JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 10, No. 2, April–June 1996

Thermal Contact Conductance of Selected Polymeric Materials

E. E. Marotta[*] and L. S. Fletcher[†]
Texas A&M University, College Station, Texas 77843-3123

The thermal conductivity and thermal contact conductance of several thermoplastic and thermosetting polymers have been studied over a range of interface pressures and temperatures. The temperature range for the thermal conductivity study varied from 10 to 100°C (50 to 212°F). The study showed that ultra high molecular weight (UHMW) polyethylene had the highest thermal conductivity through the range of temperatures and also had the highest thermal conductance values at an interface temperature of 20°C (68°F). The thermal contact conductance study was conducted over a pressure range of 510–2760 kPa (75–400 psi) and a temperature range of 20–40°C (68–104°F). The conductance values for UHMW polyethylene ranged from 1095.3 to 1659.4 W/m² K (192.9 to 292.2 Btu/h ft² °F), whereas the thermal conductivity remained constant at 0.45 W/m K (0.26 Btu/h ft °F) throughout the range of temperatures. Polycarbonate and Teflon® had the next highest thermal conductance values at the same interface temperature. The thermal contact conductance values for polyethylene, Teflon, and phenolic polymers were measured at an elevated temperature of 40°C (104°F). The thermal contact conductance values for both Teflon and phenolic increased with increasing temperature, whereas the values for UHMW polyethylene decreased due to their unique chain structure at the higher temperature. The polymers were chosen because of their widespread engineering interest applications.

Nomenclature

A_a = apparent area
A_r = real area
E = modulus of elasticity
E' = $(E_1E_2)/[E_2(1 - \nu_1^2) + E_1(1 - \nu_2^2)]$
F = flatness
H_c = hardness
H_e = elastic hardness $(E'/\sqrt{2}) \times m$
h_c = thermal contact conductance
h_e = dimension elastic conductance
h_p = dimension plastic conductance
k = thermal conductivity
m = asperity slope
P_d = profile slope
P/H_c = dimensionless plastic contact pressure
P/H_e = dimensionless elastic contact pressure
P_r = profile roughness
R = roughness
W = waviness

Subscripts

a = average
p = polymer
q = root mean square
s = roughness
subst = substrate

Introduction

THE reliability and temperature control of power-generating systems, power-control systems, instrument modules, and electronic systems are directly related to the actual operating temperature of each individual device. Thus, interstitial materials at component interfaces must possess thermal conductivities, structural integrity, noncontaminating properties, and ease-of-use to achieve maintainability of their optimum design specifications. Thermal management, therefore, can be a controlling factor in the design optimization within microelectronic components, their subsystems, and systems. One factor that can contribute to the removal of heat from microelectronic devices is an improved thermal contact conductance at component interfaces.

Several studies have been conducted on heat transfer at the interface of two contacting materials. These include studies of two similar contacting metallic surfaces[1–3] and dissimilar metallic surfaces.[4] Also, several studies have been conducted to determine the effect of interstitial materials for enhancement of the thermal contact conductance of both similar and dissimilar metallic surfaces.[5,6] The choice of interstitial material for a particular application is governed by such factors as contact pressure and temperature, environmental conditions, and the degree of enhancement that is desired for flow of heat across the interface.

These interstitial materials include thermal greases, which have shown significant improvement in thermal contact conductance[7] and can also be easily applied within the contacting interface. However, care must be taken in the selection of the molecular composition of the grease to prevent both leakage and corrosion occurring at the joint. Vapor-deposited coatings have also been shown to increase the thermal contact conductance[8–10] when compared to uncoated interfaces. However, vapor-deposited coatings are expensive to apply and can also be easily removed due to the low interfacial bonding between the metallic surface and coating.

Interstitial metallic foils are effective in increasing the thermal contact conductance. Numerous studies have been conducted[11–13] that explored several metallic foils between similar contacting metallic surfaces. The studies concluded that

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Presented as Paper 95-0421 at the AIAA 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 9–12, 1995; received March 27, 1995; revision received Sept. 29, 1995; accepted for publication Oct. 2, 1995.

[*] Graduate Research Assistant, Mechanical Engineering Department. Student Member AIAA.

[†] Thomas A. Dietz Professor, Mechanical Engineering Department. Fellow AIAA.

the ratio of the foil thermal conductivity to the foil hardness was the significant parameter that determined the degree of enhancement or isolation of the thermal contact conductance. The studies also concluded that the softer materials deformed to fill the voids and spaces between the contacting surfaces.

In a more recent study, Lambert and Fletcher[14] investigated the use of electroplated and flame-sprayed silver coatings deposited on aluminum A356-T61 in contact with anodized aluminum 6101-T61 and electroless nickel-plated copper C11000-H03 metallic materials. One of the conclusions of the study was that the electroplated silver coatings are far superior to vapor-deposited gold or flame-sprayed silver coatings in improving the conductance of junctions involving anodized aluminum 6101-T6. The electroplated silver coatings also performed better than the vapor-deposited silver coatings for enhancing the conductance of junctions employing nickel-plated copper.

Marotta et al.[15] studied the effect of using diamond-like carbon (DLC) coatings on the thermal contact conductance on aluminum 6101-T6 and copper C11000-H03 materials in contact with uncoated aluminum A356-T61. To reduce cracking of the hard diamond-like carbon layer under possibly large bending strains, a rigidizing layer of silicon nitride was deposited by sputtering prior to ion beam diamond-like carbon deposition. The conductance ratios of DLC to uncoated aluminum 6101-T6 and anodized aluminum 6101-T6 ranged from 0.07 to 0.09 and 6.5 to 10.0, respectively. The conductance ratios of DLC to uncoated copper C11000-H03 and nickel-plated copper C11000-H03 ranged from 0.05 to 0.25 and 0.30 to 0.70, respectively. No improvement in the heat transfer across the junction occurred when diamond-like carbon-coated surfaces were placed in contact with uncoated or nickel-plated junctions, however, an improvement did occur when compared to the anodized case.

Lambert et al.[16] conducted an investigation to determine the thermal contact conductance of anodized coatings synthesized at different bath temperatures and different electrolyte solutions. Their results indicated that a low-temperature sulfuric acid electrolyte bath provided an anodized coating with the highest thermal contact conductance values. The authors concluded that the lower bath temperature lowers the activity of the electrolyte as the film grows, which results in an anodized coating that has higher density, higher thermal conductivity, and higher thermal contact conductance, even though the microhardness is higher.

