

High Performance, Lightweight Graphite Heat Sinks/Spreaders

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ABSTRACT

Heat sinks have conventionally been manufactured from aluminum and copper alloys. A new natural graphite/epoxy material has been developed which has a thermal conductivity roughly equal to copper in two directions, and has a density of only 1.9 g/cm³. Computational Fluid Dynamics (CFD) has been used to demonstrate how an effective heat sink can be manufactured from a material such as natural graphite/epoxy, which has a high thermal conductivity in only two directions. Examples of early stage heat sinks and manufacturing issues are described.

MANUFACTURE OF NATURAL GRAPHITE HEAT SINKS

There is a continuing need for lighter weight, higher performance heat sinks and spreaders to meet the demanding needs of today's electronics cooling market. Natural graphite-based materials are attractive for heat sinks and spreaders because of their combination of low density (1.3-2.0 g/cm³) and high thermal conductivity in two directions. Earlier work¹ described the development of materials with in-plane thermal conductivity of ~200-230 W/mK, or roughly equal to aluminum. This paper describes recent advances in material development in which in-plane thermal conductivity of near 400 W/mK, or roughly equal to copper, has been achieved. Another challenge has been how to design and manufacture heat sinks from a material that has high thermal conductivity in only two directions. Manufacturing methods are under development in which the heat sink base and fins are manufactured from materials with different high thermal conductivity orientations. CFD has been used to examine different combinations of high thermal conductivity orientation in the heat sink base. Modeling predictions are compared with heat sinks manufactured from aluminum and copper.

MATERIAL PROPERTIES

Typical properties of the material used to manufacture the heat sinks and spreaders are shown in Table I. All measurements were performed at room temperature unless otherwise specified. Thermal conductivity values were obtained using a thermal diffusivity technique (ASTM designation C 714-85). Electrical resistivity was measured according to ASTM C-611 with flexural strength (3 point, span/thickness = 35:1) being measured according to ASTM standard D 790-71. The Coefficient of Thermal Expansion (CTE) was measured using the Parma Automated Thermal Extensometer (PATE) method. For comparison purposes, properties of typical aluminum (6063T6) and copper (C15710 0%) heat sink alloys are also shown.

The material is a composite of natural graphite and epoxy resin, manufacturing methods being described in reference 1. The proportions of graphite and epoxy can be varied over a wide range, allowing some tailoring of these properties.

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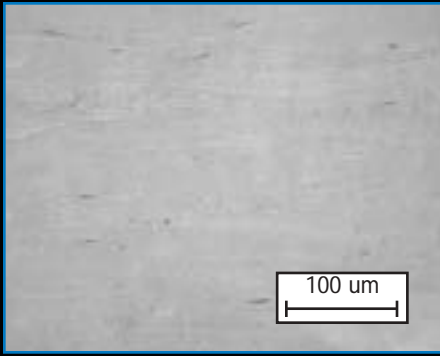


Figure 1:
Microstructure of Graphite/Epoxy Composite

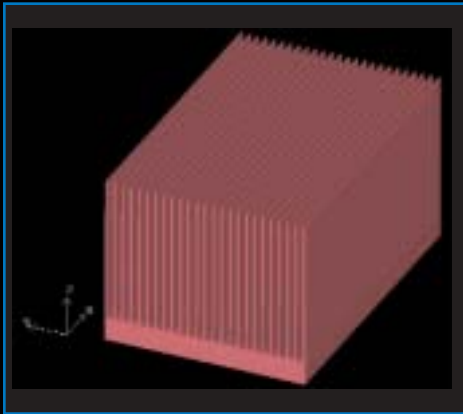


Figure 2.
3-D Model of a Heat Sink for This Study

Property	Units	Direction	Typical Value Graphite/Epoxy	Typical Value Aluminum 6063 T6	Typical Value Copper C15710 0%
Density	g/cm ³		1.94	2.70	8.82
Thermal Conductivity	W/mK	In-Plane	370	201	360
Thermal Conductivity	W/mK	Thickness	6.5	201	360
Thermal Anisotropy			57	1	1
Specific Heat Capacity	J/kgK		846	900	380
Resistivity	μohmm	In-Plane	6	0.053	0.018
Cte (30-100 °C)	10 ⁻⁶ m/m/°C	In-Plane	-2.4	23.4	19.5
Cte (30-100 °C)	10 ⁻⁶ m/m/°C	Thickness	54	23.4	19.5
Flexural Strength	MPa	In-Plane	70	214(YS)	270(YS)
Young's Modulus	GPa	In-Plane	42	68.3	105
Hardness	Rockwell R	In-Plane	96	73(HB)	60(HRB)

Source of material properties for aluminum and copper alloys: Metals Handbook, Volume 2, Tenth Edition. Values of flexural strength reported for aluminum and copper alloys are actually yield stress values. Hardness values reported are different Rockwell scales.

