Electronic Thermal Management Using Copper Coated Graphite Fibers

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Introduction

As packaging densities and power requirements increase, the reliability of the electronic components will depend on the ability to transfer heat while matching the thermal expansion coefficient (CTE) of the dielectric coating material and the electronic component. Typical heat sink materials and their properties are shown in Table 1.[1] A comparison of these materials to graphite/copper composites is shown in Table 5.

The best material properties would combine low density, high thermal conductivity and a coefficient of thermal expansion (CTE) between 5.0 and 9.0 ppm/°C. This CTE is required to match the commonly used dielectric material, alumina, which is used to electrically isolate the component from the heat sink. Alumina has a CTE very near that of the component itself, generally made from silicon.

Keeping the CTE's of all materials involved as close as possible lowers the thermal stresses generated by the heating of the component as it operates. This minimizes the failures of chips caused by leads, or electrical connections failing due to the relative movement between the chip and the heat sink. Minimizing CTE mismatches increases reliability. Surface mount technology, where the component is mounted directly to the heat sink without the use of leads, is advanced by the tailorability of thermal expansion and high thermal conductivity.

Metal matrix composites (MMC's), unlike monolithic materials, provide a tailorable CTE and high thermal conductivity. Large scale production of MMC parts will be limited by cost. The high cost of MMC's is composed of two major factors: raw materials and fabrication. While the cost of high thermal conductivity graphite fibers is of significant concern, it is not within the scope of this research. The feasibility of lowering the cost of fabrication is an approach which will be investigated.

The typical procedure is to lay-up the fibers into a unidirectional tape and orient the plies, a time consuming and therefore costly process. Additionally, binders must be used to hold the parallel fibers together into a handleable "green" tape. These tapes are then cut, oriented, stacked and consolidated into panels. Binders are not commonly used for the processing of graphite/copper composites since even small amounts of residue can destroy the thermal conductivity of the composite. This problem can be eliminated by weaving the fibers into a fabric form. The resulting cloth can be cut and oriented without introducing any impurities into the system.

In other composite systems, the impregnation of the cloth with a matrix, such as epoxy or liquid metal infiltration of molten aluminum, leaves voids and uncoated fibers at the cross over points between the warp and fill fibers. In the case of copper-graphite, the matrix material is already uniformly coated around each filament. This coating also helps protect fibers from damage during processing.

Abstract

Electronic packaging requires high thermal conductivity heat sinks with a tailorable thermal expansion coefficient (CTE) to dissipate heat generated in high density packaging without sacrificing reliability. The combination of the ductile yet thermally conductive matrix of copper with a high modulus pitch-based graphite fiber allows for a combination of these properties. Copper coated graphite fibers were woven in a commercial loom in three weave styles. The use of graphite/copper composites produced in this manner for use as heat sinks for electronic components is discussed.

The properties of the composites can be changed by varying the weave pattern, the number of threads per inch in either the warp or fill directions, and the ratio of fiber and copper. Lengths of fabric can be consolidated in continuous operations. The resulting composite can then be machined to shape. This could potentially result in metal matrix composite heat sinks with reasonable processing costs.

Experimental Procedures

A proprietary process was used to produce continuous copper coated graphite fibers. The process applied a pure copper coating corresponding to 50% by volume fiber to pitch-based graphite fibers. The fiber used in this study was P100 (Amoco Performance Products). Textile Technologies, Inc. (Hatboro, PA) used a harness-style weaving loom to produce three distinct sections of fabric with different pattern areas; plain, five-harness satin and eight-harness satin weaves.

Although no fiber breakage was apparent in the copper coated fiber in the fabric, it was considered possible to have damaged the fiber while maintaining a visually coherent coating of copper. Sections of the fabric were impregnated with epoxy resin to maintain the fabric integrity. The impregnated fabric samples were then sectioned and mounted in epoxy to cross-section for evidence of fiber damage. Optical microscopy was used to detect fiber breakage which may have occurred in the weaving process. A section of each cloth was treated with dilute (10%) nitric acid to dissolve the copper coating and then inspected for broken fiber.

For each of the three weave styles, three plies of fabric were layered to provide a preform for subsequent consolidation. Consolidation was performed at Alfred University using an Rf suscepter heated hot press. Consolidation conditions were those typically used for the hot pressing of unidirectional and cross-plied composite specimens. These conditions had been known to provide low void content composites with minimal fiber damage during several other sample preparations.[2,3]

Each of the panels was machined to provide thermophysical test specimens. By labelling the fibers running in the fill direction as X and in the warp direction as Y, thermal expansion, and thermal and electrical conductivity test specimens were prepared with a sample in each direction. These samples were sent to Purdue University for evaluation.

