Thermal Joint Resistance of Polymer-Metal Rough Interfaces

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A compact analytical model is proposed for predicting thermal joint resistance of rough polymer-metal interfaces in a vacuum. The model assumes plastic deformation at microcontacts and joint temperatures less than the polymer's glassy temperature. The joint resistance includes two components: (i) bulk resistance of the polymer, and (ii) microcontacts resistance, i.e., constriction/spreading resistance of the microcontacts at the interface. Performing a deformation analysis, it is shown that the deformation mode of surface asperities is plastic for most polymers studied. It is observed that the thermophysical properties of the polymer control the thermal joint resistance and the metallic surface properties have a second order effect on the thermal joint resistance. A new nondimensional parameter, the ratio of microcontacts over bulk thermal resistances, is proposed as a criterion to specify the relative importance of the microcontacts thermal resistance. The present model is compared with more than 140 experimental data points collected for a selected number of polymers. The averaged rms relative difference between the model and data is approximately 12.7%. [DOI: 10.1115/1.2159005]

Introduction

The continued growth in performance and functionality of microelectronic and avionic systems has resulted in a significant increase in heat dissipation rates and presents a great challenge to thermal engineers. A number of failure mechanisms in electronic devices such as intermetallic growth, metal migration, and void formation are related to thermal effects. Following the Arrhenius law, the rate of these failures is approximately doubled with every 10°C increase above 80°C in the operating temperature of the device [1]. The heat generated must pass through a complex network of thermal resistances to dissipate from the junction to the surroundings. The most significant resistance is the thermal contact resistance (TCR) at the interface between the package and its heat sink or heat pipe. TCR may be reduced by two methods: (1) increasing the real contact area, accomplished by (a) increasing contact pressure, or (b) reducing the roughness and out-of-flatness of the contacting surfaces before the interface is formed; and (2) using a thermal interface material (TIM) of higher thermal conductivity that can conform to the imperfect surface features of the mating surfaces. Load constraints on electronic components make it unfeasible to use high contact pressure. Also, manufacturing highly finished surfaces is not practical due to cost constraints. Therefore, the practical alternative is to use a TIM applied at a moderate contact pressure. Most TIMs are polymeric materials filled with thermally conductive particles. Therefore, TCR of a metal-polymer interface is an important issue in microelectronics and chip cooling. In addition to microelectronics, the use of polymers in everyday items is rapidly increasing in a wide variety of applications, see [2] for more detail.

Problem Statement

Figure 1 illustrates the geometry of a polymer-metal joint in a vacuum which has been used in the existing experimental investigations. A polymer specimen of thickness t is sandwiched between two cylindrical, rough, nominally flat metal specimens of radius b_L. Thermocouples are mounted in metal flux meters so the heat transfer rate Q can be determined. Also, metal interface temperatures are estimated by extrapolating the temperature profiles in solids 1 and 2. Three thermal resistances exist in the described joint: the contact resistance at interface 1, the bulk resistance of the polymer, and the contact resistance at interface 2. To reduce the overall mean temperature and also considering that the TCR is identical at both interfaces 1 and 2, thermal paste is applied at one of the interfaces, so that the TCR of that interface becomes very small and can be neglected.

Heat transfer via radiation across the joint remains small for most engineering applications of TCR [3] and can be neglected. In this study, the joint temperatures are assumed to be less than the polymer's glassy temperature of about 100°C; therefore, the radiative heat transfer is ignored. Since the contact is in a vacuum, heat is assumed to be transferred only by conduction through microcontacts at the metal-polymer interface; thus there is no convection heat transfer between contacting bodies. The constriction/spreading resistances at microcontacts R_s are defined as:

$$R_s = \Delta T/Q \tag{1}$$

where ΔT is the temperature drop at the polymer metal interface and Q is the heat transferred.

In addition, heat flow must overcome the bulk resistance of the polymer specimen R_b which is expressed as:

$$R_b = \frac{t}{A_a k_p} \tag{2}$$

where t, $A_a = \pi b_L^2$, and k_p are the thickness of the polymer at the applied load, the apparent contact area, and the thermal conductivity of the polymer, respectively. As shown in Fig. 1, the contact resistance R_s and the bulk resistance R_b are in series, so the joint resistance can be determined from

$$R_j = R_s + R_b \tag{3}$$

Literature Review

A few studies, mostly experimental, exist in the open literature for the TCR of metal-polymer joints. Fletcher and Miller [4] experimentally investigated the joint resistance of selected gasket materials at different applied contact pressures under a vacuum. They presented the experimental results, i.e., the joint resistance, in graphical form without proposing a model for predicting the data. Parihar and Wright [5] conducted experiments and measured the thermal joint resistance of a stainless steel 304-silicone rubber interface in atmospheric air as the applied contact pressure was varied from 0.0488 to 0.125 MPa. Their elastomer sample had a

