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EFFECTIVE THERMOPHYSICAL PROPERTIES OF THERMAL INTERFACE MATERIALS: PART I DEFINITIONS AND MODELS

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ABSTRACT

The conductivity of thermal interface materials are typically determined using procedures detailed in ASTM D 5470. The disadvantages of using these existing procedures for compliant materials are discussed along with a proposed new procedure for determining thermal conductivity and Young's modulus.

The new procedure, denoted as the Bulk Resistance Method, is based on experimentally determined thermal resistance data and an analytical model for thermal resistance in joints incorporating thermal interface materials. Two versions of the model are presented, the Simple Bulk Resistance Model, based on the interface material thickness prior to loading and a more precise version denoted as the General Bulk Resistance Model, that includes additional parameters such as surface characteristics and thermophysical properties of the contacting solids. Both methods can be used to predict material in situ thickness as a function of load.

NOMENCLATURE

A	=	area of contact (m^2)
$ASTM$	=	American Society for Testing and Materials
a	=	linear fit coefficient (slope)
BRM	=	Bulk Resistance Method
b	=	linear fit coefficient (intercept)
c_1, c_2	=	coefficients for Vickers microhardness
E	=	Young's modulus (MPa)
H	=	hardness (MPa)
h	=	thermal conductance (W/m^2K)
k	=	thermal conductivity (W/mK)
k_s	=	harmonic mean thermal conductivity (W/mK)
m	=	asperity mean absolute slope (rad)
mp	=	mean plane
n	=	number of data points in Bulk Resistance Method
P	=	contact pressure (MPa)
PCM	=	phase change material
PVC	=	Polyvinyl chloride
RTV	=	room temperature vulcanizing
Q	=	heat transfer rate (W)
R	=	thermal resistance (K/W)
RMS	=	root mean square
r	=	specific thermal resistance (m^2K/W)
T	=	temperature (K)
TIM	=	thermal interface material
t	=	thickness (m)
ΔT_j	=	joint temperature drop (K)
Y	=	mean plane separation (m)
λ	=	dimensionless mean plane separation
ν	=	Poisson's ratio
σ	=	RMS roughness (m)

Subscripts

$1, 2$	=	indices for contacting surfaces
a	=	apparent
b	=	bulk
B	=	Brinell
c	=	contact
e	=	elastic
f	=	final
g	=	gap
i	=	indices for interfaces
j	=	joint
l	=	lower
m	=	thermal interface material
o	=	initial
p	=	polymer
r	=	radiation
u	=	upper

Superscripts

$*$	=	dimensionless
$'$	=	effective

INTRODUCTION

When two surfaces are in mechanical contact, the resulting interface consists of numerous microcontacts and gaps that separate the surfaces. Because the real contact area is a small fraction of the apparent contact area, heat flow from one surface to another must overcome the thermal joint resistance. The thermal joint resistance depends on many geometric, mechanical and thermal parameters, including contact pressure, characteristics of interface surfaces, thermophysical properties of the contacting solids, and if present, the interstitial substance in the gap. Due to this resistance, a temperature drop across the interface is observable.

In nuclear power generating systems, aerospace and microelectronics applications, the interface formed between two surfaces is a very important, if not critical, part of the thermal network established between the heat source and the heat sink. The need to enhance heat transfer across the interface becomes an important issue in the design of high thermal energy dissipating systems. Therefore, the interest in interstitial materials that provide better thermal contact between the surfaces is increasing rapidly. These materials are known as thermal interface materials (TIMs) and include greases, oils, gases, thin metallic and nonmetallic coatings, metallic foils, polymeric composites and phase-change materials (PCMs).

A wide group of polymeric materials is commonly used in microelectronics cooling. Usually, silicon-based compounds with highly conductive filler particles such as ceramic powder, boron nitride and aluminum oxide are reinforced with fiberglass, aluminum foil, Kapton film or nylon mesh. Materials are manufactured in the form of thin sheets varying from a fraction of a millimeter to a few millimeters in thickness and can have adhesive on one or both sides. The performance depends on the material conductivity generally found to be 1 - 10 W/mK, and the compliance to the contacting surface which is a function of the material hardness. In addition, there is a similar group of flexible graphite-based materials, which are very compliant and show good thermal performance. The thermal interface materials are generally assessed by considering thermal conductivity and thermal resistance as the main properties.

Thermal conductivity and thermal resistance are usually reported in the material specifications and are mainly determined following the ASTM D 5470 procedure. With no information on this test procedure, a thermal design engineer would choose the material with the lowest reported resistance. With such design practice, however, in most engineering applications, the reported resistance obtained from the ASTM D 5470 procedure does not agree with the true resistance of the interface. Not surprisingly, the highest thermal conductivity does not necessarily imply the lowest thermal resistance since many geometrical, mechanical and thermophysical parameters such as thermal conductivity, Young's modulus, hardness, compliance, surface roughness and waviness effect the TIM thermal performance. Therefore, more detailed material data sheets should be available while the procedures for thermophysical characterization should be selected carefully in order to properly identify material's thermophysical properties and reduce thermal joint resistance in the real application.

The present work is confined to the study of thermal interface materials in the form of thin sheets. An analytical model for the thermal resistance of joints formed by the mechanical contact of conforming, rough, nominally flat surfaces with interface materials will be developed here. The model will give a relationship between thermal joint resistance and the joint parameters such as contact pressure, surface parameters and thermophysical properties of interface material and contacting solids.