Thermal expansion measurements were taken using dual Push-Rod Dilatometry. The differential expansion between the sample and a known reference material is measured as a function of temperature and the linear expansions determined at preselected temperatures. Thermal conductivity was measured using the Kohlrausch method which involves determining the product of the thermal conductivity and the electrical resistivity. Since the electrical resistivity is measured at the same time, the thermal conductivity can be calculated.

Other samples of the composites were taken and mounted in epoxy for cross-sectioning and metallographic polishing. Polished samples were evaluated for fiber damage as well as indications of unconsolidated areas.

MATERIAL	DENSITY (g/cm^3)	THERMAL CONDUCTIVITY (W/m^oC)	CTE ($10^{-6}/^oC$
Alumina	3.60	16-34	6.48
Copper	8.86	363	17.64
Aluminum	2.71	167	23.40
Kovar	8.31	137	5.76
Cu/Invar/Cu	8.31	122	5.76
Molybdenum	10.25	137	5.22

Table 1. Properties of Heat Sink Materials

MATERIAL	DENSITY (g/cm^3)	THERMAL CONDUCTIVITY (W/m^oC)	CTE ($10^{-6}/^oC$
Plain	5.09		
X-Direction		219	6.81
Y-Direction		210	6.90
5-Harness	5.22		
X-Direction		207	7.12
Y-Direction		217	6.32
8-Harness	5.33		
X-Direction		208	6.75
Y-Direction		230	5.99

Table 2. Properties of Composites

Results

Thermophysical analysis included thermal conductivity, electrical resistivity and thermal expansion in both the X and Y directions. The effect of temperature on thermal conductivity can be seen in Figure 1. The dependence of electrical resistivity is shown in Figure 2. The thermal expansion coefficient versus temperature can be seen for each weave style in Figure 3. The values measured at room temperature are summarized in Table 2.

Inspection of fabric which had been etched by nitric acid showed evidence of graphite fiber ends in the weave pattern, but no clear trend could be determined by visual inspection. Optical microscopy of the cross-sectioned fabric samples which had been impregnated with epoxy then potted, revealed evidence of some fiber damage in the plain weave fabric (Figure 4). Fiber damage was not evident in the 5-harness and 8-harness satin weave samples.

Inspection of consolidated panels resulted in greater understanding of results. Samples in both the fill direction (X) and warp direction (Y) were analyzed for fiber damage and unconsolidated areas. The plain weave panel showed the most evidence of unconsolidated areas in both directions (Figures 5 and 6). There is also considerable evidence of broken fibers.

The number of broken fibers and unconsolidated areas were similar in the 5-harness satin weave samples (Figures 7 and 8). The 8-harness satin weave samples appeared to be the least damaged (Figures 9 and 10). Well con-

