JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 12, No. 1, January–March 1998

Review of the Thermal Conductivity of Graphite-Reinforced Metal Matrix Composites

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The characteristics of graphite-reinforced metal matrix composites (MMCs) are increasingly important in a wide range of technologies. While most of the published studies deal with the mechanical properties of these materials, there have been limited studies characterizing the thermal properties of some of these materials. The effective thermal conductivity is of particular importance for design and applications, and experimental data are summarized and compared with accepted models of composite properties. On the basis of this review, it is evident that the thermal properties of graphite fiber-reinforced MMCs have not been adequately investigated. Modeling techniques based on limited experimental data have identified some of the important parameters, but no single model adequately predicts either the longitudinal or the transverse conductivity of these materials. This study presents a review of the experimental and analytical investigations of the thermal conductivity of these materials and concludes with recommendations for emerging and continuing areas of investigation.

Nomenclature

a = fiber radius
d = fiber diameter
h_c = fiber–matrix interface contact conductance
k = thermal conductivity
L = longitudinal
s = vertical fiber separation
T = transverse
t = horizontal fiber separation
V = fiber volume fraction
v/o = fiber volume fraction
ϕ = angle of departure from longitudinal direction of the composite

Subscripts
c = composite
e = effective
f = fiber
m = matrix
r = radial
θ = circumferential
$\perp$ = perpendicular to fiber direction
$//$ = parallel to the fiber direction

Introduction

METAL matrix composites (MMCs) have been in general use for many years. MMC materials can be used in any application where there can be some enhancement of desired properties offset by the sacrifice of other properties, e.g., trading tensile strength for thermal diffusivity. Despite the wide use of MMC materials, there are relatively few combinations of reinforcement and matrix components that are compatible enough to manufacture. One of the major problems is matching the coefficient of thermal expansion of the matrix and reinforcement. Large shear stresses at the interface can lead to mechanical degradation of the material, even debonding.

The features of high specific thermal conductivity, high specific strength, and the ability to tailor the coefficient of thermal expansion to match specific needs make these materials quite attractive to designers. As the power requirements for electronic package designs increase, the removal of heat generated by the active elements is a major factor limiting the performance of the packages. Package failures occur mainly because of chip overheating and increasingly severe coefficient of thermal expansion mismatches, resulting in the failure of solder joints between the chip carrier and the printed wiring board. As a consequence, graphite composites are being explored for many diverse applications, from structural elements to heat rejection paths.

Thermal planes are used extensively in standard electronic modules (SEMs), which are employed in military navigation and avionics systems, as well as many commercial systems. These SEMs consist of electronics components mounted to metallic frames that are inserted into closed cabinets. The upper and lower edges of the frames (the guide ribs) are fastened to the card rails by special wedge clamps. The frames and chassis, besides providing structural support for the electronics, also serve as the primary means of dissipating the heat generated by the electronics. Consequently, the thermal conductivity of the chassis card rails and card cage is one of the factors that greatly affects the operating temperature (and thus the speed and integrity) of the SEM. A second factor affecting the operating temperature is the thermal contact resistance of the guide rib–card rail joint. Much work has been done to minimize the thermal contact resistance between the guide rib and card rail of these SEMs,[1,2] but this reduction should be complemented by an increase in the thermal conductivity of the card cage and other structural components.

Recent studies have attempted to develop predictive models based on experimental values and have identified some of the important parameters. Because of the significant interest in graphite-reinforced MMCs, a review of the existing literature will provide a useful reference for the design of microelectronics systems, as well as other applications where thermal control is important.

Metal Matrix Composites

Contemporary investigations of the thermal properties of graphite-reinforced composites may be divided along the lines of the matrix material—metal, ceramic, or polymer. Often,

Received Dec. 26, 1996; revision received July 16, 1997; accepted for publication July 17, 1997.

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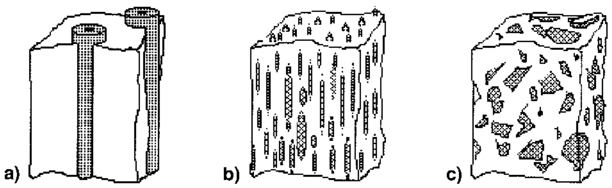

Fig. 1 Types of composite reinforcement: a) monofilaments (long fibers), b) aligned whiskers (short fibers), and c) particulate dispersion.[17]

MMCs are classified by the type of reinforcement: either particulates, whiskers, or fibers as shown in Fig. 1. Particulate MMCs offer the closest approximation to isotropic behavior but have the highest interface area-to-volume fraction ratio of the three types of composites. They suffer the least from errors in manufacturing but are most affected by the influence of the reinforcement–matrix bond. MMC materials that are reinforced by long fibers offer strong directional enhancement of properties with adequate transverse performance and tend to be used in applications where strong directionality is desired, as in structural components. Whisker- (short fiber-) reinforced composites have properties and problems somewhere in between. Short fibers are often used when there are problems with the fabrication of long fibers, or where strong directionality is not desired.