A typical density for the material is $\sim 1.9 \text{ g/cm}^3$, which is $\sim 70\%$ and $\sim 22\%$, respectively, of the density of aluminum and copper alloys. The graphite/epoxy material is a laminate and exhibits markedly different properties in-plane compared to out-of-plane (through-thickness). A typical micrograph of a graphite/epoxy laminate is shown in Figure 1 and shows the layering of the graphite and epoxy. In the in-plane direction, the properties are dominated primarily by the in-plane properties of the graphite, while in the through-thickness direction, the properties are dominated by the epoxy and out-of-plane properties of the graphite. The in-plane thermal conductivity of the material is $\sim 370 \text{ W/mK}$, which is 77% higher than aluminum and comparable to copper. The through-thickness value of thermal conductivity is low ($\sim 6.5 \text{ W/mK}$) for the graphite/epoxy material making it uniquely thermally anisotropic. The material anisotropy is also reflected in the difference in thermal expansion coefficient in the in-plane and through-thickness directions. In the in-plane direction, the CTE is slightly negative, while in the through-thickness direction it is $\sim 50 \times 10^{-6} \text{ m/m/}^\circ\text{C}$, measured over the temperature range of $30 \text{ }^\circ\text{C} - 100 \text{ }^\circ\text{C}$. The material is an electrical conductor, although its electrical conductivity, unlike its thermal conductivity, is two orders of magnitude lower than aluminum and copper alloys. The material is not as strong as aluminum and copper alloys. The material is also relatively soft and will dent if dropped on an edge.

MANUFACTURE OF GRAPHITE/EPOXY HEAT SINKS

The high in-plane thermal conductivity and low density of the graphite/epoxy material make it an ideal material for the fins of a heat sink where low through-thickness thermal conductivity is of little consequence. Graphite/epoxy fins can provide the same thermal performance as copper at only $\sim 22\%$ of the weight.

In the production of a traditional heat sink, however, thought must be given to the manufacture of not only the fins but also the base. The base usually needs to spread the heat in all three directions, depending on the dimensions of the heat source relative to the heat sink footprint. The low through-thickness thermal conductivity of the graphite/epoxy material is a disadvantage in the manufacture of a heat sink base. Despite this disadvantage, effective heat sinks can still be manufactured from graphite/epoxy materials by appropriate selection of the high thermal conductivity orientations in the base. This is made possible because the fins and base can be made independently from each other and joined at some later stage of the process. The influence of different high thermal conductivity orientations in the base is demonstrated by way of CFD analysis as discussed in the next section.

CFD MODEL DESCRIPTION AND ASSUMPTIONS

The CFD model shown in Figure 2 is implemented on commercially available finite volume software, ICEPAK™². For this study, a generic heat sink size of 90 mm length (= x direction) by 60 mm width (= y direction) x 50 mm height (= z direction) was used. The base thickness was 7 mm, the fin thickness 0.6 mm, the fin spacing 1.875 mm and the number of fins was 25. The fins were assumed to be embedded to half the thickness of the base (= 3.5 mm). The heat source is assumed to be 100 W and with heat generation spread uniformly over the active area of 42 x 42 mm² at the center of the heat sink base. An airflow rate of 3.5 m/s is prescribed in the CFD model. Adiabatic boundary conditions are specified for the outside surface of the walls. The inlet boundary conditions provide for uniform velocity profile at ambient temperature, while the outlet is treated as a free surface. Thermo-physical properties listed in Table I are evaluated at 35 °C ambient temperature. They are assumed to be independent of temperature. Radiative losses between the heat sink and the system are assumed to be negligible due to the correspondingly small view factors. Grid size of 48 x 51 x 125 (300,000 cells) is used for this study.

The fins in each case were oriented with the high thermal conductivity directions in the X-Z directions. Three base orientations were considered:

- High thermal conductivity in the X-Y direction, low thermal conductivity in the Z direction;
- High thermal conductivity in the X-Z direction, low thermal conductivity in the Y direction;
- High thermal conductivity in the Y-Z direction, low thermal conductivity in the X direction.