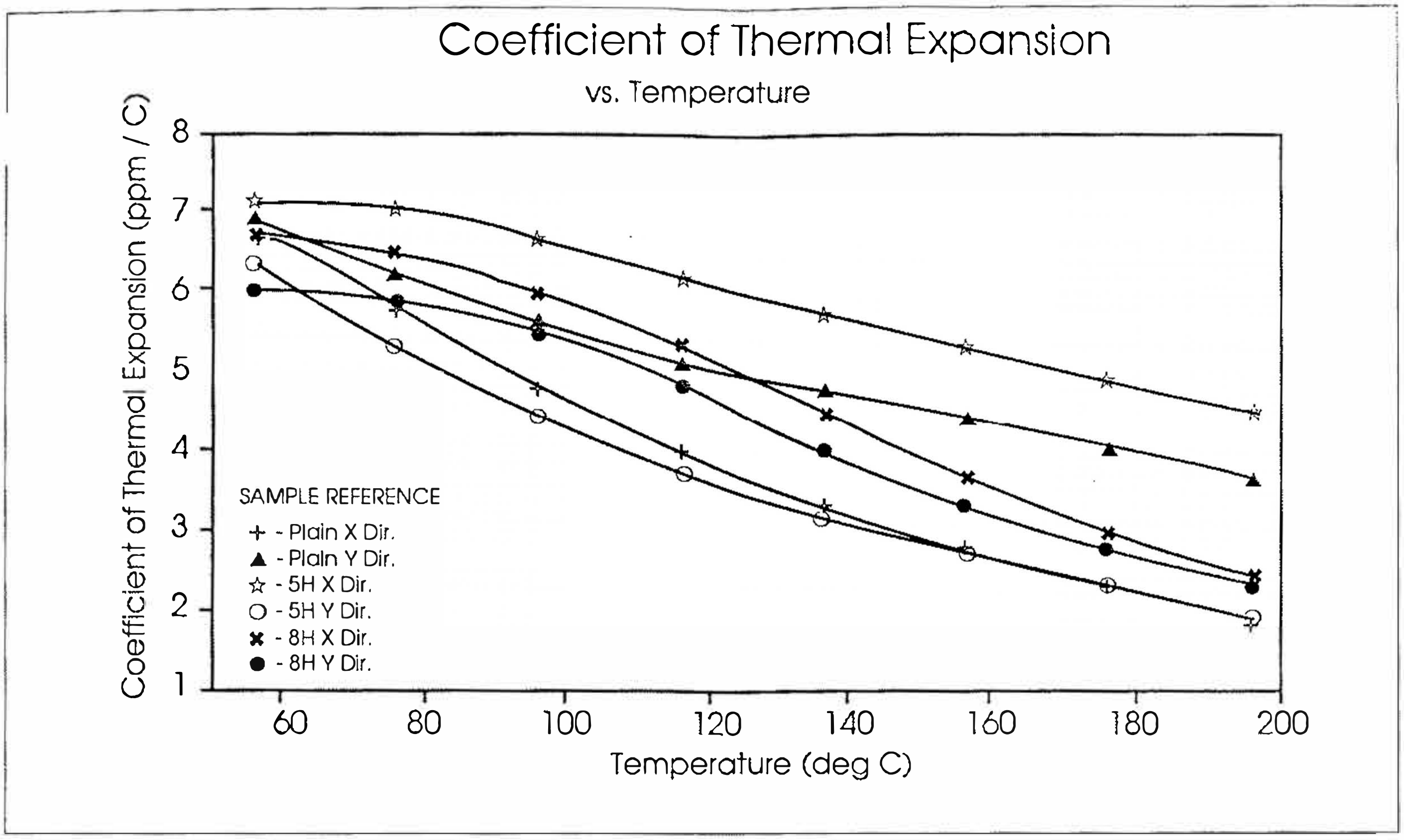


Figure 1. Effect of temperature on thermal conductivity