Composite properties are often modeled as being composed of two contributions, that of the reinforcement and that of the matrix. Usually, the weighting of the contributions is done on a volume fraction basis, as in the rule of mixtures. In many instances, the enhancement of thermal or mechanical properties is different than that predicted by the rule of mixtures.[3] One contributing factor to this difference is the effect at the interfaces between the reinforcement and the matrix, where the reinforcement may react with the matrix to form low conductivity, intermetallic compounds. This may be avoided through the use of a wetting agent or some other coating on the reinforcement that would minimize the reaction.

Through the use of composite materials, the designer can obtain the same desired engineering and cost performance as with conventional alloys, but with a savings in weight. This type of performance is important in such applications as aerospace engine components and space structures. Carbon fibers are commonly used to increase strength and thermal conductivity in a specific direction. This strong directionality is an effect of the anisotropic thermal conductivity of the graphite fibers. The thermal conductivity of some graphite fibers in the transverse (or radial/circumferential) direction is negligible compared to the conductivity in the axial direction. Other thermal properties can be enhanced through the appropriate use of composite reinforcement. By varying the volume fraction of reinforcement in an aluminum matrix, the coefficient of thermal expansion of the composite material can be tailored to match design requirements. The designer may continuously vary the properties within the part to meet the demands of the surrounding components.

Literature Review

Analytic Studies

Behrens[4] studied the problem of predicting the conductivity of composite materials from the method of long waves (in which plane waves are considered to propagate through the material and the associated damping coefficients are calculated and used to determine the conductivities in the prime directions). Among the results presented in his study are figures that show a departure from the rule of mixtures in directions normal to the direction of the fibers. This departure reflects the increasingly tortuous conduction path in the transverse direction in a fiber-reinforced composite. One reduced form of the model (for square-latticed, circular cross section, fiber-reinforced composite) is identifiable as the Rayleigh model (RM) for the effective conductivity:

$$k_c = k_m \left[\frac{\left(\dfrac{k_f}{k_m} + 1\right) + V_f\left(\dfrac{k_f}{k_m} - 1\right)}{\left(\dfrac{k_f}{k_m} + 1\right) - V_f\left(\dfrac{k_f}{k_m} - 1\right)} \right] \tag{1}$$

where the fiber orientation and distribution are assumed to be uniform. This model does not take into account interaction between the fibers or interaction between the fibers and the matrix.

Karpinos et al.[5] studied thermal and electric transport properties in nonlayered, fiber-reinforced aluminum. The RM assumes a rectangular spacing of reinforcing fibers, and is dependent on the size and spacing geometry of fibers, in addition to the thermal conductivity of the matrix and reinforcement material:

$$k = \left(\frac{k_m}{\dfrac{k_m}{k_f} + \dfrac{2ts}{\pi d^2 + 2ts}} + \frac{k_f}{\dfrac{k_f}{k_m} + \dfrac{\pi d^2 + 2ts}{2ts}} \right) \sin^2\phi + \left(\frac{k_m}{1 + \dfrac{\pi d^2}{4ts}} + \frac{k_f}{1 + \dfrac{4ts}{\pi d^2}} \right) \cos^2\phi \tag{2}$$

Karpinos et al.[5] recognized that their model did not take into consideration interface effects. The composite used in the experimental phase of the study was steel fiber-reinforced aluminum. Their experimental results had good agreement with their model (within 5–25% of the predicted values) but reported lower values than predicted. Steel and aluminum do not produce the same intermetallic compounds that carbon and aluminum do, and so the effects of interface phenomenon are less influential for steel/aluminum composites than they would be graphite/aluminum composites. Steel, unlike graphite fibers, is an isotropic material whose conductivity is relatively independent of direction within the fiber. Thus, there is reason to believe that this model would be ill-suited for aligned graphite fiber-reinforced composites.

Tsou et al.[6] studied the directional dependence of conductivity in layered composites. Their model predicted the thermal conductivity of these materials through a weighting scheme based on the tensorial thermal conductivities, volume fractions, and relative thicknesses of the constituent layers. Because the model assumed that the thermal conductivities of the constituent layers were known, it did not explicitly account for different lay directions of the plys within the composite. It also neglected the interface effects between layers.

