˚C for 7 min Up to 4000 heating-cooling cycles
Measuring warping	Shape measuring instrument Span: 50 mm
Measuring internal Inspection	Ultrasonic testing Frequency: 25 MHz

Figure 6 shows the schematic diagram of a bonded sample. In the assessment, the warping was measured and the solder joints underwent ultrasonic inspection after the samples were subjected to a specified number of heating-cooling cycles before and after making the solder joints.

Figure 7 shows the variation in the warping of MgSiC pieces before and after solder joining and after the heating-cooling cycle test. Both materials exhibit about the same behavior in warping variation because MgSiC is equivalent to AlSiC in terms of its linear thermal expansion and mechanical properties. The reason for a larger variation in

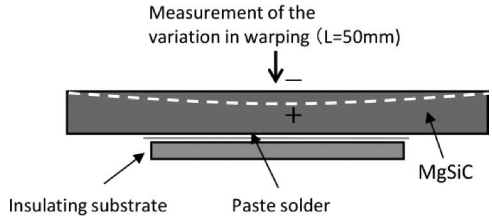

Fig. 6. Schematic diagram of an MgSiC insulating substrate sample with paste solder joint

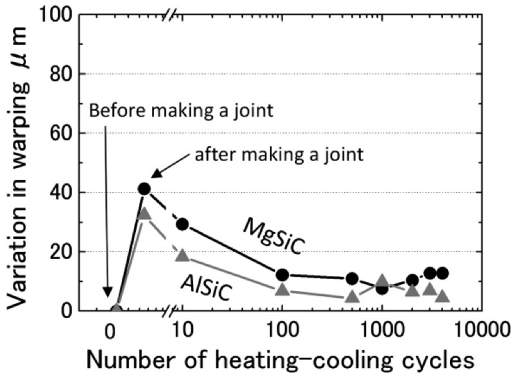

Fig. 7. Number of heating-cooling cycles and variation in warping

the warping observed immediately after solder joining in both materials is estimated to be the difference between the soldering temperature and the ambient temperature, which lead to the thermal stress generated by the difference in the linear thermal expansion between the insulating substrate and the heat sink. The stabilization of warping in the later heating-cooling cycles is estimated to be due to the release of residual stress.

Our observation has confirmed that both materials exhibited neither separation nor other abnormalities in the ultrasonic evaluation of the solder joints in the present test range.

4-5 MgSiC materials with preliminary warping

As has been explained in 4-4, joining a heat sink and an insulating substrate produces a variation in the warping due to the thermal stress caused by the difference in the linear thermal expansion between both materials.

With a power module intended for electric railway vehicles, the linear thermal expansion of a heat sink (7.5 ppm/K) is generally greater than that of an insulating substrate (4.5 ppm/K). For this reason, a power module intended for use in electric railway vehicles tends to become convex on the insulating substrate side after soldering, and as is seen from the power module shown in **Fig. 3**, it is difficult to produce a contact between the cooling unit and the heat sink. To avoid this, a heat sink is provided with warping in advance.

MgSiC can also be provided with such warping. **Figure 8** shows an example of warping adjusted for the AlN insulating substrate used in the case described in 4-4.

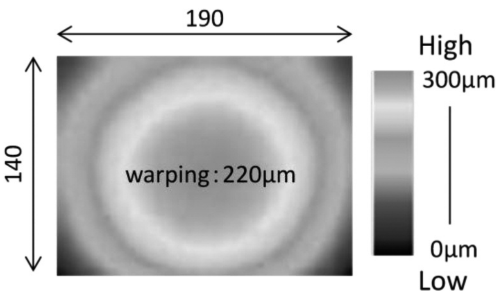

Fig. 8. Surface shape of an MgSiC piece provided with warping

4-6 Incombustibility of MgSiC in heating

To assess the incombustibility of MgSiC in heating, we measured the ignition point by means of a test based on ASTM E659. In the measurement, samples each held by using nichrome wires (with dimensions of 10 × 10 × 5 mm) were put into three flasks held at specified temperatures (500, 550, and 600°C) to confirm visually whether glowing or ignition occurs within 10 minutes.

The result was that MgSiC samples exhibited neither ignition nor glowing even at 600°C. It can be concluded that MgSiC in the form of a simple substance does not need particular consideration in heating of up to 600°C or so.

5. Conclusion

Sumitomo Electric Industries, Ltd. and A.L.M.T. Corp have jointly developed new heat sinks using a composite material (MgSiC) composed of Mg and SiC destined for power modules installed on electric railway vehicles.

A.L.M.T. Corp has started developing technologies for the mass production of the new material and introducing it to the market.

Developing power electronics technology is important from the viewpoint of efficient utilization of energy, and our group is willing to contribute to this goal through the development of new materials in this field.

Lastly, we would like to add that the newly developed material has been patented.

Technical Terms

*1 Power device: Semiconductor elements, such as IGBTs and thyristors, used to convert voltages, alternating and direct currents, and frequencies, or to turn power on or off. A packaged unit collectively containing one or more power devices and their driving circuits, self-protecting circuits, input and output terminals, and heat sinks (heat dissipating substrates) is called "Power modules."

*2 High pressure casting process: Method of making composite materials by allowing high pressure molten metal to infiltrate the gaps between porous substances like ceramics.

References

(1) J. A. Vreeling et al., Scripta mater. 42 (2000) 589–595

(2) ASTM E659

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