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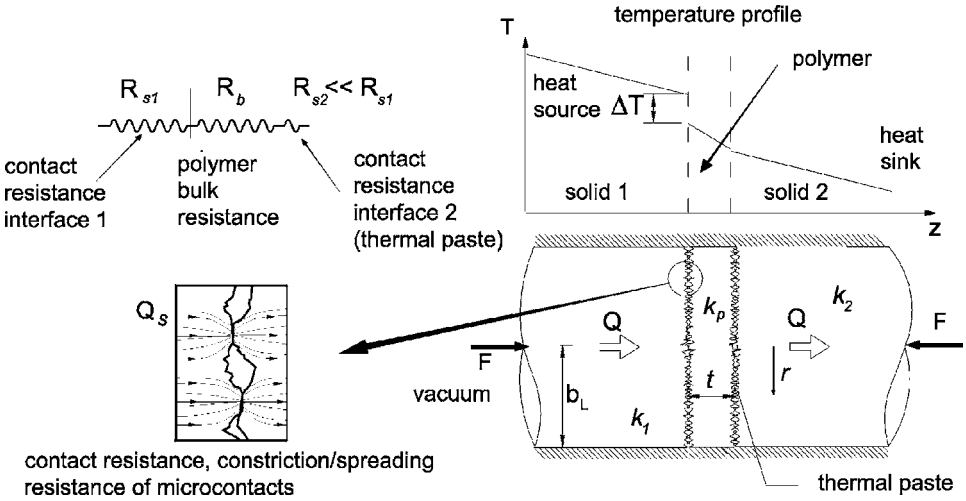

Fig. 1 Geometry and thermal resistance network. Conforming rough polymer-metal joint in a vacuum.

4.67 mm thickness and was instrumented with thermocouples. They presented the contact resistance measured at both interfaces; however, no model was proposed. Marotta and Fletcher [2] measured thermal conductivities and the thermal joint resistance of several thermoplastic and thermoset polymers over a range of temperatures and contact pressures. Thermal conductivities of the polymers reported in [2] showed small variation as the temperature was changed over the range of 10–100°C. Marotta and Fletcher [2] compared their measured thermal joint resistance data R_j with the microcontacts resistance R_s calculated from the Mikic elastic model [6] and the Cooper et al. plastic model [7]. It was shown that both models failed to predict the trend of the data [2]. However, the comparisons of Marotta and Fletcher [2] were not appropriate because their measured joint resistance, which include the microcontacts and the bulk resistances (R_s+R_b) were compared only against the microcontacts resistance R_s predicted by the models. It should be noted that their experiments were conducted in relatively high pressures where the bulk resistance R_b controls the joint resistance and the contact resistance R_s is small and often negligible. Also, they did not offer any model to predict the joint resistance.

Fuller and Marotta [8] conducted experiments in a vacuum with several polymers and developed an elastic contact model for predicting the polymer-metal joint resistance. Their model accounted for the bulk resistance and the TCR of the joint, see Eq. (3). The TCR component of their model was based on the assumption that the deformation of asperities was elastic. They showed good agreement with their experimental data. However, assuming elastic deformation of microcontacts may lead to physically impossible effective elastic microhardness for polymers, as it is discussed later.

The thermal contact resistance theory is based on the following premises: (1) 1D heat transfer and that the heat flow passes through the contact plane with the heat flow direction perpendicular to the contact plane; and (2) the equivalent contact simplification (see Fig. 2). The contact plane or the apparent area is the projection of contacting surfaces on the plane normal to the direction of the applied load, thus the real contact area is always less than, or at its limit, equal to the apparent area. Fuller and Marotta [8] and Parihar and Wright [5] stated that "*since polymers have comparatively lower modulus of elasticity, the calculated real contact area can be greater than the apparent area.*" Therefore, within the context of TCR theory, their premise is not correct.

The preceding shows the need for developing model(s) that enables one to predict the TCR of a polymer-metal interfaces. The objective of this study is to develop a compact analytical model for the thermal joint resistance of rough polymer-metal contacts in a vacuum.

Theoretical Background

Real surfaces have roughness. If the asperities of a surface are isotropic and randomly distributed over the surface, the surface is called Gaussian. Due to the random nature of roughness, the microcontacts are distributed randomly in the apparent contact area. The real contact area, A_r, the summation of these microcontacts, forms a small portion of the nominal contact area, typically a few percent of the nominal contact area [9]. The contact between two Gaussian rough surfaces is modeled by the contact between a single Gaussian surface that has the combined surface characteristics of the two surfaces with a perfectly smooth surface, as shown in Fig. 2 (for more detail, see [10]). The combined roughness σ and surface slope m can be found from

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \quad \text{and} \quad m = \sqrt{m_1^2 + m_2^2} \tag{4}$$

The relationship between the strain and stress in most polymers is similar to that of metals providing their temperature is less than the glassy temperature T_g. According to Calleja and Fakirov [11], when a polymer is cooled down from the liquid or rubbery state, it becomes much stiffer as it goes through a certain temperature range. This "glassy" transition can be recognized by the change in many properties of the material, especially the modulus of the material. The focus of this paper is on the temperature range less than the glassy temperature where a linear relationship between the bulk deformation of the polymer and the applied load exists.