The main objective of the first part of this study is to propose a method for determining material thermophysical properties. The method incorporates an analytical model and determines thermal conductivity and effective Young's modulus from thermal resistance data. Also the disadvantages of the widely used existing standard ASTM D 5470 method will be discussed and recommendations for its improvement will be presented. In the second part of this study (Savija et al. [1]) an extensive experimental invesigation of

Grafoil GTA interface material will be conducted and from the obtained thermal resistance data the material properties will be determined applying the method proposed in the first part of the study.

REVIEW OF PREVIOUS WORK

Summary of studies on thermal interface materials by Savija et al. [2] shows that new commercially available polymeric and graphite-based sheets are mainly characterized experimentally. There are few analytical studies related to the thermal behavior of sheet materials based on the material properties and the mechanical and geometrical joint characteristics. However, thermal properties of the materials used in the above studies are obtained by standard methods found to have certain limitations.

Table 1 is a summary of various experimental studies of the thermal conductance for joints with polymers. One of the first experimental investigations on thermal conductance of metal-to-polymer joints was conducted by Fletcher and Miller [3]. The joint conductance values for tested elastomers were lower than the conductance of a bare aluminum junction. It was also concluded that elastomers with metallic or oxide fillers yielded higher conductance values than plain elastomers. Fletcher et al. [4] conducted an experimental investigation of polyethylene materials to determine the effect of additives on their thermal characteristics. The samples were tested at load pressures ranging from $0.41\,MPa$ to $2.76\,MPa$ and mean junction temperatures of $29-57\,^oC$. The thermal conductance increased with increasing temperatures and content of additives such as carbon.

Ochterbeck et al. [5] conducted an experimental investigation on thermal conductance of polyamide films combined with paraffin, commercial-grade diamonds and metallic foils. The experimental data indicated that polyamide films coated with paraffin-based thermal compound showed the best thermal performance and improved contact conductance seven to ten times compared to bare joints. The hardness of the interstitial material was seen to be the most important parameter in the selection of an interface material.

Marotta and Fletcher [6] presented experimental conductance data for several polymers. The conductance of the materials tested were shown to be independent of pressure $(0.51-2.76\,MPa)$ except for polyethylene, Teflon and polycarbonate which are relatively soft and ductile thermoplastic polymers. The apparent thermal conductivity of the materials was measured at temperatures between $10\,^oC$ and $100\,^oC$ and a pressure of $1.38\,MPa$. Almost all materials tested had thermal conductivity values independent of temperature.

Parihar and Wright [7] performed a detailed experiment measuring the thermal contact resistance of stainless steel SS 304-to-silicone rubber joint in air, under light pressures $(0.02-0.25\,MPa)$. The authors observed that the resistance at the hot interface was 1.3 to 1.6 times greater than the resistance at the cold interface. The resistances were different due to the rubber conductivity dependence on temperature. The joint resistance R_j decreased with increasing load. In general, contact resistance was shown to be a strong function of temperature due to the large temperature dependence of the rubber thermal conductivity and to a lesser extent of pressure P due to the elastomer softness.

An experimental study conducted by Mirmira et al. [8] showed that thermal contact conductance of some commercial elastomeric gaskets and graphite-based materials become less dependent on the contact pressure as the load increased, with the bulk conductance becoming predominant in the high pressure range (around $1000\,kPa-1500\,kPa$). The authors observed that the change in the mean interface temperature did not significantly effect the thermal conductance values for the gasket materials. Materials with fiberglas reinforcement showed poorer thermal performance than materials without reinforcement. Also, these materials demonstrated hysteresis effects - the conductance in the loading cycle was lower than in the unloading cycle.

The most comprehensive analytical study based on polymer experimental data was conducted by Fuller and Marotta [9]. They obtained an analytical model for predicting thermal joint resistance between metals and thermoplastic or elastomeric polymers by assuming optically flat surfaces at uniform pressures in vacuum. The mode of the deformation between the metal and the softer polymer was assumed to be elastic under light to moderate load based on experimental studies conducted by Parihar and Wright [7]. Incorporating the elastic model of Mikic [10] and defining a new polymer elastic hardness from the Greenwood and Williamson [11] definition of the elastic contact hardness, a simple correlation for dimensionless contact conductance was obtained:

$$\frac{h_c \sigma}{k_s m} = 1.49 \left(\frac{2.3P}{E_p m} \right)^{0.935} \tag{1}$$

By defining the thickness in terms of strain, the following expression for the bulk conductance was derived:

$$h_b = \frac{k_p}{t_p} \quad \text{and} \quad t_p = t_{p_o} \left(1 - \frac{P}{E_p} \right) \tag{2}$$

where k_p and t_p are the polymer conductivity and thickness under load, respectively and t_{p_o} is the poly-

Table 1: Research Related to Polymer-based Interstitial Materials Tested in Vacuum

Authors	**Contact Material**	**Interstitial Materials**
Fletcher and Miller [3]	Al 2024-T4	Silicone elastomers, Fluocarbon elastomer, Nitrile elastomer
Fletcher et al. [4]	Al 2024-T4	Ethylene vinyl acetate copolymers, Ethyl vinyl acetate copolymer, Polyethylene homopolymer
Ochterbeck et al. [5]	Al 6061-T6	Polyamide in combinations with foil, paraffin, diamonds, copper
Marotta and Fletcher [6]	Al 6061-T6	Polyethylene, PVC, Polypropylene, Teflon, Delrin, Nylon, Polycarbonate, Phenolic
Parihar and Wright [7]	SS 304	Silicone rubber (elastomer)
Mirmira et al. [8]	Al 6061-T6	Elastomeric gaskets (Cho-Therm, T-pli, Grafoil)
Fuller and Marotta [9]	Al 6061, SS	Delrin, Teflon, Polycarbonate, PVC
Marotta et al. [12]	Al 6061	eGraf, Furon (graphite-based)

mer thickness at zero load. Therefore, the joint conductance was defined as:

$$h_j = \frac{1}{\dfrac{1}{h_{c,1}} + \dfrac{t_{p_o}\left[1-(P/E_p)\right]}{k_p} + \dfrac{1}{h_{c,2}}} \qquad (3)$$

Experimental data from Marotta and Fletcher [6] and Fuller and Marotta [9] were compared to the joint conductance model and good agreement was found.

