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Review of Thermal Conductance Models for Joints Incorporating Enhancement Materials

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A comprehensive review of analytical and empirical models for calculating the thermal conductance across mechanically formed joints is presented. A historical perspective of modeling procedures for a range of interface configurations is presented, including bare contacting surfaces for conforming rough surfaces as well as interfacial surfaces augmented with enhancement materials such as greases, metallic foils, polymeric compliant materials, films, and coatings. Given the wide range of interface materials available and their associated thermophysical and surface properties, the models presented provide an effective procedure for determining the significance of these properties in the prediction of contact, gap, and overall joint conductance.

Nomenclature

A	=	area, m^2
a	=	contact spot radius, m
b	=	radius of heat flux channel, m
b_t	=	surface roughness parameter
C	=	constriction parameter correction factor
c_1, c_2	=	coefficients for Vickers microhardness
d	=	equivalent Vickers interaction depth, m
E	=	Young's modulus, MPa
F	=	load, N
f_g	=	correction factor
g_1, g_2	=	temperature jump distances, m
H	=	hardness, MPa
h	=	conductance, W/m$^2 \cdot$ K
I_g	=	gap integral
Kn	=	Knudsen number, identical to Λ/δ
k	=	thermal conductivity, W/m $\cdot$ K
k_m	=	mean harmonic thermal conductivity, identical to $2k_1 \cdot k_2/(k_1 + k_2)$
M	=	gas parameter, m
m	=	mean absolute asperity slope
P	=	apparent contact pressure, MPa
Pr	=	Prandtl number
Q	=	heat flow rate, W
R	=	resistance, °C/W
T	=	temperature, K
t	=	thickness, m
Y	=	mean plane separation, m
α, β	=	accommodation coefficients
γ	=	ratio of specific heats
δ	=	effective gap thickness, m
Λ	=	molecular mean free path, m
λ	=	relative gap thickness
ν	=	Poisson's ratio
σ	=	mean rms roughness, m

Subscripts

B	=	Brinell
bare	=	bare
bulk	=	bulk
c	=	contact
e	=	elastic
f	=	foil
g	=	gap, gas
j	=	joint
ℓ	=	layer
min	=	minimum
p	=	plastic
pol	=	polymer
s	=	solid
α, β	=	indices for contacting surfaces
0	=	reference condition
1, 2	=	indices for contacting surfaces

Superscripts

$+$	=	dimensionless quantity
$'$	=	effective

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Introduction

HEAT flow across a mechanical joint results in a temperature drop, which depends on the thermal resistance of the contacting interface. Thermal joint resistance is a function of several geometric, physical, and thermal parameters such as surface roughness and waviness; surface microhardness; thermal conductivity of the contacting solids, including layers, coatings, and films; properties of any interstitial materials; and the contact pressure.

Interstitial substances, such as gases, greases, oils, liquids, etc., which completely fill the gaps formed between contacting asperities can perfectly wet interfacial surfaces, producing interfaces which have relatively high joint conductances. For instance, helium, which has a higher thermal conductivity than air, enhances the gap conductance, providing a higher overall joint conductance. Greases, such as Dow Corning DC-340, when used at low contact pressures can enhance joint conductance, whereas oils, which have higher thermal conductivities than both greases and gases, can be used to further increase the thermal joint conductance. Composites, including greases doped with particulates such as silver combine the wettability of greases with the high conductivity of metals to further enhance joint conductances.

Thin conductive layers, in the range of 1–50 μm thickness, when vapor deposited on contacting surfaces, can increase joint conductance by at least an order of magnitude. The most effective materials are those which combine high thermal conductivity with a hardness that is lower than the contacting asperities. The hardness of the deposited materials is typically more important than the thermal conductivity. As an alternative to deposited layers, interstitial metallic foils made of aluminum, copper, indium, lead, tin, etc., can be placed between contacting rough surfaces to increase significantly the joint conductance.

Other less conventional materials, such as nonmetallics, including rubber or soft plastics, can be effective when inserted between contacting surfaces especially when contact pressures are very low and the hardness of the material is much lower than that of the contacting surfaces. Phase change materials that flow at elevated temperatures have recently been used to create joints with very high joint conductances when contact pressures are very small.

The objective of this paper is to present a thorough review of joint conductance models that deal with interstitial substances, films, and coatings for the enhancement of thermal joint conductances of conforming, rough surfaces. Whenever possible, the models will be compared against experimental data.

Review of Thermal Contact, Gap, and Joint Conductances

When two real (rough) surfaces are placed in mechanical contact, an interface is formed that consists of numerous discrete, microcontact spots and a gap that separates the two surfaces as shown in Fig. 1 and in more detail in the microscopic view shown in Fig. 2. If the surfaces are nominally flat, that is, they have negligible surface waviness (out-of-flatness), if the surface asperity heights have a Gaussian distribution with respect to the mean plane, and if they are randomly distributed in the contact plane, then the discrete microcontacts are assumed to be randomly distributed throughout the apparent contact area.

The real contact area, which is much smaller than the apparent (nominal) contact area, depends on the contact spot density and the mean contact spot area. If the contact spots are modeled as circular,

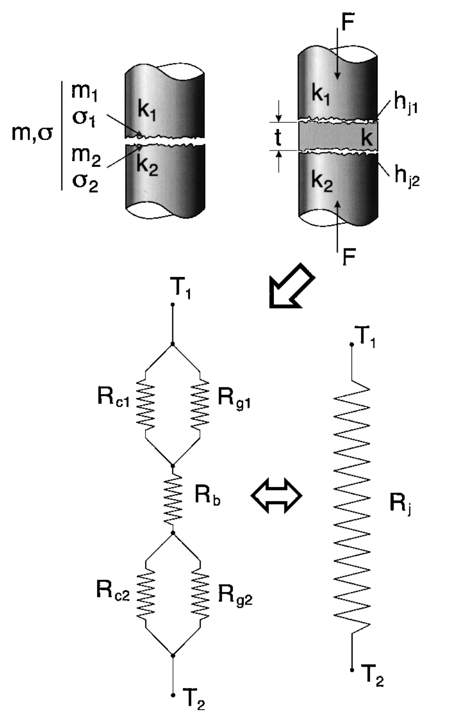

Fig. 1 Typical interface geometry for conforming rough surfaces.

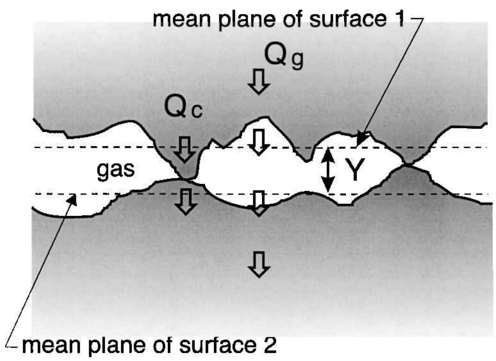

Fig. 2 Microscopic view of a contact interface in a conforming rough surface.

the real contact area is said to depend on the contact spot density and mean contact spot radius.

