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for Flexible Graphite Materials: Analytical and Experimental
Study

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The Effect of Interface Pressure on Thermal Joint Conductance for Flexible Graphite Materials: Analytical and Experimental Study

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ABSTRACT

Increasingly, thermal interstitial materials (TIM), such as metallic foils, solder, metallic coatings, polymeric matrices loaded with highly conducting filler particles (i.e., elastomers), greases, and phase-change (PCM) materials are being employed to a greater extent in power generating systems. With greater use, follow an increased interest in the thermal transport and mechanical properties of these materials. These properties include thermal conductivity, thermal diffusivity, Young's modulus, Poisson's ratio, and the thermal resistance at the interface between the interstitial material with the substrate material.

To provide additional information on the thermal joint conductance of an important interstitial material employed in microelectronic components, an experimental investigation has been conducted for this study. The experimental data were compared to an analytical model for elastic interstitial layers with and without a phase-change compound coated on its surfaces. The elastic layers, the experimental facility, and the experimental procedure will also be described. The model and the data are found to be in good agreement over the pressure range within the investigation. The proposed model can be used to predict lower bound on the joint conductance.

NOMENCLATURE

A_a, A_c, A_g = apparent, contact, and gap area; m^2
 E_p = polymer Young's modulus; GPa
 f_g = gap correction factor
 h_c, h_g, h_j = contact, gap, and joint conductances; $W/m^2 \cdot K$
 h_b = bulk conductance; $W/m^2 \cdot K$
 I_g = defined by equation (20)
 k_1, k_2 = solid thermal conductivities; $W/m \cdot K$
 k_i = interstitial conductivity; $W/m \cdot K$
 k_s = harmonic mean thermal conductivity,
 $\equiv 2k_1k_2/(k_1 + k_2)$; $W/m \cdot K$

M = gas parameter; mm
 m_1, m_2 = mean absolute asperity slopes of surfaces; rad
 m = effective mean absolute asperity slope,
 $\equiv \sqrt{m_1^2 + m_2^2}$; rad
 P = apparent contact pressure; MPa
 Q = joint heat transfer rate; W
 R_c, R_g, R_j = contact, gap, and joint resistance; K/W
 R_b = bulk resistance; K/W
 r_j = specific joint resistance, $\equiv 1/h_j$; $m^2 K/W$
 ΔT_j = joint temperature drop; K
 t_o = original thickness (m)
 t = final thickness (m)
 Y = separation of mean planes; m

Subscripts

1,2 = surface of solids 1 and 2
 a, c, j = apparent, contact, and joint
 i = index number
 p = polymer
 s = harmonic mean value

Greek Symbols

S_1, S_2 = RMS surface roughness; mm
 s = effective joint surface roughness, $\equiv \sqrt{S_1^2 + S_2^2}$
 l = dimensionless mean separation

INTRODUCTION

The heat flow across a metal/interstitial elastic-layer/metal joint is a very important problem in many microelectronic applications. Universally, it is generally known that when two surfaces are brought together, intimate solid to solid contact occurs only at discrete parts of the interface. Therefore, the actual contact area of pressed surfaces represents a very small fraction of the nominal contact surface. Even with high compressive load, and opti-

cally smooth surfaces (considered ideal surfaces), the series of randomly shaped peaks and valleys minimize the actual contact area of the solids that have been brought into contact.

Thermal contact resistance at numerous interfaces introduces a significant contribution to the total thermal resistance, especially in the field of thermal management of complex, high thermal dissipating packages. The interfaces formed between contacting surfaces can play a major role in the determination of the thermal network established between the source and sink. This is especially true in a variety of applications ranging from nuclear to aerospace applications to a host of configurations found in micro-electronic hardware. In many instances, the phenomenon of contact resistance at the interface must be well understood in order to reduce this resistance. This is eminently real if different types of interstitial materials are introduced to enhance the flow of heat through a solid to solid interface. To this end, metallic foils, greases, elastomers, adhesive tapes, and more recently, phase-change materials are added to the joint to enhance the thermal conductive path between contacting surfaces, and in turn reduce the joint resistance.

