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Effective Thermal Conductivity and Thermal Contact Conductance of Graphite Fiber Composites

S. R. Mirmira,* M. C. Jackson,† and L. S. Fletcher‡
Texas A&M University, College Station, Texas 77843-3123

The transverse and longitudinal effective thermal conductivity and contact conductance of discontinuous and misoriented graphite fiber-reinforced composites has been studied over a range of temperatures (20–200°C) and pressures (172–1720 kPa). Three different fiber types (DKE X, DKA X, and K22XX) and three fiber volume fractions (55, 65, and 75%) in a cyanate ester matrix were studied. The addition of fibers to the matrix resulted in an increase in effective thermal conductivity, but appears to level off at fiber volume fractions of 65%. Furthermore, the effective thermal conductivity in the longitudinal direction was significantly greater than in the transverse direction and was more dependent on temperature. These data were used to develop an equation relating the thermal contact conductance to the harmonic mean thermal conductivity of the fiber and matrix material, fiber volume fraction, sample thickness, and microhardness.

Nomenclature

d = diameter of the fiber
H = microhardness
h = thermal contact conductance
k = thermal conductivity
L = thickness of composite
l = length of the fiber
r = radius of fiber
T = temperature
V = volume fraction
xy = longitudinal direction
z = transverse direction

Subscripts

e = effective
f = fiber
i = interfacial
m = matrix
p = pores
r = radial direction
s = harmonic mean
v = Vickers
θ = axial direction

Introduction

THERE has been an increasing demand for new materials to meet the need for higher performance products. Fiber composites, composed of glass, graphite, or carbon embedded in organic or inorganic matrices, comprise one class of materials that is finding widespread application. Inorganic matrix composites (metal matrix), although expensive, are used for high-strength, lightweight applications. Organic matrix fiber composites are less expensive and easier to fabricate and are being explored for a number of applications that require even lighter weight.

Although different fiber materials are used in composites, graphite fiber composites appear to be of greatest interest because of their exceptional mechanical properties, especially their high strength and stiffness. Graphite fibers also possess good corrosion resistance and low friction and wear properties. Graphite fiber composites have been used extensively in some aircraft parts, space and marine structures, automobile components, and selected sporting goods.

The mechanical properties of graphite fiber composites with both organic and inorganic matrices have been reasonably well characterized.[1] The thermal characteristics of graphite fiber inorganic matrix composites have been recently studied by Lambert and Fletcher[2] and Ayers and Fletcher.[3]

The electronics packaging industry is currently exploring the use of graphite fiber organic matrix as a potential substitute of the polymeric mold compounds currently used in electronic devices because of the increasing number of thermally induced failures.[4,5] The increasing power density and compact design of electronic packages necessitate the selection of new materials that can dissipate heat more effectively. Therefore, it is important to develop a better understanding of the thermal characteristics of graphite fiber organic matrix composites. Thus, an investigation was conducted to determine the effective thermal conductivity and thermal contact conductance of discontinuous graphite fiber organic composites.

Literature Review

Researchers have studied the phenomenon of heat transport in fiber composites, but no single study comprehensively describes the influence of the various parameters (fiber and matrix type, fiber volume fraction, size of fibers, etc.) on the thermal properties. A few of these studies report experimentally determined effective thermal conductivity, whereas others have attempted to develop theoretical models to predict these values. The following section discusses relevant analytical and experimental investigations that dealt with fibrous composites.

Theoretical Studies

Techniques for the prediction of effective thermal conductivity include, model-based, self-consistent, simplified mechanics of materials equations and statistical bounds. Studies on the transverse thermal conductivity of fibrous composites began over four decades ago. Most of the analytical models developed are based on the following assumptions: macroscopic homogeneity of the graphite composite, negligible thermal resistance between the fiber and the matrix, negligible interaction between the fiber and matrix, fibers and matrix considered to be isotropic. A majority of the theoretical research for fibrous composites has been based on the findings of

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*Key Account Technologist, CMP, Applied Materials, 3111 Coronado Drive, Santa Clara, CA 95054.

†Systems Engineer, Conduction Heat Transfer Laboratory, Mechanical Engineering Department; currently Member of Technical Staff, Sandia National Laboratories, Livermore, CA 94551.

‡Thomas A. Dietz Professor, Conduction Heat Transfer Laboratory, Mechanical Engineering Department. Fellow AIAA.

Table 1 Theoretical models for effective thermal conductivity of graphite composites