The contacting asperities, depending on their microgeometry and physical properties and the apparent contact pressure, can undergo elastic, plastic, or elastoplastic deformation.

Geometric and mechanical models are available for prediction of the ratio of real to apparent contact area $A_r/A_a \ll 1$, the contact spot density n, and the mean contact spot radius a with respect to the relative mean plane separation $\lambda = Y/\sigma$ given the surface roughnesses σ_1 and σ_2 and the mean asperity slopes m_1 and m_2. The relative mean plane separation depends on the mode of contacting asperity deformation.

Steady heat transfer across the interface shown in Fig. 2 is given by the relation

$$Q_j = Q_c + Q_g + Q_r \tag{1}$$

where Q_c is the conduction via the microcontacts, Q_g conduction through the interstitial substance, and Q_r heat transfer by radiation if the interstitial substance is transparent to radiation, for example, dry air. If the interstitial substance is opaque (absorbing gases, liquids, and solids), then $Q_r = 0$ and

$$Q_j = Q_c + Q_g \tag{2}$$

If the contact is made in a vacuum with no interstitial substance in the gaps, then

$$Q_j = Q_c \tag{3}$$

In all of the preceding cases, the temperature drop across the interface is given by the relation

$$\Delta T_j = Q_j R_j \tag{4}$$

where R_j represents the joint resistance which is related to three resistances if the interstitial gap substance is transparent to radiation,

$$1/R_j = 1/R_c + 1/R_g + 1/R_r \tag{5}$$

or two resistances if the interstitial substance is opaque,

$$1/R_j = 1/R_c + 1/R_g \tag{6}$$

and only the contact resistance if the contact is made in a vacuum and there is no interstitial substance in the gaps,

$$R_j = R_c \tag{7}$$

If conductances are used to model heat transfer across the joint,

$$Q_j = h_j A_a \Delta T_j \tag{8}$$

then the corresponding conductance relationships are

$$h_j = h_c + h_g + h_r \tag{9}$$

$$h_j = h_c + h_g \tag{10}$$

$$h_j = h_c \tag{11}$$

For interface temperatures $T_j < 600°C$, radiation heat transfer can be assumed negligible, that is, $R_r \gg R_c$ or R_g.

When a material (metallic or nonmetallic) is inserted between contacting surfaces, as shown in Fig. 1, and the material thickness t is much greater than the surface roughnesses σ_1 and σ_2, that is, $t \gg \sigma = \sqrt{(\sigma_1 + \sigma_2)}$, then a more complicated mechanical and thermal joint is obtained. The joint now consists of two interfaces, each formed between the contacting surfaces and the inserted material. The two interfaces, in the general case, are different because their gaps may be occupied by different substances, their surface roughnesses may be different, and the contacting surface asperity deformation may be different.

In the general case where interstitial substances are present in the two gaps, the overall joint resistance depends on five resistances,

$$R_j = f(R_{c1}, R_{g1}, R_{c2}, R_{g2}, R_l) \tag{12}$$

and the overall joint conductance depends on five conductances,

$$h_j = f(h_{c1}, h_{g1}, h_{c2}, h_{g2}, h_l) \tag{13}$$

where the subscripts denote interfaces 1 and 2. The thermal resistance and thermal conductance of the layer are given by the relations

$$R_l = t/k_l A_a, \qquad h_l = k_l/t \tag{14}$$

If the layer is incompressible, then the layer thickness is constant under mechanical loading; otherwise, the thickness will decrease with increasing load, and it will depend on the contact pressure P and its Young's modulus E_l. For the general case, the thermal joint resistance and joint conductance are given by the relationships

$$R_j = (1/R_{c1} + 1/R_{g1})^{-1} + R_l + (1/R_{c2} + 1/R_{g2})^{-1} \tag{15}$$

$$1/h_j = 1/(h_{c1} + h_{g1}) + 1/h_l + 1/(h_{c2} + h_{g2}) \tag{16}$$

These relationships for R_j and h_j clearly show how complex the thermal problem becomes when a material is inserted between two rough surfaces that are in mechanical contact.

Many special cases can be handled by means of the relationships presented.

Fluidic Materials

Gaseous Thermal Interface Materials

When a gaseous material is used as the interstitial medium, the gap conductance depends on contact pressure, microhardness, surface roughness, mean asperity slope, gas pressure and temperature, and the ratio of the thermal conductivity of the gas to those of the contacting solids. The contribution of the gap conductance in relation to the contact conductance is more significant at lower contact pressures.

The general model for this type of interface is

$$h_j = h_c + h_g \tag{17}$$

Thermal contact conductance depends on the type of contact (elastic, plastic, or elastoplastic). A number of analytical models and experimental verification data exist in the open literature, including those by Cooper et al.[1] and Mikic.[2] Gap conductance models mainly arise from simple models for gas conduction between smooth noncontacting parallel plates. These models have been verified with experimental data. The following expression describes the gap conductance between parallel plates[3]:

$$h_g = k_g/(\delta + M) \tag{18}$$

where δ is the distance between the plates. M is a thermal resistance resulting from the rarefied gas phenomena in microscopically small gaps that is included in addition to the usual Fourier-law-based conduction. It is modeled in the form of a distance added to the physical heat flowpath. The gas parameter given in Eq. (19) depends on the

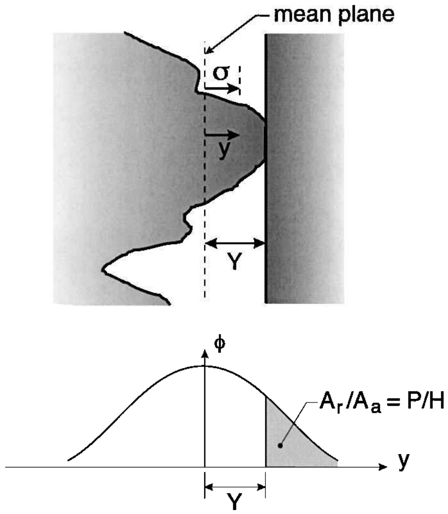

Fig. 3 Effective gap thickness: $Y/\sigma = \sqrt{2}\ \mathrm{erfc}^{-1}(2P/H_p)$ or $Y/\sigma = \sqrt{2}\ \mathrm{erfc}^{-1}(4P/H_e)$.

gas type, gas pressure and temperature, and the thermal accommodation coefficient (TAC), which is a measure of the energy exchanged between the gas molecules and the solid surfaces[4]:

$$M = \left(\frac{2 - \mathrm{TAC}_1}{\mathrm{TAC}_1} + \frac{2 - \mathrm{TAC}_2}{\mathrm{TAC}_2}\right) \cdot \left(\frac{2\gamma}{\gamma + 1}\frac{1}{Pr}\right)\left(\Lambda_0 \frac{T_g}{T_0}\frac{P_0}{P_g}\right) \tag{19}$$

where P_0 and T_0 are reference gas pressure and temperature, and Λ_0 is the molecular mean free path at the reference pressure and temperature.