Whenever there is steady heat flow across two rough surfaces under an applied pressure, a temperature drop is observed at the joint that is directly proportional to the contact pressure. The joint temperature drop ΔT_j is related to the heat transfer rate Q through the joint resistance R_j or the joint conductance h_j by the relationships:

$$Q = \frac{\Delta T_j}{R_j} \quad (1)$$

and

$$Q = h_j A_a \Delta T_j \quad (2)$$

where A_a is the apparent contact area. For most contact problems, the real area of contact A_c is much smaller than the apparent contact area, i.e., $A_c/A_a < 2\%$. Therefore, the effective gap area is approximately equal to the apparent area: $A_g \approx A_a$. However, there are contact problems where the real area of contact is much larger than the apparent contact area, thus the effective gap area is much larger than the apparent area: $A_g > A_a$, i.e., thermal greases and phase-change materials.

The specific joint resistance and joint conductance may be related as

$$h_j = \frac{1}{A_a R_j} \quad (3)$$

where a specific joint resistance can be introduced as

$$h_j = \frac{1}{r_j} \quad (4)$$

which has been called the thermal impedance.

Spreading and constriction resistance concepts and solutions for interstitial materials, such as metallic foils, solder, metallic

coatings, polymeric matrices loaded with highly conducting filler particles, i.e., elastomers, greases, and phase-change materials have recently been introduced. At the present time, joint conductance models have only been investigated for a limited number of materials under vacuum conditions.

The main objective of this paper is to develop a model for the joint conductance and specific joint resistance formed by the mechanical contact of a compliant thermal interstitial material, i.e. graphite, under light and moderate apparent pressures to conforming rough surfaces. The gaps are filled with air or phase-change material which can be characterized by its thermal conductivity. The presence of a gas or phase-change material at the interface provides a second avenue for heat flow for an interstitial material, i.e., versus a vacuum environment. A microscopic view of a contact interface in a conforming rough surface is shown in Fig. 1.

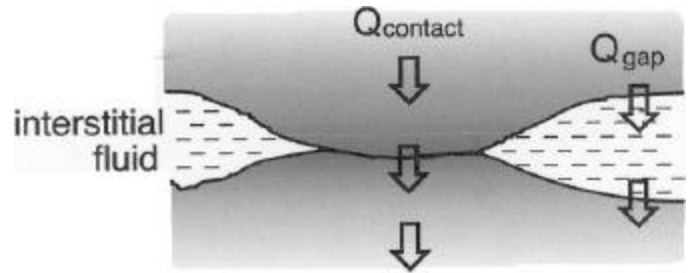


Figure 1: Microscopic view of a contact interface in a conforming rough surface.

Steady heat transfer across the solid surface to compliant material for this case is given by the relation:

$$Q_j = Q_c + Q_g \quad (5)$$

where Q_c = conduction via the micro-contacts, Q_g = conduction through air, phase-change material or pressure sensitive adhesive, i.e., interstitial fluid.

The second objective is to compare the model predictions against thermal joint resistance data recently gathered, and compute the relative error between the two.

REVIEW OF PUBLISHED LITERATURE

A review of the literature has revealed that several researchers have conducted analytical and experimental investigations of compliant thermal interstitial materials.

The first original work conducted for metal/polymer joints was performed by Miller and Fletcher [1], and Fletcher and Cerza [2]. The authors concluded that thermal conductance values of tested elastomers were lower than the thermal conductance of bare aluminum interfaces. However, they also observed that the addition of fillers, whether metallic or non-metallic, produced higher

thermal conductance value improvements than vacuum elastomers. In addition, experimentally gathered data for polyethylene materials in a range of pressures and interface temperatures resolved the effect of carbon filler loading and the effect of increasing temperature.

Ochterbeck et al. [3] investigated the effect on thermal joint conductance of various compounds applied directly onto a polyamide infrastructure. These compounds included several paraffin waxes, diamond impregnated films, and metallic foils. In all instances, the experimental data showed an increase in thermal joint conductance over bare junctions, however, the greatest improvement or thermal performance increase was begotten by the paraffin-based compound.