The most recent experimental and analytical studies on TIMs were conducted by Marotta et al. [12]. An analytical model for the resistance across the joint incorporating a sheet of interstitial elastic material and a gap filler such as gas or phase change material, was developed. The proposed joint model is compared with the experimental data obtained for several commercially available graphite materials. The specimens were placed under $0.34 - 1.03\,MPa$ pressure, between aluminum 6063 contacting surfaces of $1\,\mu m$ roughness. The joint resistance ranged from $65.8\,mm^2K/W$ to $10.3\,mm^2K/W$ showing a good agreement with the proposed model. A reduction in thermal performance of the tested TIMs was observed as the joint temperature increased from $40\,^oC$ to $80\,^oC$. This was explained by degradation in material thermal conductivity.

Thermal Conductivity Measurement Methods

There are a number of ASTM standard test procedures for quantifying thermal conductivity of thin material sheets. Some comparative test procedures are ASTM E 1530, E 1225, F 433 and C 518, while there is only one direct method, ASTM D 5470. The ASTM D 5470 method or "Standard Test Method for Thermal Transmission Properties of Thin Thermally Conductive Solid Electrical Insulation Materials," is the method that manufacturers and distributors generally refer to when reporting the material conductivity measurements.

The test method is designed for measuring joint thermal resistance of homogeneous or composite thermally conductive layers having a thickness ranging from $0.02\,mm$ to $10\,mm$ (ASTM D 5470-01 [13]). The obtained thermal resistance data are used to determine the effective thermal conductivity. The test method is applied to materials with low Young's modulus that are malleable enough to comply to the surface and exclude air from the interfaces so that thermal contact resistance is negligible. In the case of high-modulus material, test specimens are combined with the low-modulus layers. The tested material can be stacked to obtain results for different thickness specimens where it is assumed that the layers coalesce resulting in insignificant contact resistance at the interfaces.

The ASTM D 5470 apparatus is shown in Fig. 1. Meter bars are manufactured from a highly conductive material such as aluminum with contacting surface finish within $0.4\,\mu m$. The specimen thickness is measured before test using ASTM D 374 - Method C. The single material layer or stacked layers are subjected to $3\,MPa$ pressure so that the thermal contact resistance is reduced to an insignificant level. The insulating material is placed around the calorimeter sections and the joint temperature is maintained at $50\,^oC$ while the tests are conducted in air.

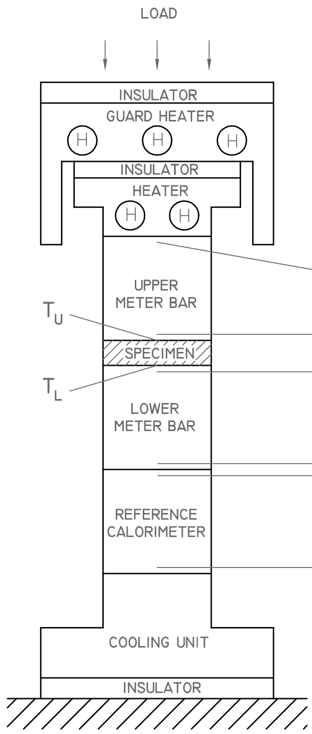

Figure 1: Test Apparatus for ASTM D 5470 Method (ASTM D 5470-01 [13])

Defining the bulk resistance as $r_b = t_o/k$, where t_o is thickness of the material before loading, and plotting the measured resistance of the single and stacked sheets as shown in Fig. 2, the apparent thermal conductivity is obtained as a reciprocal of the slope while the value at the y-intercept is the value of thermal contact resistance.

Using this method, the effective conductivity of the incompressible tested material is well predicted, while the effective conductivity of a compressible material is overestimated. The enhancement of the heat transfer across the joint due to the thickness reduction is incorrectly related to the conductivity. Determining r_c as y-intercept assumes constant r_c for all material thicknesses. This assumption is acceptable only at high pressures where the bulk resistance dominates and total r_c is negligible. Difficulties validating this assumption arise if data at only one pressure point are known so domination of the bulk resistance becomes questionable.

In industrial applications TIMs are mainly used at contact pressures of about $0.14\,MPa$ and therefore thermal resistance and conductivity are mainly determined with ASTM D 5470 procedure at this low pressure. However, contact resistance at this pressure is significant for most materials and can not be assumed to be constant for all thicknesses. This can cause a great non-linearity of thermal resistance data in Fig. 2 and lead to unreliable conductivity values. Also r_j measured at low pressures can not be used as a reference value since r_c plays a significant role and depends on surface characteristics and thermophysical properties of the contacting solids.