Modeled values of thermal resistance (Θ_{sa} heat sink to ambient) and the 3-D temperature distribution for aluminum, copper and the three base graphite orientations are shown in Table II. The worst performance ($\Theta_{sa} = 0.36$ C/W) is for the base orientation with the low thermal conductivity in the z, or through-thickness, orientation. This is easy to understand as heat cannot be conducted effectively enough through the thickness of the base to the fins.

The situation is improved when the base orientation is changed such that the low thermal conductivity direction is now in the y, or width, direction. In this case, the fins and the base now have the same orientation. Heat is now conducted effectively through the thickness and along the length of the heat sink, resulting in a reduction in Θ_{sa} of ~0.09 C/W. It is apparent from the 3-D temperature distribution that the major problem with this orientation is that heat cannot move effectively across the width of the heat sink. This orientation becomes more effective, of course, as the heat source width approaches the width of the heat sink.

The best performance is achieved, for the configuration modeled, when the low thermal conductivity direction is in the x, or length, direction. The base is now moving heat effectively across the width and through the thickness with the fins moving heat along the length. Θ_{sa} is now better than for the aluminum heat sink, although not as good as the copper. This modeling work demonstrates that effective heat sinks can be produced from graphite/epoxy materials despite their low thermal conductivity in one direction. Similar modeling procedures can be adopted for different heat sources and heat sink geometries to allow a comparison of graphite/epoxy, aluminum and copper materials for any configuration.

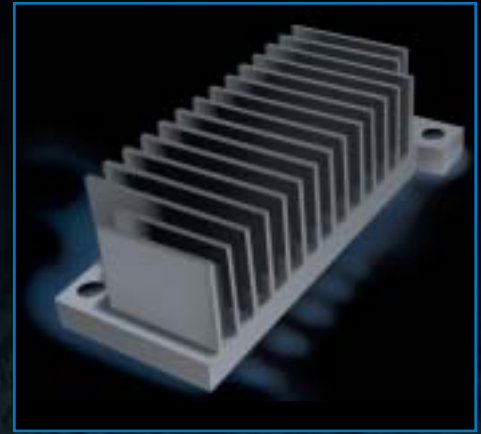


Figure 3.
Example of Early Molded
Natural Graphite Heat Sink

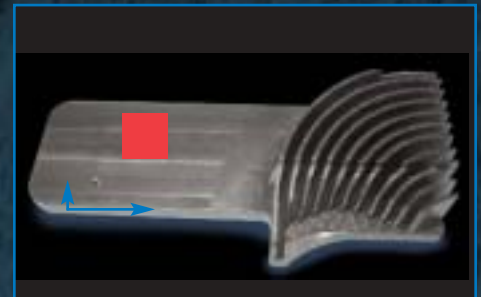


Figure 4.
Example of Machined
Natural Graphite Heat Sink

TABLE II
CFD Modeling Results

Material Option	Tmax (°C)	Θ_{sa} (°C/W)	3-D Temperature Distribution
Aluminum	60.23	0.25	
Copper	56.48	0.21	
Graphite Z=low	70.70	0.36	
Graphite Y=low	62.74	0.27	
Graphite X=low	58.92	0.24	

The calculated masses of the heat sinks produced in this analysis were respectively 186 g, 259 g and 845 g for graphite/epoxy, aluminum and copper, showing the weight advantage of graphite/epoxy over aluminum and particularly copper.

EXAMPLES OF MANUFACTURED HEAT SINKS

Manufacturing processes for the production of graphite/epoxy heat sinks are still under development and are proprietary. Examples of early stage graphite heat sinks are shown in Figures 3 and 4, respectively. Fin thickness as low as 0.5 mm has been achieved, with aspect ratio as high as 100:1. Molding technologies have been developed to produce fin spacing as low as 0.76 mm with up to 80 fins. Θ_{sa} thermal resistance values as low as 0.028 C/W have been achieved on proprietary heat sink designs, with performance numbers generally confirmed to lie between aluminum and copper and, in some cases, matching copper performance.

CONCLUSIONS

Properties of a new graphite/epoxy material have been reported and compared with traditional aluminum and copper heat sink materials. The properties of interest are low density (~1.9 g/cm³) and high thermal conductivity (~370 W/mK) in two directions. CFD has been used to demonstrate how an effective heat sink material can be produced from a material having high thermal conductivity in only two directions.

REFERENCES

1. J. Norley, et al., "The Development of a Natural Graphite Heat Spreader", Semiconductor Thermal Measurement and Management Symposium, March 20-22, 2001.
2. ICEPAK (Version 3.1.6., Advanced Modeling Software for Electronics Cooling) is a trademark of Fluent Inc.