Author	Expression for effective thermal conductivity	Comments
Rayleigh[6]	$k_e/k_m = 2V_f/\Big\{[(1+k_f/k_m)/(1-k_f/k_m)] + V_f - \big[(1-k_f/k_m)3V_f^4\big/(1+k_f/k_m)\pi^4\big](0.03235\pi^4)^2\Big\}$	Circular filament in a square lattice Transverse effective thermal conductivity Does not account for interfacial thermal resistance between fiber and matrix
Behrens[8]	$k_e = k_m\left[\dfrac{(k_f/k_m+1)+V_f(k_f/k_m-1)}{(k_f/k_m+1)-V_f(k_f/k_m-1)}\right]$	Transverse effective thermal conductivity Circular filament in a square lattice Does not account for fiber orientation or interfacial thermal resistance
Hashin[9]	$K_e^+ = k_f\left[1 + V_m\Big/\left(\dfrac{k_m}{k_f-k_m}+\dfrac{V_m}{3}\right)\right]$ $K_e^- = k_m\left[1 + V_f\Big/\left(\dfrac{k_m}{k_f-k_m}+\dfrac{V_m}{3}\right)\right]$	Bounded solution for transverse effective thermal conductivity Arbitrary phase geometry
Cheng and Vachon[10]	$k_e = k_m\Big/\left(1-\sqrt{3V_f/2}\right)$	Parabolic, random distribution of fibers Only accurate for $V_f < 66.7$
Batchelor and O'Brien[11]	$k_e = 4.0k_m \log_e(k_f/k_m)$	Random array of uniform spherical particles Accounts for point contact among particles Applicable for $k_f/k_m \gg 1$
Hashin[12]	$k_e^+ = k_f\dfrac{k_f v_f + k_m(1+V_m)}{k_f(1+V_m)+k_m V_f}, \qquad k_e^- = k_m\dfrac{k_m v_m + k_f(1+V_f)}{k_m(1+V_f)+k_f V_m}$	Fibers isotropic along their length only Lower bound equivalent to that of Behrens[8]
Nomura and Chou[13]	$k_e^+ = \dfrac{(V_m k_m + V_f k_f)^2 + k_m k_f}{(k_m+k_f)}, \qquad k_e^- = \dfrac{(k_m+k_f)k_m k_f}{(V_f k_m + V_m k_f)^2 + k_m k_f}$	Transverse effective thermal conductivity Fibers isotropic along their length only Fiber has ellipsoidal symmetry Simplified formula for an aligned long fiber composite
Chamis[14]	$k_e = \left(1-\sqrt{V_f}\right)k_m + \dfrac{k_m\sqrt{V_f}}{1-\sqrt{V_f}(1-k_m/k_f)}$	Long, continuous, circular fibers in square array Unidirectional fibers Transverse effective thermal conductivity
Hatta and Taya[15]	$k_e = k_m\left[1 + V_f\Big/\left(\dfrac{1-V_f}{3}+\dfrac{k_m}{k_f-k_m}\right)\right]$	Three-dimensional misoriented short fibers Fibers are not in contact Simplifies to Hashin's[9] lower bound
Caruso and Chamis[16]	$k_e = (1-\sqrt{V_f})k_m + \dfrac{k_m\sqrt{V_f}}{1-\sqrt{V_f}(1-V_m/V_f)}$	Transverse effective thermal conductivity Unidirectional continuous fibers Fibers arranged in a square cell
Mottram and Taylor[17]	$\dfrac{k_e}{k_m} = \left(\left(\left\{\sqrt{\left[\left(1-\dfrac{V_f}{1-V_p}\right)^2\left(\dfrac{k_f}{k_m}-1\right)^2+\dfrac{4k_f}{k_m}\right]} - \left(1-\dfrac{V_f}{1-V_p}\right)\left(\dfrac{k_f}{k_m}-1\right)\right\}^2\Big/4\right)(1-V_p)\left(\dfrac{X+1}{x}\right)\right.$ $x = 2$ for spheres $= 1$ for cylinders perpendicular to heat flow	Accounts for shape of discontinuous phase. Model does not account for interface resistance and spacing of the fibers.
Hasselman and Johnson[18]	$k_e = k_m\left\{\left[2V_f\left(\dfrac{k_f}{k_m}-\dfrac{k_f}{rh_i}-1\right)+\dfrac{k_f}{k_m}+2\dfrac{k_f}{rh_i}+2\right]\Big/\left[V_f\left(1-\dfrac{k_f}{k_m}+\dfrac{k_f}{rh_i}\right)+\dfrac{k_f}{k_m}+2\dfrac{k_f}{rh_i}+2\right]\right\}$	Randomly dispersed spherical inclusions with a coating Dilute fiber volume fractions No interaction between fiber and matrix

Lord Rayleigh.[6] When the fibers are assumed to be uniformly sized cylinders in a matrix with the fibers oriented perpendicular to the heat flow, Lord Rayleigh derived a solution for the effective transverse thermal conductivity for a square array of fibers of any volume fraction, as indicated in Table 1.

Hamilton and Crosser[7] developed an equation for the thermal conductivity of mixtures with particles of arbitrary shapes. In their formulation, Hamilton and Crosser provided a shape factor that accounted for the shape of the particles in the matrix. They found that when the ratio of the conductivities (k_f/k_m) of the two phases is above 1000, the effect of the shape factor is extremely important. The disadvantage of this method is that the shape factor has to be determined experimentally. For low fiber volume fractions ($V_f < 0.3$), the theory displayed good agreement with experimental results. Unfortunately, higher fiber volume fractions were not investigated.

Behrens[8] developed a model to predict the conductivity of composite materials by the method of long waves. In this method, plane waves are considered to propagate through the composite, and the associated damping coefficients are calculated and used to determine the effective thermal conductivity. For composites containing circular cross section fibers arranged in a square lattice, Behrens' model reduces to the equation indicated in Table 1. The model does not account for the interfacial thermal resistance and fiber dimensions.

In 1968, Hashin[9] developed the self-consistent scheme as a model to predict the thermal conductivity of composites. Exact values of the effective thermal conductivity depended on the phase geometry rather than only the fiber volume fraction. Therefore, without experimentation to determine the unknown phase geometry parameter, Hashin concluded that the only result possible for the self-consistent method to model the effective thermal conductivity composites with unknown geometries was to provide an upper and lower bound as indicated in Table 1.

Assuming a parabolic distribution of the fibers in the composite, Cheng and Vachon[10] determined the thermal conductivity of a two-phase solid mixture. The fibers were considered randomly dispersed particles inside the matrix. The parabolic distribution expression, which is dependent on the constituent phases was solved to obtain the expression indicated in Table 1. The equation is applicable only for a parabolic distribution of fibers in the composite and is accurate for fiber volume fractions less than 66.7%.