Marotta and Fletcher[17] studied the effect of using several different high-temperature refractory ceramic coatings on the thermal contact conductance deposited on aluminum 6101-T6 metallic surfaces in contact with uncoated aluminum A356-T61. All other previous studies involved metallic coatings, anodized coatings, or bulk ceramic materials between electronic components. Ceramic coatings of titanium nitride (TiN), silicon nitride (S3N4), boron nitride (BN), and aluminum nitride (AlN), and one oxide coating of beryllium oxide (BeO) were deposited by physical vapor deposition (PVD) onto aluminum 6101-T6 and then placed in contact with uncoated aluminum A356-T61. A comparison of the five coating types to a bare aluminum 6101-T6 surface in contact with bare aluminum A356-T61 indicated that the TiN coatings have the highest thermal contact conductance values for the range of parameters tested.

Ochterbeck et al.[18] measured the thermal contact conductance for several new polymeric film materials that were embedded with several different compounds that included paraffin, commercial grade diamonds, and metallic foils. The most significant improvement in thermal contact conductance was obtained with the use of Kapton type MT polyimide film coated on both sides with a paraffin-based thermal compound. Both material types resulted in thermal contact conductance values an order of magnitude higher than the bare junction. The lowest thermal contact conductance resulted from the Kapton type HN polyimide film without any coatings or embedded compounds. The polyimide film decreased the conductance by an order of magnitude below the bare junction. The polyimide films embedded with commercial grade diamonds also resulted in thermal contact conductance values lower than the bare junction, however, the measured values were higher than the uncoated polyimide film conductance values.

Scialdone et al.[19] conducted an experimental investigation to measure the thermal contact conductance of two polymeric materials containing different thermal conductive compounds between two different thermal plate assemblies. The first thermal assembly configuration consisted of two 1.27-cm (0.5-in.) plates made of aluminum 6061 and a copper alloy, whereas the other thermal assembly consisted of two anodized aluminum 7075 plates to simulate a spacecraft modular power system. The two interstitial materials tested were Cho-Therm 1671, a silicone-reinforced fiberglass containing boron nitride, and McGhan Nusil Cv-2946, which is a two-part thermal conductive RTV® silicone with boron nitride also as a filler material. At an optimum clamping pressure of 1.39 MPa (200 psi), the maximum thermal conductance for Cho-Therm 1671 was measured to be 6664.9 W/m^2 K (4.3 $W/in.^2$ °C) in air with input power fluxes varied up to 10,849.9 W/m^2 (7 $W/in.^2$). The maximum thermal conductance of the McGhan CV-2946 polymeric material was measured to be 7749.9 W/m^2 K (5 W/ $in.^2$ °C)in air with a material thickness of 0.00063 m (0.025 in.) and an average clamping pressure of 2.41 MPa (350 psi). The thermal conductance for both polymeric materials decreases substantially when measured in a vacuum environment.

To date, very little published data regarding the thermal contact resistance or conductance between commercially available polymers and metallic surfaces exist. Any model simulation for electronic component cooling rates or extrusion characteristics for a thermoplastic part must take into account the thermal contact resistance at the polymer/metal interface. Thus, it is clear that the thermal contact resistance or conductance at the gap or interface will effect the cooling rate and either increase or decrease the cooling times of an injection-molded part dependent on the polymer's material properties.

Based on this literature review, there do not appear to be any in-depth studies of commercially available polymeric materials for thermal contact resistance or conductance over a suitable range of interface pressures and interface temperatures. As a consequence, researchers must estimate these results for their modeling packages for greater accuracy of cooling times. Also, a comparison of thermal contact resistance or conductance values for polymeric materials to any existing model (which have been developed for metallic surfaces), has not been made. This study experimentally determines the thermal conductivities and thermal contact conductance for several polymers over a range of interface temperatures and pressures that can be used for model simulation of cooling rates of electronic components or injection-molded parts. Accurate cooling rates and times will result in greater accuracy of the molded part surface temperature distribution and greater control of part shrinkage, and as a result, lower manufacturing cost due to lower defect rates. This study also examines the appropriateness of the use of two existing models developed for metallic surfaces for the prediction of thermal contact conductance of polymer/metallic junctions or whether a new model correlation based on new dimensionless parameters must be developed to accommodate the new data.

The polymer materials have been chosen based on commercial importance and current engineering applications. Polyethylene is commercially used for packing films and wire insulation; polyvinyl chloride (PVC) is made into automobile roofs, pipes, valves, and fittings; polypropylene is incorporated into military hardware and communication equipment; Teflon® is used as a seal, valve, nonstick coating, and within electronic equipment. Acrylonitrile–butadiene–

Table 1 Thermal conductivity, thermal contact conductance, and surface metrological data for test specimen

Sample surface[a]	Interface temperature, °C	Specimen thickness, mm	Pressure range, kPa	k_p/k_{subst}, W/mK	h, W/m^2 K	R_a, μm	R_q, μm	W_a, μm	W_q, μm	F, μm	m_q, rad
ABS	20	12.70, 6.35 3.17, 1.65	510–2760	0.18/208	140.8–188.4	0.70	0.90	48.10	55.90	195.80	0.135
Delrin	20	12.70, 6.35 3.17, 1.65	510–2760	0.38/208	279.9–414.7	1.12	1.40	1.61	1.96	20.55	0.148
Teflon	20, 40	12.70, 6.35 12.70, 6.35	510–2760	0.25/208	372.6–1230.4	1.10	1.50	12.90	16.10	72.80	0.176
Nylon 6,6	20	12.70, 6.35 3.17, 1.65	510–2760	0.31/208	366.5–447.4	1.00	1.20	2.10	2.50	18.80	0.221
LE phenolic	20, 40	12.70, 6.35 3.17, 1.65	510–2760	0.65/208	260.1–603.2	0.95	1.18	5.46	6.26	25.90	0.127
Polycarbonate	20	12.70, 6.35 3.17, 1.65	510–2760	0.22/208	410.4–938.6	0.62	0.78	5.58	6.51	27.85	0.126
UHMW polyethylene	20, 40	12.70, 6.35 3.17, 1.65	510–2760	0.45/208	684.5–1659.4	1.50	1.90	8.90	11.40	67.00	0.216
Polypropylene	20	12.70, 6.35 3.17, 1.65	510–2760	0.21/208	276.7–324.0	1.04	1.31	5.57	6.4	28.95	0.174
PVC	20	12.70, 6.35 3.17, 1.65	510–2760	0.17/208	306.7–408.3	0.40	0.50	1.20	1.50	12.20	0.134

[a] Prime base material = aluminum 6101-T6.

styrene (ABS) has commercial use for electronic housings; nylon within electrical and electronic equipment; delrin to replace metal in mechanical and structural applications; polycarbonate for machine parts and propellers and phenolic is incorporated in all electrical equipment.

