IN-24

68231

P-19

NASA Technical Memorandum 105233

Thermal Conductivity and Thermal Expansion of Graphite Fiber/Copper Matrix Composites

David L. Ellis
Case Western Reserve University
Cleveland, Ohio

and

David L. McDanels
Lewis Research Center
Cleveland, Ohio

NASA

THERMAL CONDUCTIVITY AND THERMAL EXPANSION OF GRAPHITE

FIBER/COPPER MATRIX COMPOSITES

David L. Ellis[*]
Case Western Reserve University
Cleveland, Ohio 44106

and

David L. McDanels
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

The high specific conductivity of graphite fiber/copper matrix (Gr/Cu) composites offers great potential for high heat flux structures operating at elevated temperatures. To determine the feasibility of applying Gr/Cu composites to high heat flux structures, composite plates were fabricated using unidirectional and cross-plied pitch-based P100 graphite fibers in a pure copper matrix. Thermal conductivity of the composites was measured from room temperature to 1073 K, and thermal expansion was measured from room temperature to 1050 K. The longitudinal thermal conductivity, parallel to the fiber direction, was comparable to pure copper. The transverse thermal conductivity, normal to the fiber direction, was less than that of pure copper and decreased with increasing fiber content. The longitudinal thermal expansion decreased with increasing fiber content. The transverse thermal expansion was greater than pure copper and nearly independent of fiber content.

INTRODUCTION

Many aerospace applications require materials with high thermal conductivity to reduce component operating temperature, extend service life, and reduce system weight. Hypersonic vehicle applications such as high conductivity heat exchangers require service lives of hundreds to thousands of hours. They require materials with good elevated temperature tensile and creep strengths, thermal fatigue resistance and oxidation resistance. The materials for the heat exchangers must be usable at temperatures ranging from 800 K for the cooling channels up to 1200 K for the hot side in the combustor. Space power system applications include high conductivity radiator fins with service lives of 10 to 30 years. They require high stiffness and low density. The materials for the radiator fins must be usable at temperatures ranging from 300 K for solar power systems up to 1050 K for nuclear power systems.

Several materials can be used for high heat flux thermal applications. Copper offers the second best thermal conductivity of the elements (ref. 1). It is widely available in many forms and can be easily machined and formed. The primary problem with using copper for aerospace applications is its high density (8.96 g/cc) (ref. 1). Copper also suffers from a low yield strength and stiffness (ref. 2). Beryllium is often considered for aerospace applications because of its low

---

[*]NASA Resident Research Associate at Lewis Research Center.

density (1.85 g/cc) and high stiffness (303.6 GPa) (ref. 3). Because of the low density of beryllium, the density compensated properties are very high. Beryllium suffers from toxicity concerns and product availability. Beryllium also has a maximum use temperature of around 900 K due to a significant decrease in strength above 600 K (ref. 3). While copper and beryllium can be strengthened through alloying to increase their maximum use temperature, alloying elements significantly lower their thermal conductivity (ref. 4). For the hypersonic vehicle and high temperature radiator fin applications, a material with better elevated temperature strength such as titanium, niobium, or a superalloy would be used to meet the mechanical property requirements of the applications. These materials suffer from low thermal conductivities and, for the superalloys and niobium, high densities (ref. 1).

More recently carbon/carbon (C/C) composites have been proposed for use in applications such as space power radiator fins (ref. 5). While some of these fins have been made, they have used low conductivity polyacrilonitrile-based (PAN) graphite fibers. These fins have a density of less than 1.85 g/cc, but the thermal conductivity of the fibers is only 2 to 4 percent that of copper (ref. 6). Because of the low thermal conductivity of the fibers, the fins must be thick to carry the thermal flux required for the space power system. The result is a fin with little or no weight advantage over fins made with denser but higher thermal conductivity materials (ref. 7). In the future, pitch-based graphite fibers with thermal conductivities greater than Cu may be successfully substituted for the PAN-based fibers. Several production problems, primarily weaving a fiber with a strain to failure of 0.3 percent, must be overcome first. If these problems can be overcome, C/C fins using pitch-based fibers are an attractive material for use in space power systems. For hypersonic vehicle applications, the C/C composites still face the problem of oxidation protection that has stopped the successful introduction of C/C composites in the past. As alternatives to these materials, NASA Lewis Research Center has begun investigating high conductivity, copper matrix composites using a variety of reinforcing fibers.

Graphite fiber/copper matrix (Gr/Cu) composites are a promising high thermal conductivity material under development for hypersonic and space power system applications. Preliminary results (refs. 8 and 9) show that Gr/Cu composites possess a high thermal conductivity that is equivalent to copper, a modulus of elasticity comparable to beryllium, and a density comparable to titanium for the volume percents of graphite fiber of interest. Recent analysis (ref. 7) has shown that high thermal conductivity Gr/Cu radiator fins could reduce the total space power radiator system mass by as much as 6 percent compared with lower density but lower thermal conductivity beryllium or carbon/carbon composite fins.

The Gr/Cu composite is also of interest as a model composite system. The graphite and copper components do not react with one another to form a compound. They are also mutually insoluble. As a result the only bond between the fiber and the matrix is a mechanical bond. The graphite fibers and copper also have greatly different thermal expansion coefficients. This combination of factors makes it unique among the composites currently being studied.

Some key parameters required for design of high heat flux structures for elevated temperature service are thermal conductivity, thermal expansion and density. A variety of mechanical properties such as strength, stiffness, and thermomechanical fatigue resistance are also required, and work is ongoing to evaluate these properties for Gr/Cu composites. The results will be presented later when testing is completed. This paper will only discuss the thermal properties of the Gr/Cu composites.

2

Thermal conductivity and density data are required to determine the feasibility and basic design parameters of Gr/Cu components. Thermal expansion data for Gr/Cu composites is required to design joints to minimize thermal expansion mismatch with heat pipes and coolant manifolds. The effect of temperature and fiber content of unidirectionally reinforced Gr/Cu composites on thermal conductivity and thermal expansion are described in this paper.

DESIGN, FABRICATION AND TESTING OF Gr/Cu COMPOSITES

Before describing the results obtained for Gr/Cu composites, some terms used to describe metal matrix composite (MMC) lay up and the property anisotropy of MMCs and the graphite fibers will be introduced. All unidirectional MMCs have anisotropic properties. However, the highly aligned crystallinity of the ultra-high modulus (UHM) P100 fibers causes very large anisotropy in UHM graphite fiber reinforced composites. Figure 1 shows the directional axes that will be used in the discussion of the effect of longitudinal and transverse orientations on Gr/Cu composite properties. Conductivity, modulus, and strength are maximized in the longitudinal direction and minimized in the long transverse and short transverse directions. In addition, figure 1 also shows angle-plied composites can be produced by orienting the fiber direction in the individual plies. By angle-plying the properties in the longitudinal and long transverse directions can be tailored to the application requirements.

The results previously reported (refs. 8 and 9) on Gr/Cu composites were from vendor supplied panels or NASA fabricated composite panels. Some contractor supplied panels used P-120 and P-130 graphite fibers to compare the effects of different graphite fiber types. All NASA fabricated panels were made with copper-coated P100 graphite fibers supplied by American Cyanamid Co. (ref. 10). Selected results from the NASA fabricated panels in the previous studies (refs. 8 and 9) of Gr/Cu composites are reported in this paper for comparison. These Gr/Cu composites were made using a labor intensive hand layup of a copper coated graphite fiber tow. The volume percent fiber was determined from the density of the samples to be 67 volume percent (vol %). Optical microscopy of the samples revealed some porosity in the samples due to incomplete consolidation. The actual volume percent fiber is therefore somewhat lower than the calculated value.

The Gr/Cu composites containing 20 to 50 vol % graphite fibers discussed in this paper were made by a new fabrication technique developed at NASA Lewis. Yarns were supplied with different coating thicknesses to provide nominal fiber contents from 20 to 60 vol % of graphite fibers. The copper coated yarns are passed through a series of cleaning baths to remove any surface contamination and wound onto a drum at a precise spacing (fig. 2(a)). After winding, a thin coating of copper is arc sprayed onto the yarns using the arc spray process described in reference 11. This produces a well aligned unidirectional monotape such as the ones shown in figure 2(b) that can be cut, handled and positioned with ease. After arc spraying, the monotapes were laid up as 6-ply unidirectional composites and hot isostatically pressed into panels 200 mm long by 100 mm wide by 1.0 to 1.5 mm thick. An example of the panels is shown in figure 2(c). Microstructures of the as-pressed Gr/Cu composites (fig. 3) show a uniform fiber distribution and good consolidation of the monotapes with grain boundaries and twins extending through the prior particle boundaries. No porosity was observed in any of the consolidated panels. Fiber contents of the panels were determined by specific gravity measurements.