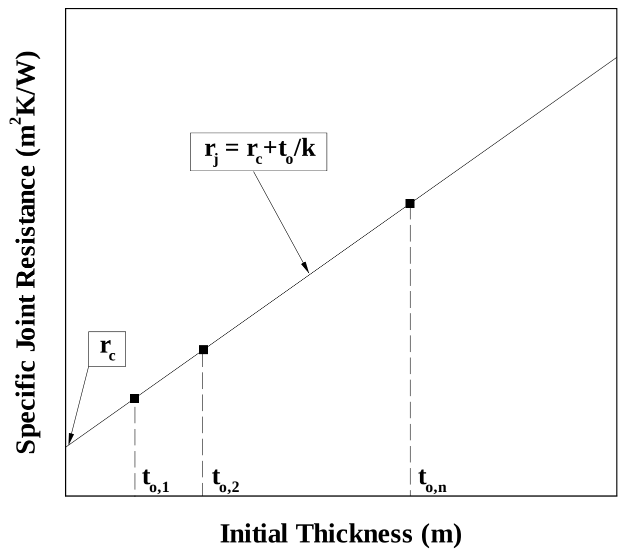

Figure 2: Determining Thermal Conductivity Using ASTM D 5470 Method

MODELING OF THERMAL JOINT RESISTANCE

A typical joint incorporating a thermal interface material in the form of a sheet is presented in Fig. 3. Two industrial surfaces, non-flat and rough, are in contact with a sheet of softer, non-flat and rough interface material. The vertical dimensions in Fig. 3 a) are exaggerated for clarity and the material thickness t_m is much greater than the surface roughness σ_1 and σ_2 so that $t_m \gg \sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$. k_1 and k_1 are conductivities of contacting bodies and k_m is the conductivity of the TIM. Because of the flatness deviations and the surface roughness, contact between the surfaces occurs at only a few points. The distribution of these points is hard to determine, making geometrical and thermal problems difficult to solve. Referring to Fig. 3 b), if the contact surfaces of the solids numbered 1 and 2 are machined to be flat and sufficient load flattens the interface material then a thermal joint which is easier to analyze is created in the form of two conforming interfaces.

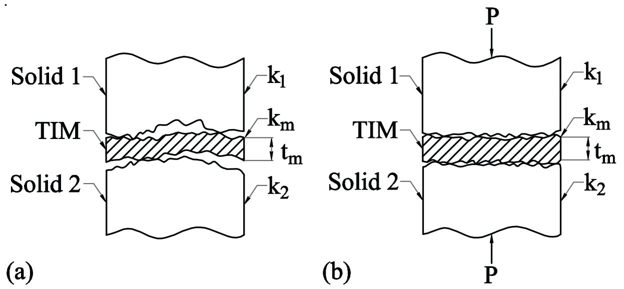

Figure 3: a) Real Joint b) Conforming Surfaces Joint with TIM

At the microscopic level, the interface between the sheet and the contacting solid, or another TIM sheet, consists of numerous discrete microcontacts and gaps which separate the two surfaces as shown in Fig. 4.

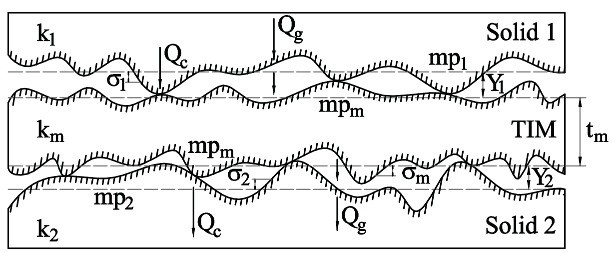

Figure 4: Conforming Rough Surfaces-Thermal Interface Material Joint

When steady heat transfer is present the following heat flow paths are possible: conduction through the microcontacts (Q_c), conduction through the gaps (Q_g), and radiation (Q_r) if the interstitial substance is transparent to radiation. The heat transfer rate across the joint is (Yovanovich [14], Yovanovich et al. [15]):

$$Q_j = Q_c + Q_g + Q_r \tag{4}$$

and

$$Q_j = \frac{\Delta T_j}{R_j} \quad \text{and} \quad Q_j = h_j A_a \Delta T_j \tag{5}$$

where ΔT_j is the temperature drop, R_j is the thermal joint resistance, h_j is the thermal joint conductance, and A_a is the apparent contact area. The joint conductance and resistance are related as follows:

$$h_j = \frac{1}{A_a R_j} \equiv \frac{1}{r_j} \tag{6}$$

where r_j is the specific joint resistance introduced to define thermal joint resistance for the apparent contact area.

The thermal resistance is affected by a great number of geometric, mechanical and thermophysical parameters: surface roughness, mean asperity slope, apparent contact pressure, contact or elastic hardness, compressive modulus of elasticity of the TIM, thickness of the layer and thermal conductivities of all bodies in contact. If the radiation at the joint is neglected (reasonable assumption for most applications where the joint temperature is below 600 ^oC) the corresponding thermal resistance network can be presented with Fig. 5.

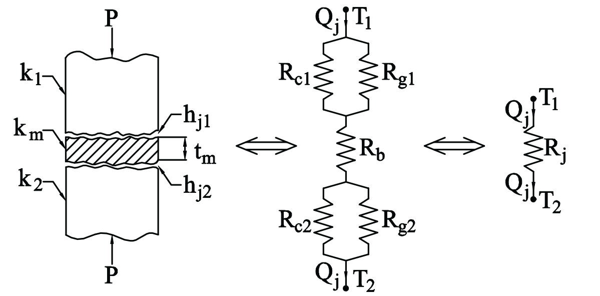

Figure 5: Joint with Thermal Interface Material Thermal Resistance Network

In the general case, the thermal joint resistance and conductance are defined as follows (Yovanovich et al. [15]):

$$\begin{aligned} R_j &= \left[\frac{1}{R_{c1}} + \frac{1}{R_{g1}}\right]^{-1} + R_b + \left[\frac{1}{R_{c2}} + \frac{1}{R_{g2}}\right]^{-1} \\ \frac{1}{h_j} &= \frac{1}{h_{c1} + h_{g1}} + \frac{1}{h_b} + \frac{1}{h_{c2} + h_{g2}} \end{aligned} \tag{7}$$

where R_c, R_g and R_b are the contact, gap and bulk resistance respectively and h_c, h_g and h_b are the corresponding thermal conductances. The two interfaces generally have different contact and gap resistances since contacting surfaces can have different properties and gaps can be occupied with different substances.