Experimental Program

To provide more information on polymeric materials, an experimental investigation was conducted in a manner similar to previously reported investigations.[14–16] The facility, polymer material selections, and procedure are described in this section. Material characteristics for the experimental program are shown in Table 1.

The experimental test facility incorporated a vertical column consisting of a frame with sliding plates for support of two combination heat source/sink specimen holder assemblies, the test samples, a load cell, and pneumatic bellows. The axial force on the test column was applied by pressurizing the bellows and the contact load was monitored by a BLH® load cell and signal amplifier. Uniform contact pressure over the test interfaces was assured by the use of two hardened stainless steel balls that transfer load from the frame to the source–sink–holder assemblies and, in turn, the specimens. Flexible neoprene hoses were used to supply coolant to the holder assemblies in order to essentially eliminate lateral loads that would skew the pressure distribution over the interfaces.

The experimental facility was housed in a vacuum environment at a pressure of 1.4×10^{-1} Pa (1×10^{-5} torr), which was maintained by a Varian VHS-6 oil diffusion pump backed by an Alcatel 2300 two-stage rotary pump. The vacuum pressure was monitored by thermocouple and filament gauges connected to a Perkin Elmer Monitor 300 indicator. Figure 1 shows a schematic of the experimental facility.

The vertical test column was composed of an aluminum 6101-T6 fluxmeter, a polymeric material sample, and another aluminum 6101-T6 fluxmeter. The test specimens were 2.54-cm- (1.00-in.-) diam polymeric materials with three different thicknesses. The aluminum 6101-T6 fluxmeters and polymer specimens were instrumented with 30-gauge, Teflon/Teflon sheath, "special limit of error" Type K Chromel/Alumel thermocouples to enable the calculation of the temperature gradient, the temperature variation across the junction, and the heat flux normal to the interface. Each polymer specimen had one thermocouple located at its center that was evenly spaced from the surface edges. Both aluminum 6101-T6 fluxmeters had five thermocouples that are located at 0.00635-m (0.250-in.) intervals. The single thermocouple was utilized to read the polymer material's bulk temperature during thermal conductivity measurements.

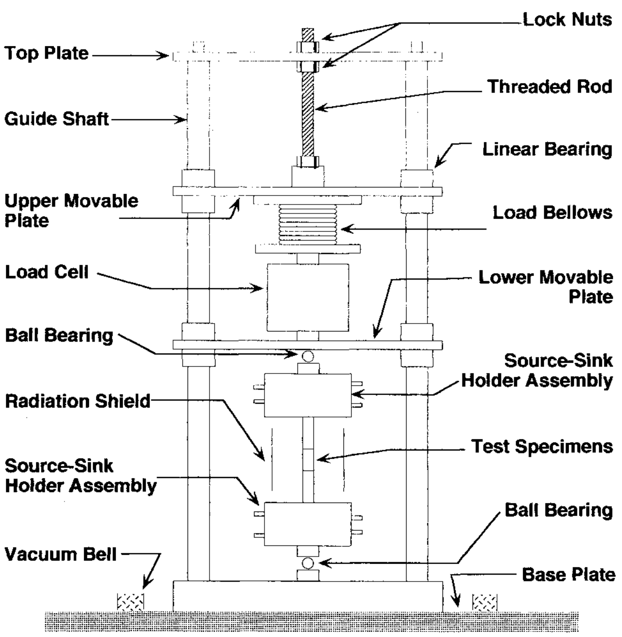

Fig. 1 Experimental apparatus.

The polymeric specimens were machined from a 2.54-cm (1.0-in.) cylindrical rod to specimen thicknesses of 0.317, 0.635, and 1.270 cm (0.125, 0.250, and 0.500 in.) from which the thermal conductivity values were measured. The polymeric materials used for this experimental study are provided in Table 1. The polymeric materials encompass both the thermoplastic and thermosetting polymer materials from which many industrial applications are derived.

The surface characteristics of the aluminum 6101-T6 fluxmeters and polymer materials were measured with a Surfanalyzer 5000/400 manufactured by Federal Products Corporation. A complete surface characterization was conducted, including rms surface roughness, average and rms waviness, and the overall flatness deviation, all of which are also provided in Table 1.

Experimental Procedure

For experimental determination of thermal conductivity, successive tests were conducted on specimens of three different lengths at several different temperatures for validation purposes. The polymer specimens were inserted into the test facility and carefully aligned. An axial force was then applied to the heat fluxmeters to ensure that the surfaces remained in contact and aligned during the evacuation of the chamber. The pressure and temperature were automatically controlled by a personal computer via an IEEE-488 bus and a feedback loop through a Hewlett–Packard datalogger. The temperature gradients and thermal conductivities of the heat fluxmeters were used to determine the heat fluxes in both the upper and lower fluxmeters and through the polymeric specimen. The temperature change across the polymer–metal interface was determined by extrapolating the thermal gradient in the heat fluxmeters to the junction interface. To minimize contact resistance between the polymeric specimens and the two contacting interfaces, Dow Corning 340 silicone heat sink compound was employed. In addition, to further reduce the influence of contact resistance an interface pressure of 200 psi (1378.6 kPa) was applied. To also minimize both convective and radiative losses the entire vertical test column was placed within a glass bell jar that maintained a vacuum of 1×10^{-5} torr and each polymeric test specimen was surrounded with an aluminum shield.