For specified gas types at a given temperature and pressure, M is constant. It is observed from Eq. (18) that as δ decreases h_g approaches the asymptote k_g/M. For the fully rarefied situation ($\delta \ll M$), the thermal gap conductance is independent of the gap thickness. As shown in Fig. 3, the effective gap thickness, δ or Y, which is a function of surface roughness, contact pressure, and the elastic properties or the microhardness depending on the asperity deformation, serves as an important parameter when modeling heat transfer within the gaps of a contacting interface. For elastic deformation, the effective gap thickness is obtained from[2]

$$\lambda = Y/\sigma = \sqrt{2}\,\mathrm{erfc}^{-1}(4P/H_e) \tag{20}$$

where the effective surface roughness and mean absolute asperity slope are defined as

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{21}$$

$$m = \sqrt{m_1^2 + m_2^2} \tag{22}$$

For surfaces having Gaussian roughness and slope, the effective elastic microhardness is defined as

$$H_e = mE' \big/ \sqrt{2} \tag{23}$$

where the effective Young's modulus of the interface is defined as

$$1/E' = \left(1 - \nu_1^2\right)\big/E_1 + \left(1 - \nu_2^2\right)\big/E_2 \tag{24}$$

For plastic deformation of the softer surface, then[1]

$$\lambda = Y/\sigma = \sqrt{2}\,\mathrm{erfc}^{-1}(2P/H_p) \tag{25}$$

where the relative contact pressure is given by Song et al.,[5]

$$P/H_p = \left[P\big/c_1(1.62\sigma/m)^{c_2}\right]^{1/(1+0.071c_2)} \tag{26}$$

Table 1 Gap-conductance models and correlations[a]

Models	Correlations
Cetinkale and Fishenden[6]	$h_g = \dfrac{k_g}{0.305b_t + M}$
Rapier et al.[7]	$h_g = k_g\left\{\dfrac{1.2}{2b_t + M} + \dfrac{0.8}{2b_t}\ln\left(1 + \dfrac{2b_t}{M}\right)\right\}$
Shlykov[8]	$h_g = \dfrac{k_g}{b_t}\left\{\dfrac{10}{3} + 10\left(\dfrac{M}{b_t}\right) + 4\left(\dfrac{M}{b_t}\right)^2 - 4\left[\left(\dfrac{M}{b_t}\right)^3 + 3\left(\dfrac{M}{b_t}\right)^2 + 2\left(\dfrac{M}{b_t}\right)\right]\ln\left(1 + \dfrac{b_t}{M}\right)\right\}$
Veziroglu[9]	
For $b_t > 15$ μm	$h_g = \dfrac{k_g}{0.264b_t + M}$
For $b_t < 15$ μm	$h_g = \dfrac{k_g}{1.78b_t + M}$
Lloyd et al.[10]	$h_g = \dfrac{k_g}{\delta + \beta\Lambda/(\mathrm{TAC}_1 + \mathrm{TAC}_2)}$, δ not given
Garnier and Begej[11]	$h_g = k_g\left\{\dfrac{\exp(1 - 1/Kn)}{M} + \dfrac{\exp(1 - 1/Kn)}{\delta + M}\right\}$, δ not given
Loyalka[12]	$h_g = \dfrac{k_g}{\delta + M + 0.162(4 - \mathrm{TAC}_1 - \mathrm{TAC}_2)\beta\Lambda}$, δ not given
YIGC model[13]	$h_g = \dfrac{k_g/\sigma}{\sqrt{2\pi}}\displaystyle\int_0^\infty \dfrac{\exp\left[-(Y/\sigma - t_g/\sigma)^2\right]}{t_g/\sigma + M/\sigma}\,\mathrm{d}(t_g/\sigma)$
	$\dfrac{Y}{\sigma} = \sqrt{2}\,\mathrm{erfc}^{-1}\left(\dfrac{2P}{H_c}\right)$
	$\dfrac{P}{H_c} = \left[\dfrac{P}{c_1(1.62\times 10^6\,\sigma/m)^{c_2}}\right]^{1/(1+0.071c_2)}$

[a]Here $b_t = 2(\mathrm{CLA}_1 + \mathrm{CLA}_2)$ and $M = \alpha\beta\Lambda$.

and the Vickers microhardness correlation coefficients c_1, c_2 are related to the Brinell hardness by the relationships

$$c_1/3178 = \left[4.0 - 5.77H_B^* + 4.0\left(H_B^*\right)^2 - 0.61\left(H_B^*\right)^3\right]$$

$$c_2 = -0.370 + 0.442(H_B/c_1) \tag{27}$$

where H_B is Brinell hardness and $H_B^* = H_B/3178$ for a Brinell hardness range of 1300–7600 MPa.

Song et al.[5] present a review of various gap-conductance models, as summarized in Table 1 where b_t is given in terms of the centerline average surface roughness (CLA) (see Refs. 6–13). Note that only the Yovanovich integral gap-conductance (YIGC) model (see Ref. 13) accounts for the effect of the mechanical load, whereas the other models estimate effective gap thickness by correlating the gap conductance measurements in the terms of the surface roughness.

The Yovanovich et al.[13] model assumes that the temperatures of the two surfaces in contact are uniform at T_1 and T_2 and that the entire interface gap consists of many elemental flux tubes of different thermal resistance. The resistances of these elemental tubes are then connected in parallel by integration over the nominal contact area to give the overall gap resistance,

$$h_g = (k_g/\sigma)I_g \tag{28}$$

where

$$I_g = \frac{1}{\sqrt{2\pi}}\int_0^\infty \frac{\exp\left[-(Y/\sigma + t_g/\sigma)^2/2\right]}{t_g/\sigma + M/\sigma}\,\mathrm{d}\left(\frac{t_g}{\sigma}\right) \tag{29}$$

and Y is mean plane separation distance or effective gap thickness and t_g is the local gap thickness.