Han and Cosner[7] considered the thermal conductivity of fiber-reinforced composites for two cases: 1) unidirectional composites, and 2) those composed of unidirectional laminae layed 90 deg to each other. Among the results presented (in graphical form) is the observation that for fiber-to-matrix conductivity ratios between 0 and 2, the model represented in Eq. (1) is a fairly good approximation to the more involved model presented in their study.

Taylor and Kelsic[3] studied the effects of fiber orientation on the conductivity and diffusivity of fiber-reinforced composites. Their study demonstrated that given knowledge of the conductivities in the three principle directions, directional cosines may be used to predict the conductivity of the composite in any orientation. However, they also noted that high fiber/matrix conductivity ratios (greater than 100) would result in deviations from this behavior.

Goddard et al.[8] studied graphite fiber-reinforced magnesium (Gr/Mg) MMCs to ascertain their utility in rotary engine castings. They cited the combination of high strength and stiffness at ambient and elevated temperatures, light weight, good fatigue and damping characteristics, and high thermal conductivity as support for their use in this application. In this investigation, the fabrication and performance testing of a rotor housing were studied. Computer-aided design techniques were used to determine optimal fiber orientations for both mechanical and thermal performance. The authors conclude by pointing out that with current composite laminate technology, it is possible to design a complex assembly with varying performance requirements throughout as one piece.

Ke-Da et al.[9] investigated the transverse conductivity of irregular geometry, fiber-reinforced composites. Their study, prompted by the reality of irregular fiber alignment and spacing, assumed perfect contact between the matrix and the reinforcement, and took into account the effects of volume fraction, fiber clustering, nonuniform fiber diameter, and fiber misalignment. They concluded that the effects of nonideal fiber geometry are significant only when the volume fraction approaches the percolation threshold (the volume fraction is such that the fibers begin to touch each other and a continuous path forms through the fibers in the composite).

Hasselman et al.[10-12] studied uniaxial fiber-reinforced MMCs and developed a model for both the longitudinal and transverse thermal conductivities of the composite. The longitudinal conductivity (see Fig. 2) is described by the rule of mixtures, and the transverse conductivity, assuming transversely anisotropic fibers, by

$$k_c = k_m \left[\frac{\left(\frac{\sqrt{k_\theta k_r}}{k_m} - \frac{\sqrt{k_\theta k_r}}{a h_c} - 1 \right) V_f + \left(1 + \frac{\sqrt{k_\theta k_r}}{k_m} + \frac{\sqrt{k_\theta k_r}}{a h_c} \right)}{\left(1 - \frac{\sqrt{k_\theta k_r}}{k_m} + \frac{\sqrt{k_\theta k_r}}{a h_c} \right) V_f + \left(1 + \frac{\sqrt{k_\theta k_r}}{k_m} + \frac{\sqrt{k_\theta k_r}}{a h_c} \right)} \right] \tag{3}$$

which reduces to the RM as h_c approaches infinity.

Dolowy et al.[13] conducted a study of the thermophysical properties of MMCs, with applications in electronic substrates and space-based thermal management systems. The ideal material requirements for many of these applications are very low coefficients of thermal expansion, maximum thermal conductivity, and minimum density. They determined that MMCs seem to be the only materials capable of satisfying these criteria (thermal conductivities greater than and composite densities less than that of pure aluminum), and they specifically identified graphite fiber-reinforced, copper or aluminum matrix MMCs as having great promise in electronic/thermal management applications. Unfortunately, not much of the thermal property data is presented in this paper, much less temperature-dependent data.

Beasley[14] evaluated graphite fiber-reinforced aluminum and copper composites for use as module frames for SEMs. He made comparisons of the requirements of the SEM and the properties of the thermophysical materials (density, thermal conductivity, coefficient of thermal expansion, vibration dumping, and mechanical integrity). Beasley[14] found that the flatness and thermal expansion properties of the materials needed to be improved. Data from this work was to be used to optimize SEM-E module frame design.

Drolen and Johnson[15] studied several advanced graphite composite materials for use as two dimensional fins. The reinforcement was type K1100 graphite fibers inside the metal matrix. They found conditions where the poor through-conductivity precludes these materials for fins, and presented an exact analysis as well as a numerical analysis of an anisotropic fin. Drolen and Johnson[15] suggested that the results of their analyses indicated some significant dimensionless groups and dependencies and showed important material tradeoffs. They concluded that the K1100 graphite composites are thermally well suited to many fin applications.