In 1977, Batchelor and O'Brien[11] developed an equation for the effective thermal conductivity of a granular material with a random array of uniform spherical particles with contact points. When an average number of contact points is used, the equation shown in Table 1 accounts for a close-packed bed of particles making point contact. Expanding on his previous model, Hashin[12] developed an expression for transverse thermal conductivity that accounted for the anisotropy in the composite fiber. In this study, a unidirectional fiber composite was considered with fibers isotropic along the length of the fiber. The lower bound of this model is equivalent to that developed by Behrens.[8]

Nomura and Chou[13] developed a tighter bounded solution for the transverse effective thermal conductivity of a unidirectional short fiber composite with transverse isotropy. After developing a solution for an aligned continuous fiber composite (Table 1), the authors compared their results with previous bounded methods and obtained a tighter and more accurately bound solution.

In 1984, Chamis[14] developed a unified set of simple equations to determine composite properties. Chamis assumed a square array of unit cells with circular fibers centered in a square. The author developed an equation (Table 1) to determine the transverse effective thermal conductivity of continuous, unidirectional fiber composites. Unfortunately, no comparisons were made with experimental results to validate this model.

Hatta and Taya[15] examined the transverse effective thermal conductivity of misoriented short fiber composites. Their theoretical analysis is based on the equivalent inclusion method for steady state heat conduction. Their model (Table 1) does not account for the interfacial thermal resistance, the dimensions of the fibers, and the possibility of utilizing transversely anisotropic fibers. Furthermore, the model assumes that the fibers are completely surrounded by the matrix; hence, the model is not valid for fiber volume fractions greater than 50%.

Extending the research performed by Chamis,[14] Caruso and Chamis[16] assessed the accuracy of the simplified micromechanics equations used to determine the thermal properties of unidirectional continuous fiber composites. The authors developed a finite element solution for the effective thermal conductivity for comparison with the micromechanics model as indicated in Table 1. For transverse thermal conductivity, the results of the micromechanical model and finite element method were in good agreement. Furthermore, the agreement improves as the fiber volume fraction decreases from 62.2 to 0%.

Mottram and Taylor[17] considered the effect of porosity of the material. Their model (Table 1) accounts for the shape of the discontinuous phase by introducing a shape factor X. The assumptions made are that the fibers are completely surrounded by the matrix, the fibers are parallel and untwisted, and the pores are assumed to be elongated in the direction of the fibers. The model does not account for the interfacial resistance between the fiber and the matrix, the spacing of the fibers, or the shape of the fibers.

Hasselman and Johnson[18] modified the original theory by Rayleigh[6] to derive an expression for the effective thermal conductivity of composites consisting of a continuous matrix phase with dilute concentrations of dispersions with spherical, cylindrical, and flat plate geometry. The expression accounts for the interfacial thermal resistance between the fiber and matrix phases, but is not applicable for transversely anisotropic fibers.

Based on this review, it appears that modeling the effective thermal conductivity of fiber composites should account for the geometrical arrangement of the fibers, the dimensions of the fibers, the fiber volume fraction, and thermal conductivity of the fiber and matrix. The model should also account for the interfacial thermal resistance between the fiber and the matrix and the possibility of transversely anisotropic fibers.

Experimental Investigations

Researchers have conducted experimental investigations to determine the effective thermal conductivity of fibrous composite materials. These studies have concerned themselves with materials used for very specific applications. These comparisons have been limited to studies that have utilized carbon or graphite fibers embedded in an organic matrix, a majority of which have been epoxies. In general, the data indicate that the effective thermal conductivity of these materials is strongly dependent on temperature between 75 and 200 K, beyond which the influence of temperature decreases.

Gille[19] determined the thermal conductivity of composites consisting of thornel fibers bonded with polaris epoxy resin. Both transverse and longitudinal direction thermal conductivity were determined over a temperature range of 31–309 K. Hertz et al.[20] investigated the effective thermal conductivity of a unidirectional panel consisting of high tensile strength (HTS) graphite fibers in a X-904 epoxy resin, as well as another panel of high modulus strength (HMS) graphite fibers in the same matrix. The laminates consisted of fibers orientated parallel and perpendicular to the heat flow. The temperature ranged from 50 to 420 K.

Pilling et al.[21] determined the thermal conductivity of a series of unidirectional and bidirectional composites consisting of an epoxy resin (DX210/$BF_3$400) reinforced with Morganite high modulus (HMS) and high strength (HTS) carbon fibers. The fiber volume fraction varied from 45.9 to 71.9%, and the maximum void content was 2.8%. Knibbs et al.[22] also determined the thermal conductivity of HMS and HTS fiber composites of an epoxy resin based on diglycidyl ether (MY750). Between the two fibers studied by Pilling et al.,[21] the HMS fiber samples had a higher thermal conductivity compared to HTS fibers for approximately the same fiber volume fraction. Further, with an increase in temperature from 80 to 270 K, the thermal conductivity in the longitudinal direction increased more than five times, while the thermal conductivity in the transverse direction increased by approximately 40%.

James et al.[23] determined the transverse and longitudinal effective thermal conductivity of a carbon fiber composite (GY70 fibers) with fiber volume fraction 50% in an epoxy resin. The authors employed a comparative technique by using standards of known thermal conductivity to measure the heat flow. The paper reports thermal conductivity values at room temperature of approximately 2 and 100 W/mK in the transverse and longitudinal directions, respectively. Furthermore, the thermal conductivity values are rather independent with respect to temperature.