This problem can be simplified for some special cases. If there is no substance present in the gaps and the thermal joint is in vacuum, then $R_{g1} \to \infty$, $R_{g2} \to \infty$, $h_{g1} \to 0$ and $h_{g2} \to 0$, and:

$$\begin{aligned} R_j &= R_{c1} + R_b + R_{c2} \\ \frac{1}{h_j} &= \frac{1}{h_{c1}} + \frac{1}{h_b} + \frac{1}{h_{c2}} \end{aligned} \tag{8}$$

At relatively high contact pressure, where the bulk resistance dominates over the contact resistance, i.e. $h_{c1} >> h_b$ and $h_{c2} >> h_b$, a further simplification is possible:

$$R_j = R_b \quad \text{and} \quad h_j = h_b \tag{9}$$

The relations for contact and bulk resistances and corresponding conductances can be obtained from models that are based on the following simplifying assumptions:

(a) nominally flat rough surfaces with a Gaussian asperity height distribution

(b) random distribution of surface asperities over the apparent area

(c) thermal conductivity of interface material does not vary with pressure

(d) thickness change is linear under an applied load

Plastic Contact Conductance Model

If the surface asperities of the softer material, i.e. TIM, experience plastic deformation, the contact conductance can be defined using the relation for conforming rough surfaces and plastic deformation of contacting asperities (Cooper et al. [16]):

$$h_c = \frac{\sqrt{2}k_s}{4\sqrt{\pi}}\frac{m}{\sigma}\frac{\exp(-\lambda^2/2)}{\left[1-\sqrt{\frac{1}{2}\mathrm{erfc}(\lambda/\sqrt{2})}\right]^{1.5}} \tag{10}$$

where k_s is the harmonic mean thermal conductivity:

$$k_s = \frac{2\,k_i k_m}{k_i + k_m} \tag{11}$$

The effective surface roughness is:

$$\sigma = \sqrt{\sigma_i^2 + \sigma_m^2} \tag{12}$$

and absolute asperity slope is:

$$m = \sqrt{m_i^2 + m_m^2} \tag{13}$$

where i=1,2 refers to the interface i.e. contacting solid and subscript m refers to the interface material. The effective gap thickness λ is given by the theoretical relation (Yovanovich [14]):

$$\lambda = \sqrt{2}\ \mathrm{erfc}^{-1}\ \frac{2P}{H_c} \tag{14}$$

where P is the apparent contact pressure and H_c is the contact hardness of the softer material.

Equation (10). is reduced to a simpler form (Yovanovich [14]):

$$h_c = 1.25\,k_s\frac{m}{\sigma}\left(\frac{P}{H_c}\right)^{0.95} \quad \text{and} \quad r_c = \frac{1}{h_c} \tag{15}$$

Song and Yovanovich [17] showed that the relative contact pressure is:

$$\frac{P}{H_c} = \left[\frac{P}{c_1(1.62\sigma/m)^{c_2}}\right]^{\frac{1}{1+0.071c_2}} \tag{16}$$

The Vickers microhardness correlation coefficients c_1 and c_2, are related to the Brinell hardness by the relationships (Sridhar and Yovanovich [18]):

$$\frac{c_1}{3178} = 4.0 - 5.77H_B^* + 4.0\left(H_B^*\right)^2 - 0.61\left(H_B^*\right)^3$$

$$c_2 = -0.370 + 0.442\left(\frac{H_B}{c_1}\right) \tag{17}$$

where H_B is the Brinell hardness, and $H_B^* = H_B/3178$ for a Brinell hardness range from $1300\,MPa$ to $7600\,MPa$.

Elastic Contact Conductance Model

For conforming rough surfaces and elastic deformation of contacting asperities, Mikic [10] obtained the following relations for contact conductance:

$$h_c = \frac{k_s}{4\sqrt{\pi}}\frac{m}{\sigma}\frac{\exp(-\lambda^2/2)}{\left[1-\sqrt{\frac{1}{4}\mathrm{erfc}(\lambda/\sqrt{2})}\right]^{1.5}} \tag{18}$$

or

$$h_c = 1.55\,\frac{k_s m}{\sigma}\left(\frac{\sqrt{2}\,P}{E'm}\right)^{0.94} \quad \text{and} \quad r_c = \frac{1}{h_c} \tag{19}$$

The effective gap thickness is obtained from the following approximation (Yovanovich [14]):

$$\lambda = \sqrt{2}\,\mathrm{erfc}^{-1}\frac{4\,P}{H_e} \tag{20}$$

where the elastic contact hardness is defined as:

$$H_e = \frac{mE'}{\sqrt{2}} \tag{21}$$

The effective Young's modulus of the solid-interface material interface, E', is:

$$\frac{1}{E'} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_m^2}{E_m} \tag{22}$$

where ν_i, E_i and ν_m, E_m are Poisson's ratio and Young's modulus of the contacting solid and thermal interface material respectively.