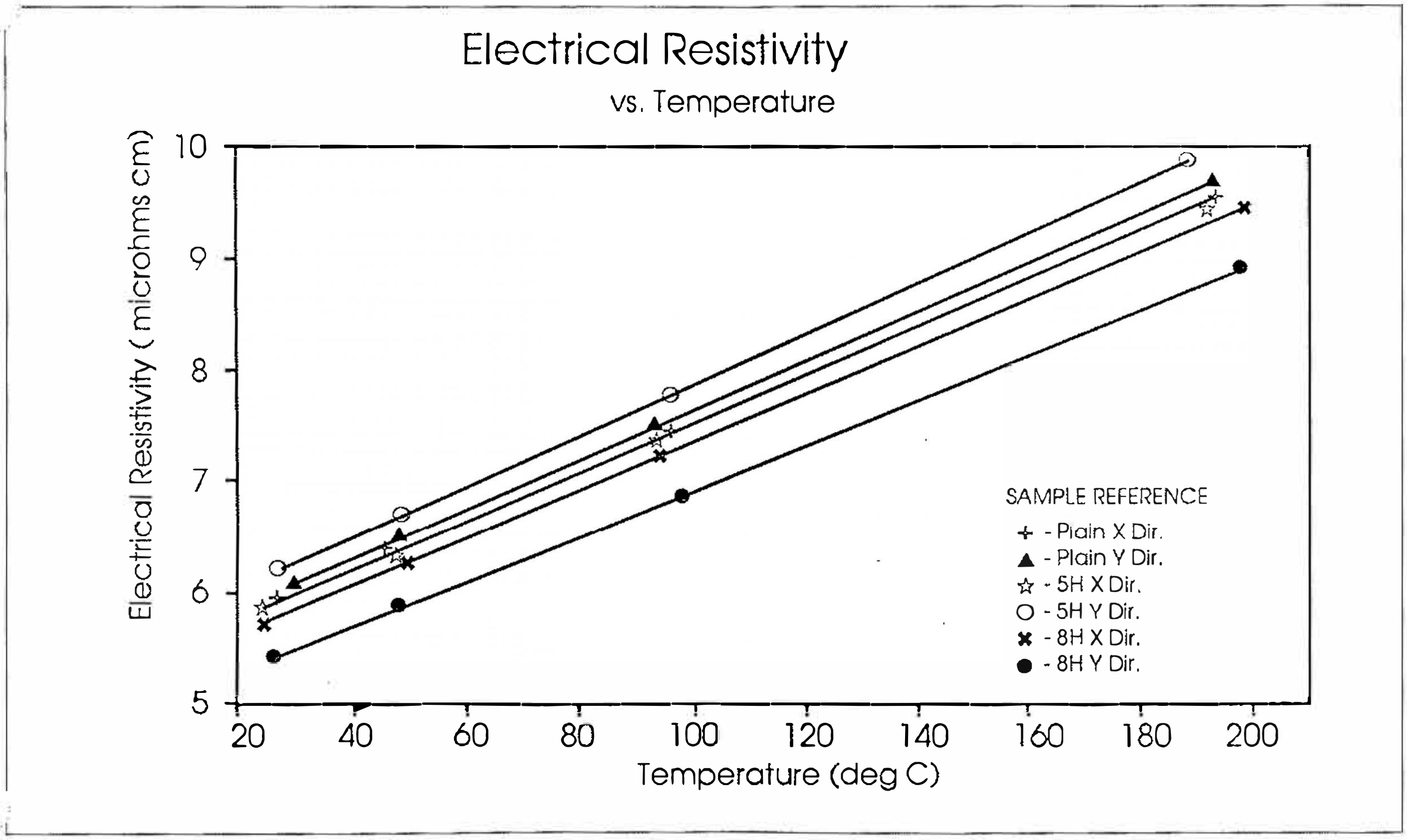
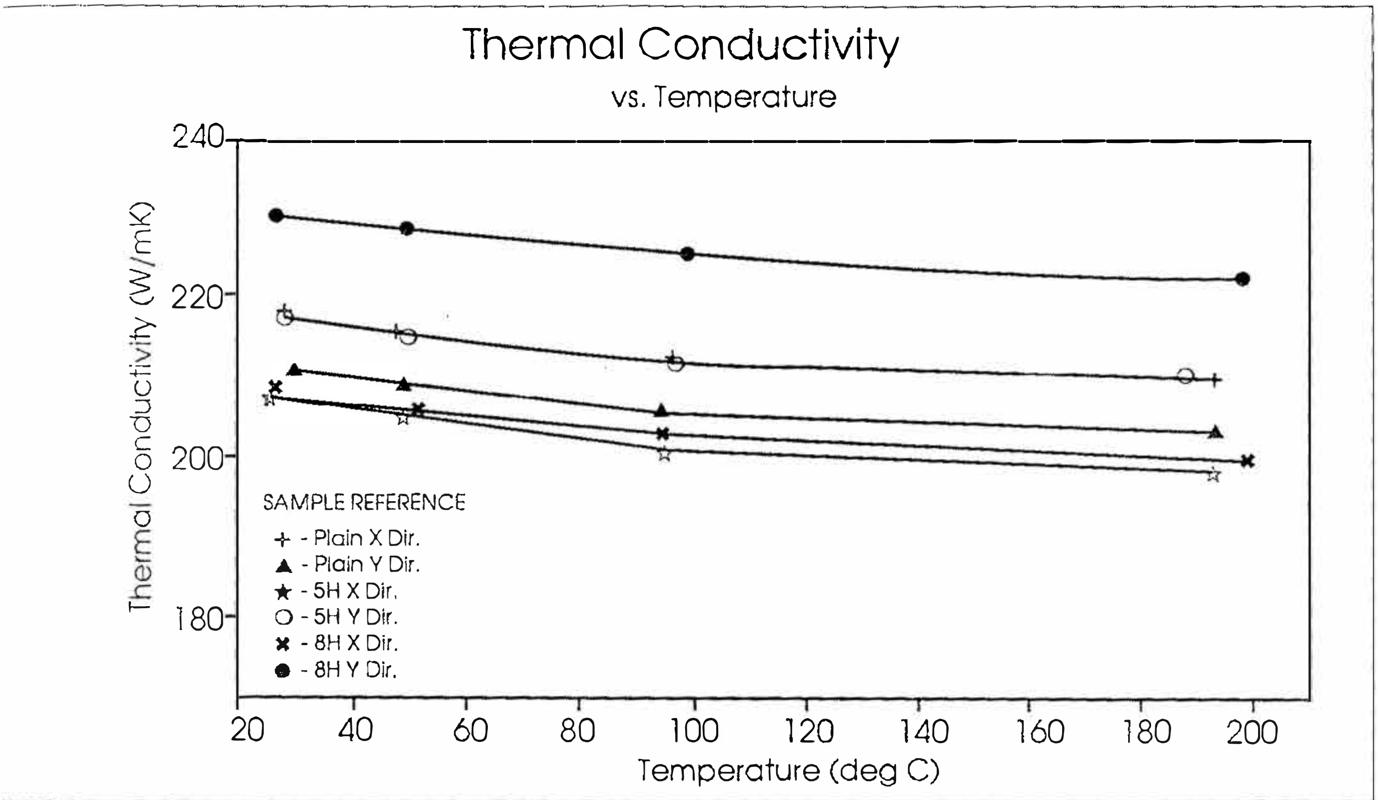