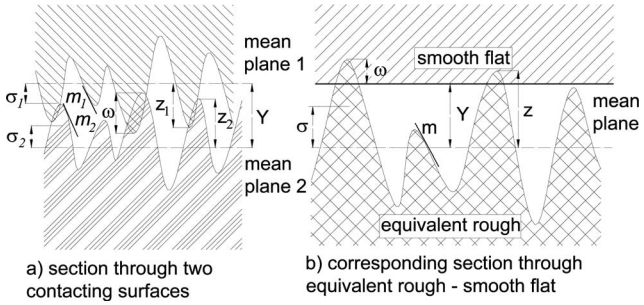

Fig. 2 Equivalent contact of conforming rough joints

Table 1 Polymers characteristic data [2]

Test material	σ (μm)	m	E (GPa)	H_{mic} (GPa)	k_p (w/mK)	t_0 (mm)	γ
ABS	0.93	0.17	2.90	0.17	0.18	1.59	0.30
Delrin	1.42	0.21	3.59	0.37	0.38	1.62	0.46
Nylon	1.23	0.20	2.11	0.41	0.31	1.65	0.90
Phenolic	1.13	0.19	6.80	0.36	0.65	1.56	0.26
Poly1[a]	0.82	0.16	2.39	0.14	0.22	1.62	0.32
Poly2[b]	1.92	0.24	3.00	0.13	0.45	1.66	0.17
Poly3[c]	1.33	0.20	1.90	0.41	0.31	1.64	0.97
PVC	0.56	0.14	2.50	0.15	0.17	1.62	0.37
Teflon	1.52	0.22	0.46	0.20	0.25	1.68	1.78
Al 6061	0.51	0.05	72.1	—	208	—	—

[a]Poly1: Polycarbonate
[b]Poly2: Polyethylene
[c]Poly3: Polypropylene

As a result, Hooke's Law can be used to determine the bulk elastic deformation of the polymer specimen shown in Fig. 1 as

$$\varepsilon = \frac{\Delta t}{t_0} = \frac{P}{E_p} \tag{5}$$

where $\Delta t = t_0 - t$, E_p, and P are the bulk deformation, polymer Young's modulus, and the nominal contact pressure, respectively.

Polymer Microhardness

Microhardness of polymers can be measured by static penetration of the specimen with a standard indenter at a known pressure similar to metals [11]. The strain boundaries for plastic deformation below the indenter are critically dependent on microstructural factors, e.g., crystal size and perfection and the degree of crystallinity. Indentation during a microhardness test permanently deforms only a small volume element, on the order of $10^9 - 10^{11}$ nm^3, for a nondestructive test [11]. Thus the contact stress between the indenter and the specimen is much larger than the compressive yield stress of the specimen. The material under the indenter consists of a zone of severe plastic deformation, about 4 to 5 times the penetration depth of the indenter into the specimen, surrounded by a larger zone of elastic deformation. Together, these zones generate stresses that supports the force exerted by the indenter. Table 1 lists the Vickers microhardness measured for several polymers. Applied loads used to measure the microhardness were less than 500 g except for Phenolic where a 1000 g load was applied. The reported values are the averaged of 5 measurements.

Thermal Resistance of Microcontacts

For temperatures less than the glassy temperature, a polymer's mechanical response, both macro and micro, is similar to metals. Therefore, one can apply existing TCR models, originally developed for metals, to determine the joint resistance of polymers. TCR models can be categorized into two main groups: plastic and elastic. The fundamental assumptions of the TCR theory, which are common in both groups as listed below:

(1) Contacting surfaces are rough and isotropic with a Gaussian asperity distribution;
(2) The behavior of a given microcontact is independent of all other microcontacts;
(3) The interfacial force on any microcontact spot acts normally (no frictional or tangential forces);
(4) The deformation mechanics, i.e., the stress and displacement fields, are uniquely determined by the shape of the equivalent surface.

With the concept of equivalent roughness, the plastic model assumes that the asperities are flattened or equivalently penetrate into the smooth surface without any change in the shape of the part of surfaces not yet in contact. As mentioned in the previous section, the pressure at microcontacts is sufficiently large, i.e., larger than the strength of the materials in contact. Tabor [9] suggested that these contact pressures were equal to the flow pressure of the softer of the two contacting materials. Therefore, in plastic models the pressure at microcontacts is effectively independent of load and the contact geometry. The real area of contact is then proportional to the load, $A_r/A_a = P/H_{mic}$, where P is the apparent contact pressure. Cooper et al. (CMY) [7], used the level-crossing theory and equivalent surface approximation to derive relationships for mean microcontact size and number of microcontacts by assuming hemispherical asperities whose heights and surface slopes have Gaussian distributions. The CMY model was essentially based on the assumption that each microcontact consists of two hemispherical asperities in symmetric plastic contact. Later Yovanovich [12] summarized the CMY [7] model and reported relationships for calculating the contact parameters and also proposed a compact expression for calculating the TCR of conforming rough joints:

$$h_p = 1.25 k_s \left(\frac{m}{\sigma}\right)\left(\frac{P}{H_{mic}}\right)^{0.95} \tag{6}$$

where k_s is the harmonic mean of the thermal conductivities

$$k_s = \frac{2k_1 k_p}{k_1 + k_p}$$

Considering that the plastic deformation is irreversible and cannot be repeated on subsequent loadings, Archard [13] stated that the normal contact of rough surfaces could be plastic at sites of the first several contacts, but for moving machine parts that meet millions of times during their life the contact must reach an "elastic" state. Archard [13] showed that any elastic model based on simple Hertzian theory in which the number of contacts remains constant as the load increases will give $A_r \sim F^{2/3}$ which does not satisfy the observed proportionality $A_r \sim F$ reported by Tabor [9]. But, if the average contact size remains constant and the number of microcontacts increases, the area would be proportional to the load. This approach led to an "effective elastic hardness" H_e.

Mikic [6], based on the CMY model, proposed an elastic model. He assumed that the elastic real contact area is half of the plastic contact area, i.e., $A_{elastic}/A_{plastic} = 1/2$. Mikic's model satisfied the linear proportionality between the applied load and the real contact area. He also proposed an effective elastic microhardness [6]:

$$H_e = \frac{E' m}{\sqrt{2}} \tag{7}$$

where,

$$\frac{1}{E'} = \frac{1 - \upsilon_1^2}{E_1} + \frac{1 - \upsilon_2^2}{E_2}$$

where E and υ are the elastic modulus and Poisson's ratio, respectively. Mikic proposed an expression for calculating the TCR of conforming rough joints assuming elastic deformation [6]

$$h_e = 1.55 k_s \left(\frac{m}{\sigma}\right)\left(\frac{P}{H_e}\right)^{0.94} \tag{8}$$

It can be seen from Eqs. (7) and (8) that h_e is a very weak function of m. Another correlation was suggested by Mikic, assuming a typical value of $m = 0.1$, as $h_e = 1.9(k_s/\sigma)(P/E')^{0.94}$. Table 2 summarizes the relationships of the CMY [7] plastic model and the Mikic [6] elastic model.

Deformation Mode of Asperities

A priori assumptions of the deformation mode of asperities could lead to wrong conclusions. The effective elastic microhardness H_e, calculated from Eq. (7), could result in unrealistic values

Table 2 Mikic/CMY elastic and plastic models

Model	Relation
$\kappa=1$ elastic $\kappa=2$ plastic $\lambda=Y/\sqrt{2}\sigma$ $A_a=\pi b_L^2$	$\frac{A_r}{A_a}=\frac{\kappa}{4}\,\mathrm{erfc}(\lambda)$ $n_s=\frac{1}{16}\left(\frac{m}{\sigma}\right)^2\frac{\exp(-2\lambda^2)}{\mathrm{erfc}(\lambda)}A_a$ $a_s=\frac{2\sqrt{\kappa}}{\sqrt{\pi}}\left(\frac{\sigma}{m}\right)\exp(\lambda^2)\mathrm{erfc}(\lambda)$
plastic [7]	$\lambda=\mathrm{erfc}^{-1}(2P/H_{\mathrm{mic}})$
elastic [6]	$\lambda=\mathrm{erfc}^{-1}(4P/H_e)$

larger than the material microhardness, i.e., $H_e > H_{\mathrm{mic}}$. This is physically impossible. To avoid this, Mikic [6] performed an analysis to determine the mode of deformation and proposed a plasticity index as follows:

$$\gamma=\frac{H_{\mathrm{mic}}}{E'm} \tag{9}$$

According to [6] for surfaces with $\gamma \geqslant 3$, 90% of the actual area will be exposed to the elastic contact pressure, thus the contact will be predominantly elastic. For $\gamma \leqslant 0.33$, 90% of the actual area will have the plastic contact pressure; thus the contact will be predominantly plastic.

$$\begin{cases} \gamma \leqslant 0.33 & \text{asperities deform plastically} \\ 0.33 \leqslant \gamma \leqslant 3.0 & \text{transition} \\ \gamma \geqslant 3.0 & \text{asperities deform elastically} \end{cases} \tag{10}$$

Mikic [6] concluded that for most engineering surfaces the asperity deformation mode is plastic and the average asperity pressure is the microhardness. It can be seen that the deformation mode of asperities depends on material properties (E' and H_{mic}) and shape of the asperities m. Mikic also reported that the mode of deformation, as was also stated by Greenwood and Williamson [14], is not sensitive to the pressure level.