Bulk Conductance Model

The specific bulk resistance of the material itself is directly related to its thickness and thermal conductivity:

$$r_b = \frac{t_m}{k_m} \quad \text{and} \quad h_b = \frac{k_m}{t_m} \tag{23}$$

Material thickness can vary with load depending on the Young's modulus. If the material is compressible and shows linear deformation under load, the bulk resistance becomes:

$$r_b = \frac{t_{m_o}\left(1 - \dfrac{P}{E_m}\right)}{k_m} \tag{24}$$

where t_{m_o} is the initial thickness at zero load and E_m is the effective Young's modulus of the material. The smaller the elastic modulus, the larger the material deformation. As a direct consequence of the material thickness decrease under a load, the bulk and overall thermal joint resistance is reduced. Although bulk resistance is an additional term in the resistance network, the overall joint resistance generally decreases when TIM is present at the joint since the contact resistance is greatly reduced.

Summary of Conductance Models

From the presented contact and bulk resistance models for joints incorporating TIMs in the form of sheets, it can be concluded that a TIM's thermal conductivity, hardness and Young's modulus are important parameters in the thermal resistance network. As expected, a TIM with higher thermal conductivity enhances the heat transfer through the joint. The hardness and Young's modulus define the material's compliance to the surface and effect on contact resistance. If the material is soft enough to completely occupy the gaps then the contact resistance is greatly reduced.

A plot of modeled thermal joint resistance versus contact pressure (Fig. 6) shows the three resistance regions. The first region, referred to as the contact resistance region, appears at relatively low pressures where the contact resistance dominates the trend of the joint resistance. The second region is the transition region where the contact resistance becomes significantly smaller. The third region, occurring at higher pressures, is the bulk resistance region, where contact resistance is significantly reduced. If the material thickness reduction under load is linear, the linear trend of the bulk resistance region can be observed. The position of these three regions on such a plot depends on material hardness, Young's modulus, and the characteristics of all surfaces in contact.

Generally, the waviness of the TIM and contacting solids is significant which makes mechanical and thermal modeling difficult due to the lack of analytical models for random non-conforming surfaces. The thermal joint resistance for conforming surfaces can be accepted as the lower bound of the thermal joint resistance for wavy surfaces. The waviness of TIM diminishes at higher pressures while the bulk resistance dominates over the contact resistance.

BULK RESISTANCE METHOD

A new method for determining the TIM's thermal conductivity from thermal resistance data incorporating the above analytical model is developed by Savija [19]. The method is named the Bulk Resistance Method (BRM) since it is applied to the data in the bulk resistance region. Unlike the ASTM D 5470 procedure, the BRM considers material thickness changes under load and in addition to thermal conductivity predicts a value of the effective Young's modulus and *in situ* thickness.

In order to apply the BRM to the thermal resistance data, the following experimental parameters need to be known:

(a) interface temperature,
(b) material initial thickness,
(c) surface characteristics of contacting solids and thermal interface materials:
  (i) RMS roughness,
  (ii) mean asperity slope and
  (iii) waviness;
(d) material properties of contacting solids:
  (i) conductivity (at the interface temperature),
  (ii) Young's modulus and
  (iii) Poisson's ratio;
(e) properties of thermal interface materials:
  (i) contact hardness and
  (ii) Poisson's ratio.

If the surface characteristics and thermophysical properties are not known or difficult to measure, the Simple BRM is applicable as the above properties affect contact resistance and are assumed to be insignificant in the bulk region. If all of the above properties are known or measured then the General BRM can be applied. The thermal interface temperature does not directly influence this method, but it should be recorded since thermal conductivity of some material properties can show significant dependence on temperature.

Development of Simple Bulk Resistance Method

From the thermal resistance data obtained at various loads the bulk resistance region is identified as the region where data points fit a linear trend as shown in Fig. 6.

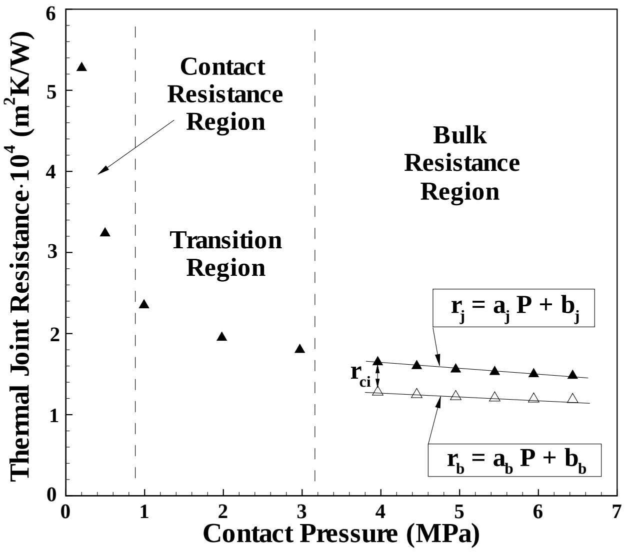

Figure 6: Specific Thermal Joint Resistance for Al 2024 - Grafoil GTA - Al 2024 Joint