The polymeric materials used for the measurement of thermal contact conductance had a thickness of 0.1524 cm (0.065 in.) and were aligned between the aluminum 6101-T6 fluxmeters. Because of the small thickness of the samples used to measure the thermal contact conductance at the polymer/aluminum 6101-T6 interface, the specimens could not be instrumented with a thermocouple. The temperature difference across the specimen was calculated from the average heat flux through the two aluminum fluxmeters, the calculated surface temperatures of the upper aluminum 6101-T6/polymer interface (these were assumed to be equal since Dow Corning 340 heat sink compound was employed), the measured thermal conductivity of the polymer specimen, and the measured polymer specimen thickness. Once the temperature drop across the polymer specimen was determined, the temperature difference at the polymer/aluminum 6101-T6 interface was easily calculated. The thermal contact conductance at the polymer/aluminum 6101-T6 was then computed from the interface temperature drop and the average heat flux through the two aluminum 6101-T6 fluxmeters. No prior loading of the polymeric/aluminum surfaces was conducted for this investigation.

The reported contact conductance data are for the case of the heat flux passing from the polymer material to bare aluminum 6101-T6 fluxmeter. The experimental investigation was conducted at interface contact pressures of 517–2760 kPa (75–400 psi) and mean interface temperatures ranging from 15 to 60°C (59 to 140°F). The experimental results include the thermal conductivity and thermal contact conductance for several polymer materials in contact with aluminum 6061-T6.

Uncertainty Analysis

The uncertainties in the various quantities that are used in calculating thermal contact conductance can be combined to determine the overall relative uncertainty in the reported thermal conductivity and thermal contact conductance data. The techniques described within Kline and McCintock[20] have been employed to calculate the overall relative uncertainty for thermal conductivity and thermal contact conductance.

The uncertainty in the thermal conductivity and contact conductance consists of the uncertainty in the thermal conductivity of the base materials (aluminum 6101-T6 fluxmeters and polymer specimens), the temperature gradients within the two aluminum 6101-T6 fluxmeters, the thermocouple location tolerance, and the temperature difference across the junctions.

The total average overall uncertainty of the thermal conductivities of each polymer is 11.7%, which is comprised of the accumulation of the uncertainty in the thermal conductivity of the National Institute of Science and Technology (NIST) iron fluxmeters (1.5%), the uncertainty in the temperature reading of the special limit error K-type thermocouple (i.e., the maximum difference between the reading and true temperature is the greater of 1.1 K or 0.4% above 0°C), thermal temperature gradients within the two NIST iron fluxmeters (5.0%), and the location tolerance of the thermocouple holes drilled within the NIST iron fluxmeters and polymer specimens (the maximum variability in the location of a given thermocouple from a given nominal position is 4.8% for the smallest polymer thickness).

The total average uncertainty in thermal contact conductance values for each polymer is 16.7%. Again, the average overall uncertainty in the thermal contact conductance for each polymer was the accumulation of the uncertainties mentioned previously, but with the added uncertainty due to the temperature drop at the polymer/aluminum 6101-T6 interface. This additional uncertainty for the temperature difference at the interface had a maximum magnitude of 5.0%.

Results and Discussion

Thermal contact conductance and thermal conductivity results were obtained for several polymer materials over a range of interface pressures of 517–2760 kPa (75–400 psi) and interface temperatures between 10–80°C (50–176°F), to encompass the range of pressures and temperatures generally experienced in electronic systems. The thermal conductivity and thermal contact conductance data are presented as a function of mean interface pressure and temperature. The data obtained in this investigation will be useful in the thermal analysis of polymer materials for electronic systems and extrusion machinery.

Thermal Conductivity

The thermal conductivity was determined as a function of mean bulk temperature for three different thicknesses of linen impregnated (LE) phenolic polymer as shown in Fig. 2. The thermal conductivity shows very little variation above 30°C (86°F) where the data converges to single value. The variation in thermal conductivity below 30°C (86°F) may be attributed to the contact resistance at the two interfaces even though thermal grease was applied, while at higher temperatures this resistance is negligible due to the higher heat fluxes and higher temperatures. Phenolics are thermosetting polymers that have excellent thermal stability up to 150°C (300°F). They may be compounded with a large number of fillers and resins that affect their thermal properties. Figure 2 shows the comparison between pure phenolic polymer with LE phenolic that has an impregnated linen fabric. A factor of 3 increase in thermal conductivity can be observed between the two polymer materials. Phenolics have a complex network of bond order and are amorphous in nature, which leads to their low value for thermal conductivity for unfilled polymers.

A group of polymers described in the following sections are classified as thermoplastic which soften when heated and harden when cooled; this process is totally reversible and may be repeated numerous times. On a molecular level, as the temperature is increased, secondary bonding forces are diminished by the increased molecular motion, so that the relative movement of adjacent chains is facilitated and movement occurs when a stress is applied. Irreversible damage occurs to the polymer chain when the temperature is increased to the point at which molecular vibrations become severe enough to break the primary covalent bonds.

The thermal conductivity as a function of mean bulk temperature for various thicknesses of polytetrafluoro-ethylene (Teflon), polycarbonate, polyvinyl chloride, and polypropylene is also shown in Fig. 2. The thermal conductivity of Teflon shows very little dependence on mean temperature for all three specimen thicknesses and compares quite favorably with the published literature value of 0.25 W/m-K. The crystalline state for Teflon varies between 50–70%, however, each specimen