Figure 2. Effect of temperature on electrical resistivity



;ure 3. Effect of temperature on thermal expansion coefficient

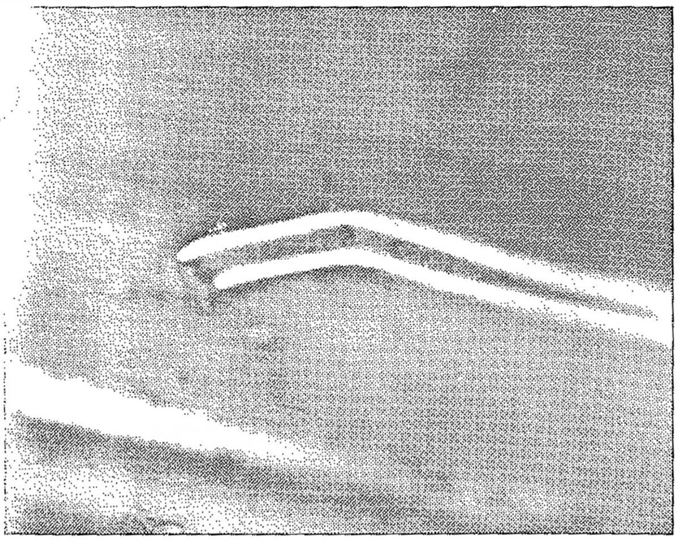


Figure 4. Broken fiber in plain weave fabric

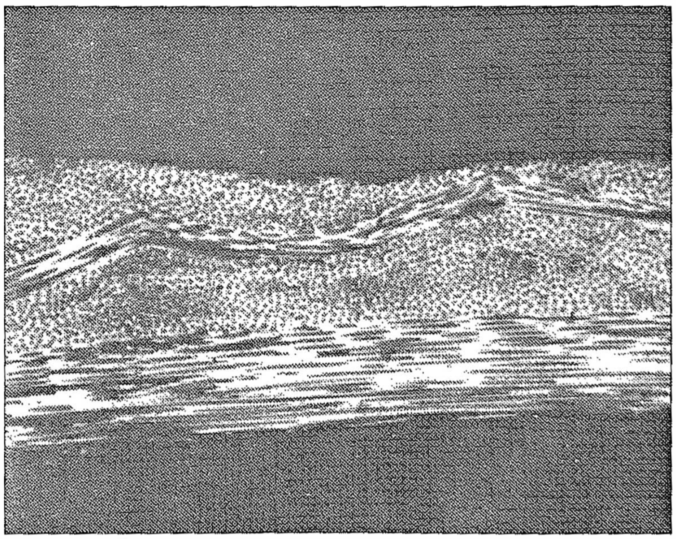


Figure 5. Cross-section of plain weave panel parallel to X-direction

solidated areas with evidence of minimal fiber damage can be seen in both the X and Y directions in all samples (Figure 11). In all cases the Y-direction fibers seem to have the greater amount of fiber damage, although the 8-harness sample appears to have the minimum number of damaged sections in both directions.