A linear fit in the form:

$$r_j = a_j\,P + b_j \tag{25}$$

is applied to n available data points in the bulk region. For the Simple BRM, the thermal joint resistance in the bulk region is assumed to be the same as the bulk resistance:

$$r_j = r_b = \frac{t_{m_o}\left(1 - \dfrac{P}{E_m}\right)}{k_m} \tag{26}$$

Differentiating with respect to contact pressure, the following expression results:

$$\frac{dr_j}{dP} = -\frac{t_{m_o}}{k_m}\,\frac{1}{E_m} \tag{27}$$

Solving Eqs. (26) and (27) for k_m and E_m, and introducing the slope of the linear fit a_j:

$$\frac{dr_j}{dP} = a_j \tag{28}$$

the expressions for thermal conductivity and effective modulus of elasticity become:

$$k_m = \frac{t_{m_o}}{r_j - P\,a_j} \tag{29}$$

$$E_m = -\frac{t_{m_o}}{k_m}\,\frac{1}{a_j} \tag{30}$$

Discretizing Eq. (29), the values of conductivity are obtained for each pressure point, P_i, and corresponding thermal joint resistance, r_{j_i}:

$$k_{m_i} = \frac{t_{m_o}}{r_{j_i} - P_i\,a_j} \tag{31}$$

where $i = 1, 2, ..., n$. The resulting thermal conductivity is calculated by averaging k_{m_i} values:

$$k_m = \frac{1}{n}\sum_{i=1}^{n} k_{m_i} \tag{32}$$

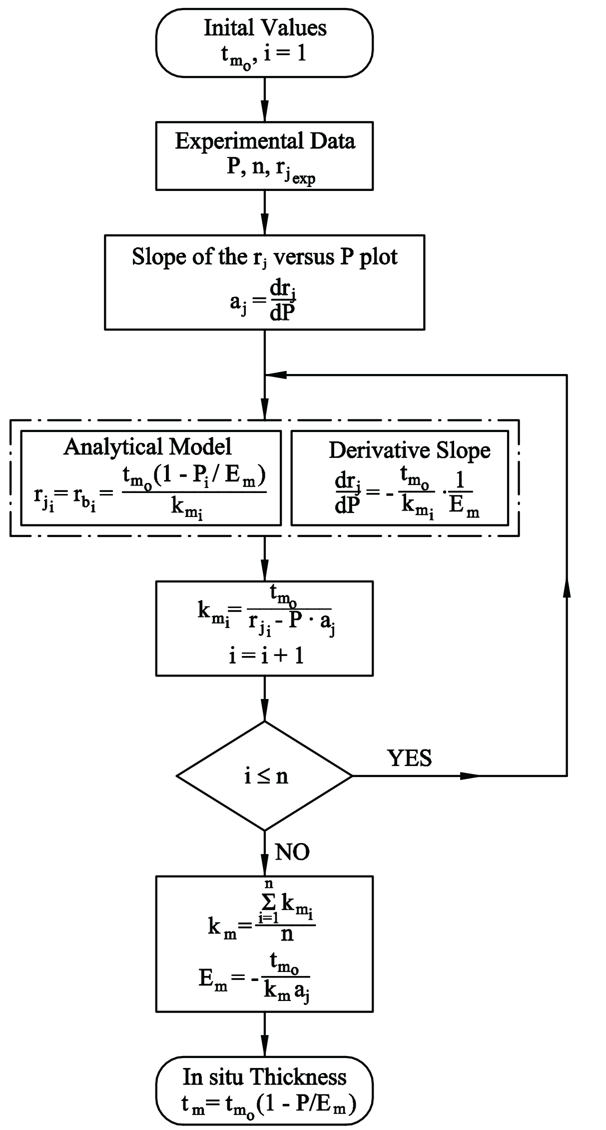

Figure 7: Simple Bulk Resistance Method-Flow Chart

Knowing k_m and going back to Eq. (30), the effective Young's modulus, E_m, is easy to determine. The *in situ* thickness of the material can be obtained as a function of pressure:

$$t_m = t_{m_o}\left(1 - \frac{P}{E_m}\right) \quad (33)$$

The uncertainty in the obtained values of material thermophysical properties depends on the experimental data and the slope of the linear fit - the more data obtained in the bulk resistance region, the more accurate the slope and the less erroneous final result. The Simple Method is presented in the flow chart in Fig. 7.

Development of General Bulk Resistance Method

Similar to the Simple BRM, the bulk resistance region is identified. Based on the surface characteristics and properties of the contacting solids and TIM, the thermal contact resistance is calculated as a function of pressure using Eqs. (15) or (19) The type of asperities deformation can be determined from the difference between loading and unloading cycle. If the asperity deformation is elastic, the contact resistance remains the same in unloading cycle, so the discrepancy between loading and unloading data is actually the difference between the bulk resistances in these two cycles caused by the material permanent bulk deformation, if present. If the asperities are plastically deformed, thermal contact resistance becomes smaller in the unloading cycle and therefore, the difference between the loading and unloading thermal joint resistances is greater than the difference between the corresponding bulk resistances.

For the thermal contact resistance calculation, it is necessary to know the conductivity and Young's modulus of the tested material as well as Poisson's ratio and contact hardness. It should be noted that Poisson's ratio and contact hardness are usually not available in commercial data sheets and therefore should be measured or estimated. Thermal conductivity and effective modulus of elasticity are not known, but can be initially guessed and iteratively solved using the General BRM. To reduce the total number of required iterations, the Simple BRM can be applied first to obtain k_m and E_m values to be used as the initial guess in the General BRM.