One Gr/Cu composite plate was made with eight plies cross-plied at a 90° angle. The outer two plies on each face of the plate were parallel to the longitudinal axis of the plate. The

inner four plies were oriented at 90° to the longitudinal axis of the plate. This sample was used to evaluate the effect of cross-plying on the thermal expansion of the composites.

Specimens were cut from the panels for thermal expansion testing in the longitudinal and short transverse directions. Specimen size was 50 mm long by 10 mm wide. Thermal expansion tests were conducted over a temperature range of room temperature to 1073 K using an Netzsch dilatometer.

Thermal conductivity and specific heat capacity samples were also made from arc-sprayed copper coated P100 graphite composites. Because of the sample geometry required for the thermal conductivity tests, a thicker panel was required to test thermal conductivity in all three principle directions. Ninety to 110 monotapes were laid up and hot pressed into blocks 32 mm square by 12.5 mm high. These blocks were EDM machined into test samples 12.5 mm square by 6.25 mm thick for each of the three testing directions. In addition, a 6.25-mm diameter by 1.75 mm thick specific heat sample was machined from each block. The thermal conductivity and specific heat of the samples from room temperature to 1073 K were determined using the laser flash technique (ref. 12). The testing was conducted by the Thermophysical Properties Research Laboratory (TPRL) at Purdue University.

RESULTS AND DISCUSSION

In this discussion, a comparison of properties at a temperature of 800 K will be used. This temperature represents the upper range of service temperatures for space power system radiator fins and the lower end of the service temperature of hypersonic vehicle heat exchangers. As such the comparisons are valid for both applications.

Thermal Conductivity of Gr/Cu Composites

To determine the thermal conductivity of a material using the laser flash technique, the specific heat, room temperature bulk density, and thermal diffusivity of the material must be determined. The specific heat of the Gr/Cu composites increased with increasing fiber content and temperature. Since the specific heat is dependent only on mass, the specific heat of the Gr/Cu composites at 800 K is plotted against the mass fraction of P100 fibers in figure 4. The fiber content in volume percent of each Gr/Cu composite is also shown in figure 4. Since there is no reaction or interdiffusion between the copper matrix and graphite fibers, the values are expected to have a linear dependence on the mass fraction of graphite fibers. The line shown is a least-squares fit of the Gr/Cu data. For comparison, the value of grade GBH graphite (ref. 13) is presented as the graphite endpoint since no specific heat data is available for P100 graphite fibers. Grade GBH graphite is a fully dense graphite and should approximate the specific heat of the P100 graphite fibers. The data shows a good fit to a linear increase in specific heat capacity with increasing mass fraction. The extrapolated P100 specific heat value is also near the GBH graphite value. If the value for the 67 vol % sample is discarded, the data gives an extrapolated P100 graphite fiber heat capacity almost identical with the GBH graphite. The good fit of the data and the closeness of the extrapolated P100 heat capacity to GBH graphite shows the data is valid. Therefore, the heat capacity for GBH graphite can be used for the heat capacity of P100 graphite fibers when it is needed.

4

Thermal conductivity is calculated using the equation (ref. 12)

$$\sigma_T(T) = C_P(T) \cdot \rho \cdot \lambda(T) \tag{1}$$

where

$\sigma_T(T)$ calculated thermal conductivity at temperature T

$C_P(T)$ measured specific heat at temperature T

ρ room temperature bulk density

$\lambda(T)$ measured thermal diffusivity at temperature T

Thermal conductivity in both the longitudinal and short transverse directions is shown in figure 5 for Gr/Cu composites with a variety of fiber contents. In the longitudinal direction, the thermal conductivities of the composites fell in the narrow band shown in figure 5. Within this band there was no correlation of fiber content with the upper or lower limit of the band. This is because the longitudinal thermal conductivity of the P100 fibers used is near that of pure copper. At the lower temperatures the Gr/Cu composites have a higher thermal conductivity than copper, but at higher temperatures the thermal conductivity drops to values near copper. The observed drop in thermal conductivity is caused by the greater decrease in thermal conductivity of P100 fibers compared to Cu over the temperature range.

In the transverse directions, the thermal conductivity is less than in the longitudinal direction and decreases with increasing fiber content (fig. 6). The decrease is caused by the anisotropy of the UHM P100 graphite fibers. As graphite crystallites become more aligned, lattice orientation dependent physical properties such as elastic modulus and thermal conductivity become higher in the direction of the fiber axis. However, the anisotropy of the properties in the radial direction becomes even more pronounced (ref. 14). While the thermal conductivity of the fiber along the axis of the fiber is very high, it is extremely low in the radial direction. In the transverse directions of Gr/Cu composites, heat is conducted almost exclusively through the copper matrix. Extrapolation of the thermal conductivity versus fiber content curves indicates that the radial thermal conductivity of the P100 graphite fibers is near zero. Thus the higher the fiber content, the lower the transverse thermal conductivity of the composite. Despite the decrease in thermal conductivity, composites with fiber contents up to 60 vol % have thermal conductivities higher than titanium and niobium alloys (fig. 6), the primary competitive materials at higher temperatures where Be and Cu cannot be used.

The thermal conductivity in the long transverse direction is about 10 percent higher than the short transverse direction. This difference is caused by the sample processing. Heat must pass around all fibers in the short transverse direction. In the long transverse direction there are thin layers of copper rich material that are the result of the arc spray process. These thin layers allow for easier diffusion of the heat than in the short transverse direction. With the increase in thermal diffusivity, the thermal conductivity increases as shown in equation (1).

The density dependent specific thermal conductivity (thermal conductivity divided by density) is a more important design criterion for the reduction of mass in thermal management structures. The effect of fiber content on the specific thermal conductivity of Gr/Cu composites is shown in figure 7. In the longitudinal direction, specific thermal conductivity increases with increasing fiber content though the absolute thermal conductivity is relatively unchanged. This

is a result of the decrease in density of the Gr/Cu composites with increasing graphite fiber content. Specific thermal conductivity in the transverse direction is more influenced by the decrease in the absolute thermal conductivity than the decrease in density. As a result, the specific thermal conductivity in the transverse direction decreases with increasing fiber content. However, between 20 and 40 vol % P100 graphite fibers the Gr/Cu composites retain 50 to 75 percent of the specific thermal conductivity of pure copper.

Although the transverse specific thermal conductivities of the Gr/Cu composites are below that of copper and beryllium, it should be emphasized that these materials would normally not be used for applications requiring them to operate at 500 to 1050 K. This is above the maximum service temperature of pure copper and beryllium. Alloying the copper and beryllium to increase the use temperature of the materials would significantly reduce their thermal conductivities (ref. 4). The primary competition for Gr/Cu composites at these elevated temperatures would be titanium- and niobium-based alloys and superalloys. As shown in figure 7, the longitudinal specific thermal conductivity of P100 Gr/Cu composites was far superior to the values for these materials at all temperatures. The transverse specific thermal conductivity of P100 Gr/Cu composites is comparable to or better than these competitive materials. With fiber contents between 20 and 50 vol %, the longitudinal specific thermal conductivity of P100 Gr/Cu composites would be five times greater than the competitive high temperature materials. The transverse specific thermal conductivity would be two to three times greater. Because of this the Gr/Cu composites offer significant potential for high heat flux thermal management structures operating above 500 K.

Thermal Expansion of Gr/Cu Composites

While the thermal conductivity of Gr/Cu composites is important, the composites must be joined to other components to make radiator fins and heat exchangers. Excessive thermal mismatch can cause failure in joints with heat pipes and coolant manifolds connected to these structures. To minimize the thermal stresses in braze joints the thermal expansion mismatch must be minimized. This requires a knowledge of the thermal expansion behavior of the Gr/Cu composites with respect to fiber orientation and volume fraction. As part of this examination of P100 Gr/Cu composites, the thermal expansions in the longitudinal and long transverse directions were studied.

Thermal strain for the heating portion of the tests of Gr/Cu composites is shown in figure 8 for temperatures up to 1050 K. Thermal strain for pure copper is also shown in the plot for comparison. In the long transverse direction, the thermal strains of the Gr/Cu composites fall in a narrow band that is greater than the value for copper. As with the longitudinal thermal conductivity values, there is no correlation between volume fraction of graphite and position within the band. No radial thermal expansion data at elevated temperatures is available for P100 graphite fibers from direct experiments, but experimental data is available for orientated pyrolytic (OP) graphite (ref. 15) and has been calculated for AS4 PAN-based graphite fibers (ref. 16).

OP graphite has a coefficient of thermal expansion (CTE) greater than copper in the direction of the c axis, the axis comparable to the radial direction of the fiber. In the direction of the a axis, the axis equivalent to the fiber length, the thermal expansion was negative, a result consistent with the available low temperature data for P100 graphite fibers. Gaitonde and Lowson (ref. 16) calculated the CTE for AS4 PAN-based fibers in a Gr/PEEK composites

6

using available data on the thermal expansion of the PEEK matrix and the transverse thermal expansion of the Gr/PEEK composite. The results led to a calculated CTE of 23×10^{-6}/K for temperatures up to 200 °C compared to a copper CTE of 17.2×10^{-6}/K over the same temperature range (ref. 1). With the fibers expanding more rapidly than copper, the total matrix thermal strain in the long transverse direction exceeds the thermal strain for pure copper as is observed in the Gr/Cu samples.