Fuller and Marotta [8] developed an elastic model for calculating the TCR of polymer-metal interface and showed good agreement with the experimental data. They reported an effective elastic microhardness as

$$H_{e,\mathrm{FM}}=\frac{E_p m}{2.3} \tag{11}$$

It should be noted that in developing Eq. (11) only the polymer Young's modulus E_p was considered instead of the effective elastic modulus E'. In other words, Eq. (11) neglects the lateral strain, i.e., the effect of Poisson's ratio υ.

Fuller and Marotta [8] did not follow the deformation analysis proposed by Mikic. Applying this deformation analysis, one observes that the deformation mode of asperities is plastic for most polymers studied. Assuming elastic deformation mode of asperities may result in unrealistic situations where the effective elastic microhardness becomes larger than the actual (measured) hardness value, i.e., $H_e > H_{\mathrm{mic}}$.

The deformation mode of asperities in [8] was assumed elastic based on the conclusion made by Parihar and Wright [5]. Parihar and Wright [5] measured the surface roughness and asperities slope of a stainless steel flux meter and a silicone rubber specimen before and after loading. They concluded that the contact was elastic since the before and after roughness measurements were identical. This conclusion may not be correct. The mean rms roughness σ and the mean absolute surface slope m, based on their definitions, are *statistical* measures of rough surfaces. These values will not be influenced by the deformation due to contact since the real contact area is a small fraction of the apparent area. Clausing and Chao [15] measured roughness of metallic specimens before and after loading and also reported identical values. They also measured the joint resistance as the applied load was varied, then removed the load and broke the joint and rotated the upper specimen by 90° and repeated the test with the same pair. No changes were observed in thermal joint resistance measurements [16] which was consistent with their roughness measurements before and after loading.

In conclusion, as stated by Mikic [6] and Greenwood and Williamson [14], the deformation mode of asperities is not an arbitrary choice and should be determined using the plasticity index.

Present Model

The present model is based on the premise that the load-displacement behavior of polymers is similar to metals in the temperature range of interest, i.e., temperatures below the glassy temperature. A successful thermal joint resistance model accounts for both the bulk and the thermal contact resistance of the polymer metal joint. The bulk resistance of the polymer can be calculated combining Eqs. (2) and (5) as:

$$R_b=\frac{t_0(1-P/E_p)}{A_a k_p} \tag{12}$$

Equation (12) was first used by Fuller and Marotta [8] to calculate the bulk conductance. A deformation analysis is performed and the plasticity indices detailed in Eq. (9) are listed for the polymers used in this study in Table 1. Since the plasticity index γ approaches 0.33 and for most polymers is less than 3, the deformation mode of asperities is assumed to be plastic in this study.

The microcontacts are often assumed to be isothermal [10]. Thermal constriction/spreading resistance of microcontacts can be modeled using a flux tube geometry [7], or if microcontacts are considered to be located far enough from each other, the solution of isothermal heat source on a half-space solution [3] can be used. These solutions were compared in [17] and it was concluded that the microcontacts can be considered as heat sources on a half-space for most engineering applications. Bahrami et al. [17] assumed plastically deformed asperities and used scale analysis techniques to develop a compact model to predict thermal constriction/spreading resistance through the microcontacts, R_s:

$$R_s=\frac{0.565H_{\mathrm{mic}}(\sigma/m)}{k_s F} \tag{13}$$

where F is the applied load. Equation (13) yields values close to those obtained with Yovanovich [12] expression, Eq. (6), thus both relationships can be used. The joint resistance then can be calculated from Eq. (3) as:

$$R_j=\frac{0.565H_{\mathrm{mic}}(\sigma/m)}{k_s P A_a}+\frac{t_0(1-P/E_p)}{A_a k_p} \tag{14}$$

Equation (14) is limited to joints where (i) the mean joint temperature is less than the polymer's glassy temperature and (ii) the deformation mode of asperities is plastic. Since the thermal conductivity of polymers is relatively small compared to metals, the harmonic mean of thermal conductivities of a metal-polymer interface is controlled by the polymer thermal conductivity, i.e., $k_s \simeq k_p$. Also, values of the effective elastic modulus E' and the joint microhardness H_{mic} are controlled by the polymer values. Therefore, the joint resistance is dominated by the polymer parameters.

The surface slope values reported by Fuller and Marotta [8] are relatively large compared to previously measured slope values published by Marotta and Fletcher [2] (almost 3× higher). To verify the surface slope values, polymer samples (PVC and nylon) were prepared at the Microelectronics Heat Transfer Laboratory at the University of Waterloo. Roughness and the surface slopes of these samples were measured and compared with the reported

Table 3 Polymers characteristic data [8]

Test material	σ (μm)	m	E_p (GPa)	H_{mic} (GPa)	k_p (w/mK)	t_0 (mm)	γ
Delrin1	2.19	0.26	3.59	0.37	0.38	1.27	0.37
Delrin2	2.29	0.26	3.59	0.37	0.38	1.32	0.36
Polyethylene	0.81	0.15	2.38	0.15	0.22	1.44	0.38
PVC	0.74	0.15	4.14	0.15	0.17	1.31	0.23
Al 6061	0.51	0.05	72.1	—	183	—	—

values by [2] and similar results were found. Therefore, it was concluded that the surface slope values of [8] must be modified. Using Marotta and Fletcher [2] slope values, the following correlation was developed to estimate the surface asperity slope as a function of roughness:

$$m = 0.19(\sigma/\sigma_0)^{0.52} \tag{15}$$

where σ is in micron and $\sigma_0 = 1$ μm. The slope values listed in Tables 3 and 2 are the estimated values based on Eq. (15).