Kinna,[16] prompted by the increasing demands on electronics packaging materials, studied the use of K1100 graphite-reinforced MMCs for use in thermal planes. He determined that the MMCs provided higher thermal conductivities than layered metal thermal planes (copper–invar–copper and copper–molybdenum–copper). Further, Kinna[16] reported that ceramic matrix composites have the potential of reduced coefficient of thermal expansion mismatch between the thermal plane and the electronic components, and exhibit a desirable reduction in material density.

Clyne and Withers[17] presented a modeling scheme based on work done by Eshelby.[18,19] Although these models are primarily concerned with mechanical properties and the effects of thermal stresses and strains on the mechanical strength of the composite, they have some application to a method of predicting the thermal characteristics of the MMC material.

Gu[20] compared several analytical methods for computing the effective transverse conductivity of composites, including the Rayleigh method, the method of transformation field (MTF), and the collocation method (CM). These models are compared in Fig. 3 for different values of matrix-to-fiber conductivity ratios as a function of volume fraction. The author concludes by saying that the RM is an excellent means of obtaining a simple relation for the effective conductivity of the composite. However, the simplifications that make this method tractable exclude all but those composites with cylindrical or spherical inclusions, and without overlapping inclusions. Gu[20] also mentions that the method of transformation field deals with arbitrary microstructures adequately, and has been used

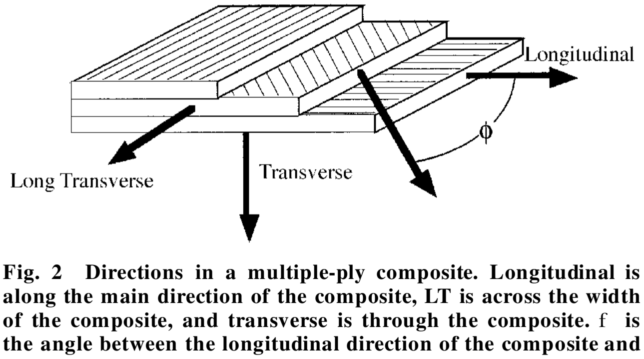

Fig. 2 Directions in a multiple-ply composite. Longitudinal is along the main direction of the composite, LT is across the width of the composite, and transverse is through the composite. f is the angle between the longitudinal direction of the composite and the lay direction within a ply.

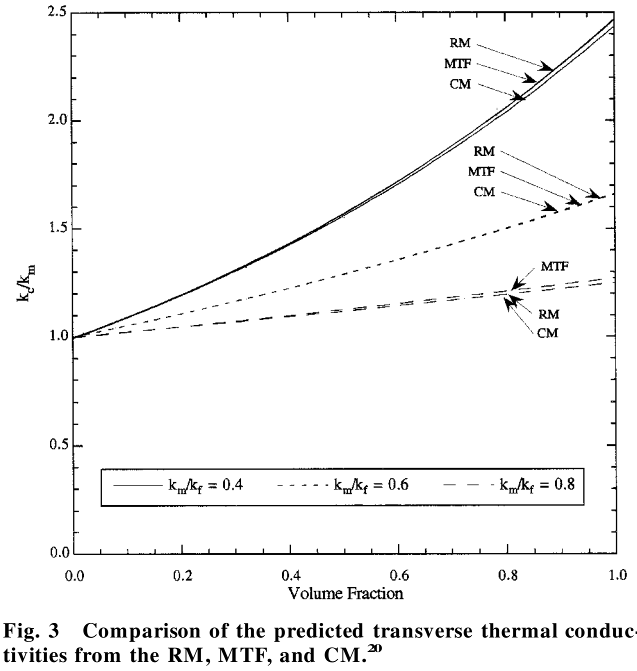

Fig. 3 Comparison of the predicted transverse thermal conductivities from the RM, MTF, and CM.[20]

to determine the effective thermal conductivities of composites. There are difficulties in applying this method to discontinuous temperature or heat generation fields. He further notes that the collocation method is most useful if general solutions of the governing equations are known, and that even though it can deal with discontinuous temperature fields, it still has difficulty handling overlapping inclusions. Further, it is limited, as is the RM, to spherical or cylindrical inclusions, which leads Gu[20] to comment that it appears to be a remedy for RM when the Rayleigh identity cannot be obtained.