Scott and Beck[24] used a transient technique to determine the transverse thermal conductivity of composite materials consisting of surface treated AS4 fibers (Hercules, Inc.) in a BADGE–mPDA Bisphenol-A-diglycidylether/metaphenylenediamine epoxy matrix. Different fiber orientations [0] and [30, −30, 60, 90] deg were investigated as a function of temperature ranging from 298 to 398 K. Their results indicated an increase in thermal conductivity with temperature between 25 and 145°C. Further, the thermal conductivity of the composites with an orientation of [0] deg were approximately 10% higher than the composites with [0, 30, −30, 60, 90]-deg fiber orientation. Ishikawa[25] also determined the thermal conductivity of carbon fibers in a BADGE epoxy by using an infrared technique. The results obtained are rather comparable to those obtained by Scott and Beck.[24]

Ibrahim[26] evaluated the thermal conductivity of two pitch-graphite (P-120 and P-130) fiber-reinforced polymer composites for use as heat sinks in high-density electronic packages. The thermal conductivity in the longitudinal and transverse directions was determined by laser flash and Kohlrausch methods over the temperature range 123–523 K. On one hand, the thermal conductivities of the unidirectional and 50/50 cross-plied epoxy in the longitudinal direction were approximately 412 and 253 W/mK, respectively. On the other hand, the thermal conductivities in the transverse direction were significantly lower (0.8–1.9 W/mK). The paper concludes that due to these very high thermal conductivity values in the planar direction, polymer composites may be used as heat sink materials.

Mirmira et al.[27] conducted an experimental investigation to determine the effective thermal conductivity and thermal contact conductance of carbon (AS-4 and IM-7) and glass (S and E glass) fiber-reinforced epoxies. Their results indicate a majority of the samples possessed effective thermal conductivities in the range of 0.4–0.8 W/mK and were rather independent of temperature. Further, the thermal contact conductance values for all of these materials were rather invariant with pressure. This was because the thickness of the samples did not change with pressure.

Experimental Program

To provide additional experimental data on the effective thermal conductivity and thermal contact conductance of discontinuous graphite fiber composites, under controlled conditions, an experimental program was undertaken. The following sections describe the materials selected, the test facility, experimental procedure, and the uncertainty associated with results.

Material Selection

The test samples consisted of graphite fiber composites with a cyanate ester matrix of nine different compositions. Table 2 indicates the composition and characteristics of the composite materials used. The average uncertainty in the fiber volume fraction was approximately 1%. Table 2 also indicates a few of the thermal and physical properties of these fibers, as reported by the fiber and composite manufacturers. The dimensions of the samples used to measure the effective thermal conductivity and thermal contact conductance in the transverse direction were 2.54 cm in diameter and 0.635 cm thick, whereas the longitudinal thermal conductivity samples were 2.54-cm squares of 0.635 cm in thickness.

Test Facility

The test facility consisted of a frame with sliding plates that supports two heat source/sink specimen holder assemblies, the test samples, a load cell, and pneumatic bellows, as shown in Fig. 1. An axial force was applied on the vertical column incorporating the test specimens by pressurizing the bellows with nitrogen. Uniform contact pressure over the contacting test sample interfaces was assured by the use of two hardened ceramic spheres which transferred the load from the frame to the source/sink-holder assemblies and in turn to the test interface. Further, a load cell and signal amplifier monitored the apparent interface pressure. A band heater was placed around the upper fluxmeter holder to provide the heat flux, while coolant (ethylene glycol) was circulated through the lower fluxmeter holder.

To avoid convection losses, the entire test facility was housed in a vacuum of 1×10^{-5} torr maintained by an oil diffusion pump backed by a two-stage rotary pump. Further, radiative losses from the fluxmeters and samples were reduced by placing a segmented radiation shield around the vertical test column.

Table 2 Composition of graphite fiber organic matrix samples and selected properties of fibers utilized

Fiber type (sample no.)	Fiber volume, %	Fiber diameter, μm	Fiber length	Fiber thermal conductivity[a] (parallel to axis), W/mK	Fiber coefficient of thermal expansion,[b] ppm/°C
(1)	0	—	—	—	—
DKE X[c]					
(2)	55	10	6 mm	617	−1.36
(3)	65	10	6 mm	617	−1.36
(4)	75	10	6 mm	617	−1.36
DKA X[c]					
(5)	55	10	200 μm	900	−1.45
(6)	65	10	200 μm	900	−1.45
(7)	75	10	200 μm	900	−1.45
K22XX[d]					
(8)	55	10	3–5 μm	600	−1.76
(9)	65	10	3–5 μm	600	−1.76
(10)	75	10	3–5 μm	600	−1.76

[a]Provided by the manufacturer. [b]Samples manufactured by Bryte Technologies. [c]Amoco fibers. [d]Mitsubishi fiber.

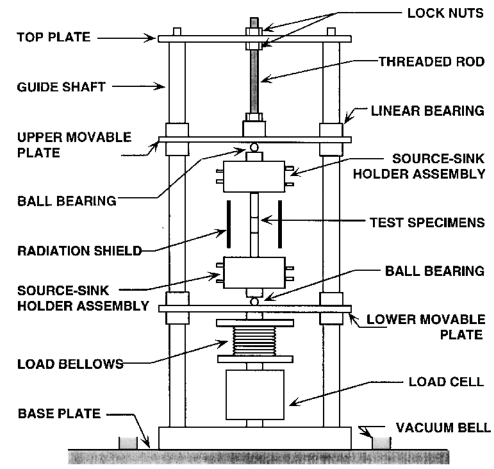

Fig. 1 Schematic of test facility.