In the longitudinal direction, thermal strain decreased with increasing fiber content. The 20 vol % Gr/Cu composite showed an almost uniformly increasing curve paralleling the copper curve. For the 30 vol % Gr/Cu composite, the curve started on an upsweeping curve parallel to the copper curve, but changed slope around 650 K and flattened out to a nearly uniform expansion up to 1050 K. The 40 vol % Gr/Cu composite shows similar behavior. At 50 vol % graphite fiber, the curve started with a negative expansion similar to the P100 fibers and reached a minimum near 650 K. Above 650 K the samples expanded slightly, but were still near zero thermal expansion.

Based on the behavior of the samples, some general ideas were developed to explain the longitudinal thermal strain data. The graphite fibers contract in the longitudinal direction but expand in the radial direction during heating. The radial expansion pushes the fibers against the copper matrix and forces a mechanical or frictional bond. The contraction of the fibers in the longitudinal direction restrains the thermal expansion of the copper matrix and therefore the Gr/Cu composite. This results in a thermal strain curve roughly parallel to the pure copper curve but at a lower absolute thermal strain value. This is the type of behavior seen during the heating of the 20 vol % Gr/Cu composite. With increasing graphite fiber content, the fibers constrain the matrix more, and the thermal strain at a given temperature is decreased. For the 50 vol % Gr/Cu composite the fibers totally dominate the thermal expansion of the Gr/Cu composite, and the composite shows a near zero thermal strain throughout heating.

The 30 and 40 vol % Gr/Cu composites show a change in slope of the thermal strain curves during heating. The observed change in slope of the thermal strain curves can be explained by yielding of the copper matrix. At elevated temperatures the yield strength of copper drops to very low values. The large CTE mismatch between the fibers and the matrix can therefore generate sufficient thermal stresses to cause compressive yielding of the matrix. Evidence of this was seen as macroscopic slip bands and cracks on the surfaces of the samples. As a result of the compressive yielding, the matrix expands less than it would otherwise. The slope of the thermal strain curve would decrease as is observed in figure 8.

Modeling is currently underway to understand better the stress states of the composites and will be presented in a later paper. For now it is sufficient to know that thermal stresses sufficient to cause compressive yielding of the copper matrix can be generated by the CTE mismatch between the fiber and matrix after heating only a few hundred degrees Celsius.

The thermal strain of P100 Gr/Cu composites in the longitudinal and long transverse directions at 800 K are plotted in figure 9. The plot shows the thermal strain in the long transverse direction increases at low fiber contents but is essentially constant above 20 vol % Gr. The longitudinal thermal strain decreases with increasing fiber content from the copper value and becomes negative around 50 vol % Gr. Above 50 vol % Gr, the thermal strains would extrapolate to a negative value equal to the thermal strain of P100 graphite fibers at 100 percent P100 graphite fibers. The longitudinal CTE values for Gr/Cu composites at 800 K is presented in figure 10. For these tests the zero point was defined as 300 K. The transverse CTE of the

Gr/Cu composites at 800 K was 25.2×10^{-6}/K above 20 vol % graphite fiber. The longitudinal Gr/Cu CTE significantly decreases from the CTE of Cu with increasing graphite fiber content and is near zero at 50 vol % P100 graphite fibers. The near zero CTE of the Gr/Cu composites may prove useful for applications where thermal expansion mismatch must be minimized, i.e., when Gr/Cu is being used with low thermal expansion ceramics.

Thermal strain curves presented to this point were for the heating portion of the thermal cycle only. Thermal strain curves for a combined heating and cooling cycle are shown in figure 11 for one long transverse and two longitudinal samples with a low and high volume fraction of graphite fibers. The transverse 20 vol % Gr/Cu composite showed an initial expansion upon cooling and then contracted almost linearly with a cooling curve paralleling its heating curve. The longitudinal 20 vol % Gr/Cu composite which also tended to parallel the copper curve during heating showed a contraction parallel to but slightly above the heating curve at temperatures above 650 K. Below 650 K the curve flattened out to a near zero slope. At room temperature the samples retain about 0.65 percent elongation. Specimens with graphite fiber volume fractions between 30 and 50 vol % tested in the longitudinal orientation show a near zero slope upon cooling with a permanent room temperature deformation slightly greater than the elongation at 1050 K. Evaluation of these curves is ongoing to determine the behavior for single and multiple heating/cooling cycles to determine the hysteresis behavior of Gr/Cu composites under thermal cycling conditions. However, some preliminary ideas have been developed to explain the observed hysteresis.

For the long transverse direction during heating, the thermal expansion in the radial direction of the fibers is greater than the thermal expansion of copper. This is caused by the fibers expanding more than the copper in the radial direction (refs. 1 and 16). The CTE mismatch between the fibers and copper induces stresses in the matrix that are greater than the yield strength of copper. This results in plastic deformation of the copper matrix with a positive elongation of the sample in the long transverse direction during heating. Upon cooling, the lack of a bond between the fiber and the matrix produces no compressive stresses to deform the matrix back to the original length. The sample therefore has a permanent, positive elongation caused by the thermal cycle. During subsequent thermal cycles, the permanent deformation of the copper matrix will make it more difficult to develop stresses that exceed the yield strength of the matrix, minimizing the hysteresis problem. While it has not been experimentally confirmed, most of the deformation in the transverse directions is expected to occur in the first few thermal cycle.

While the transverse directions have a net positive strain following the thermal cycle, so does the longitudinal direction. During heating, the contraction of the fibers restrains the matrix in the longitudinal direction. For samples with greater than 20 vol % P100 fibers this restraint is sufficient to show evidence of compressive yielding in the form of macroscopic slip bands and other gross deformations in the samples. Upon cooling, the fibers expand and the matrix contracts. The stress states in the fibers and matrix are reversed. The compressive stress on the matrix is decreased and changes to a tensile stress with decreasing temperature. Likewise the fibers change from a tensile stress to a compressive stress. The tensile yield strength of copper is very low at elevated temperatures (ref. 2), so tensile deformations can easily occur once a tensile stress is developed in the copper matrix. Some delay in the changing the stress states occurs due to a need to cool the sample sufficiently to completely reverse the stress states. Strain hardening of the matrix can also lead to a somewhat higher yield stress and delay the onset of tensile yielding. The combined effect of the processes occurring during cooling is seen as a leveling off of the thermal strain versus temperature curve at near constant value.

8

For the samples with a larger volume fraction of P100 graphite fibers, the reversal of stress states occurs at higher temperatures, and the net room temperature strain is near the value for 1073 K.

Kural and Min (ref. 17) analyzed the thermal deformation of P100 graphite fiber reinforced magnesium (Gr/Mg) and P100 graphite fiber reinforced 6061 aluminum (Gr/6061) composites during low temperature thermal cycling. The Gr/Mg and Gr/6061 composites had a near zero CTE. For the Gr/6061 composite, the graphite fiber plies were angleplied at $\pm 26°$ to achieve the desired longitudinal CTE. Kural and Min's analysis of the lamina in the composites showed a similar hysteresis loop. They also explained the observed behavior in terms of plastic yielding in the matrix combined with a stress state reversal during the thermal cycle. While direct comparisons between the two composites and the Gr/Cu composites studied here are complicated by several metallurgical factors, the results from the Gr/Mg and Gr/6061 composites do indicate that the basic ideas put forth for the Gr/Cu composites are probably valid. A more detailed analysis is required to confirm and quantify the results for the Gr/Cu composites.

The observed hysteresis of the thermal strain curves indicates two potential problems in using the Gr/Cu composites for applications with thermal cycling. The increase in size of the samples indicates the CTE mismatch may induce matrix stresses that are large enough to nucleate and grow voids. Voids have been observed in Gr/Cu samples following thermal exposure (ref. 18). Thermal ratcheting also could be caused by the accumulation of strains in the composite with repeated thermal cycling. For space power applications, there would be only a few thermal cycles associated with the manufacturing and testing of the composites. Once the space power system is activated in space, the radiator fins will remain at a constant temperature for the life of the system. Proper design and materials selection can be used to mitigate the problem. For hypersonic vehicles and similar applications, the composites will be required to undergo hundreds or thousands of complex thermal cycles during the life of the parts. They also will be required to maintain the integrity of the seal with manifolds and other parts of the thermal structures. As such, large thermal deformations cannot be tolerated. More work is required to address this problem.