Rauch [4] conducted an experimental study of phase-change interface materials where compounds with and without a supporting system, such as an aluminum foil or a polyamide film, were examined. The nominal melting temperature for these materials was in the range of 51 to 60°C. The author ascertained complete wetting at the interface surfaces with the observation that the thermal resistance was zero at zero thickness, thus eliminating contact resistance. This assured that the overall thermal joint resistance would be only a function of the support thickness t and its thermal conductivity k of the phase-change wetting material. The experimentally measured thickness of the phase-change material was observed to decrease in proportion to the applied pressure, and depending on PCM's viscosity and surface geometric profiles of the contacting surfaces, achieved a minimum value. As a corollary observation, the corresponding joint resistance decreased as the time dependent thickness decreased.

Marotta and Fletcher [5] investigated the thermal conductance of several commercially important polymers. Within the range of apparent interface pressure, the thermal conductance values indicated independence at moderate to high loading. For several thermoplastic polymers, which are soft and ductile, an increase in thermal joint conductance was measured at the higher apparent pressures, which was attributed to material deflection.

An experimental investigation by Mirmira et al. [6] revealed that the thermal joint conductance of several commercially available elastomeric materials became less dependent on apparent interface pressure. These values occurred as the interface loading increased significantly, with the bulk conductance becoming predominant at the high-pressure range (1000 to 500 kPa). This work was later summarized by Marotta and Han [7]. In addition, for some filled silicone elastomeric materials, such as silver-coated copper powders and silver flakes, thermal conductance values indicated mostly independence on pressure due to increase rigidity from the powders and flakes incorporated within its structure. The authors also observed that the change in thermal conductance values was negligible with respect to increased mean interface temperature for several gasket materials.

Fuller and Marotta [8] developed an analytical model for the prediction of thermal joint conductance for both thermoplastic and elastomeric polymers placed between metallic solids. The assumptions included nominally flat contacting surfaces, uniform pressure distribution at the interface, elastic deformation of the polymer layer and asperities, and a vacuum environment. The

analytical model developed employed the Greenwood and Williamson [9] definition for the elastic contact hardness to define a new polymer elastic hardness:

$$h_c = \frac{k_s}{4\sqrt{p}} \frac{m}{s} \frac{\exp(-I^2/2)}{\left[1 - \sqrt{\frac{1}{4} \operatorname{erfc}(I/\sqrt{2})}\right]^{3/2}} \quad (6)$$

$$H_{ep} = E_p m / 2.3 \quad (7)$$

From the analytical model and polymer elastic hardness, the authors were able to obtain a simple correlation for the dimensionless microscopic contact conductance:

$$\frac{h_c s}{k_s m} = 1.49 \left(\frac{2.3P}{E_p m} \right)^{0.935} \quad (8)$$

By defining the final thickness in terms of the strain, and the bulk thermal conductance with respect to the polymer thickness t and thermal conductivity, the authors obtained a final expression for the joint conductance defined as

$$h_b = k_p / t \quad (9)$$

$$t = t_o \left(1 - \frac{P}{E_p} \right) \quad (10)$$

$$h_j = \frac{1}{\left[\frac{1}{h_{c,1}} + t_o \left(1 - P/E_p \right) / k_p + \frac{1}{h_{c,2}} \right]} \quad (11)$$

Experimental data from Marotta and Fletcher [5] and Fuller and Marotta [8] were compared to the joint conductance model, and good agreement was achieved for the range of parameters employed in their studies.

Narh and Sridhar [10] gathered experimental thermal conductance data on polystyrene as a function of thickness at constant pressure and mean specimen temperatures (65°C and 75°C). The authors resolved that at temperatures slightly above the polymer's glass transition temperature, where the polymer's surface becomes relatively soft and ductile, the thermal contact resistance varied as a logarithmic function of pressure.

In general, analytical studies have been conducted for numerous interstitial materials with respect to their effect on thermal contact conductance. However, the applicability of analytical models to the prediction of joint conductance, and comparison to experimental data, still is quite limited. At the present time, joint conductance models have only been investigated for a limited number of materials under vacuum conditions.

This study investigates the effect on thermal joint conductance for a solid to interstitial layer joint caused by the variation of interface pressure. This investigation was conducted for a particular interstitial layer (i.e., graphite) joint that has shown great potential to greatly enhance conductance for an atmospheric or gaseous environment. The presence of a gas at the interface provides a second avenue for heat flow through the interface for an uncoated interstitial material (i.e., versus a vacuum environment). The experimental data were compared to an analytical model for elastic interstitial layers with and without a phase change compound coated on its surfaces. The elastic layers, the experimental facility, and the experimental procedure will also be described.