Once the contact resistance is calculated as a function of pressure, it is subtracted from the measured thermal joint resistance in the bulk region, yielding the bulk resistance data points which can also be approximated with a linear fit (Fig. 6). The further steps are then the same as for the Simple BRM - instead of r_j

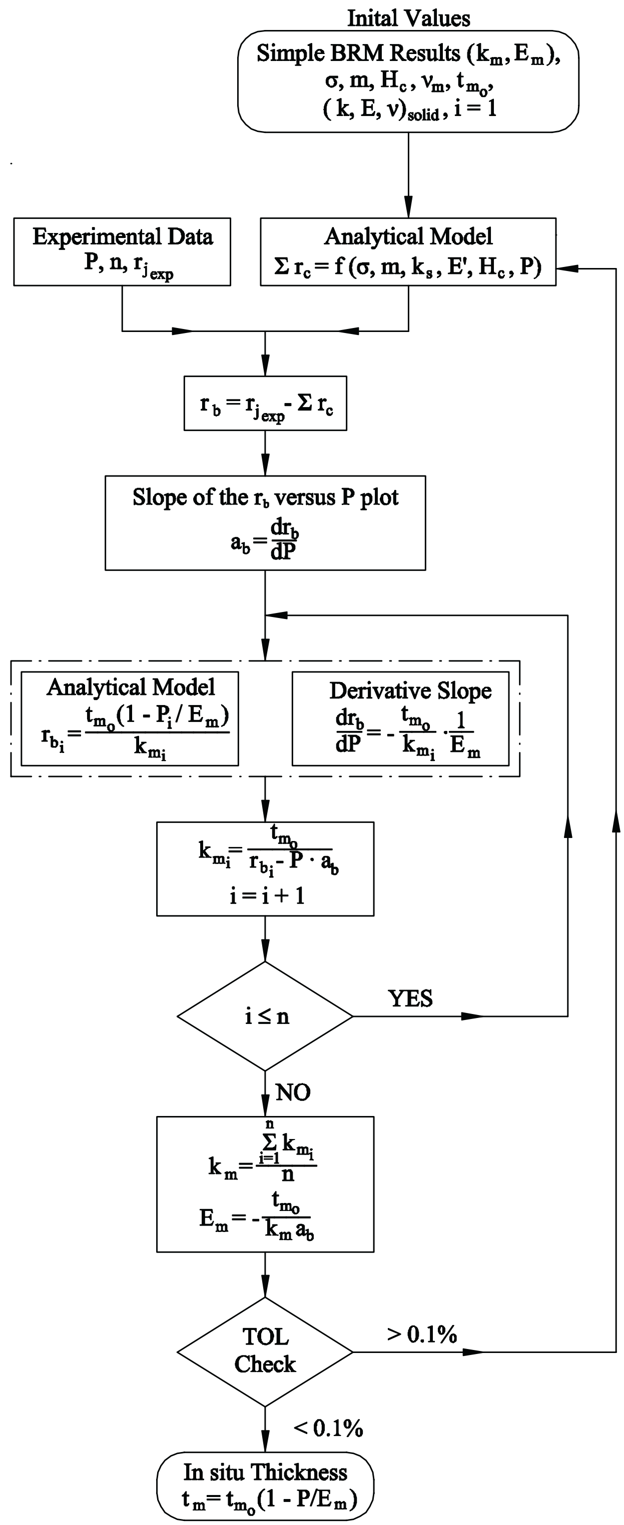

Figure 8: General Bulk Resistance Method-Flow Chart

and dr_j/dP, calculated r_b and dr_b/dP are used in the calculation of the thermal conductivity and effective Young's modulus. The value of thermal conductivity is slightly larger compared to the result of the Simple BRM since $r_b < r_j$ and $|dr_b/dP| < |dr_j/dP|$ due to the contact resistance dependence on pressure.

This method is applicable at low pressures but since the TIM surfaces are generally non-flat, the plastic and elastic analytical models underpredict thermal contact resistance. Therefore, it is recommended to use the bulk region data. The General Method is presented in the flow chart in Fig. 8.

There are two possible procedures for BRM validation:

(a) The material thickness calculated using the model is compared to the measured *in situ* thickness determined during testing using an experimental set up;

(b) The final thickness after the loading-unloading cycle, denoted as t_{m_f}, can be determined using the unloading cycle data. A procedure similar to the Simple BRM is applied if the material thickness change is linear during unloading (unloading bulk resistance region has linear trend). The thermal joint resistance in the bulk region of the unloading cycle is approximated with the thermal bulk resistance ($r_j \approx r_b$). The y-intercept of the approximated linear fit of the bulk resistance data represents the thermal bulk resistance at zero load, referred to as the final bulk resistance r_{b_f}. Using the value of the thermal conductivity found with the BRM applied to the loading cycle, the final thickness can be determined from the following relation:

$$t_{m_f} = r_{b_f}\, k_m \tag{34}$$

The obtained value can be compared to the measured final thickness in order to validate the method.

The two Bulk Resistance methods proposed above are also applicable to a stack of TIM sheets. If the Simple BRM is applied, the additional contact resistance between the sheets is ignored while in the case of General BRM, contact resistance is calculated. To find the average thermal conductivity of different thickness samples, a procedure similar to the ASTM D 5470 method can be applied. While the ASTM D 5470 standard recommends a plot of joint resistance versus initial material thickness, joint resistance and bulk resistance versus *in situ* thickness are required for the Simple and General BRM, respectively. The slope of the linear approximation is the reciprocal of average conductivity for the tested material.

SUMMARY AND CONCLUSIONS

The principal disadvantage of using ASTM D 5470 for determining thermal conductivity in compressible materials is the inherent overprediction of k_m due to the deformation of the sample during loading. The Bulk Resistance method eliminates this problem, providing a more precise estimation of the thermal conductivity.

The method was developed primarily for materials tested in a vacuum, but it can be easily extended to joints in air or some other gaseous environment. In the case of non-vacuum conditions, the gap resistance term should be integrated into the proposed method if the method is to be applied to more complex joints. The method should be tested on a wider range of TIMs and if the change in the material thickness is non-linear under an applied load, the proposed method should be modified to accommodate non-linear material deformation. In this case, the measurements of *in situ* thickness would be of great benefit.

This study considered smooth and nominally flat surfaces The current method could be extended to include contacts of non-flat surfaces, however, initially it would be necessary to develop a thermal joint resistance model for such contacts.

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