Figures 3–5 illustrate comparisons between the present model, Eq. (14), and the experimental data sets for Delrin1, Delrin2, and Polyethylene collected by Fuller and Marotta [8], respectively. Their experimental arrangement is schematically shown in Fig. 1 with $b_L = 12.7$ mm. In both experimental arrangements [2,8], thermal paste was used in one of the interfaces to reduce the overall temperature drop across the joint, as shown in Fig. 1. The mean temperature of the polymer specimens were maintained at $40 \pm 1\,^{\circ}$C which was significantly lower than the glassy temperature for the polymers tested. The combined roughness σ and surface asperities slope m (corrected values using Eq. (15)), thermal conductivity k_p, microhardness H_{mic}, and elastic modulus E_p for polymer specimens are summarized in Table 3.

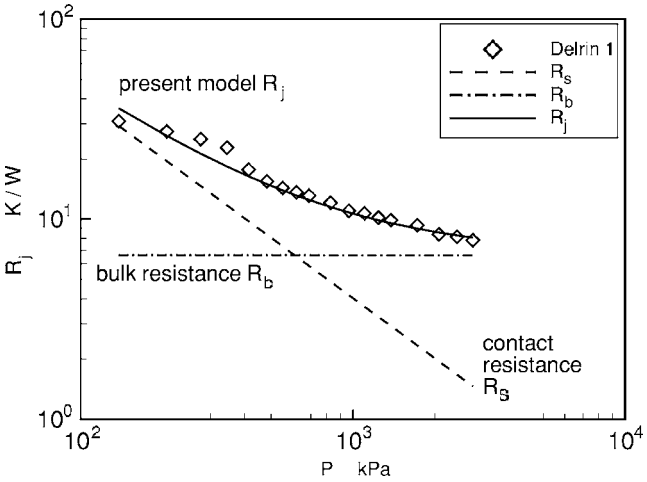

Fig. 3 Comparison between present model and delrin 1. Data collected by [8].

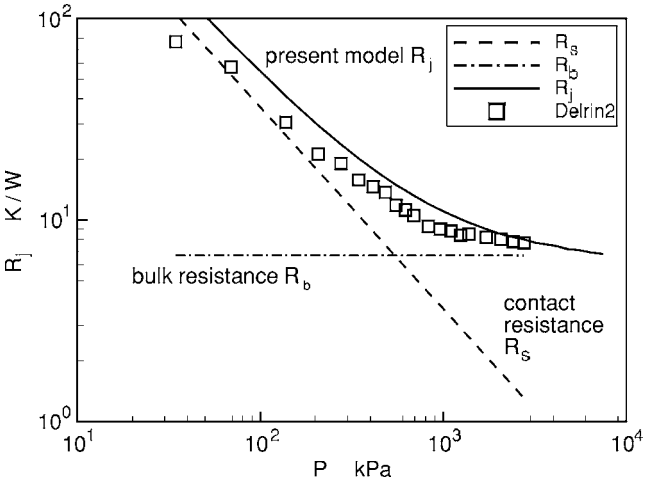

Fig. 4 Comparison between present model and delrin 2. Data collected by [8].

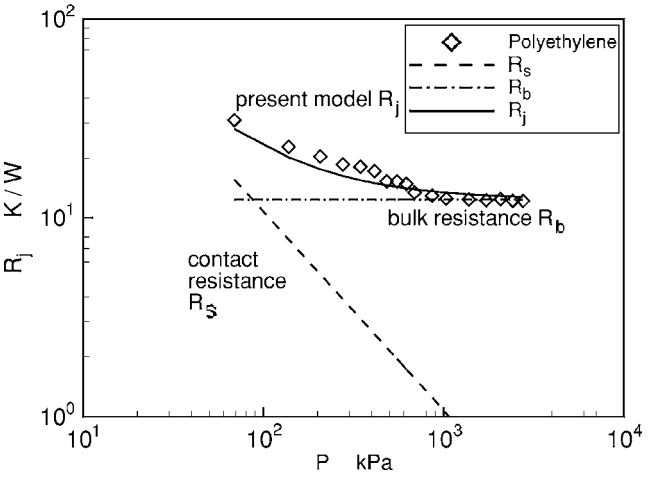

Fig. 5 Comparison between present model and polyethylene. Data collected by [8].