Experimental Studies

Fitzer et al.[21] studied the thermal and electrical conductivities of aligned fiber-reinforced composites, including graphite-reinforced aluminum and graphite- (Thornel 400) reinforced nickel. Their model was derived from an equivalent thermal resistance network, with the addition of a shape factor that accounted for the size and spacing of the reinforcement fibers. Fitzer[21] provided limited parallel and normal thermal conductivity data of Gr/Ni composites at room temperature for various fiber volume fractions.

Kvasha et al.[22] investigated the thermophysical properties of a high-density MMC made by sintering PMS-2 copper powder with 10% S-2 colloid graphite. The resulting heterogeneous system was characterized by the presence of interdiffused components and closed inclusions. They reported that current models were able to predict the effective thermal conductivity of the material (between 20 and 800°C) to within 20%.

Greenfield[23] studied the thermal expansion, electrical resistivity, and thermal conductivity of several chopped graphite fiber-reinforced copper 301 and aluminum 201 matrix composites, formed through power metallurgy techniques. The volume fractions of the composites varied from 0.1 to 0.6, and the aspect ratio was varied from 30 to 100. It was determined that the thermophysical properties of interest were dependent on the distribution of fiber orientations, processing parameters (temperature, pressure), and the nature of the fiber–matrix interface. No actual data for the thermal conductivity were provided.

Researchers described a unidirectional graphite fiber-reinforced, aluminum MMC developed at NASA Lewis Research Center.[24] Primary applications for this material (available as sheets, tubes, and bars) are likely to include heat rejection paths for electronics components and the leading edges of high-speed aircraft. While the transverse conductivity is described to be approximately two-thirds that of the aluminum matrix, the longitudinal conductivity is much higher.

Havis et al.[25] studied the effects of fiber orientation on the effective thermal conductivity of unidirectional fiber-reinforced composites. They found that deviations in the fiber angle from the longitudinal direction severely reduces the effective conductivity of the composite.

McGuire and Vollerin[26] developed a new, high conductivity graphite fiber for use in space structures and other high-performance thermal components. They report that the fibers demonstrate a thermal conductivity up to 1100 W/m-K (hence, the designation K1100), a negative coefficient of thermal expansion, low density, and a high stiffness. The fibers were found to be usable in such matrix material as aluminum, copper, and some polymers.

McDanels et al.[27] investigated graphite fiber-reinforced copper MMCs for use in space power systems. They asserted that a major design criteria for these power systems, high specific conductivity, indicates that MMCs are suitable materials for heat rejection systems. They further suggested that because the properties of graphite–copper MMCs can be designed for a particular application, they are ideal for space power applications. The weight reduction due to the increased specific thermal conductivity is matched by the near zero longitudinal coefficient of thermal expansion and the anisotropic properties of these engineered materials.

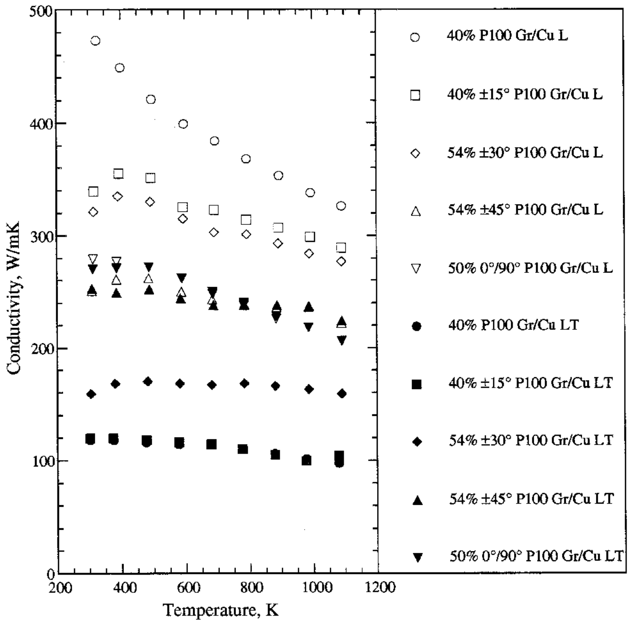

Fig. 4 Effective thermal conductivity in angle-plied P100 Gr/Cu composites as a function of temperature.[31]

Taylor et al.[28] studied the thermal diffusivity and conductivity of carbon fiber-reinforced copper and aluminum MMC materials. The composites were fabricated by vacuum hot-pressing short graphite fibers mixed with metal powder (fiber volume fractions ranging from 0.1 to 0.5). Their results indicate that the diffusivity of the MMCs decrease with increasing volume fraction. Taylor et al.[28] also noted that as the volume fraction increases, the effects of porosity become significant, with the aluminum MMCs being more susceptible to this phenomenon.