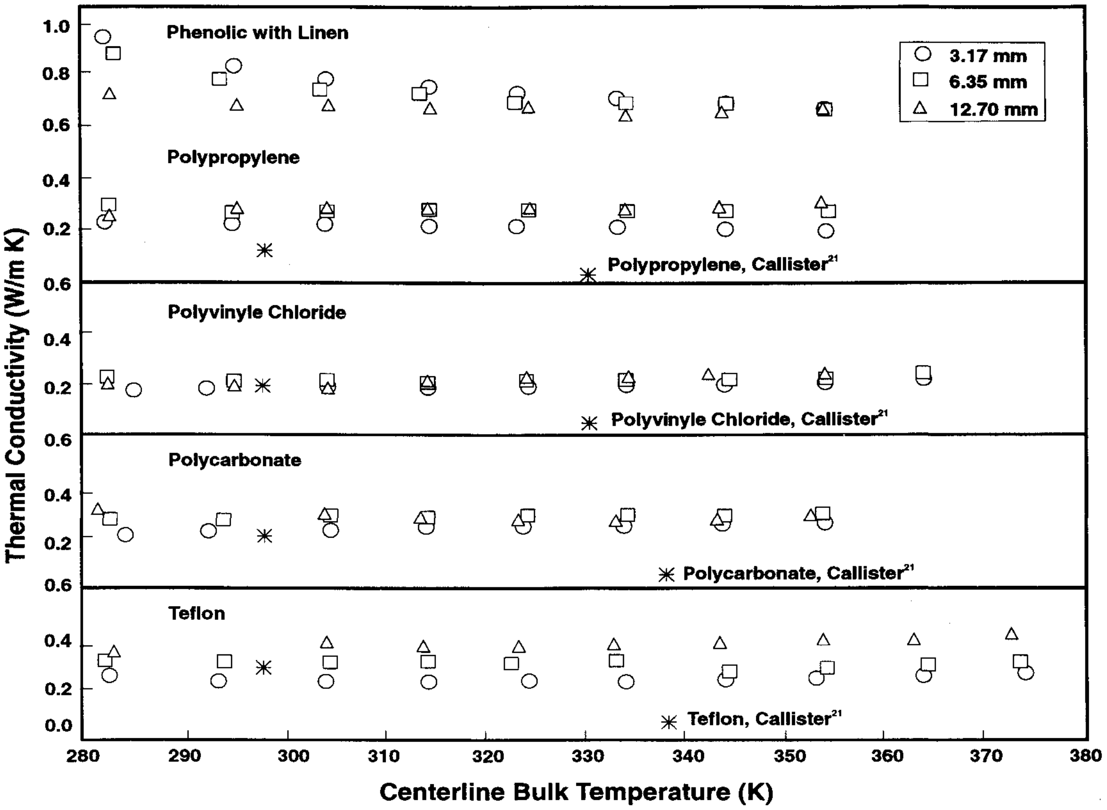

Fig. 2 **Thermal conductivity as a function of mean bulk temperature for Teflon, polycarbonate, PVC, polypropylene, and LE phenolic.**

was machined from the same rod stock that minimized this parameter for the investigation.

The thermal conductivity of polycarbonate and polyvinyl chloride polymers also show independence throughout the range of temperatures tested. In addition, both thermoplastics have amorphous chain structures that contribute to the low thermal conductivity values for the range of parameters tested. The experimental values compare favorably with literature values of 0.20 and 0.18 W/m-K (Ref. 21), respectively, measured at 25°C (77°F).

The variation of thermal conductivity with mean bulk temperatures for polypropylene and ultra high molecular weight (UHMW) polyethylene is shown in Figs. 2 and 3, respectively. Both thermoplastics show very little dependence on temperature within the range considered. The published literature value for UHMW polyethylene compares very favorably with the experimentally measured value, 0.48 compared to 0.46 W/m-K (Ref. 21), respectively. However, the experimentally measured thermal conductivity for polypropylene is a factor of 3 higher than the published value of 0.12 W/m-K (at room temperature). The published value for polypropylene is for an atactic chain structure (methyl pendent groups are randomly placed on each side of the polymer chain), but commercial polypropylene is isotactic (all methyl pendent groups are on one side of the polymer chain), which results in a highly crystalline structure. This structural difference may explain the discrepancy between measured and published values since the polymer type tested in this investigation is commercial grade. Also, the difference between the two thicker specimens and the thinnest specimen may be attributed to the higher contact resistance at both specimen interfaces.

The thermal conductivity for polyhexamethylene adipamide (nylon 6,6), delrin (polyoxymethylene), and acrylonitrile–butadiene–styrene terpolymer (ABS) as a function of mean bulk temperature is shown in Fig. 3. Both nylon 6,6 and delrin polymers show a dependence on mean bulk temperature for thermal conductivity below a room temperature of 25°C (77°F) but become less dependent as the temperature is increased from 25 to 70°C (77 to 158°F). The published values for nylon 6,6 and delrin are 0.24 and 0.38 W/m-K (Ref. 21), respectively, measured at a bulk temperature of 25°C (77°F). The experimentally measured values for nylon 6,6 and delrin at room temperature are 0.31 and 0.38 W/m-K, respectively. The experimentally measured value is roughly 31% higher than the literature value for nylon 6,6 and compares quite favorably for delrin.

The thermal conductivity values of the ABS polymer are independent of increasing temperature throughout the range of parameters and also compare favorably with the published literature value of 0.17 W/m-K (Ref. 21).

Thermal Contact Conductance

A comparison of the thermal contact conductance values for the various polymers tested in this investigation is shown in Fig. 4. The thermal contact conductance for interface pressures ranging from 510 to 2760 kPa (75 to 400 psi) clearly indicates that polyethylene has the highest thermal contact conductance values among the polymers investigated. The thermal contact conductance values for polyethylene ranged from 1095.33 to 1659.42 W/m^2 K (192.90 to 292.24 Btu/ft^2 h °F) for the range of pressures tested, while the majority of the polymers showed no increase in thermal contact conductance values as pressure increased. Teflon and polycarbonate were the other polymers that showed an increase in contact conductance values at the higher interface pressures. The values for polycarbonate ranged from 410.46 to 938.59 W/m^2 K (72.29 to 165.30 Btu/ft^2 h °F) for the range of parameters.

The thermal contact conductance values for Teflon and phenolic polymers are shown in Fig. 5 for a specimen thickness of 0.00165 m (0.065 in.) at two interface temperatures and two separate specimens. Both polymers show a slight increase in thermal contact conductance with increasing interface pressure at an interface temperature of 20°C (68°F), however, the effect of the increased interface temperature to 40°C (104°F) on thermal contact conductance is more dramatic for Teflon than it is for phenolic. This may be attributed to the fact that phenolic