Yovanovich[14] presented a simplified form of the integral I_g

$$I_g = 1/(Y/\sigma + M/\sigma) \tag{30}$$

The expression is accurate to within 10% for large values of Y/σ and M/σ, but significantly underpredicts the gap conductance by 50–100% for small values of Y/σ and M/σ. Negus and Yovanovich[15] proposed a new correlation to overcome this problem by modifying Eq. (30) with a correction factor f_g, where the integral I_g now becomes

$$I_g = f_g/(Y/\sigma + M/\sigma) \tag{31}$$

Exact values of f_g were calculated by numerically integrating Eq. (29) over a wide range of Y/σ and M/σ. Based on the trends and the limiting points in these data, a simple approximate expression for f_g was derived:

$$f_g = 1.063 + 0.0471(4 - Y/\sigma)^{1.68}[\ln(\sigma/M)]^{0.84} \tag{32}$$

for $2 \le Y/\sigma \le 4$ and $0.01 \le M/\sigma \le 1$ and

$$f_g = 1 + 0.06(\sigma/M)^{0.8} \tag{33}$$

for $2 \le Y/\sigma \le 4$ and $1 \le M/\sigma \le \infty$. The maximum error associated with the correlations in Eqs. (32) and (33) is 2% when compared to numerically integrated data.

Song and Yovanovich[4] have reported nitrogen and helium gap-conductance data for interfaces formed by contacting bead-blasted/lapped stainless steel 304 and nickel 200 pairs over a range of gas and interface pressures at a fixed interface temperature of approximately 400 K. They observed that the mechanical load effect was less significant when the gas pressure was low because the gap thickness plays a less important role. In the rarefaction regime, the gap conductance was linearly dependent on the gas pressure.

Wahid and Madhusudana[16] generated gap-conductance data for a range of interfacial gases: helium, argon, carbon dioxide, nitrogen, and mixtures of argon and helium. Tests were conducted with stainless steel specimens at a contact pressure of 0.433 MPa, with interface gases at an average gas pressure of 0.12 MPa. The effective gap thickness at the interface was determined experimentally, and the mean separation distance was deduced by subtracting the temperature jump distance from the effective gap thickness. A simple relation was found between the mean separation distance and the surface roughness for all gases and gas mixtures.

Das and Sadhal[17] obtained an analytical solution for thermal constriction resistance between two solids. A two-dimensional idealization was considered where the areas at the interface in perfect contact were assumed to be flat stripes, and the curved surfaces of the noncontacting interstitial region gaps were assumed to be circular in profile. The model was developed for cases of sparsely distributed contacts and gaps. The analytical solution showed that for symmetric gaps, the interface areas that are in perfect contact are isothermal only in certain special cases of adiabatic or zero-thickness gaps, or when the two solids have the same conductivity. The contact resistance is shown to be strongly dependent on gap thickness and the conductivity of the interstitial fluid, especially at the lower values of these parameters.

Grease and Phase Change Materials

Greases, oils, and phase change materials exhibit a better thermal performance compared to other types of interface materials due to their ability to completely wet the contacting surfaces. They typically consist of a polymeric matrix loaded with highly conducting filler particles. In general, greases are not well suited for microelectronic systems because they tend to migrate and/or vaporize at high temperatures and low surrounding pressures.

The general contact conductance model for interfaces with grease can be expressed as

$$h_j = h_c + h_g \tag{34}$$

however, when the gap is filled with grease, which perfectly wets the two contacting surfaces, the gap controls ($h_g \gg h_c$) and the joint resistance for $2 < Y/\sigma < 5$ can be written as

$$h_j = h_g = k/Y \tag{35}$$

Yovanovich[14] compares this model with results from Seely and Chu[18] of silicone grease in an interface formed between copper and molybdenum blocks. The experimental joint conductance was found to be $h_j = 71{,}760\ \mathrm{W/(m^2K)}$. The model, from Eq. (35), gives a value of gap conductance of $h_g = 62{,}360\ \mathrm{W/(m^2K)}$ when the contact conductance h_c is given by an expression from Yovanovich[14]:

$$\sigma h_c/k_m = 1.25m(P/H)^{0.95} \tag{36}$$

Using the calculated value for h_g, a joint conductance of $h_j = 68{,}590\ \mathrm{W/(m^2K)}$ is obtained.

Rauch[19] conducted an experimental investigation of phase change thermal interface materials where compounds with and without carriers, such as aluminum or fiberglass weaves, were examined. The phase change materials typically entered a liquid state at temperatures in the range of 51–60°C. By measuring the thickness of the interface material and the thermal joint resistance, Rauch observed that thermal resistance was zero at zero thickness, indicating that the interface surfaces were completely wetted by the compound, eliminating contact resistance, so that the overall thermal contact resistance would be the function of the thickness t and the conductivity of thermal interface material k. The thickness of the phase change materials decreased in proportion to the applied pressure and achieved a minimum value dependent on the viscosity of the material and planarity and curvature of the interface surfaces. Rauch also observed that a time-dependent decrease in the material thickness led to a corresponding decrease in the thermal resistance.

Prasher[20] developed two analytical models for thermal resistance for joints with fluidic thermal interface materials: a complete wetting model and a surface chemistry model, which includes the thermal contact resistance. The models indicate that the thermal contact resistance depends on surface tension, contact angle, thermal conductivity, roughness, and pressure. The experimental data were obtained for silicone-based greases with k in the range of 0.2–3.1 W/mK and paraffin-based phase change materials with k of 0.2 and 0.7 W/mK. Test specimens were copper blocks with $\sigma = 3.5$, 1.0, and 0.12 μm. The data agreed well with the surface chemistry model but not with the complete wetting model.

Nonfluidic Materials

Nonfluidic thermal interface materials can be categorized with respect to physical properties and the method of application to the contacting solids: 1) metallic foils and screens, 2) polymers and other nonmetallic interstitial materials, 3) coatings (metallic and nonmetallic), and 4) adhesives, epoxies, and cements.

A general model for the thermal contact conductance of all interstitial materials is very difficult to obtain due to the range of thermophysical properties associated with these types of materials.

From the joint conductance model, given in Eq. (16), several special cases can be obtained. For conforming rough surfaces that are relatively smooth ($\sigma \ll t$) in vacuum ($h_{g1} = h_{g2} = 0$), the thermal contact conductance is reduced to

$$1/h_j = 1/h_{c1} + 1/(k/t) + 1/h_{c2} \tag{37}$$

Equation (37) assumes that the thickness of the interface material is not affected by the interface pressure. In the case of a slightly compressible layer, the bulk resistance decreases with increasing pressure and the joint conductance can be expressed as

$$1/h_j = 1/h_{c1} + 1/[k/t(1 - P/E)] + 1/h_{c2} \tag{38}$$

The overall thermal circuit can be further reduced for relatively high contact pressures when the bulk resistance of the layer controls (h_{c1} and $h_{c2} \gg h_{\mathrm{bulk}}$), and the thermal joint conductance can be written as

$$h_j = k/t \tag{39}$$

or

$$h_j = k/t(1 - P/E) \tag{40}$$

Metallic Foils and Screens

There are numerous experimental studies dealing with metallic foils and screens with the majority of studies involving aluminum, copper, brass, gold, tin, and indium foils. The best thermal performance was observed for indium, lead, and tin foils, which are softer than aluminum or copper foils. In the earliest investigations, it was observed that the reduction of joint resistance was inversely proportional to the hardness of the foil material. The existence of an optimum thickness was also revealed, as well as a greater dependence of the joint resistance on pressure than on temperature.