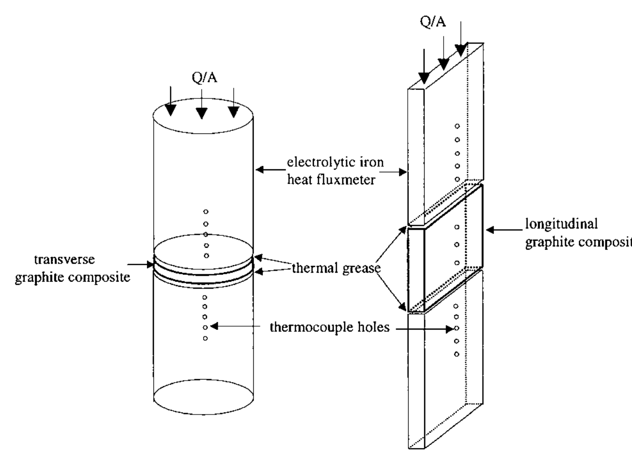

Fig. 2 Schematic representation of vertical test column to determine the effective thermal conductivity.

Experimental Procedure

The effective thermal conductivity in the transverse and longitudinal directions were determined by using upper and lower heat fluxmeters of electrolytic iron. The thermal contact conductance was determined by using aluminum 6061 heat fluxmeters. These fluxmeters were 2.54 cm in diameter, and the lengths were 10.16 cm. In the case of determining the thermal conductivity in the longitudinal direction, fluxmeters of rectangular cross section (0.635×2.54 cm) were used. Figure 2 indicates the vertical test column. The fluxmeters were instrumented with 30-gauge, Teflon® sheath, special limit of error type K-Chromel/Alumel thermocouples to enable the calculation of the temperature gradient, the temperature difference across the composite, and the heat flux normal to the interface.

The effective thermal conductivity in the transverse and longitudinal directions was determined over a mean composite temperature range of 20–200°C. To minimize the contact resistance at the sample interfaces, the effective thermal conductivity tests were conducted at a mean interface pressure of 2067 kPa, and thermal grease was applied between the sample and fluxmeter surfaces.

The thermal contact conductance between the graphite fiber composite and the aluminum 6061 surfaces was determined at pressures ranging from 172 to 1725 kPa and at interface temperatures of 20 and 60°C. Furthermore, to determine the effective thermal conductivity no thermal grease was applied at the interfaces between the sample and the heat fluxmeters. Last, due to the small thickness of the transverse thermal conductivity samples, they were not instrumented with thermocouples. However, the longitudinal specimens were instrumented with thermocouples spaced 0.635 cm apart and 0.0635 cm from the edges.

Uncertainty Analysis

The Kline and McClintock[28] method was employed to determine the overall relative uncertainty in the effective thermal conductivity and thermal contact conductance of the composites.

The overall uncertainty in the reported values of effective thermal conductivity and contact conductance of the composite materials comprises various parameters. These parameters include the uncertainty in thermal conductivity of the base material (electrolytic iron), the heat flux, the temperature gradients within the iron fluxmeters, the location tolerances for the thermocouples, the temperature readings, and the temperature difference across the interface. The average overall uncertainty of the effective thermal conductivity of each sample was approximately ±3.2%.

The average overall uncertainty in the thermal contact conductance for each sample was the accumulation of the uncertainties mentioned for the effective thermal conductivity case with the addition of uncertainties due to the temperature difference across the junction and the dimensional tolerance for the cross-sectional area of the sample and has been determined as ±5.3%.

Results and Discussion

The effective thermal conductivity of the graphite fiber organic matrix composites in the transverse and longitudinal directions was determined over a temperature range of 20–200°C. The thermal contact conductance was measured over an apparent interface pressure range of 172–1772 kPa and at mean interface temperatures of 20 and 60°C.

Figure 3 indicates the effective thermal conductivity for the transverse and longitudinal directions of the nine different graphite fiber samples and the pure organic matrix material. It is apparent that the effective thermal conductivity is greater in the longitudinal direction than in the transverse direction. With the addition of fibers to the cyanate ester matrix, the effective thermal conductivity increases. However, with an increase in fiber volume fraction beyond 65%, a slight decrease in the effective thermal conductivity was observed for DKE composites. This is contrary to the expected because the fiber possesses a thermal conductivity more than three orders of magnitude of the matrix. A possible explanation for this occurrence is that with an increased number of discontinuous fibers, the total interfacial resistance between the fibers and the matrix increases, thus reducing the influence of the fiber thermal conductivity. The magnitude of the interfacial resistance may be more pronounced in the present investigation due to lack of a wetting agent used in fabricating the samples.

The longitudinal effective thermal conductivity is also shown in Fig. 3 and indicates a slight dependence on temperature, with a decrease in thermal conductivity with increasing temperature. This is especially true at temperatures beyond 127°C. This decrease may be because the thermal conductivity of the graphite fibers decreases with an increase in temperature. Among the three fibers evaluated, composites containing the DKA X fiber had the highest effective thermal conductivity, as well as the greatest temperature dependence. This high value of thermal conductivity was anticipated because the thermal conductivity of the fiber was the highest. In addition, DKE X composites had a higher thermal conductivity than K22XX fiber composites.

A comparison of previously published experimental results with those obtained by the present investigation for 65% volume fraction