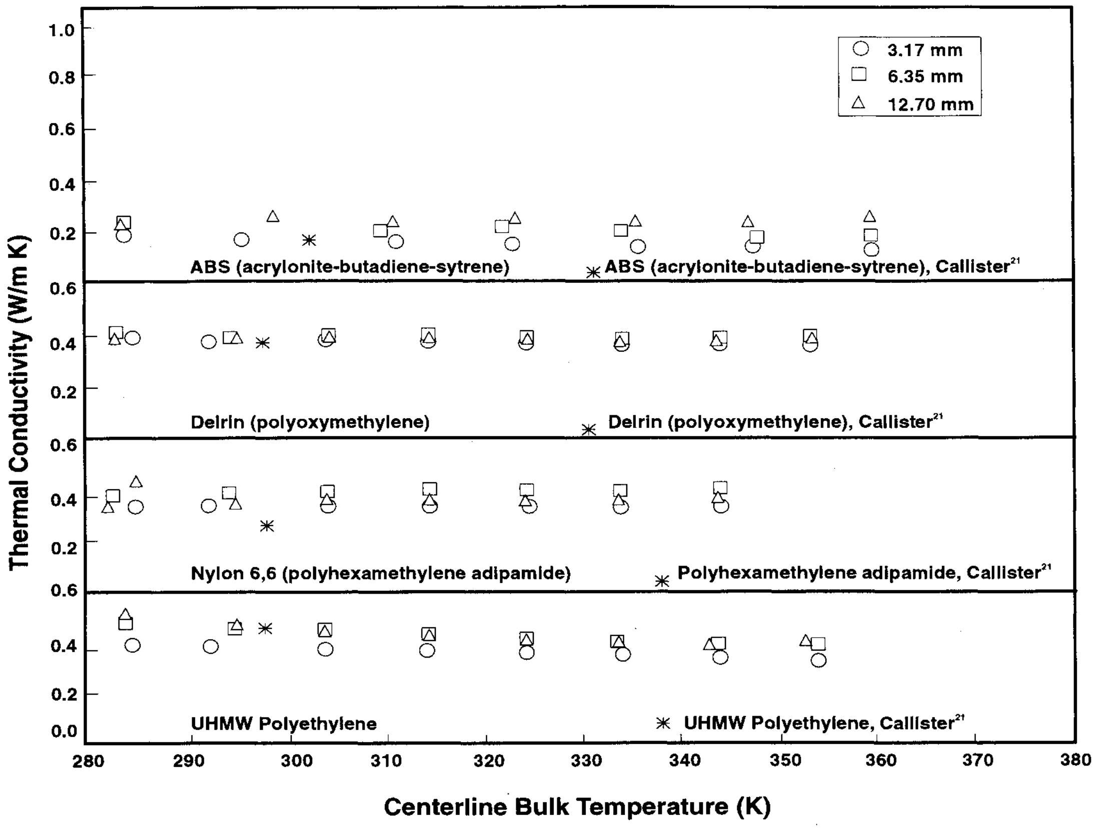

Fig. 3 Thermal conductivity as a function of mean bulk temperature for UHWM polyethylene, nylon 6,6, delrin, and ABS.

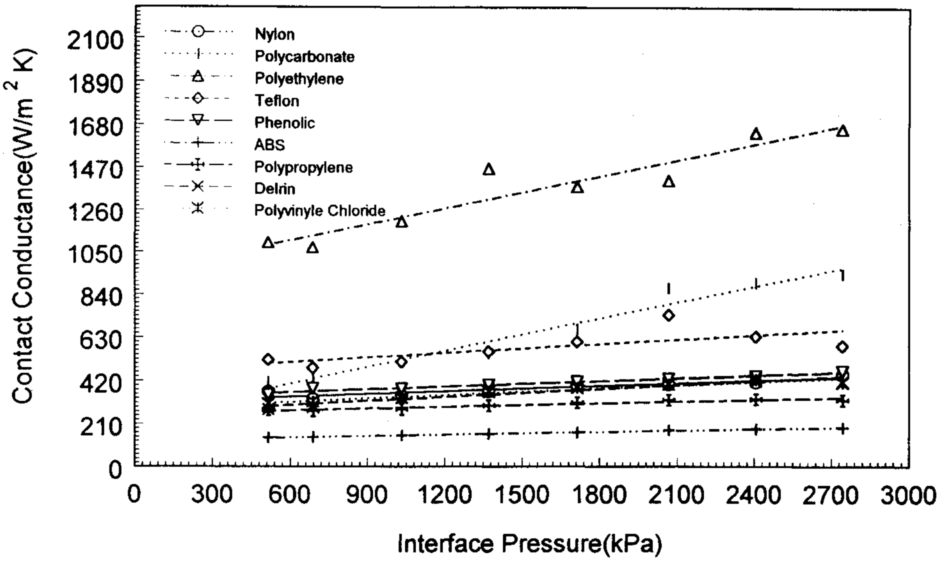

Fig. 4 Comparison of the thermal contact conductance values for the various polymers at an interface temperature of 20°C for a range of interface pressures.

is a thermosetting polymer, generally harder, stronger, and much more brittle than a thermoplastic polymer, which is what Teflon is classified as (thermoplasts are relatively soft and ductile).

The thermal contact conductance values for polyethylene are also shown in Fig. 5 for two interface temperatures and for a range of interface pressures. The thermal contact conductance values at 40°C (104°F) were roughly half the thermal conductance values measured at a temperature of 20°C (68°F). This decrease in thermal contact conductance with increased temperature is directly opposite the effect seen for Teflon and phenolic polymers. These polymers were chosen among the tested polymers since, under an applied stress, they could withstand higher temperatures without severe deformation. In addition, Teflon and polyethylene exhibited the highest thermal contact conductance values at a temperature of 20°C (68°F).

Teflon and polyethylene are thermoplastics whose structure becomes rubbery at room and elevated temperatures as evidenced by their glass transition temperatures [both are −90°C (−130°F)]. However, the melting temperatures are significantly different between the two polymers with Teflon having the higher value of 327°C vs 137°C (620.60°F vs 278.60°F). Thus, UHMW polyethylene's structure becomes more amorphous (rubbery) than Teflon's at the higher interface temperature and, as a consequence, results in lower thermal contact conductance values. The reverse is true at the lower temper-