Yovanovich[21] performed extensive experimental research for both loading and unloading cycles to determine the thermal contact resistance of an optically flat surface in contact with a lathe-turned surface. The fact that joint resistance for the unloading cycle was less than the loading cycle was deemed as proof the foils deformed plastically. The greatest reduction of resistance for a constant foil thickness occurred with tin, then lead, followed by aluminum and copper, for all contact pressures, for both loading and unloading cycles. The optimum foil thickness for tin and lead was 100 μm or about two times the rms roughness of the turned surfaces, for all contact pressures. The optimum thickness of the aluminum was 25–30 μm and was slightly dependent on contact pressure. The optimum thickness of copper behaves in a similar manner to the aluminum, with an optimum thickness in the range of 30–40 μm. As shown in Fig. 4, Yovanovich normalized the minimum resistance corresponding to the optimum thickness as a ratio of the minimum resistance to the corresponding bare joint resistance.

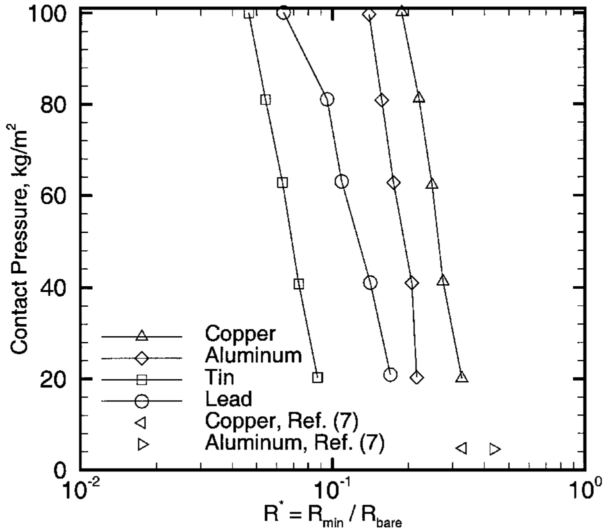

Fig. 4 Dimensionless minimum resistance to bare joint resistance (Yovanovich[21]).

The normalized resistance as the function of the contact pressure and foil material is expressed in the following way:

$$R^* = R_{\min}/R_{\text{bare}} = 1\big/\exp\big[0.0072P + 15.5(k/H_f)^{0.92}\big] \qquad (41)$$

where the constants were determined from the test results and here k is in watts per centimeter Kelvin, H_f is in kilograms per square millimeter, and P is in kilograms per square centimeter.

Peterson and Fletcher[22] conducted an investigation of selected metallic foils (copper, aluminum, lead, and tin), for a wide range of hardness (40–800 MPa), conductivity (33–380 W/mK), and surface roughness (1.15/8.57 μm) and showed that, for optimum conditions of foil thickness and surface roughness, a sevenfold reduction in the bare junction resistance could be achieved. They also confirmed the importance of the parameter k/H_f proposed by Yovanovich.[21]

Couedel et al.[23] used the experimental data from Peterson and Fletcher[22] and developed a dimensionless conductance ($h_f/k_f t$), which was presented as a function of dimensionless hardness [$\sigma \cdot H_s h_{\text{bare}}/(H_f k_s)$], where h_f is the experimental thermal contact conductance for joints including thin metal foils, h_{bare} is the experimental thermal contact conductance of the corresponding bare joint, H_f and H_s are the mean hardness of the foil and the solid, and k_f and k_s are the thermal conductivities of the foil and the solid. The thickness $t = f(t', P, H_f, \sigma)$ is the actual mean thickness of the foil, and t' is the effective foil thickness.

Based on the experimental data, they developed the following correlation:

$$h_f t/k_f = 0.52[(H_s/H_f)(h_{\text{bare}}/k_s)\sigma]^{1.02} \qquad (42)$$

where the term k_f/H_f was previously described by Yovanovich[21] and the term H_s/k_s was obtained from the Cooper et al.[1] thermal conductance model. Couedel et al.[23] suggested additional experimental work to verify that the physical behavior of the foil–solid system may be predicted using an actual mean thickness averaged over the pressure range and presented as a function of the roughness only and that the actual mean thickness does not depend on the solid and foil type and effective thickness, when the effective thickness is optimized with the roughness. They also concluded that the foil modulus of elasticity was an important parameter when P/σ is high.

Wire screens can be used to reduce or enhance the thermal performance of the joint. Fried and Costello[24] showed in some of their experiments that copper wire screens reduced the thermal contact conductance, whereas in other investigations, wire screens were shown to act as a means of thermal insulation for surfaces in contact. Gyorog[25] also confirmed the insulation performance of stainless steel and titanium wire mesh screens. He also noted that the finer the mesh the larger the conductance because the number of contact spots is greater. Sauer et al.[26] confirmed the results of Gyorog[25] in his experimental work of stainless steel wire screens as the interstitial material. Cividino and Yovanovich[27] proposed a theoretical model to predict the contact conductance of woven metallic wire screens as an interstitial material between two smooth solids in vacuum. They assumed elastic deformation and equal loading at all nodes. The model was based upon Hertzian theory and the Yovanovich general constriction resistance theory. When compared to the experimental values, this model was found to overestimate the conductance consistently.

O'Callaghan et al.[28] investigated the thermal contact resistance of steel-to-steel contact with inserted copper gauze. The experimental results showed that the thermal contact resistance increased in air and decreased in a vacuum. Further experimental and theoretical investigations of the copper wire gauzes were led by Al-Astrabadi et al.[29] They concluded that insertion of a wire screen decreased the resistance when there were large-scale surface irregularities, and if the surfaces were flat and conforming, the resistance would increase. They also noted that the weave was series of interlaced straight wires resulting in a contact of the gauze and the solid at every other wire crossing. Their experimental investigations and developed correlations also showed that the foil or screen material hardness was a dominant factor in enhancing the thermal contact conductance.

Fletcher[30] compared the thermal enhancement characteristics of metallic foils and screens by means of a conductance ratio and concluded that the thermal enhancement characteristics of metallic foils and screens decreased with increasing contact pressure. It was also noted that very thin foils, necessary to reach the optimum thickness, can be very difficult to handle, which can decrease the conductance due to the unintentional creation of folds and wrinkles. Also a decrease in conductance was observed due to the plastic deformation, which can occur in some materials used repeatedly.