All the data discussed thus far dealt with unidirectionally reinforced Gr/Cu composite plates. Figure 13 shows the thermal strain in the longitudinal and long transverse directions for a cross-plied 50 vol % Gr/Cu composite plate. Figure 13 also shows the heating cycle thermal strain of a unidirectionally reinforced 50 vol % Gr/Cu composite and copper for comparison. This plot shows that thermal strains of both the longitudinal and long transverse directions of the cross-plied composite fall significantly below the unidirectional longitudinal experimental data and above the unidirectional long transverse thermal experimental data. The cross-plied composites show a behavior dominated by the P100 graphite fibers.

The thermal strain results presented indicate that the thermal expansion behavior of Gr/Cu composites can be tailored by modifying the volume fraction of the fibers and orientation of the plies to meet the desired design criteria. By proper selection of fiber content and the orientation and number of plies in each direction, the thermal expansion of Gr/Cu composites can be varied from near zero to values greater than copper. This would encompass the range of most materials anticipated for use as manifolds or heat pipes to be used with Gr/Cu composites in high heat flux thermal management structures.

9

CONCLUSIONS

A study to determine some key design properties for applying P100 Gr/Cu composites to high heat flux structures operating at elevated temperatures led to the following conclusions.

1. The high specific thermal conductivities of P100 Gr/Cu composites offers promising potential for application to high heat flux structures.

2. The absolute longitudinal thermal conductivities of P100 Gr/Cu composites were comparable to copper, while the specific thermal conductivities of Gr/Cu composites with more than 35 vol % graphite fibers were greater than both copper and beryllium.

3. The absolute transverse thermal conductivities of P100 Gr/Cu composites were less than copper and decreased with increasing fiber content. The specific thermal conductivities of the P100 Gr/Cu composites were also less than both copper and beryllium. However, for applications above the maximum use temperature of copper and beryllium, the absolute and specific transverse thermal conductivities were superior to titanium- and niobium-based alloys and superalloys, the materials that would be used in place of copper or beryllium.

4. The longitudinal thermal expansion of P100 Gr/Cu composites decreased with increasing fiber content and was dominated by the fiber properties and thermally induced yielding of the copper matrix.

5. The transverse thermal expansion of P100 Gr/Cu composites was greater than pure copper, showing that the thermal expansion of the P100 graphite fibers in the radial direction is greater than that of copper.

REFERENCES

1. Brandes, E.A.: Smithells Metals Reference Book, Sixth Edition, Butterworths, London, 1983, pp. 14-1 and 14-3.

2. Crosby, R.L. and Desy, D.H.: Dispersion-Strengthening in Copper-Alumina and Copper-Yttria Alloys. BM-RI-7266, Bureau of Mines, Washington, DC, June 1969.

3. Designing with Beryllium. Brush Wellman, Inc., Cleveland, OH.

4. Shapiro, E. and Crane, J.: Optimizing Conductivity, Formability and Relaxation Resistance in Copper-Alloys. High Conductivity Copper and Aluminum Alloys, E. Ling and P. Taubenblat, eds., TMS, Warrendale, PA, 1984, pp. 53-62.

5. Rovang, R.D., et al.: SP-100 High-Temperature Advanced Radiator Development. Proceedings 8th Symposium on Space Nuclear Power Systems, M.S. El-Genk and M.D. Hoover, eds., CONF-910116, Vol. 2, 1991, pp. 702-707.

6. Thornel Product Information. AMOCO Performance Products, Inc., Atlanta, GA.

7. McDanels, D.L., Baker, K.W., and Ellis, D.L.: Graphite Fiber/Copper Matrix Composites For Space Power Heat Pipe Fin Applications. Proceedings 8th Symposium on Space Nuclear Power Systems, M.S. El-Genk and M.D. Hoover, eds., CONF-910116, Vol. 1, 1991, pp. 313-319.

8. Diaz, J.O., and McDanels, D.L.: Preliminary Feasibility Studies of Graphite Fiber Reinforced Copper Matrix Composites For Space Power Radiator Panels. Transactions 6th Symposium on Space Nuclear Power Systems, CONF-890103-Summs., 1989, pp. 199-204.

9. McDanels, D.L. and Diaz, J.O.: Exploratory Feasibility Studies of Graphite Fiber Reinforced Copper Matrix Composites For Space Power Radiator Panels. NASA TM-102328, 1989.

10. Hutto, D.A., Lucas, J.K., and Stephens, W.C.: Development of Copper-Graphite Composites from Metal Coated Carbon Fibers. Proc. 31st International SAMPE Symposium and Exhibition, J.L. Bauer and R. Dunaetz, eds., SAMPE, 1986, pp. 1145-1153.

11. Wesfall, L.W.: Tungsten Fiber Reinforced Superalloy Composite Monolayer Fabrication by an Arc-Spray Process. NASA TM-86917, 1985.

12. Buckman, M.A., et al.: Measurement of the Thermal Conductivity of Refractories by the Laser-Flash Method. Trans. J. Brit. Ceram. Soc., vol. 82, no. 1, 1983, pp. 18-23.

13. Touloukin, Y.S. and Buyco, E.H.: Thermophysical Properties of Matter, Vol. 15, Specific Heat, Nonmetallic Solids, IFI/Plenum, New York, NY, 1970, pp. 9-14.

14. Schulz, D.A.: Production and Properties of Ultra-High Modulus Pitch-Based Carbon Fibers. Proceedings 6th Metal Matrix Composites Technology Conference, MMCIAC-000673, Metal Matrix Composites Information Analysis Center, Santa Barbara, CA, 1985, pp. 29-1 to 29-14. (Avail. NTIS, AD-B120199.)

15. Touloukian, Y.S., et al.: Thermophysical Properties of Matter, Vol. 13, Thermal Expansion, Nonmetallic Solids, IFI/Plenum, New York, 1977, p. 79.

16. Gaitonde, J.M. and Lowson, M.V.: Low Temperature Thermal Expansion of PEEK, HTA and Some of Their Composites Reinforced With Carbon Fibres. Compos. Sci. Technol., vol. 40, no. 1, 1991, pp. 69-85.

17. Kural, M.H. and Min, B.K.: The Effects of Matrix Plasticity on the Thermal Deformation of Continuous Fiber Graphite/Metal Composites. J. Compos. Mater., vol. 18, 1984, pp. 519-535.

18. DeVincent, S.M., Ellis, D.L., and Michal, G.M.: Graphite/Copper Alloy Interfacial Energies Determined Using the Sessile Drop Method. NASA CR-187087, 1991.
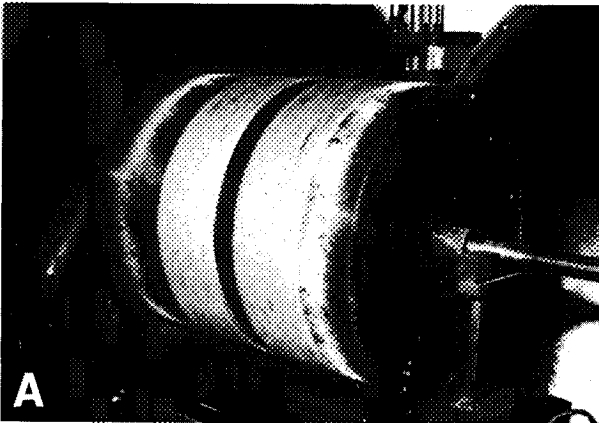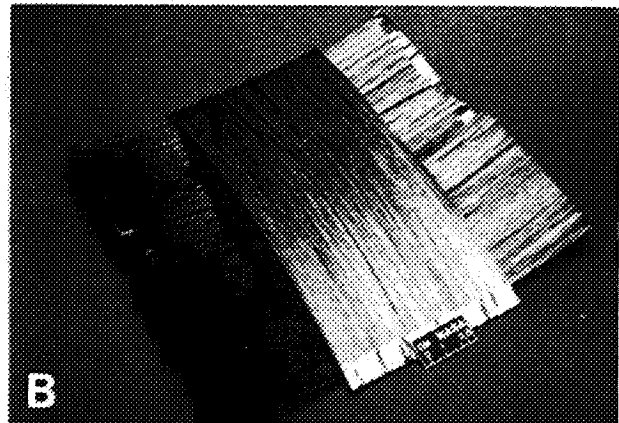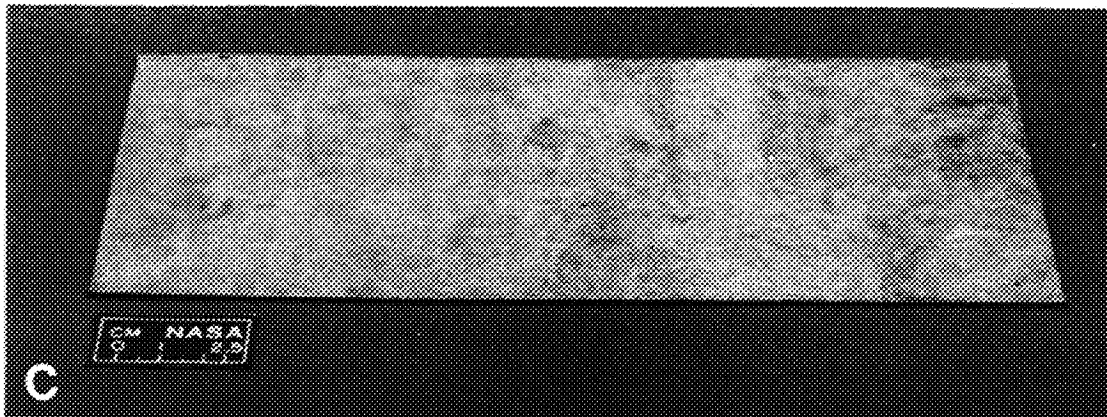
TYPICAL ANGLEPLIED FIBER PLIES