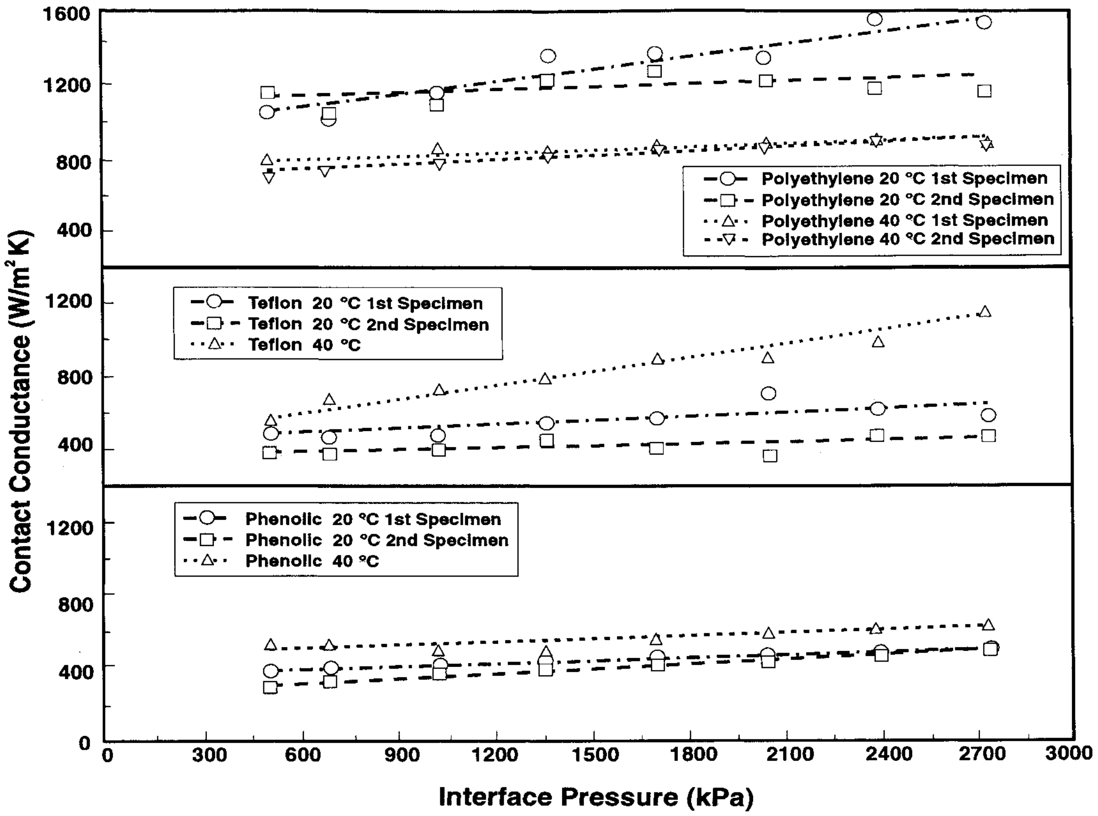

Fig. 5 Comparison of the thermal contact conductance values for LE phenolic, Teflon, and UHMW polyethylene at two interface temperatures.

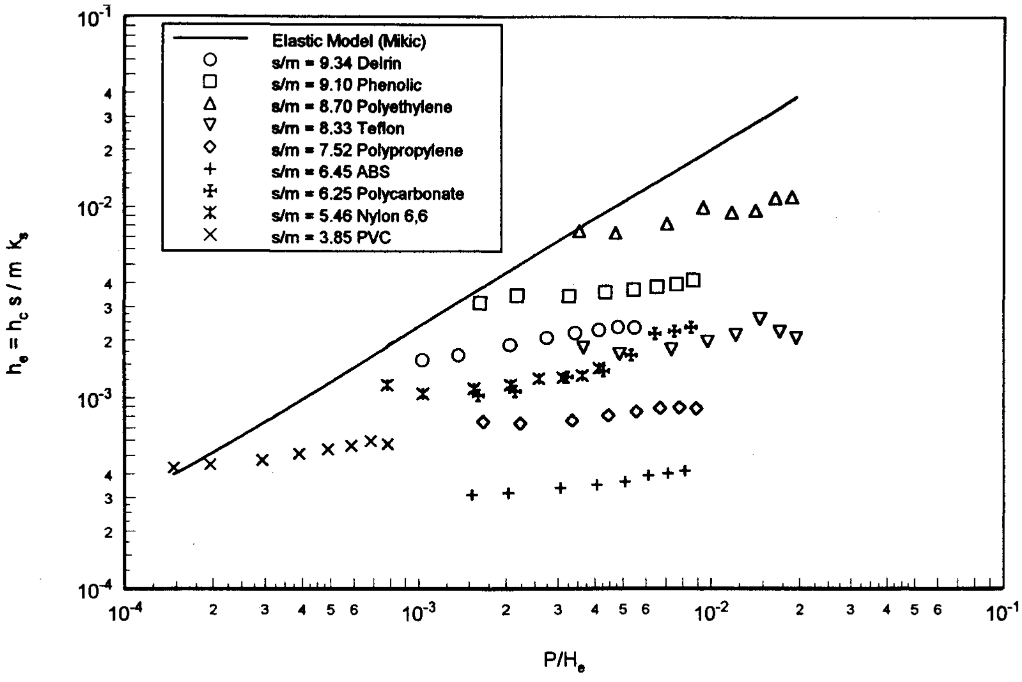

Fig. 6 Comparison of the dimensionless thermal contact conductance values with Mikic's elastic model correlation.

atures where polyethylene has a higher degree of crystallinity (70–80%) than Teflon (50–70%), resulting in higher thermal conductivity and higher thermal contact conductance values. The thermal contact conductance data for the other polymers at the higher temperatures could not be measured since they showed severe deformation under the applied loads.

A comparison of the dimensionless thermal contact conductance values with existing elastic and plastic models developed by Mikic[22] and Cooper, Mikic, and Yovanovich (CMY),[23] respectively, is shown in Figs. 6 and 7. Both existing models incorporate microscopic parameters such as surface roughness and asperity slope to nondimensionalize the thermal contact conductance. Since polymeric materials exhibit lower material hardness than metallic materials, macroscopic parameters such as profile roughness and slope may be a more appropriate means to nondimensionalize the thermal contact conductance.