Densities of all panels was determined by Archimedes method.[2] The densities of panels increase from the plain weave to the 5-harness sample to the 8-harness sample (Table 3).

Determination of the fiber content of the samples seemed relatively constant throughout the samples as determined by gravimetric methods (Table 3). The void fraction was calculated for each sample. Voids accounted for 9.7% of the volume in the plain weave sample, 7.2% of the 5-harness sample and 5.4% in the 8-harness sample. The purity of the copper coating in the composites, as determined by Inductively Coupled Plasma Spectroscopy, was 99.95% or better for all the samples (Table 4).

Discussion

The effect of temperature on thermal conductivity between room temperature and 200°C is shown in Figure 1. There is only a slight decrease in conductivity of the composite in this temperature range. The highest thermal conductivity material is the 8-harness satin weave composite. The maximum value of 230

Sample	Density (g/cm³)	Fiber Volume (Weight %)
Plain	5.090	18.39
5-Harness	5.226	18.26
8-Harness	5.334	18.31

Table 3. Densities of composite panels.

Impurities (mg/kg)	Plain	5-Harness	8-Harness
Pd	70	60	60
B	280	230	230
Fe	30	10	20
Ti	40	40	40
Al	20	10	10
Ca	50	40	40
Sn	20	40	30

Table 4. Impurities in composite specimens.

MATERIAL	DENSITY (g/cm³)	THERMAL CONDUCTIVITY (W/m°C)	CTE (10^{-6}/°C
8-Harness Gr/Cu	5.33	219	6.37
Kovar	8.31	137	5.76
Cu/Invar/Cu	8.31	122	5.76

Table 5. Companion of 8-harness satin weave composite to standard heat sink materials.

W/m°C is slightly lower than should be expected. Computer modeled values for a balanced woven structure with no porosity suggest a thermal conductivity closer to 300 W/m°K.[5] The electrical resistivity data shown in Figure 2 agrees with the thermal conductivity results in the purity of the copper as seen in Table 4.

The CTE values for all the composites show a decrease in expansion as temperature increases as show in Figure 3. This effect of temperature on the CTE of graphite/copper composites has been reported previously[3] and is believed to be due to the expansion behavior of the high modulus graphite fiber. The values for the CTE of these composites range between 7.3 and 4.0 ppm/°C in the operating range of electronic components. A slightly higher thermal expansion coefficient would be preferred and can be obtained at slightly higher copper content, approximately 40-45% by volume fiber. A composite of this type should have a CTE between the 5-9 ppm/°C range required by electronic heat sinks.

Although there was evidence of fiber damage only in the plain weave fabric sample, some damage may have occurred in all of the weave types during weaving. The damage may have been undetectable due to the difficulty in seeing a large number of fibers in the plane of the cross-section. The fact that several broken fibers were seen in the plain weave sample could suggest more broken fiber in this sample compared to the others. A note of interest is that even though the underlying fiber has been broken, the ductile metal coating has held the copper coated fiber together.

The consolidated composite samples showed more conclusive evidence of the distribution of fiber damage, but it is not possible to determine whether fiber damage occurred during the weaving or consolidation processes. As indicated previously, the most damage appeared in the plain weave samples while the least appeared in the 8-harness satin weave sample.

The densities of the samples demonstrate that the amount of porosity in the samples decreases from about 10% in the plain weave sample to about 5% in the 8-harness satin sample. If the plain weave sample is visualized as a two harness satin weave, the trend is for a greater amount of porosity for the lower count harness weaves. The trends seen