Gr/Cu RADIATOR PANEL

HEAT PIPE

LONGITUDINAL DIRECTION

LONG TRANSVERSE DIRECTION

SHORT TRANSVERSE DIRECTION
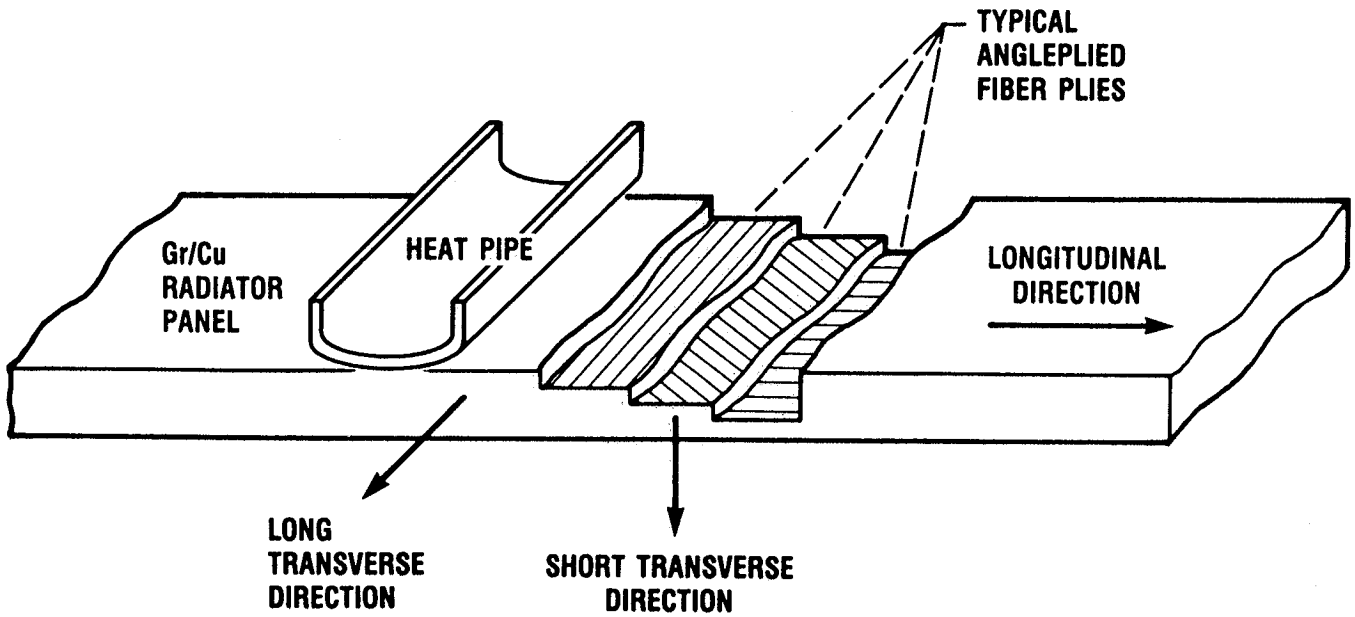
Figure 1.–Gr/Cu radiator fin showing orientation directions referred to in this paper.

(a) Copper coated P100 graphite fibers would onto drum prior to arc spraying.

(b) P100 Gr/Cu composite monotapes.

(c) P100 Gr/Cu composite plate produced by hot pressing monotapes.

Figure 2.–Production of graphite fiber reinforced copper matrix composites.

12
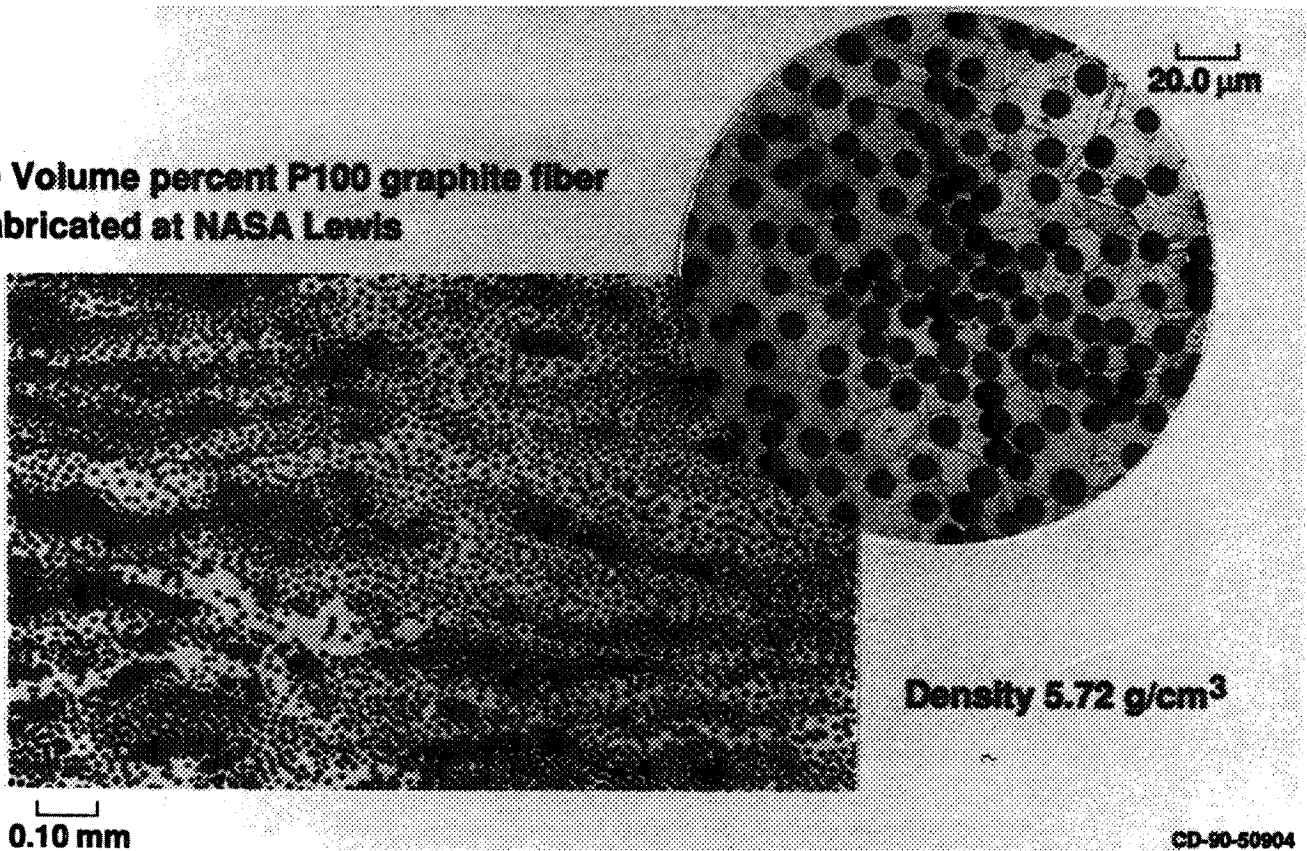
Figure 3.–Microstructure of 50 v/o P100 Gr/Cu composite. Transverse Cross-section.
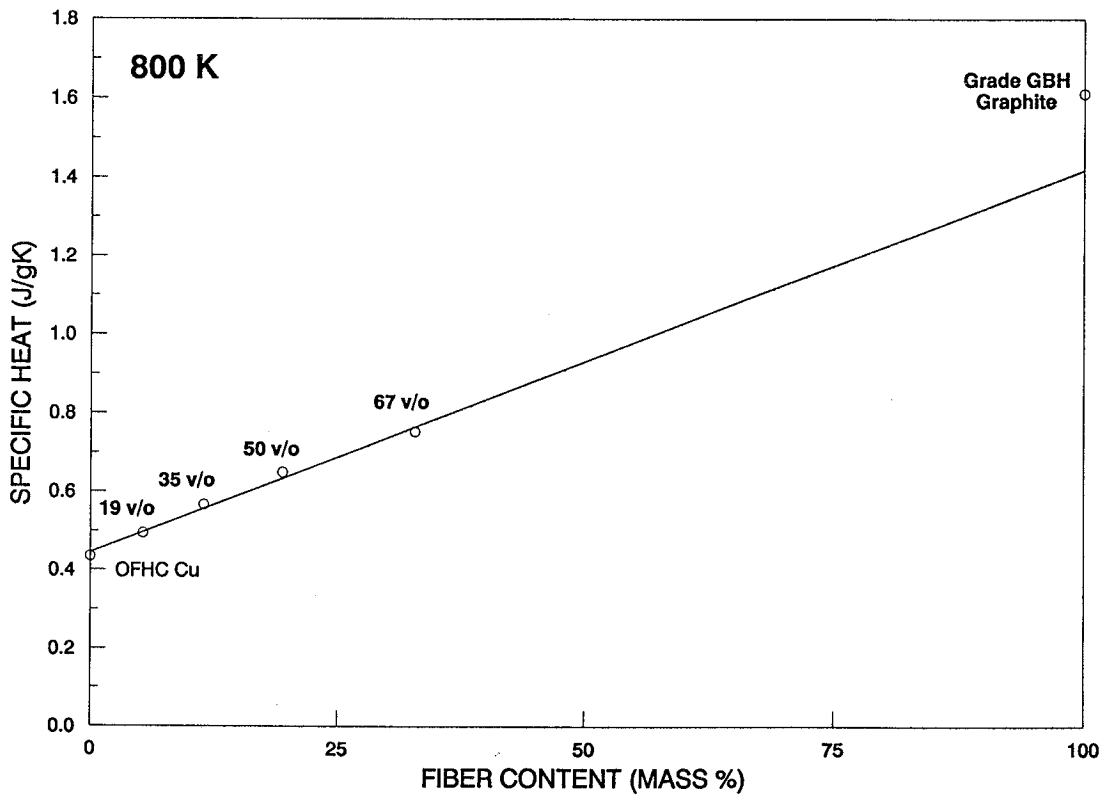
Figure 4.–Effect of fiber content on specific heat of P100 Gr/Cu composites at 800 K .