Hasselman et al.[29] studied the effects of particle size on particulate-reinforced MMCs. Among their conclusions is that as the reinforcement size approaches zero, the difference between the experimental data and the conductivity predicted by the rule of mixtures can, in turn, predict the interface conductance between the reinforcement and the matrix.

Titran et al.[30] investigated several materials for use in spaceborne power systems, among them refractory metal alloys and MMCs. The main objective of their study was characterization of the thermophysical properties of these materials for design use. Of particular interest are the graphite fiber-reinforced copper MMCs recommended for heat rejection components.

Ellis[31] and Ellis and McDanels[32,33] investigated the use of graphite fiber-reinforced copper MMCs for space applications. The thermal conductivities of the MMCs were determined as a function of fiber volume fraction and orientation (Fig. 4), and showed that for the fiber used (P100 graphite), the thermal conductivity in the longitudinal direction of aligned fiber composites was not very dependent on volume fraction, instead, being strongly influenced by fiber orientation. The transverse thermal conductivities were inversely dependent on volume fraction. Ellis[31] and Ellis and McDanels,[32,33] reported that thermal expansion tests showed a considerable mismatch between the fibers and the copper matrix. They also reported that the composites showed a coefficient of thermal expansion hysteresis that could be reduced through the use of wetting agents and fiber preparation prior to casting the matrix. They proposed that the conductivities of angle-plied fiber-reinforced composites be predicted by the following relation:

$$k_e = k_{//} \cos^2\phi + k_{\perp} \sin^2\phi \tag{4}$$

which can be modified for composites that have several different lay directions in different plies.

In a later study, Ellis and McDanels[33] studied the feasibility of using P-100 graphite fiber-reinforced copper MMCs in components that experience high heat fluxes and temperatures. Plates were fabricated using both unidirectional and cross-plied fibers in a pure copper matrix. They measured the thermal conductivity of the composites between 300 and 1073 K, and the coefficient of thermal expansion between 300 to 1050 K. They found that the conductivity in directions parallel to the fiber orientation was similar to that of the copper matrix, whereas conductivity in directions normal to the fiber orientation was found to be less than that of the copper matrix (and decreased with increasing fiber volume fraction). Ellis and McDanels[33] also found that the coefficient of thermal expansion in directions parallel to the fiber orientation decreased with increasing fiber volume fraction, and that the expansion in directions normal to the fiber orientation, while greater than that of the copper matrix, were relatively independent of volume fraction.

Given the influence of the reinforcement volume fraction on the thermal conductivity of MMCs, it is not unreasonable to assume that volume fraction must also have an effect on the thermal contact conductance behavior of MMC materials. Blanchard and Fletcher[34] showed a decrease in dimensionless thermal contact conductance with an increased particulate reinforcement volume fraction for Al 2124 and Al 6061-T6, for several silicon carbide reinforcement volume fractions. Data collected on K1100 Gr/Al 6063 by Lambert and Fletcher[35] (shown in Fig. 5), for thermal plane applications, may prove useful when compared with results for unreinforced material (OFHC Copper and Aluminum A356-T6).

Braun and Bosset[36] studied the use of graphite aluminum MMCs for thermal regulation in space-borne electronic systems. Test results for electronics enclosures, cards, and card cages made of graphite/aluminum MMCs were compared to results for components made of standard materials (Al 6061, Al 6063). Modifications included the use of P120 fiber-reinforced Al 6061-T6 heat sinks and K1100-reinforced Al 6061 cards and enclosures.

The thermal conductivities of various Gr/Cu MMCs are presented in Fig. 6. It is evident that the volume fraction of reinforcement and fiber orientation has a large influence on the effective conductivity of the composite. Longitudinal conductivity is inversely proportional to the ply angle, as transverse conductivity is inversely proportional to the volume fraction.

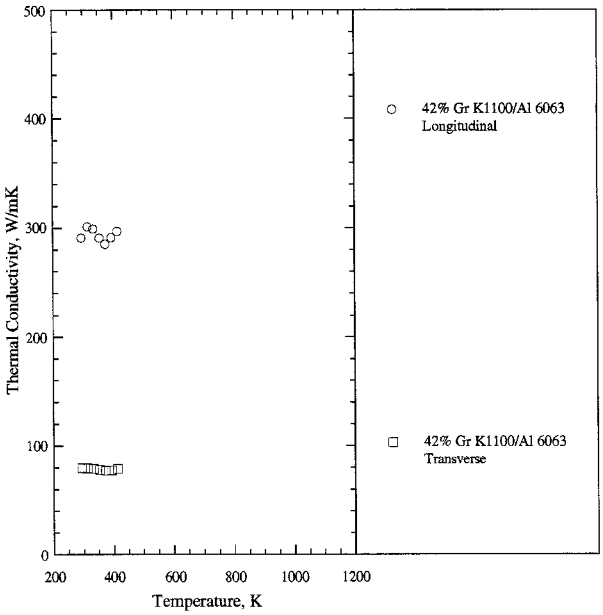

Fig. 5 Effective thermal conductivity as a function of temperature for K1100 Gr/Al 6063 MMCs.[35]