The comparisons show the two components of the joint resistance (i) constriction/spreading resistance of microcontacts R_s, i.e., the TCR resistance at the metal-polymer interface and (ii) the polymer bulk resistance R_b. As shown, the bulk resistances of polymers remains almost constant as the applied load is increased during the tests. This is due to the relatively small changes in the polymer thickness t. It can also be seen that at relatively light loads the microcontacts resistance controls the joint resistance. As the applied load increases, the contact resistance decreases linearly (see Eq. (13)) and the joint resistance approaches the bulk resistance at relatively high loads. These trends can be observed in all experimental data.

The present model is also compared with the experimental data collected by Marotta and Fletcher [2]. The experimental equipment was similar to that used in [8] with $b_L = 12.7$ mm. The mean temperature of the polymer specimens were maintained at $40\,^{\circ}$C. They measured the joint resistance of several polymer specimens. The combined roughness σ and surface asperities slope m, thermal conductivity k_p, microhardness H_{mic}, and elastic modulus E_p for the polymer specimens tested in Ref. [2] are summarized in Table 1.

Figures 6 and 7 show the comparison between the present model, Eq. (14), and the experimental data sets ABS and PVC collected by Marotta and Fletcher [8], respectively. As can be observed, the range of applied load is relatively high in the experiments of [2]. As a result, the bulk thermal resistance is the controlling component and the contact resistance is relatively small. As shown, the present model predicts the trend of the data very well.

The proposed model can be nondimensionalized with respect to the bulk thermal resistance as follows:

$$R_j^* = \frac{R_j}{R_b} = 1 + \Theta \tag{16}$$

where the nondimensional parameter Θ is

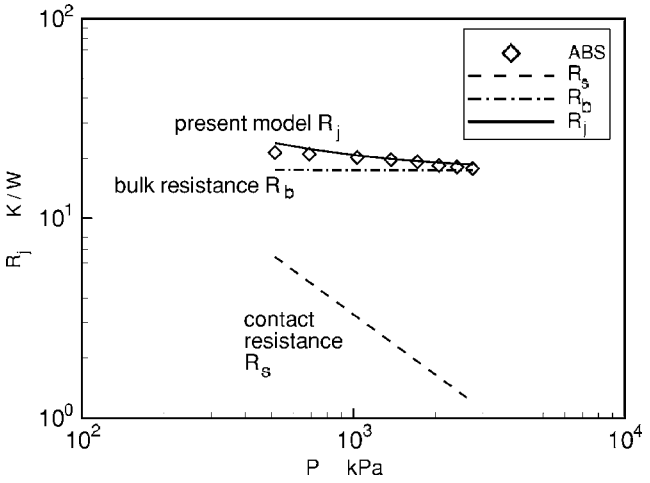

Fig. 6 Comparison between present model and ABS. Data collected by [2].

$$\Theta = \frac{R_s}{R_b} = \frac{0.565k^*(\sigma/m)}{P^* t_0(1 - P/E_p)} \tag{17}$$

where $k^* = k_p/k_s$ and $P^* = P/H_{\text{mic}}$. The nondimensional parameter Θ includes all the joint parameters: contact pressure, the macro and micro geometrical parameters σ, m, and t_0, thermal conductivities k_p and k_s, and elastic and plastic mechanical properties of the joint E_p and H_{mic}. Based on this nondimensional parameter, we define a criterion to specify the relative importance of the thermal joint resistance components as a function of the joint input parameters

$$\begin{cases} \Theta \ll 1 & R_b \text{ controls } R_j \\ \Theta \sim 1 & \text{both } R_s \text{ and } R_b \text{ are important} \\ \Theta \gg 1 & R_s \text{ controls } R_j \end{cases} \tag{18}$$

Figure 8 presents a nondimensional comparison between the data and the model expressed in Eq. (16), where the nondimensional pressure $P^* = P/H_{\text{mic}}$ is varied over a wide range. All experimental data collected by [2,8], more than 120 data points in 13 data sets, are included in the comparison. Two asymptotes of Eq. (16) are also shown in the plot. As the nondimensional pressure varies from relatively small to large values, the nondimensional joint resistance predicted by the model moves from the TCR asymptote to the bulk resistance asymptote. The experimental data covers a

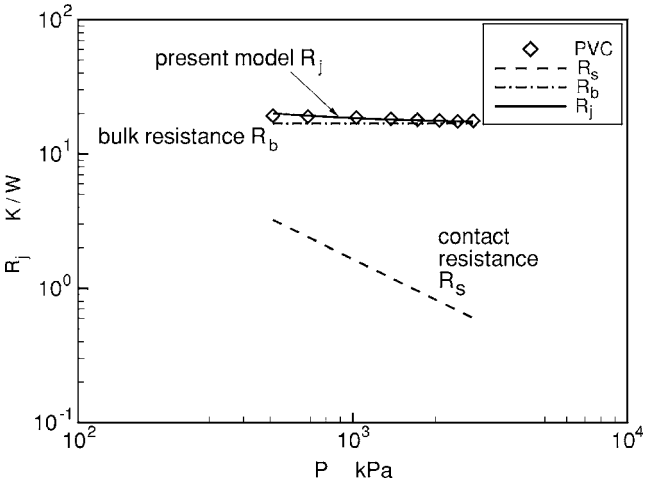

Fig. 7 Comparison between present model and PVC. Data collected by [2].