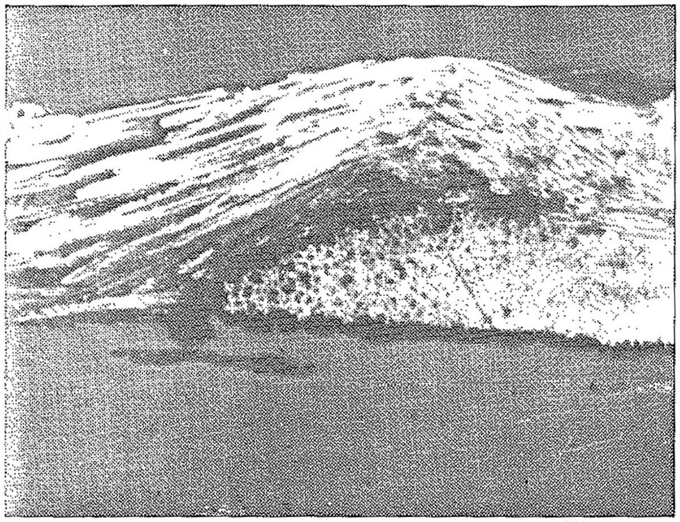


Figure 6. Cross-section of plain weave panel parallel to Y-direction

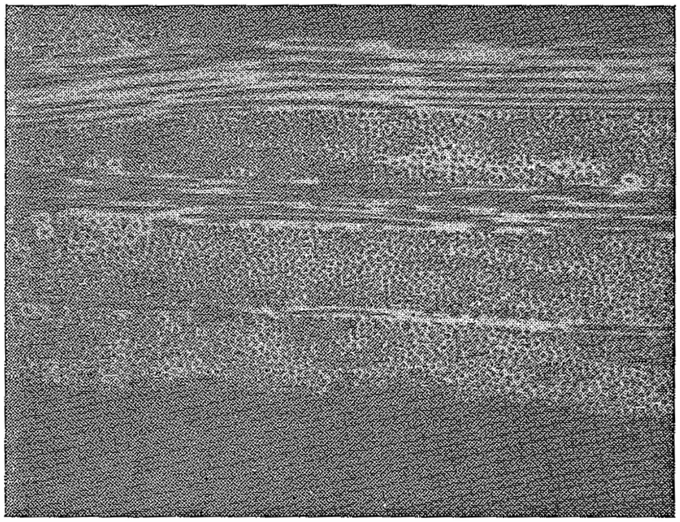


Figure 7. Cross-section of 5-harness panel parallel to X-direction

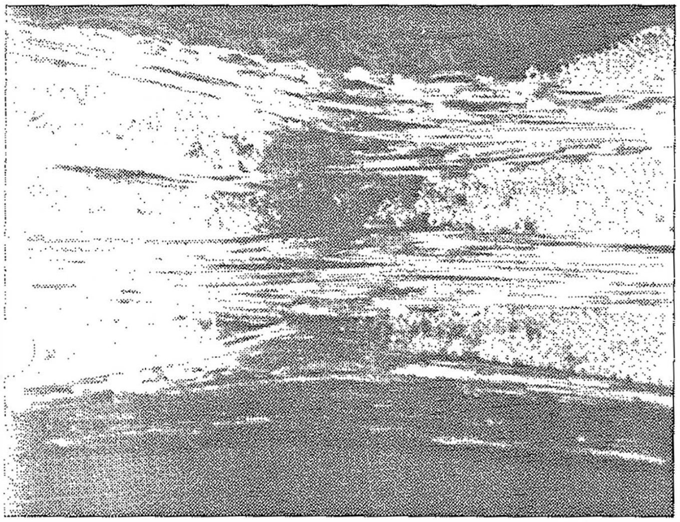


Figure 8. Cross-section of 5-harness panel parallel to Y-direction

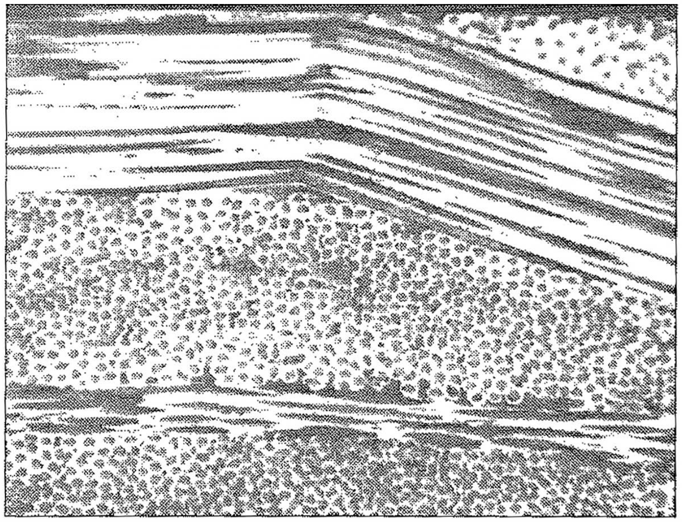


Figure 9. Cross-section of 8-harness panel parallel to X-direction

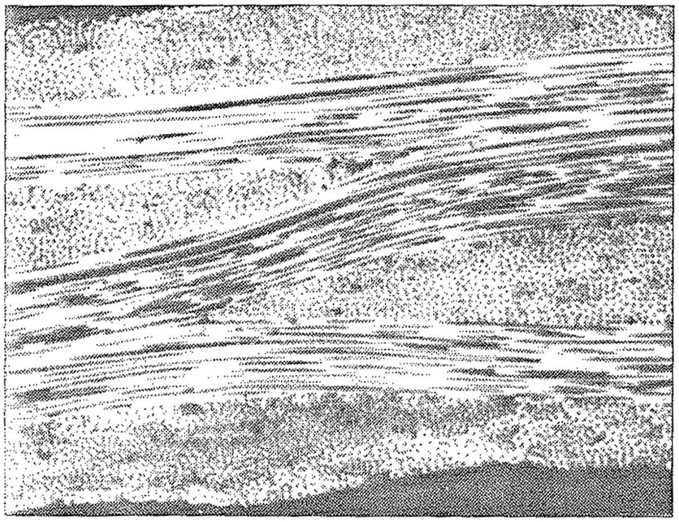


Figure 10. Cross-section of 8-harness panel parallel to Y-direction

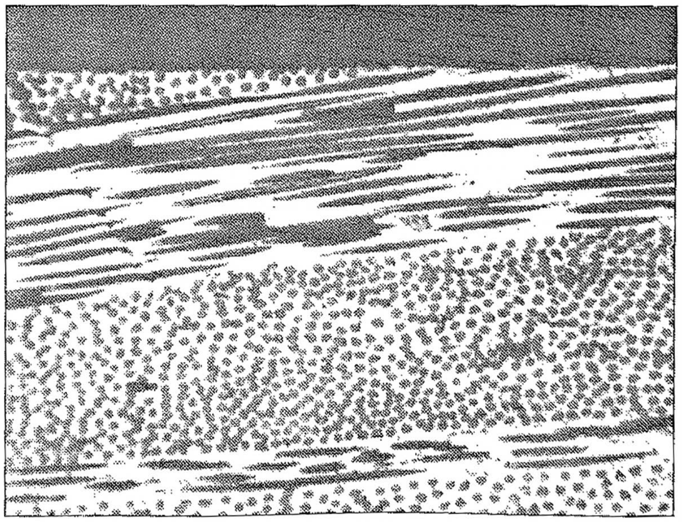


Figure 11. Cross-section of plain weave panel parallel to X-direction

in the porosity and amount of broken fiber explain the slightly lower values for the thermal conductivity of the composites.

The purity of the copper in the composites is typical of copper coated graphite fiber as produced by this process i.e. greater than 99.9% copper, with the exception of the boron content. The boron is suspected to be from the flexible graphite foil which was used as a parting sheet between the sample and the graphite dies. Boron has no appreciable effect on the electrical and therefore the thermal conductivity of copper.[4] No loss of thermal conductivity can be attributed to the boron content resulting from the graphite parting sheet.

Conclusions

Graphite/copper composite panels can be fabricated by weaving copper coated graphite fibers into a fabric and then consolidating by hot pressing. These panels show a thermal conductivity greater than that of aluminum. The thermal expansion coefficient demonstrated in this work is slightly lower than that required by electronic heat sink applications but can be increased by applying a slightly greater volume fraction of copper.

Some damage to the fragile graphite fibers does occur in the woven panels, but is minimized by using harness fabrics. Twelve harness fabrics can be woven and would be expected to show even less fiber breakage. Moreover, the conditions used in consolidation were those commonly used in uni-directional or cross-plied composites. Optimizing of conditions for woven structures could minimize fiber damage and porosity.

A comparison of the values obtained for the 8-harness satin weave composite to Kovar and copper/Invar/copper is shown in Table 5. The X and Y direction values for the thermal conductivity and CTE were averaged to represent the behavior of an actual heat sink. These values show the advantages of using a graphite/copper electronic heat sink over traditional systems.

The processing of graphite/copper composite electronic heat sinks by weaving a fabric and consolidating by hot pressing is feasible and presents a potential technique for low cost processing of metal matrix composite electronic heat sinks.

References

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[2]D.A. Hutto, J.K. Lucas, W.C. Stevens, "Development of Copper-Graphite Composites from Metal Coated Graphite Fibers," Proc. of 31st Internat. SAMPE Symposium and Exhibition, SAMPE, Covina, CA (April 1986), pp. 1145-1153.

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