Polymeric Materials

Polymers are a group of relatively new materials used in the enhancement of thermal contact conductance. Polymers are generally classified into three groups: thermoplastics, elastomers, and thermosets, which are harder and more brittle compared to the other two groups of ductile polymers. The thermoplastics and elastomers are of special interest because of their elastic deformations under large strains and because their mechanical properties, such as elastic modulus and bulk modulus, may be a function of time and temperature, which is defined as viscoelastic behavior. The thermal performance of polymers used for increasing thermal conductance of a joint can be enhanced with fillers, such as boron nitride, aluminum, and diamond, and they can be supported with fiberglass, nylon mesh, aluminum carrier, and glass cloth. Table 2 is a summary of test

Table 2 Research related to polymer-based interstitial materials tested in vacuum conditions

Author	Contact material	Interstitial material
Miller and Fletcher[31]	Aluminum 2024-T4	Silicone elastomers, fluocarbon elastomer, nitrile elastomer
Fletcher and Cerza[32]	Aluminum 2024-T4	Ethylene vinyl acetate copolymers, ethyl vinyl acetate copolymer, polyethylene homopolymer
Ochterbeck et al.[33]	Aluminum 6061-T6	Polyamide in combinations with aluminum foil, paraffin, diamonds, copper
Marotta and Fletcher[34]	Aluminum 6061-T6	Polyethylene, PVC, polypropylene, Teflon, delrin, nylon, polycarbonate, phenolic
Parihar and Wright[35]	Stainless steel 304	Silicone rubber
Mirmira et al.[36]	Aluminum 6061-T6	Elastomeric gaskets, commercially available (Cho-Therm, T-pli, Grafoil)
Narh and Sridhar[41]	Mold steel	Polystyrene
Fuller[38]	Aluminum 6061,	Delrin, Teflon
	Stainless steel	Polycarbonate, PVC

conditions for various experimental studies of thermal conductance in joints with polymers.

One of the first experimental investigations on thermal conductance of metal/polymer joints was conducted by Miller and Fletcher.[31] The thermal conductance values of tested elastomers were lower than the conductance of bare aluminum junction. It was also concluded that elastomers with metallic or oxide fillers yielded higher conductance values than unfilled elastomers. Fletcher and Cerza[32] also 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 0.4 to 2.75 MPa and mean junction temperatures of 29–57°C. The thermal conductance increased with increasing temperatures and carbon content as well as other additives.

Ochterbeck et al.[33] conducted an experimental investigation on thermal contact conductance of polyamide films, which were combined with several different compounds such as 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 thermal contact conductance 7–10 times compared to bare joints. The diamond-embedded films slightly increased thermal joint resistance compared to bare junction, but the measured values of conductance were higher than for uncoated polyamide film.

Marotta and Fletcher[34] presented experimental conductance data for several polymers. The conductance of the materials tested were shown to be independent of pressure (300–3000 kPa range), except for polyethylene, Teflon®, and polycarbonate (thermoplastic polymers, relatively soft and ductile). These materials showed an increase in contact conductance values at the higher interface pressures, due to the deflection.

Parihar and Wright[35] performed detailed experimental studies of thermal contact resistance of metal (SS304)/silicone rubber/SS304 joint, in air, under light loads (0.02–0.25 MPa) for the different heat flux inputs (2.4–8.6 kW/m^2). They measured R_{c1} and R_{c2} separately and observed that the resistance at the hot interface, R_{c1}, was 1.3–1.6 times greater than the resistance at the colder interface, R_{c2}. The resistances were different due to the large difference in the interface temperatures and the ratios of thermal conductivities of the contacting materials because the thermal conductivity of rubber decreased as the temperature of the specimens increased. The joint resistance R_j decreased with increasing load due to a reduction of R_{c1} and R_{c2}. The authors observed that the reduction in R_{c2} with load was smaller, probably due to the greater hardness of the elastomer at the colder interface. It was concluded that the near constant resistances at higher pressures were probably due to the air that was trapped between the voids and inhibited a further increase in the contact spots.

In general, contact resistance was shown to be a strong function of temperature due to the large temperature dependence of the thermal conductivity of the rubber and to a lesser extent the pressure P due to the elastomer softness.

An experimental program by Mirmira et al.,[36] later summarized by Marotta and Han,[37] showed that thermal contact conductance of some commercial elastomeric gaskets becomes less dependent on the contact pressure as the load increased with the bulk conductance becoming predominant in high-pressure range (around 1000–1500 kPa). For some materials, such as silicone elastomers with silver-coated copper powder and silver flakes, conductance values appeared to be mostly independent of pressure, likely due to increased stiffness, leading to no change in the material thickness. Mirmira et al.[36] observed that the change in the mean interface temperature did not significantly affect the thermal conductance values for the gasket materials, but at higher temperatures the composition may change and cause degradation of conductance. Materials with fiberglass reinforcement showed poorer thermal performance than materials without reinforcement. Also, these materials demonstrated a hysteresis, for example, the conductance during the loading cycle was lower than during the unloading cycle.

Fuller[38] obtained an analytical model for predicting thermal joint resistance between metals and thermoplastic and elastomeric polymers, assuming optically flat surfaces at uniform pressures and a vacuum environment. The mode of the deformation between the metal and the softer polymer was assumed to be elastic during light to moderate loading based on experimental studies conducted by Parihar and Wright[35]:

$$h_c = \frac{k_m}{4\sqrt{\pi}}\frac{m}{\sigma}\frac{\exp(-\lambda^2/2)}{\left[1-\sqrt{\frac{1}{4}\,\mathrm{erfc}\left(\lambda/\sqrt{2}\right)}\right]^{1.5}} \tag{43}$$

They employed the Greenwood and Williamson[39] elastic contact hardness,

$$H_e = CEm \tag{44}$$

where C is a constant found by plotting dimensionless mean pressure vs dimensionless load. In Fuller's[38] investigation, the constant was found to be 0.433, and so the polymer elastic hardness was defined as

$$H_{\mathrm{epol}} = E_{\mathrm{pol}} m/2.3 \tag{45}$$

With the use of the analytical model and polymer elastic hardness, a simple correlation was obtained for the dimensionless microscopic contact conductance:

$$h_c \sigma / k_m m = 1.49(2.3P/E_{\mathrm{pol}} m)^{0.935} \tag{46}$$

The bulk thermal conductance was defined as

$$h_{\mathrm{bulk}} = k_{\mathrm{pol}}/t \tag{47}$$

where t is the polymers final thickness after load compression. When the final thickness was defined in terms of strain, the following expression was derived:

$$t = t_0[1-(P/E_{\mathrm{pol}})] \tag{48}$$

The joint conductance was defined as

$$h_j = 1/\{1/h_{c,1} + t_0[1-(P/E_{\mathrm{pol}})]/k_{\mathrm{pol}} + 1/h_{c,2}\} \tag{49}$$

Experimental data from Marotta and Fletcher[34] were compared to the joint conductance model, and good agreement was found as shown in Fig. 5.