JOINT CONDUCTANCE MODEL FOR CONFORMING ROUGH SURFACES

The thermal joint resistance or conductance of a joint formed by two nominally, flat rough surface depends on several geometric, physical, and thermophysical properties. Figures (2a-b) schematically shows the joint thermal resistance with a thermal interstitial material (TIM) introduced at the interface of two solids (see below).

The resistance and conductance relations are obtained from models that are based on the following simplifying assumptions:

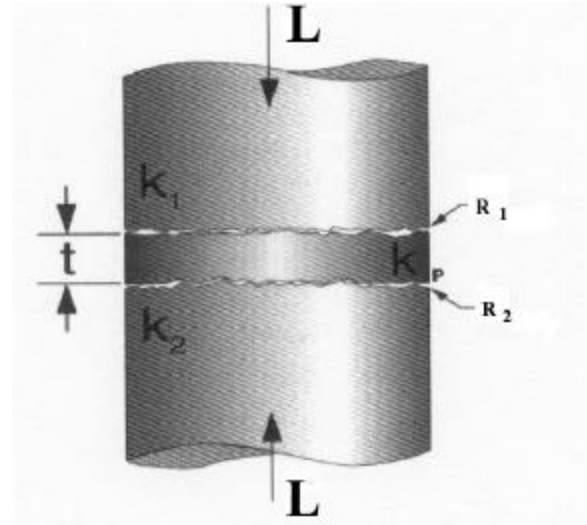
- Nominally flat, rough surfaces with gaussian asperity height distributions
- Random distribution of surface asperities over the apparent area
- Elastic deformation of the contacting asperities and bulk layer
- Homogeneous properties for the interstitial material in the layer thickness direction

The joint thermal resistance to heat flow that incorporates the bulk properties of the interstitial layer can be defined as

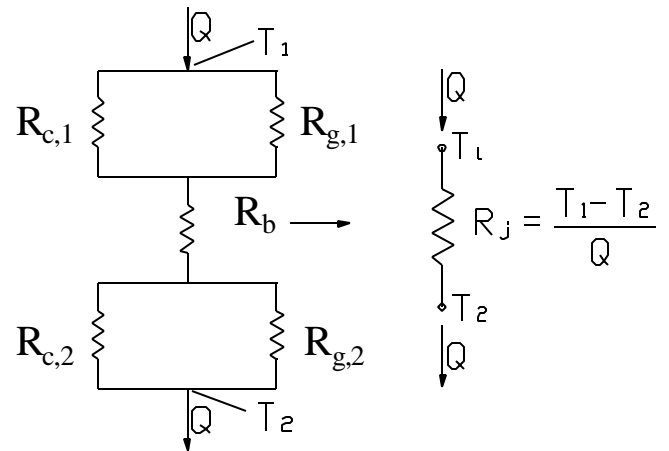
$$R_j = \left[\frac{1}{R_{c,1}} + \frac{1}{R_{g,1}} \right]^{-1} + R_b + \left[\frac{1}{R_{c,2}} + \frac{1}{R_{g,2}} \right]^{-1} \quad (12)$$

where $R_{c,1}$, $R_{c,2}$, $R_{g,1}$ and $R_{g,2}$ are the thermal contact resistances, and the thermal gap resistances at each interface, respectively, and R_b is the thermal resistance due to the bulk properties of the layer. The thermal joint resistance is defined as the temperature drop across the entire joint divided by the total heat-flow rate. Thus,

$$R_j = \frac{\Delta T_j}{Q} \quad (13)$$



(a)



(b)

Figure 2(a-b): A General Diagram of the Modeled Joint Conductance (after Yovanovich et al. [11])

and, therefore, we can write the following relationship between the thermal joint resistance and the thermal joint conductance:

$$R_j = \frac{1}{h_j A_a} \quad (14)$$

The thermal contact conductance and bulk conductance can be written as

$$R_{c,i} = \frac{1}{h_{c,i} A_a} \quad i \rightarrow 1 \text{ to } 2 \quad (15)$$

$$R_b = \frac{1}{h_b A_a} \quad (16)$$

$$R_{g,i} = \frac{1}{h_{g,i} A_a} \quad i \rightarrow 1 \text{ to } 2 \quad (17)$$