13
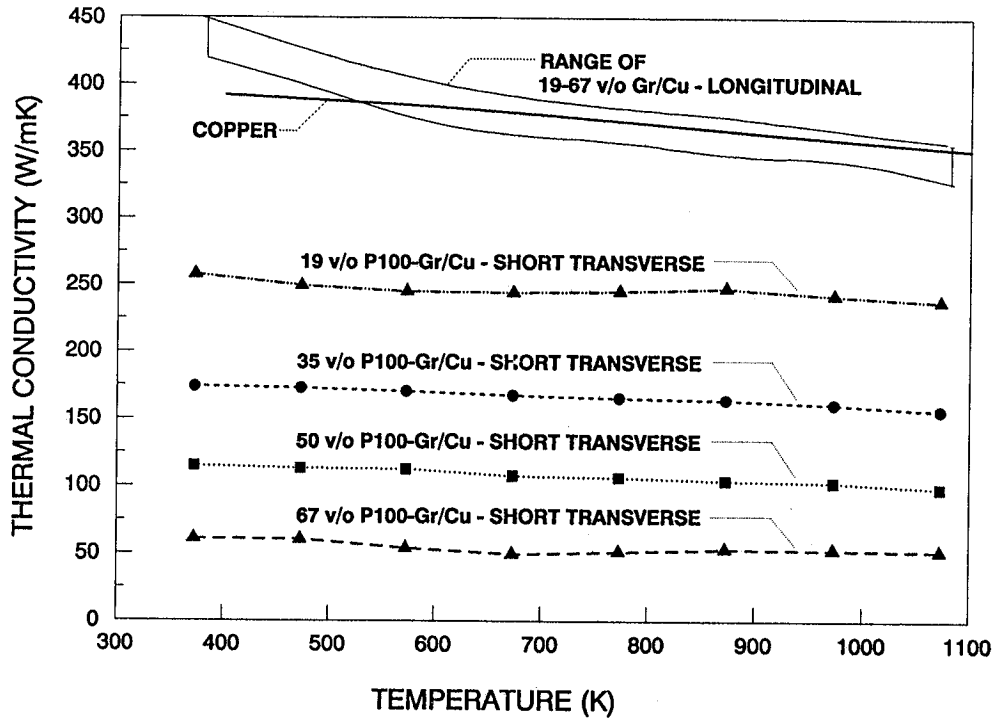
Figure 5.–Effect of temperature and fiber content on thermal conductivity of P100 Gr/Cu composites.
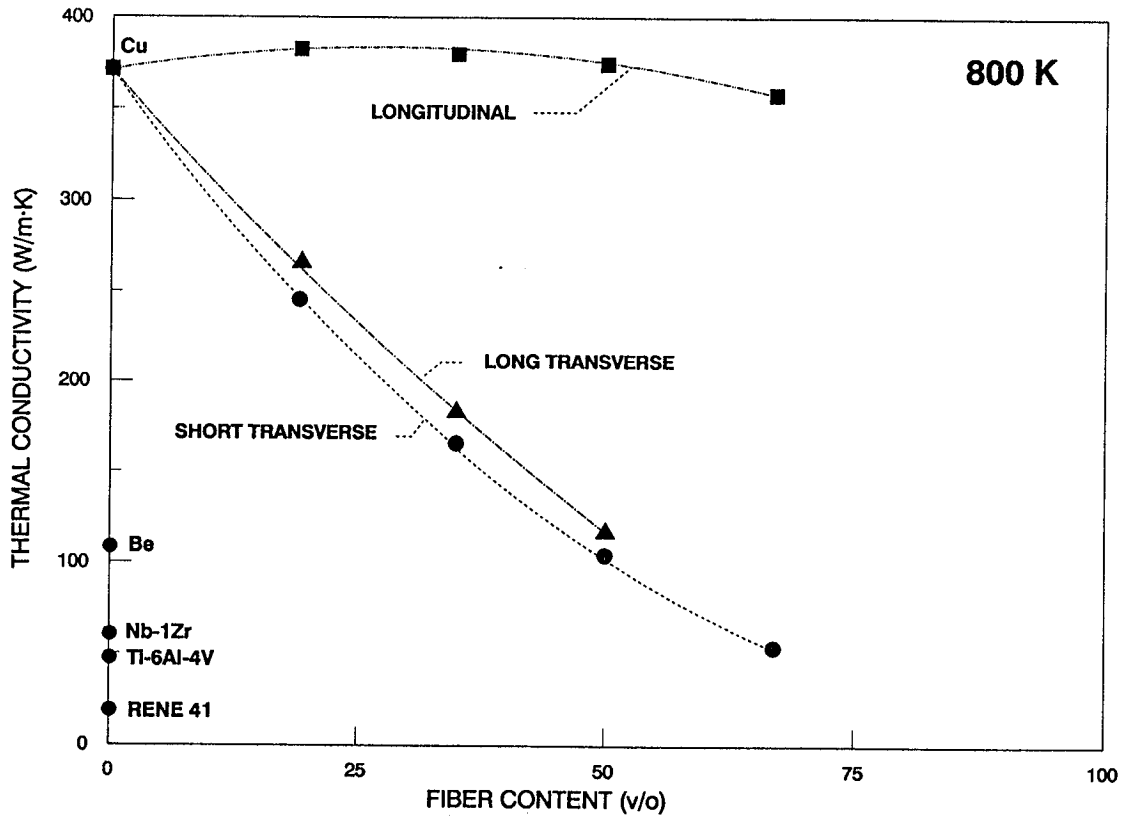
Figure 6.–Effect of fiber content on thermal conductivity of P100 Gr/Cu composites at 800 K.