Narh and Sridhar[40] measured the thermal contact conductance of polystyrene as a function of thickness at constant pressure and temperature (average specimen temperature of 65 and 75°C). They concluded that at temperatures just above the glass transition temperature the plastic surface was relatively soft and that thermal contact resistance varied mainly as a logarithmic function of pressure.

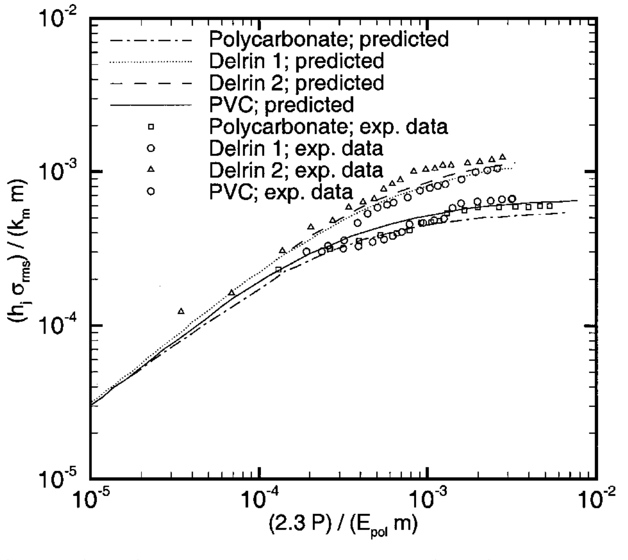

Fig. 5 Dimensionless contact conductance vs dimensionless pressure for selected polymers.

Coatings and Films

Another means of enhancing thermal contact conductance is treating contact surfaces with vapor-deposited, plasma-sprayed, electroplated coatings or films, which may be metallic or nonmetallic. The greatest enhancement of thermal contact conductance has been accomplished by using metallic coatings.

Despite the extensive experimental research on the thermal contact resistance of coated surfaces, only a few analytical models are available. Antonetti and Yovanovich[41] have developed a thermomechanical model for predicting the contact conductance of nominally flat, rough surfaces enhanced with metallic coatings. They showed that a coated joint can be reduced to an equivalent bare joint. The two analytical models presented were based on the effective microhardness of the particular coating–substrate combination, evaluated using both mechanical analysis and experimental means. The effective microhardness for a silver/nickel combination was given as

$$H' = H_s(1 - t_\ell/d) + 1.81H_\ell(t_\ell/d) \tag{50}$$

for the region $t_\ell/d < 1.0$, and

$$H' = 1.81H_\ell - 0.208H_\ell(t_\ell/d - 1) \tag{51}$$

when $4.9 \geq t_\ell/d \geq 1.0$. When $t_\ell/d > 4.9$ the effective microhardness is equivalent to the layer microhardness. Here, d is the equivalent Vickers indentation depth of the harder contacting surface, t_ℓ is the thickness of the coating layer, and subscripts s and ℓ refer to the substrate and coating layer, respectively. The effective conductivity is

$$k' = \frac{k_\alpha + k_\beta}{C_\alpha k_\beta + C_\beta k_\alpha} \tag{52}$$

where α and β refer to the two sides of the contact. Conductivity k' and parameter C appeared to be strongly dependent on the coating thickness and only slightly dependent on surface texture. Experiments were performed on silver-coated nickel specimens in contact with bare nickel specimens in vacuum. The applied contact pressure ranged from 500 to 3700 kPa, the mean interface temperature ranged from 85 to 206°C, and specimens with three ranges of roughness were tested. A correlation for coated contacts was obtained based on the correlation for bare contacts as well as the effective microhardness and conductivity:

$$h_j'\sigma/mk' = 1.25(P/H')^{0.95} \tag{53}$$

Figure 6 shows excellent agreement of the model with the experimental data.

It is observed that silver coating can enhance the thermal contact conductance of nominally flat, rough-contacting nickel specimens by an order of magnitude and that, for a given coating thickness, the smoother the bare contacting surface the greater the enhancement.

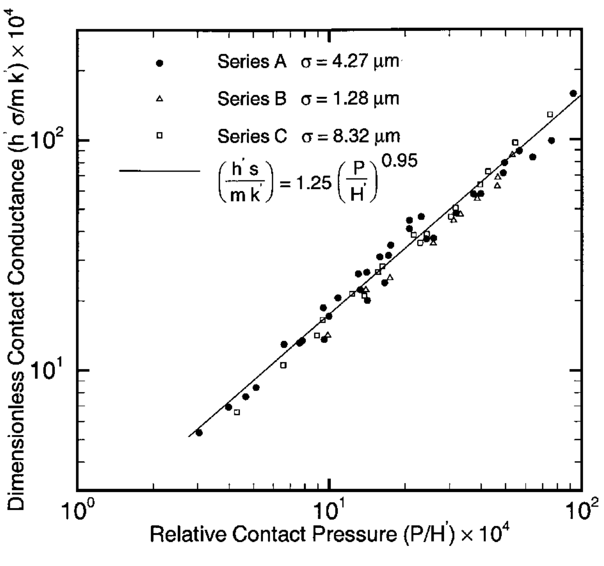

Fig. 6 Conductance for silver layer on nickel substrate.

O'Callaghan et al.[42] developed a theoretical model that can be used to predict the optimum thickness of metallic coatings. In their analysis, they assumed ideal plastic deformation of the contacting surfaces and the coating. They stated that the thermal contact resistance depends on the hardness of the coating and the ratio of the thermal conductivities of the coating and the base material. They also developed a model for different ranges of t_ℓ/σ. The minimum thermal contact resistance should occur when the coating thickness t_ℓ is of the same order of the surface roughness σ. The experimental analysis conducted on stainless steel specimens with ion-deposited tin showed good agreement with the proposed theory.

Snaith et al.[43] introduced a criterion for assessing the thermal performance of a coating in a joint $H_s k_\ell/(H_\ell k_s)$, where H is the microindentation hardness. The greater the ratio is, the lower thermal contact resistance is.

Kang et al.[44] led an experimental investigation to determine the thermal contact conductance at the contact of turned aluminum surfaces with vapor-deposited lead, tin, and indium coatings. These results showed a marked drop-off in h_c with increasing thickness due to oxidation between layers of the lead, tin, and indium physical vapor deposition (PVD) coatings. A similar problem was encountered by Howard et al.[45] The Kang et al.[44] results also showed that an optimum coating thickness exists, and the enhancement factors for thermal contact conductance were found to be in the order of 700, 400, and 150% for indium, lead, and tin, respectively. Based on the experimental data, they concluded that the hardness of the coating material seems to be the most important parameter in ranking the substrate and coating material combinations. They also observed that, for a given coating thickness, thermal contact enhancement was greatest at low pressures, decreasing with increases in contact pressure. The optimum thickness showed the same trend with increasing pressure.