¹Therefore, the thermal joint resistance can be rewritten in terms of thermal conductance as

$$h_j = \frac{1}{\frac{1}{h_{c,1} + h_{g,1}} + \frac{1}{h_b} + \frac{1}{h_{c,2} + h_{g,2}}} \quad (18)$$

Equation (18) is the generalized expression from which the overall joint conductance can be calculated, however, the complexity in computing the individual constituents makes this a very challenging task indeed.

Expressions (8) to (10) (see above) can be employed for the calculation of the contact conductance h_c and bulk conductance h_b for equation (18). The gap conductance h_g may be computed from gap conductance models first developed by Yovanovich et al. [12]. The model assumes that the two surfaces in contact are uniform in temperature, and the interface gap consists of many elemental flux tubes of varying thermal resistances. The integration of these tubes over the nominally contacting area gives the overall gap conductance:

$$h_g = \frac{k_g}{s} I_g \quad (19)$$

$$I_g = \frac{1}{\left(\frac{Y}{s} + \frac{M}{s}\right)} \quad (20)$$

The above expression for I_g is accurate to within 10% for large values of the dimensionless relative gap and gas parameter, however, its accuracy diminished considerably for small values. Therefore, Negus and Yovanovich [13] proposed a new correlation that incorporated a correction factor f_g that modified the above expression for the integral function:

$$I_g = \frac{f_g}{\left(\frac{Y}{s} + \frac{M}{s}\right)} \quad (21)$$

A simple approximate expression for f_g was derived as

$$f_g = 1.063 + 0.0471 \left(4 - \frac{Y}{s}\right)^{1.68} \left(\ln \frac{s}{M}\right)^{0.84} \quad (22)$$

for $2 \leq Y/s \leq 4$ and $0.01 \leq M/s \leq 1$, and

$$f_g = 1.0 + 0.06 \left(\frac{s}{M}\right)^{0.8} \quad (23)$$

for $2 \leq Y/s \leq 4$ and $1 \leq M/s \leq \infty$.

For phase change materials or other types of filler materials present within the gap, instead of a gas, the overall gap conductance becomes:

$$h_g = \frac{k_i}{Y} \quad (24)$$

The mean plane separation Y or gap parameter is the distance between the mean planes passing through the two rough surfaces. This parameter is related to the effective RMS surface roughness and asperity slope, contact pressure, and the interstitial material Young's modulus via the expression developed for elastomeric materials (see below):

$$\frac{Y}{s} = \sqrt{2} \operatorname{erfc}^{-1} \left(\frac{2.3P}{E_p m} \right) \quad (25)$$

These relations for joint conductance are compared against recently gathered experimental data for graphite materials, i.e., eGraf(tm)¹ thermal interface grades 1205, 1210, and 1220.

EXPERIMENTAL AND PROPOSED MODEL COMPARISONS

The experimental facility itself and its operation, employed for the experimental portion of this study, has been described in numerous published literature, thus, a formal discussion will not be given within this manuscript, i.e., see Fuller and Marotta [5] and Marotta and Fletcher [8].

The joint model proposed is compared against recently gathered experimental data for an important commercial material which shows great promise for enhancing the joint conductance for many microelectronic applications, as well as other non-microelectronic utilization. The joint conductance data are shown plotted against the joint apparent pressure in Fig. 3. The joint resistance ranged from 0.102 to 0.016 $\text{in}^2\text{C/W}$ for an apparent pressure range of 5 to 150 psi (34.4 to 1033.7kPa). The data points clearly show that the joint resistance increases with respect to increased material thickness, and that the apparent interface has a significant influence on thermal joint conductance. The trend of both the experimental data and model predictions shows that at light interface pressures, the thermal path that dominates the overall joint resistance stems from the gap resistance. While

¹ "eGraf is a trademark of Graftech Inc."

this is true at light interface pressure, at moderate to high interface pressures, the bulk resistance becomes the dominant mechanism. The comparison between the model and experimental data points is shown below for 50W-power source. In general, both the experimental data and model predictions show the same trend as the data is plotted against interface pressure.