Results and Discussion

Figure 7 shows that Eq. (3) accurately predicts the transverse thermal conductivity of aligned fiber composites for a wide range of volume fractions. The model slightly overpredicts the conductivity, but these deviations may be due to interaction between the fiber and the matrix. Figure 7 also compares the experimental and predicted longitudinal conductivities of the K1100 Gr/Cu and P100 Gr/Cu aligned fiber composites. Nominal thermal conductivity values of 400 and 200 W/m^{2}K are used for the copper and aluminum matrix materials, respectively, and longitudinal thermal conductivities of 1100 and 600 W/m^{2}K for the K1100 and P100 graphite fibers, respectively. Transverse conductivities of the K1100 and P100 graphite fibers are assumed to be near zero. Figure 7 also shows that the rule of mixtures (ROM) severely overpredicts the longitudinal conductivity of aligned fiber composites. Again, this may be because of the interaction between the carbon fiber and the

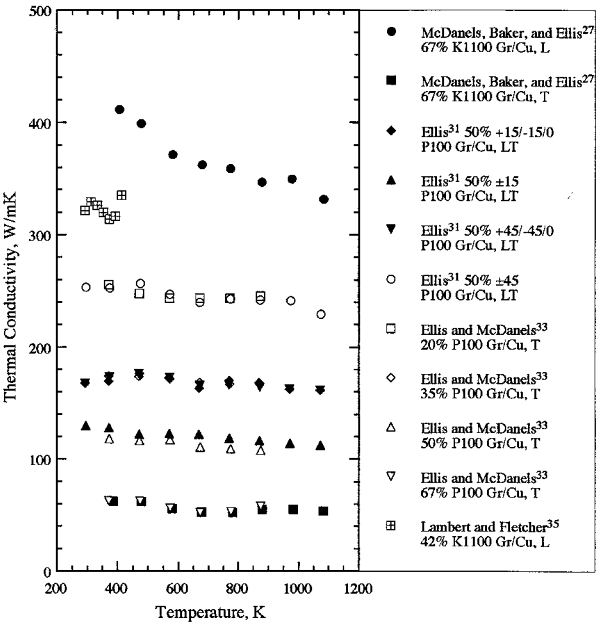

Fig. 6 Summary of effective thermal conductivity as a function of temperature for K1100 and P100 Gr/Cu MMCs.

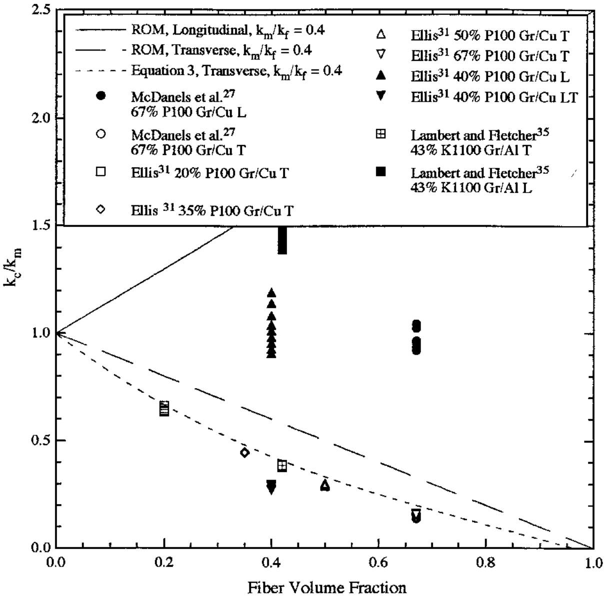

Fig. 7 Comparison of predictions from the ROM, RM, and Eq. (3) with longitudinal and transverse conductivities of nonangle-plied composites.