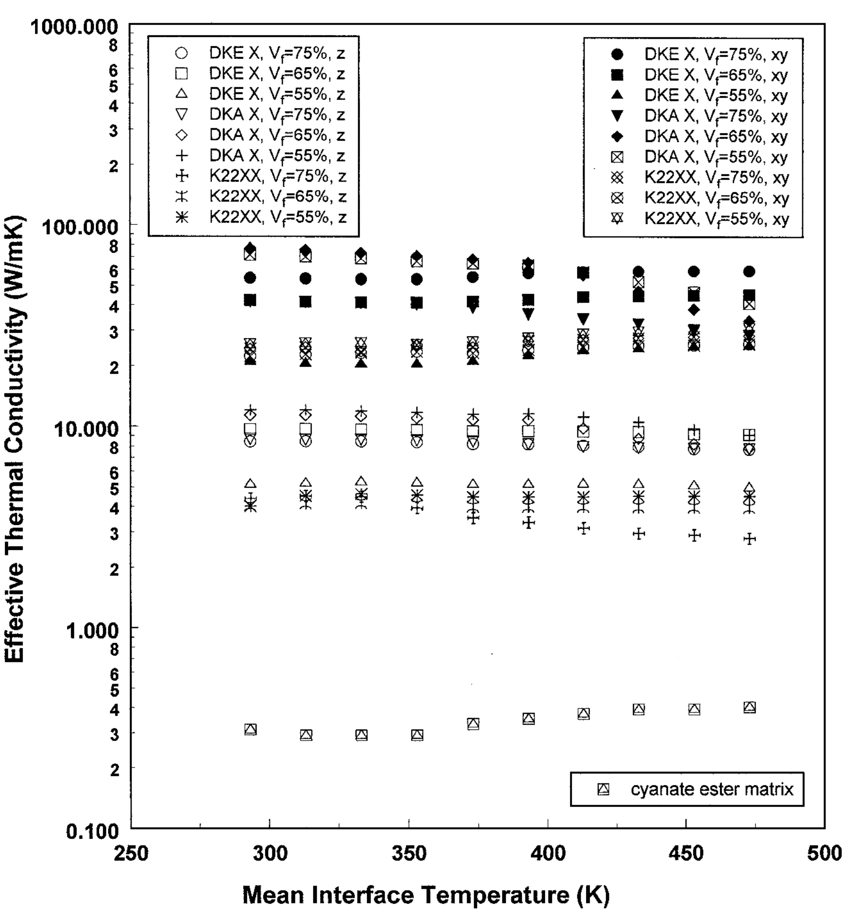

Fig. 3 Transverse and longitudinal thermal conductivity of graphite composite samples as a function of temperature.

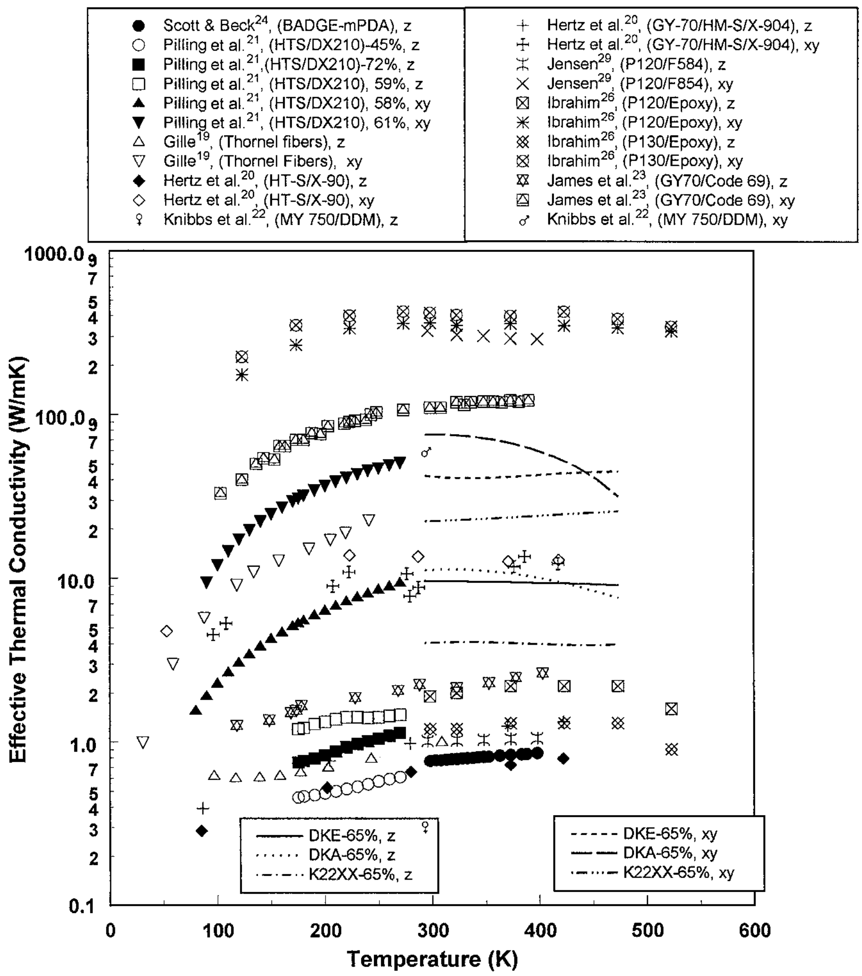

Fig. 4 Comparison of experimental results obtained by previous experimental studies with present study for DKE X fibrous composites.

composites are shown in Fig. 4. In the transverse direction, the results obtained by Gille[19] for thornel fiber composites are lower than the results obtained by the present study, but in the longitudinal direction, the results are rather comparable. The effective thermal conductivity data for an epoxy resin reinforced with HTS and HMS carbon fibers as determined by Hertz et al.[20] are also shown in Fig. 4. Their results are significantly lower in both the transverse and longitudinal directions.

The results by Pilling et al.[21] are also lower than those obtained by the present investigation and the results obtained by Knibbs et al.[22] are slightly higher than those obtained by Pilling et al.,[21] although an extrapolation of the latter's results indicates that the results have similar magnitudes.