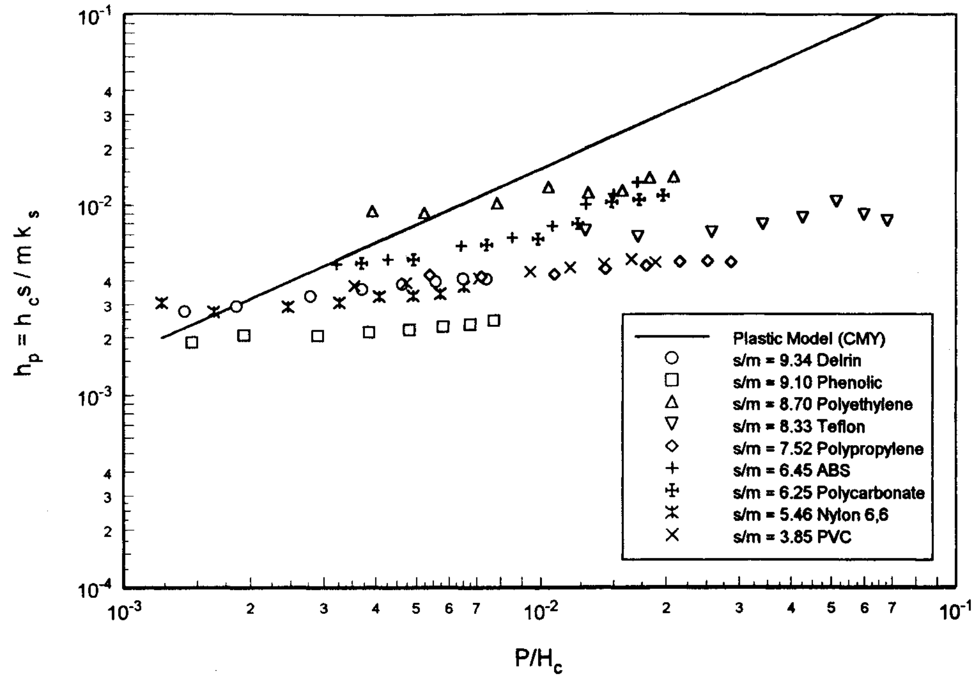

Fig. 7 Comparison of the dimensionless thermal contact conductance values with CMY plastic model correlation.

The equations for the elastic and plastic model correlation as developed, respectively, by Mikic and CMY are

$$\text{Mikic model correlation:} \quad h_e = sh_c/mk_s = 1.54(P/H_e)^{0.94}$$

$$\text{CMY model correlation:} \quad h_p = sh_c/mk_s = 1.25(P/H_e)^{0.95}$$

$$P/H_c = (A_r/A_a)_{\text{plastic}}, \qquad P/H_e = (A_r/A_a)_{\text{elastic}}$$

$$A_{\text{elastic}}/A_{\text{plastic}} = \tfrac{1}{2}$$

Both the Mikic elastic model and CMY plastic model assume an elastic or plastic deformation a priori of the surface asperities to reduce the experimental data into their corresponding dimensionless parameters. Thus, in comparing the experimental data to either model an elastic or plastic deformation of the polymeric asperities was assumed. This assumption then allows the experimental thermal contact conductance data for each polymeric material to be compared to the elastic or plastic model.

The slopes of the individual polymers as shown by both Figs. 6 and 7 are quite small in comparison to the slopes of the two existing models, however, this may be a result of the polymeric material's low Vicker's hardness. This exhibited softness may explain the inconsequential effect on thermal contact conductance with increasing interface pressure. Thus, the initial loading pressure may be sufficient to maximize contact area between the metallic and polymeric surfaces and that any further increase in interface pressure will not significantly effect contact area and ultimately thermal contact conductance. However, the experimental thermal contact conductance data exhibited less scatter with the CMY plastic model than with the Mikic elastic model. Because of the amorphous chain structure of the polymeric material, which lends itself to viscoelastic behavior (dependent on time and temperature), this result is understandable.

Conclusions and Recommendations

The thermal conductivity of several commercially important polymers has been measured between the temperatures of 10–100°C (50–212°F), whereas the interface pressure was maintained at 200 psi (1378.6 kPa). In addition, the thermal contact conductance for each polymer was measured at an interface temperature of 20°C (68°F) for a range of interface pressures between 510–2760 kPa (75–400 psi). The results show that a majority of the polymers tested had thermal conductivity values independent of the range of temperatures tested. UHMW polyethylene had the highest thermal conductivity value [0.45 W/m-K (0.26 Btu/h ft °F)] among the unfilled polymers tested and also had the highest thermal contact conductance values throughout the range of interface pressures tested. UHMW polyethylene was followed by polycarbonate and Teflon as the next two polymers with the highest thermal contact conductance measured at an interface temperature of 20°C (68°F). Both polycarbonate and Teflon had similar values for thermal conductivity over the range of temperatures tested.

The thermal contact conductance values for UHMW polyethylene, Teflon, and phenolic polymers were measured at an interface temperature of 40°C (104°F) to determine the effect of elevated temperature. These polymers were chosen since they exhibited no significant physical deformation at higher temperatures. The thermal contact conductance for Teflon and phenolic increased with increases in interface temperature and pressure, whereas UHMW polyethylene showed a significant decrease at the elevated temperature. This may be explained by the fact that polyethylene's chain structure has a greater tendency to become rubbery while the physical structure of Teflon and phenolic can withstand the higher temperatures as evidenced by their higher melting temperatures.

The thermal contact conductance values were compared to two existing models that assumed either elastic or plastic deformation of the microscopic asperities. The experimental values do not correlate well with the two existing models that have been developed for metallic surfaces. New surface parameters that incorporate macroscopic characteristics such as profile roughness and slope may be needed to better predict thermal contact conductance. In addition, polymeric materials are viscoelastic and their behavior is dependent on both time and temperature. Thus, a better method of nondimensionalizing the interface pressure should incorporate the polymer's relaxation modulus [$E_r(t)$] instead of the Vickers microhardness.

This investigation has been centered around widely available commercial polymers whose applications are very diverse and widespread. A group of thermosetting polymers called polyamides-imide are important to the aircraft and aerospace industries along with the microelectronic industry and should be studied for their effect on thermal contact conductance. Polyimides consist of a ring structure that contains a nitrogen atom. These polymer groups can operate continuously at temperatures of 175°C (347°F) and do not decompose until reaching 460°C (860°F). Thus, due to their unique properties this group of polymers should be investigated.

Acknowledgments

Support for this study was provided in part by the TEES Center for Space Power and NSWC Contract N00164-94-C-0185.

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