14
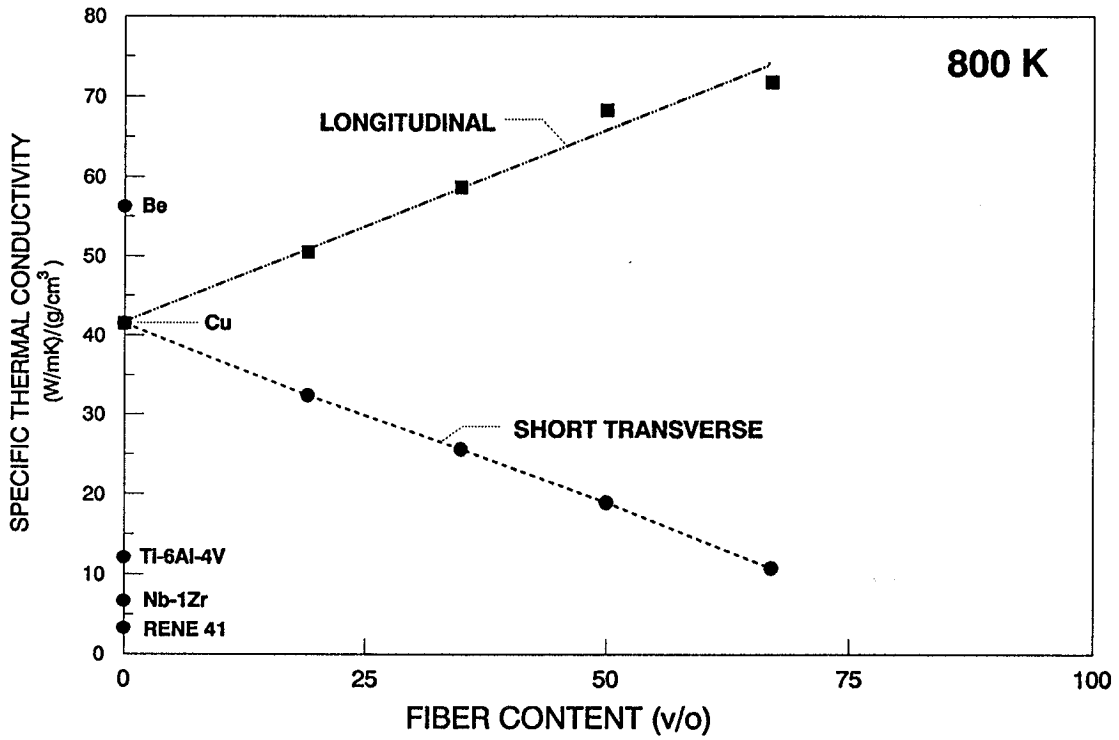
Figure 7.–Effect of fiber content on specific thermal conductivity of P100 Gr/Cu composites at 800 K.
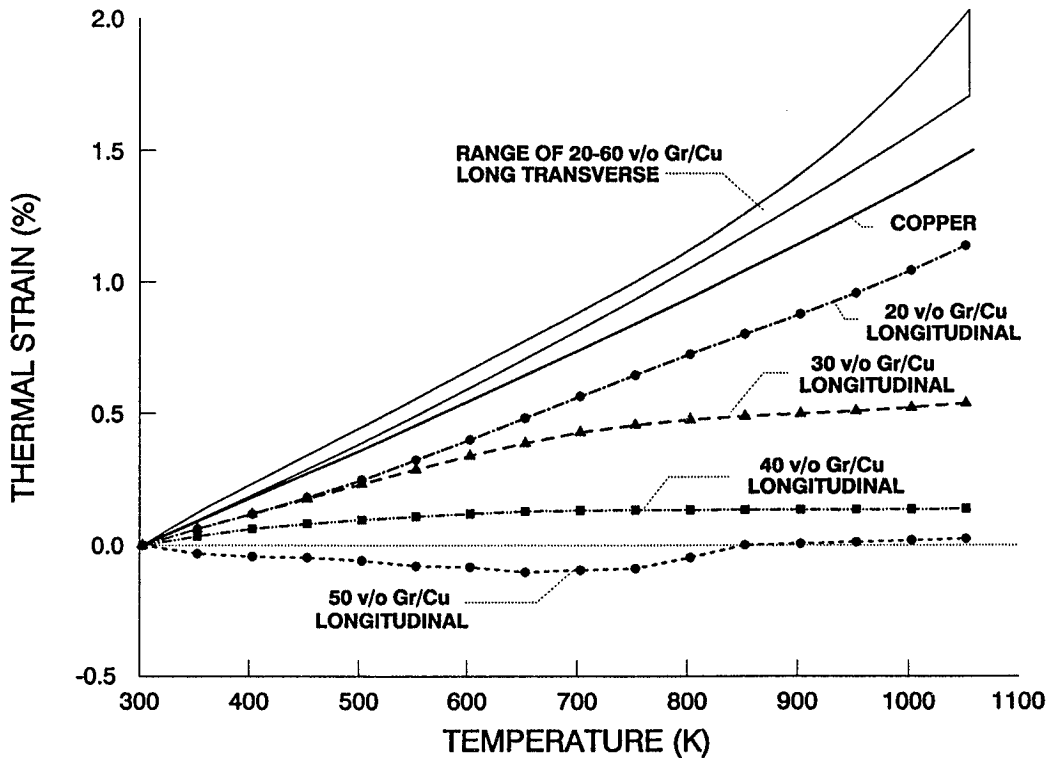
Figure 8–Effect of fiber content on thermal strain of P100 Gr/Cu composites during heating from 300 K to 1050 K.