Figure 4 also compares the effective thermal conductivity results of the present study with those conducted by Scott and Beck[24] and Ibrahim.[26] On one hand, in the transverse direction, the present study results are greater than the other mentioned investigations. On the other hand, the effective thermal conductivity results in the longitudinal direction of both Scott and Beck[24] and Ibrahim[26] exceed our values. The values obtained by Ibrahim exceed that of copper and aluminum heat sink materials. Also shown in Fig. 4 are results obtained by Jensen.[29]

Figure 5 compares the experimental data for effective thermal conductivity obtained in the current study with the previously published theoretical models. As a representative case, samples consisting of 65% volume fraction DKE X fibers were selected for comparison. As indicated, the data obtained by the present investigation are within the bounds proposed by Hashin[9,12] and Nomura and Chou.[13] Note that the theory developed by Batchelor and O'Brien,[11] based on random particles, predicts the transverse thermal conductivity rather closely, whereas Cheng and Vachon's[10] theoretical model comes close to predicting the longitudinal results. Assuming negligible thermal resistance, transversely isotropic fibers, and no porosity in the composite, Fig. 5 makes a comparison with the theoretical studies of Mottram and Taylor[17] and Hasselman and Johnson.[18] Figure 5 also indicates that the other unbounded theories[14–16] do not come close to predicting the effective transverse and longitudinal thermal conductivity.

Figure 6 shows the transverse thermal contact conductance of the graphite composites as a function of apparent interface pressure at 20 and 60°C. With an increase in pressure from 172 to 1720 kPa, the transverse thermal contact conductance increased. A possible explanation for this is that with the application of pressure, the interfacial thermal resistance between the fiber and the matrix decreases and facilitates the easier transport of energy through the composite. Furthermore, the cyanate ester matrix tends to deform at higher pressures resulting in a reduction in thickness of the sample, thus further contributing to the increase in conductance values. Over the temperature range selected, temperature had little influence on the conductance data. Among the samples consisting of the three different fibers, the K22XX fibers possessed the lowest thermal conductivity and, hence, the lowest thermal contact conductance.

Figure 7 indicates the nondimensional transverse thermal contact conductance of the graphite composites as a function of nondimensional apparent interface pressure. The thermal contact conductance was nondimensionalized by the thickness of the sample and the harmonic mean thermal conductivity of the fiber and the matrix, whereas the applied pressure was nondimensionalized by the harmonic mean Vickers microhardness of the fiber and the matrix. The resulting equation is of the following form:

$$h = 28.016(k_h/LV_f)(P/H_v)^{0.211}$$

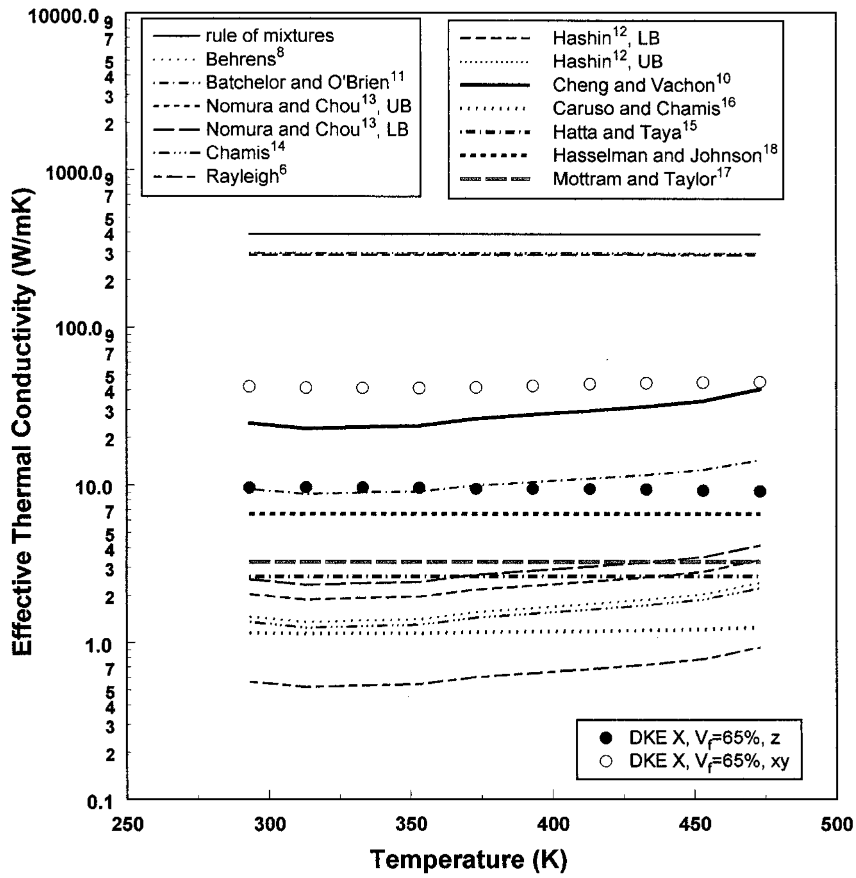

Fig. 5 Comparison of experimental results obtained by present investigation with previously developed theoretical models for DKE X fiber samples of 65% volume fraction.