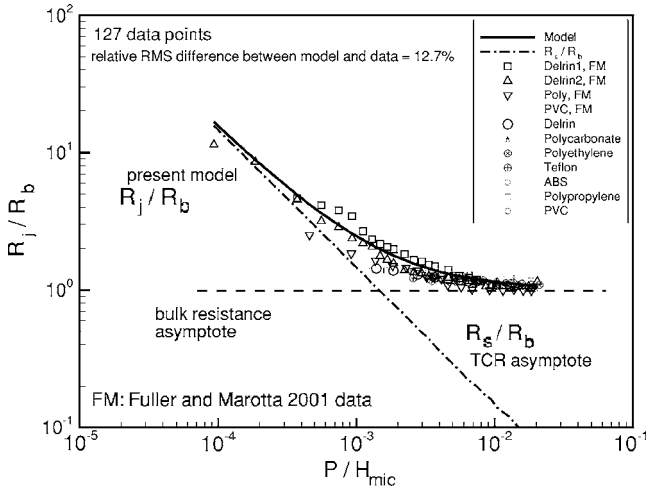

Fig. 8 Comparison between nondimensional joint resistance predicted by present model and experimental data collected by [2,8]

relatively wide range of the nondimensional parameter Θ, from 0.03 to 15.72 and follows the trend of the model. The rms relative difference between the proposed model and all experimental data is approximately 12.7%. The total average uncertainity of both experimental data sets were reported to be approximately 17% by [2,8].

Summary

The thermal joint resistance of rough polymer-metal interfaces in a vacuum is studied and a compact analytical model is developed for temperatures less than the glassy temperature. Performing a critical review, we show that the existing model in the literature is based on incorrect assumptions that may result in unrealistic values for microhardness of the polymers.

The present model assumes that the mechanical behaviors of polymers are similar to metals for temperatures below the glassy temperature. The existing plastic and elastic TCR models are reviewed and the deformation modes of surface asperities are discussed. It is shown that the deformation mode of asperities, for most of the tested polymers, is close to plastic. The proposed joint resistance model includes two components: (i) bulk resistance of the polymer and (ii) TCR of the microcontacts at the interface.

It is observed that the thermophysical properties of the polymer control the thermal joint resistance and the metallic body properties have only a second order effect.

A new nondimensional parameter is introduced which represents the ratio of the TCR over the bulk thermal resistances. Based on this nondimensional parameter, a criterion is proposed for specifying the relative importance of TCR for a joint.

The present model is compared with 13 polymer-metal data sets, 127 experimental data points collected and discussed in [2,8] that cover a variety of polymers and shows relatively good agreement. The rms difference between the model and data is approximately 12.7% over the entire range of the comparison.

Further experimental investigation is highly recommended for lighter loads where the thermal microcontacts resistance controls the joint resistance. The nondimensional parameter Θ can be used to identify the light load range. Also, additional microhardness and surface measurements are required at different roughness levels to confirm the deformation mode of asperities for polymers.

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Nomenclature

A = area (m^2)
a_s = radius of microcontacts (m)
b_L = specimen radius (m)
E = Young's modulus (Pa)
E' = effective elastic modulus (Pa)
F = applied load (N)
H_{mic} = microhardness (Pa)
H_e = elastic microhardness (Pa)
h = thermal conductance ($W/m^2 K$)
k = thermal conductivity (W/mK)
k^* = nondimensional thermal conductivity $=k_p/k_s$
m = combined mean absolute surface slope, (−)
n_s = number of microcontacts
P = apparent contact pressure (Pa)
P^* = nondimensional pressure $=P/H_{\text{mic}}$
Q = heat flow rate (W)
R = thermal resistance (K/W)
T = temperature (K)
t = thickness of polymer specimen (m)
TCR = thermal contact resistance
TIM = thermal interface material
Y = mean surface plane separation (m)

Greek

γ = plasticity index $=H_{\text{mic}}/E'm$
λ = nondimensional separation $=Y/\sqrt{2}\sigma$
σ = combined rms surface roughness (m)
Θ = nondimensional parameter $=R_s/R_b$
υ = Poisson's ratio
ω = deformation of asperities (m)

Subscripts

0 = reference value
1,2 = solid 1,2
a = apparent
b = bulk
c = contact
e = elastic
FM = Fuller Marotta
g = glass temperature
j = joint
mic = micro
p = plastic
r = real
s = solid, micro

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