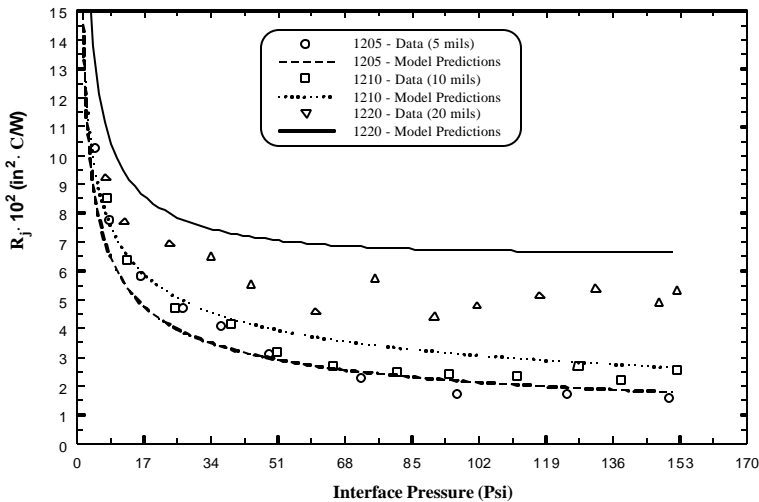


Figure 3: Thermal joint resistance as a function of apparent interface pressure for various thicknesses

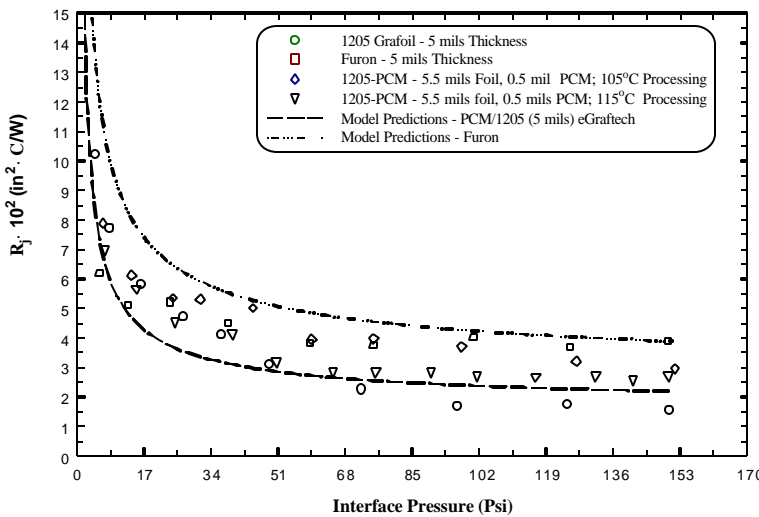


Figure 4: Thermal joint resistance as a function of apparent interface pressure for Phase Change Paraffin compound and another commercial graphite material

The contacting surfaces were aluminum 6063 with thermal conductivity of $k = 180 \text{ W/m} \cdot \text{K}$ and 1200 series material $k \approx 11 \text{ W/m} \cdot \text{K}$. The rms surface roughnesses for the eGraf(tm) and aluminum contacting surfaces were $3 \mu\text{m}$ and $1 \mu\text{m}$, respec-

tively. Figure 4 shows the effect of a high temperature phase change paraffin wax coated on just one single surface while the opposite surface remains bare, i.e., uncoated.

The parameters of each test are shown in the legend of each figure. For the phase change compound, the model predictions are below the experimental data which is what one would expect since it incorporates many simplifying assumptions. These assumptions would make it an ideal case, thus a lower bound or best case performance would be realized. However, for the Furon graphite material the experimental data at low interface pressures seem to be higher than the model predictions, which must indicate a thermophysical or mechanical property that is not well understood. Thus, the differences may be the result of several factors with the material Young's modulus one such factor.