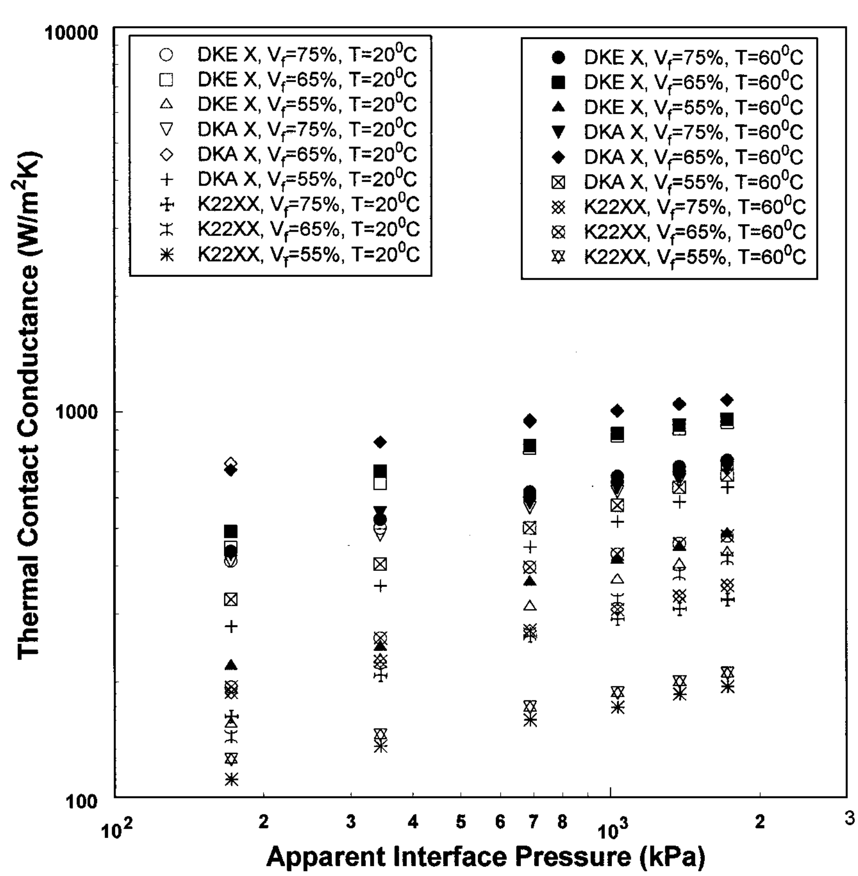

Fig. 6 Transverse thermal conductance of graphite composites ($t = 0.635$ cm) as a function of apparent interface pressure at 20 and 60°C.

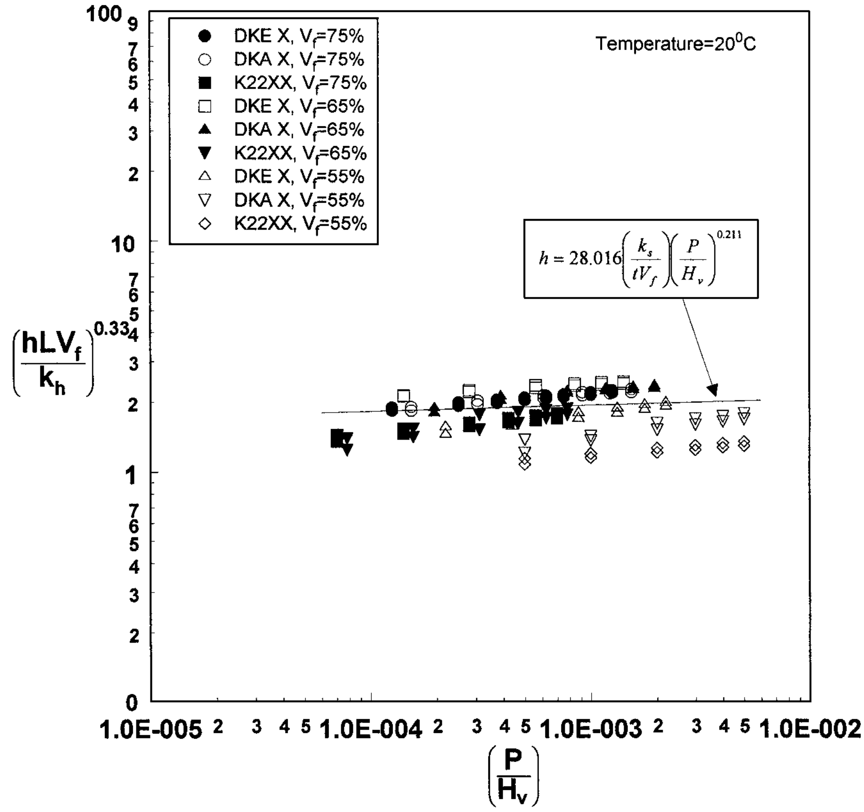

Fig. 7 Nondimensional thermal contact conductance as function of nondimensional apparent interface pressure.

It is apparent that the harmonic mean thermal conductivity, the thickness of the sample, and the fiber volume fraction play an important role. On the other hand, the apparent interface pressure does not seem to influence the conductance significantly. The developed correlation may be considered as a preliminary step toward the prediction of the thermal contact conductance because it does not account for the surface characteristics of the contacting surfaces.

Conclusions

The effective thermal conductivity in the transverse and longitudinal directions as well as the thermal contact conductance were determined over a range of temperatures and pressures. On one hand, the transverse effective thermal conductivity of the composites was highest for fiber volume fractions of 65%, above which the increased interfacial thermal resistance between the fiber and matrix negated any benefit due to greater fiber volume. On the other hand, the longitudinal effective thermal conductivity increased for higher fiber volume fractions. The longitudinal thermal conductivity was approximately one order of magnitude greater than the transverse. Furthermore, the effective thermal conductivity of the composites did not vary significantly over the selected temperature range. The developed equation relating the dimensionless thermal contact conductance and pressure indicates that the harmonic mean thermal conductivity, fiber volume fraction, and thickness play an important role.

Considering the importance of the interfacial thermal resistance between the fiber and the matrix, it is recommended that a fundamental experiment be conducted (ideally with known number of fibers) to quantify this value as a function of material properties. It is also recommended that the effect of cryogenic temperatures on the thermal conductivity be examined and a larger range of fiber volume fractions be tested. Further, it is apparent that the present models do not accurately predict the thermal conductivity of graphite composites. It would be beneficial to develop a model that accounts for the various influencing parameters, including the interfacial thermal resistance between the fibers and the matrix. Electron microscopy studies would reveal the nature of bonding between the fibers and the matrix, as well as the presence of voids.

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