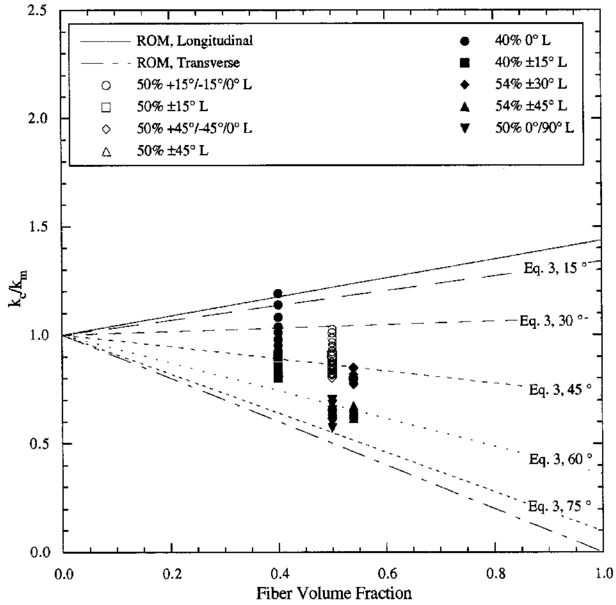

Fig. 8 Comparison of predictions from the ROM and Eq. (3), and angle-plied P100 Gr/Cu composite longitudinal conductivity data.[31]

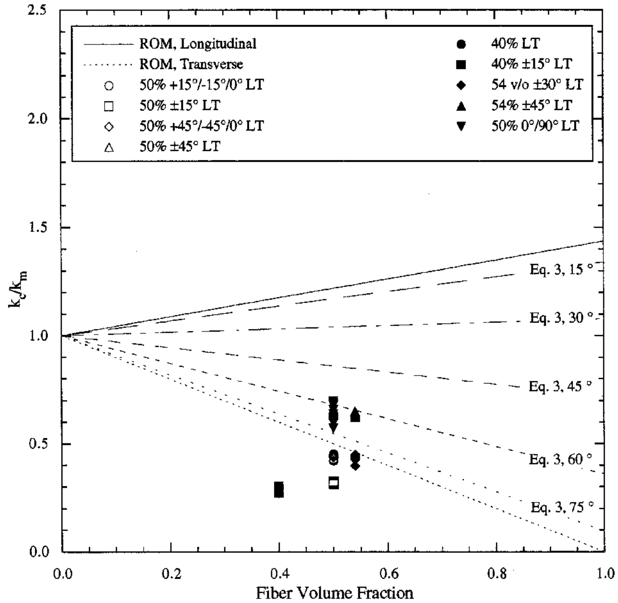

Fig. 9 Comparison of predictions from the ROM and Eq. (4), and angle-plied P100 Gr/Cu composite LT conductivity data.[31]

matrix metal, but the degree of the overprediction is such that there may be other factors, perhaps discontinuities at the interface between the fiber and the matrix, or that constriction resistance due to nonuniform fiber distribution may be more significant than previously supposed.

Figures 8 and 9 show that the model described by Eq. (4) overpredicts the longitudinal and long transverse (LT) conductivities of angle plied composites by as much as 100% (as in the case of the ±15-deg composite). The longitudinal conductivity for the 40% volume fraction composite is far lower than the rule of mixtures would predict, suggesting that there may be some formation of copper–carbon compounds within the matrix. Photomicrographs of a 50% P100 Gr/Cu composite[33] show some fiber–fiber contact and a nonuniform fiber distribution within the matrix. If appropriate parameters were available, the analysis of Ke-Da et al.[7] might be used to modify the models described by Gu,[20] Hasselman et al.,[10–12] and Ellis[31] to account for these irregularities.

Conclusions and Recommendations

While it is agreed that the high conductivity MMCs are of great utility in reduced density, high-performance heat rejection systems, relatively little has been done to model these composites beyond the rule of mixtures. Some programs make an effort to predict the behavior of MMC systems, but they too depend on the rule of mixtures to model thermal properties. This approach, while providing approximate values suitable for initial estimates, neglects the effects of the fiber–matrix bond.

This paper serves as a summary of current work done in the field of graphite fiber-reinforced MMC materials and illustrates the variation in the properties of these materials. Thermal conductivity is usually overpredicted by existing models. In many cases, the conductivity is lower than that predicted by simply replacing the reinforcement by vacuum, even in those models that take conduction path into consideration. This can partly be accounted for by chemical interactions between the reinforcement and the matrix.

Research examining the effect of fiber orientation, volume fraction, and specimen size is needed, and existing material property correlations should be altered to take into account the nonhomogeneous nature of the MMC material. More work needs to be done in this area, particularly in the identification of other dominant parameters suitable for future predictive correlations, and attention should be given to the nature of the reinforcement–matrix bond.

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