Figure 5 shows the effect on thermal joint resistance as a function of interface pressure that an increased power level (see below) has on the experimentally gathered values. This effectively causes an increased joint temperature, i.e., 50 to 100W, which can cause a degradation in thermal conductivity with increased temperature. The plot clearly indicates that light loading pressure, where gap resistance dominates, has very little effect but delineation does start to occur roughly after 60 psi . At this point, the bulk thermophysical properties, and its bulk resistance, begins to overshadow the gap resistance. However, one can observe that degradation does occur in thermal performance for each material thickness as the power is doubled. Again, this may be due to degradation in material thermal conductivity, which effectively dropped to $k \approx 11$ to $7.5 \text{ W/m} \cdot \text{K}$.

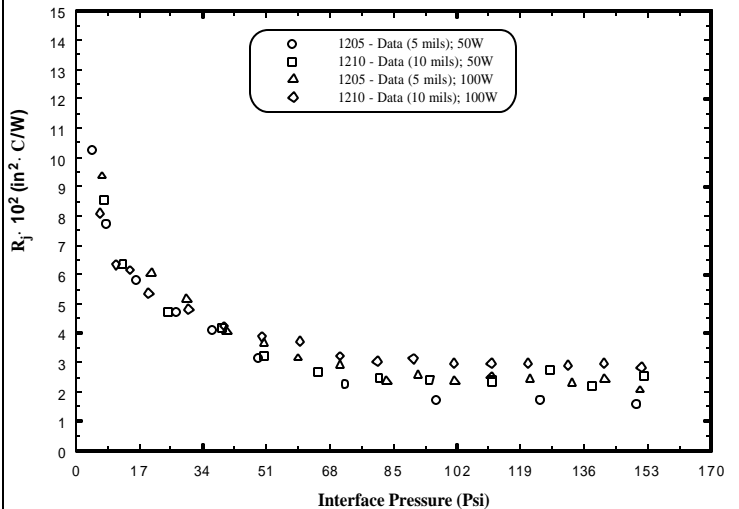


Figure 5: Thermal joint resistance as a function of apparent interface pressure at 50 and 100W

A comparison between the experimentally measured joint resistance values and the analytical predictions are shown in Tables 1 and 2. In addition, geometric and thermophysical properties for each 1200 series graphite material, which was employed in the present investigation, is shown. The comparison is performed at

25 *psi* since this is a typical interface pressure in many micro-electronic applications.

Table 1: Comparison of predicted versus experimental data at 25 *psi*

Material	Power W	Experimental (in ² °C/W) •10 ²	Model (in ² °C/W) •10 ²	% diff.
1205	50	4.70	3.24	18.9
1210	50	4.69	4.15	11.5
1220	50	6.94	7.84	12.9
1205/PCM	50	5.21	6.35	21.9
Furon	50	4.53	3.62	20.1

Table 2: Geometric and Thermophysical data

Material	Thick- ness (mm)	<i>k</i> (W/m-K)	<i>s</i> (µm)	<i>m</i> (rad)
1205	0.127	10.9	3.0	0.194
1210	0.254	12.2	3.0	0.194
1220	0.508	11.9	3.0	0.194
1205/PCM	0.127	4.8	4.0	0.218
Furon	0.127	5.7	4.0	0.218

The experimental data and model predictions for the materials employed are quite good when one considers that the uncertainty for these types of measurements are large, i.e., typically 10 to 15%. However, what is more important is that the fact that the model can predict the trend of the experimental data, and distinguish the regimes of importance, i.e., gap versus bulk resistance.

Summary and Conclusions

A model has been proposed to predict the joint conductance and joint resistance for conforming rough surface whose contacting asperities and interstitial layer undergo elastic deformation. The model was obtained from the general, more complex model that can be used for a wide range of pressures where heat transfer can occur across the joint at both micro-contacts and gaps because of surface roughness effects.

The proposed model when compared against experimental data for several commercially available graphite materials shows trends similar to the experimental data when plotted with respect to interface pressure. There does exist a large difference for the thickest 1220 graphite material however, the observed difference may be partially due to the incorporated Youngs modulus which was obtained from the 1210 graphite material.

Since the proposed model is based on nominally flat, rough surfaces, these predicted values might be used to predict a lower bound on the joint resistance for non-flat surface profiles. Further testing is required to validate the proposed model for interface

pressure greater than 150 *psi* , and other thermal interstitial materials with compositions different then graphite materials.

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