15
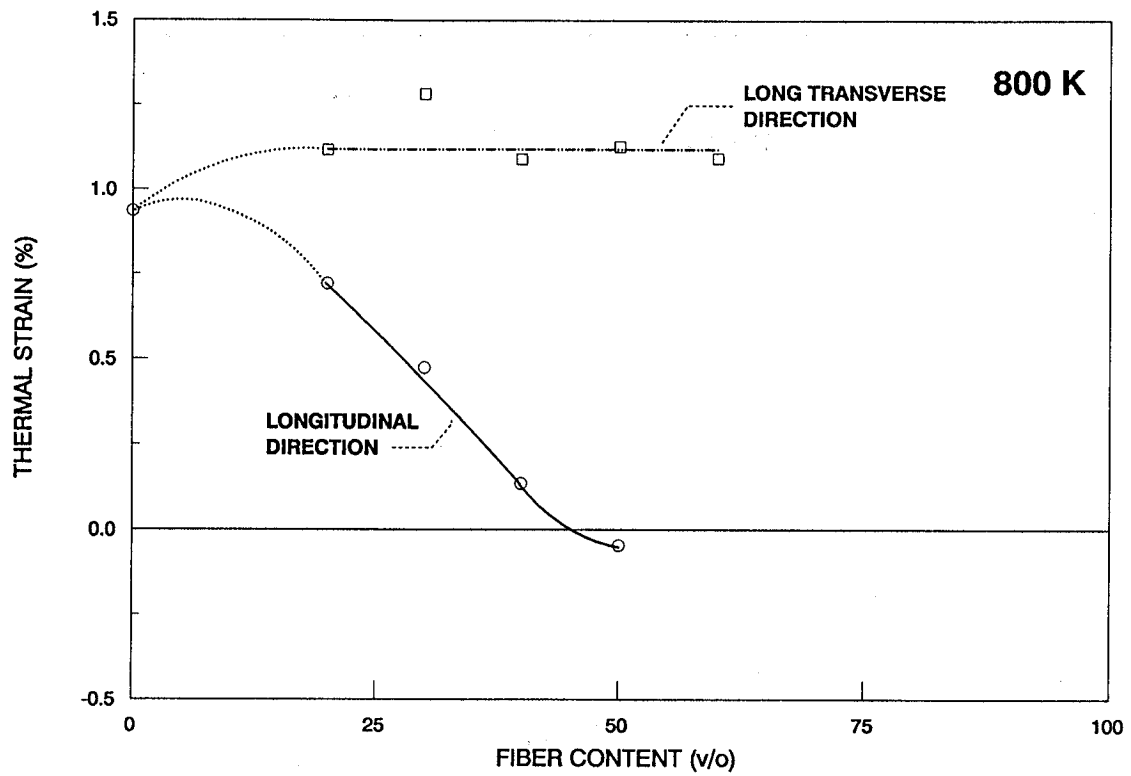
Figure 9.–Effect of fiber content on measured thermal strain of P100 Gr/Cu composites at 800 K after heating from 300 K.
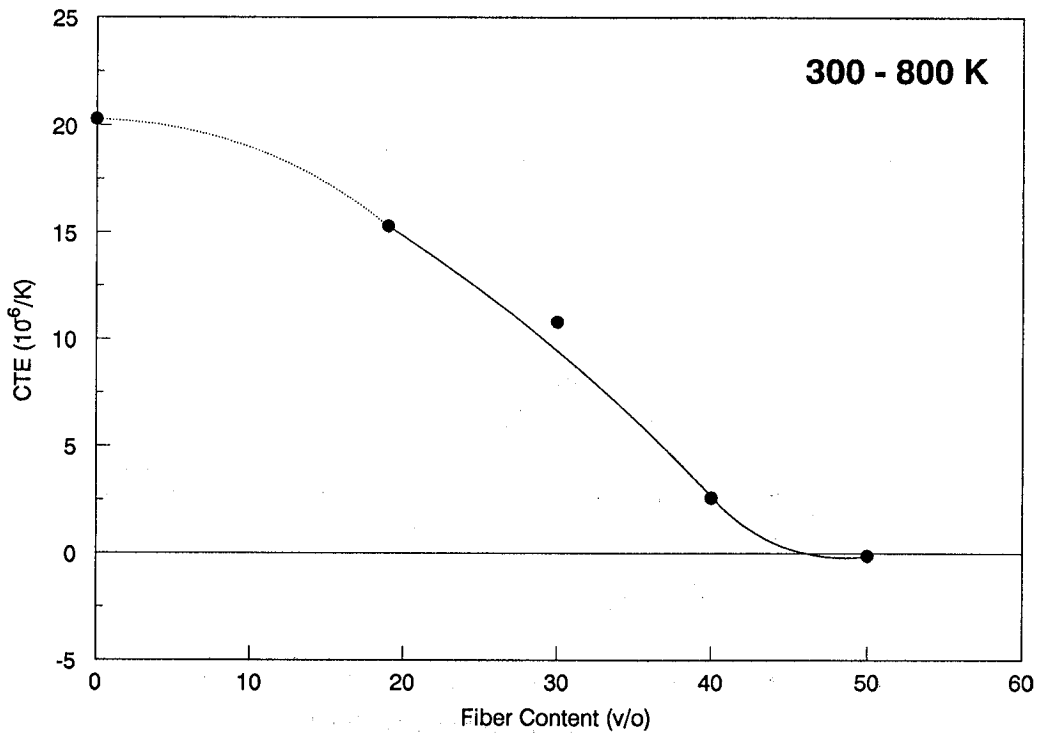
Figure 10.–Effect of fiber content on average CTE of Gr/Cu composites between 300 K and 800 K.
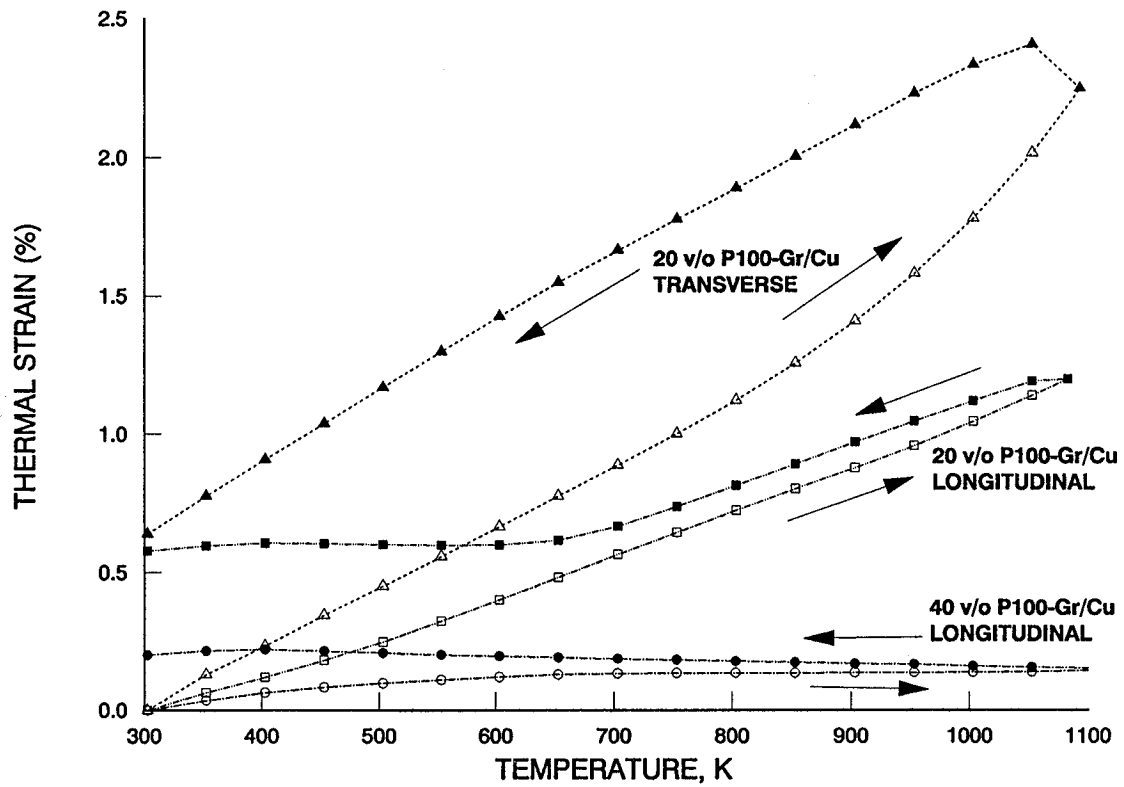
Figure 11.–Thermal strain of three typical P100 Gr/Cu composites for both heating and cooling curves.
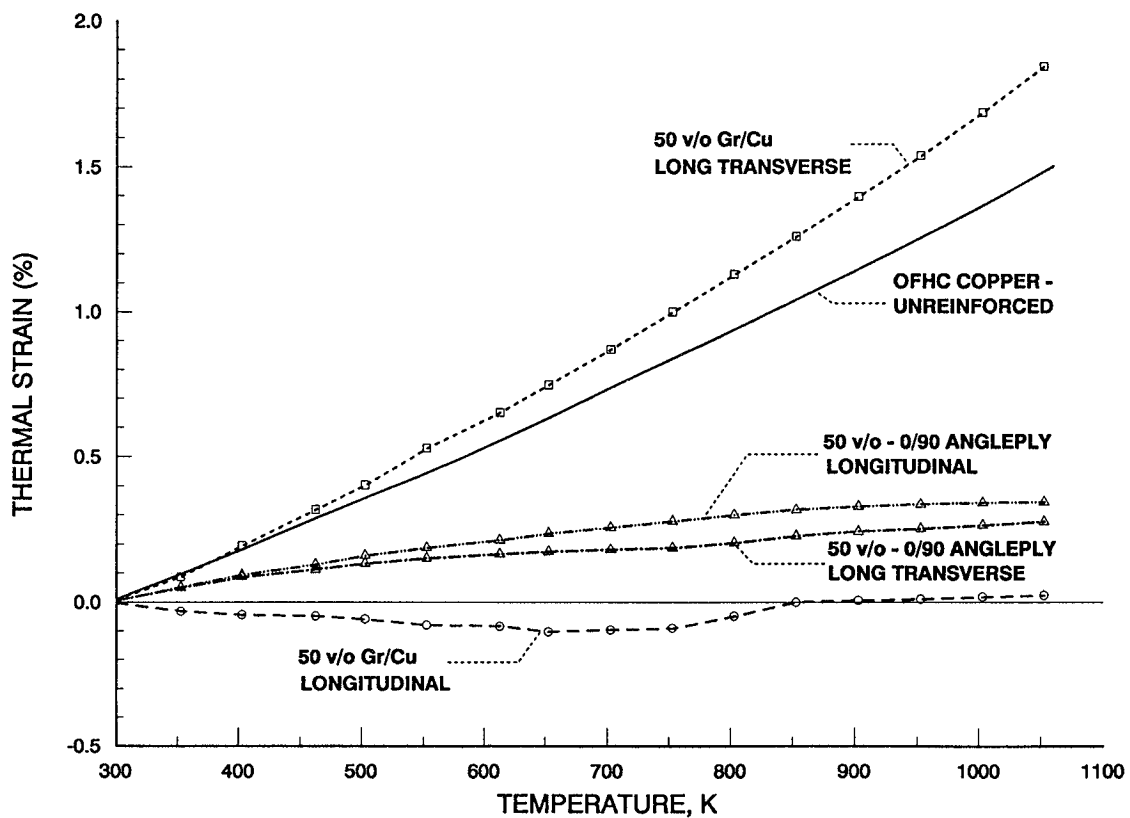
Figure 12.–Effect of fiber orientation on thermal strain of 50 v/o P100 P100 Gr/Cu composites during heating from 300 K to 1073 K..

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		Technical Memorandum

4. TITLE AND SUBTITLE

Thermal Conductivity and Thermal Expansion of Graphite Fiber/Copper Matrix Composites

5. FUNDING NUMBERS

WU – 590 – 13 – 11

6. AUTHOR(S)

David L. Ellis and David L. McDanels

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135 – 3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E – 6557

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546 – 0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM – 105233

11. SUPPLEMENTARY NOTES

Prepared for the Annual Meeting of The Metallurgical Society, New Orleans, Louisiana, February 17 – 21, 1991. David L. Ellis, Case Western Reserve University, Cleveland, Ohio 44106 and NASA Resident Research Associate at Lewis Research Center, (work funded by NASA Cooperative Agreement NCC3 – 94); David L. McDanels, NASA Lewis Research Center. Responsible person, David L. Ellis, (216) 433 – 8736.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified – Unlimited
Subject Category 24

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The high specific conductivity of graphite fiber/copper matrix (Gr/Cu) composites offers great potential for high heat flux structures operating at elevated temperatures. To determine the feasibility of applying Gr/Cu composites to high heat flux structures, composite plates were fabricated using unidirectional and cross-plied pitch-based P100 graphite fibers in a pure copper matrix. Thermal conductivity of the composites was measured from room temperature to 1073 K, and thermal expansion was measured from room temperature to 1050 K. The longitudinal thermal conductivity, parallel to the fiber direction, was comparable to pure copper. The transverse thermal conductivity, normal to the fiber direction, was less than that of pure copper and decreased with increasing fiber content. The longitudinal thermal expansion decreased with increasing fiber content. The transverse thermal expansion was greater than pure copper and nearly independent of fiber content.

14. SUBJECT TERMS

Thermal conductivity; Thermal expansion; Graphite fibers; Copper composites

15. NUMBER OF PAGES

18

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	