Fried and Kelly[46] stated that general elasticity and plasticity methods cannot be applied in most thermal contact problems due to the possibility of sliding contacts, elastoplastic and elastoviscous contact intersections, and different properties at the surface of the material. However, they suggested that statistical or semi-empirical prediction methods can be applied to similar classes of material with similar surface finish. An experimental investigation was performed on stainless steel specimens coated with vapor-deposited aluminum and magnesium. The contact conductance of the joints were enhanced by as much as an order of magnitude over the bare joints at high pressures. They concluded that rough surfaces allow more reliable contact conductance predictions and provide more reproducible test data than finely finished surfaces.

Malkov and Dobashin[47] investigated the thermal resistance of stainless steel specimens with electroplated coatings of silver, nickel, and copper in a vacuum. They concluded that the microgeometry of the substrate defines the microgeometry of the coating surface, especially in the case of a silver coating. The contact resistance of the coated joint was reduced by factors of 2–10 from the value of the bare joint.

The Mikic and Carnasciali[48] model for predicting the ratio of coated-to-bare contact conductance of an elemental heat channel uses three ratios that affect thermal contact resistance: t_ℓ/a, a/b, and k_ℓ/k_s. An increase in each of these ratios reduces the $R_{\text{coated}}/R_{\text{uncoated}}$ ratio. Mikic and Carnasciali verified the theory in an experimental investigation on a single constriction where the stainless steel was coated with copper. They also noted that, when both surfaces in contact are coated, the improvement of conductance is greatest.

An experimental study of phase mixed coatings by a new metallic coating technique, transitional buffering interface, was conducted by Chung et al.[49,50] The advantages of the new process include excellent adhesion of coatings to wide range of substrates and very fine control of coating thickness, flatness, and roughness. The coating process involves plasma-enhanced deposition onto a cold surface. Silver, copper, silver–carbon, and copper–carbon mixtures (transitional buffering interfaces) were examined on aluminum specimens of different roughness. The improvement of the thermal contact conductance for pure copper coatings was greater than copper–carbon phase mixture coatings by a factor 1.1–1.3 and for pure silver coatings was greater than silver–carbon phase mixtures by a factor of 1.1–2.6. Although the thermal contact resistance of the pure coatings is higher than that of phase mixture coatings, the adhesion strength of the new coating process can obtain 20–240% improvement in thermal contact conductance of phase mixture coatings and provide a choice for some specific longlife requirements under conditions of repeated loads. Analytical expressions were developed for thermal constriction resistance with cylindrical contact spots with phase mixed coatings.[49]

To evaluate the effect of surface deformations on thermal contact conductance of coated joints, Chung[51] performed complete loading cycles on one- and two-surface coating contacts using aluminum, lead, and indium, as well as on phase change mixture coatings contacts using copper, copper–carbon and silver, silver–carbon. Results showed a hysteresis effect and that coating interfaces deform plastically during the first loading–unloading process under a light load. It was observed that the hysteresis effect is greater at the softer coatings, and no definite dependence of coating thickness on the hysteresis effect was evident.

Howard et al.[45] investigated the effect of vapor-deposition process and coating thickness on the overall joint conductance of metallic interfaces. Aluminum specimens coated with indium were tested while in contact with uncoated aluminum specimens in vacuum. It was observed that thermal conductance enhancement factors for contacts with multilayered coatings were significantly lower than for those with single-layer coatings of an equivalent thickness due to poor layer adhesion caused by oxidation and thermal cycling.

In a thorough literature review of metallic coatings, Lambert and Fletcher[52] reduced the data of the numerous studies to the same nondimensional form as Antonetti and Yovanovich.[41] To improve the heat transfer between standard electronic module guide ribs and card rails, Lambert and Fletcher[53,54] performed an experimental investigation on thermal contact conductance for anodized aluminum and electroless nickel-plated copper in contact with bare as well as vapor-deposited, electroplated, and flame sprayed silver-coated aluminum and vapor-deposited gold-coated aluminum.

Ying et al.[55] conducted an experimental investigation on contact conductance at interfaces of stainless and mild steel specimens coated with tin, copper, silver, and aluminum in a vacuum environment. They found that the optimum coating thickness depended on the coating material and the pressure, whereas an increase in optimum thickness was noted for an increase in microhardness. They also noted that the optimum thickness enhancement factor decreased as the applied pressure was increasing for tin and copper, whereas for silver and aluminum it increased with the contact pressure.

Mian et al.[56] conducted the first experimental study on thermal contact conductance of oxide films on mild steel surfaces, which were first lapped and then sandblasted to prescribed roughnesses. They concluded that these films had a significant effect on increasing contact resistance.

Peterson and Fletcher[57] conducted an experimental analysis to determine thermal contact conductance and effective conductivity of anodized coatings on chemically polished aluminum specimens. It was observed that overall joint conductance decreased with increasing thickness of the coating and increased with increasing interface pressure. The experimental data were used to develop expressions that related the overall thermal joint conductance to the coating thickness, the surface roughness, the interface pressure, and the properties of the aluminum substrate. Also, the effective thermal conductivity was estimated as a function of pressure, by subtracting the thermal contact conductance from the measured overall joint conductance.

Marotta et al.[58] presented a review of nonmetallic coatings. They were categorized as oxides, carbon-based coatings, ceramics, and polymer-based coatings, and their main thermal, mechanical, electrical, and tribological properties were revealed. Beryllia (BeO) was selected as a potential coating due to its high thermal conductivity. Very good thermophysical and tribological properties of carbon-based coatings (diamondlike films) were noted.

Marotta and Fletcher[59] examined thermal contact conductance for four ceramic coatings (silicon nitride, boron nitride, aluminum nitride, and titanium nitride) deposited on aluminum and copper. All materials showed at least two orders of magnitude improvement in thermal contact conductance, when compared to an anodized layer. Experimental data indicated that interfaces with titanium nitride have the best thermal performance. Marotta et al.[60] measured the thermal contact conductance of diamondlike films deposited on aluminum and copper specimens in contact with bare aluminum. A rigidizing layer of silicon was deposited before an ion beam diamondlike film to reduce cracking of the hard diamondlike film. Experimental data showed that thermal contact conductance was increased compared to the bare contact conductance, and the highest conductance was achieved with the thinnest coatings.

Adhesives

Adhesives are often used to attach a silicon device to a heat spreader or ceramic substrate, and they generally increase the heat transfer across the material junction. Very few studies of adhesives are available in the literature. Peterson and Fletcher[61] measured the thermal contact resistance of silicon chip bonding materials. Seven epoxies in contact with aluminum were evaluated. The contact resistance was shown to be independent of the joint temperature, but increased dramatically with respect to the thermal conductivity of the epoxies. An empirical expression was derived that correlated the overall thermal contact resistance to the thickness and thermal conductivity of the bonding material and the fraction of voids in the bonded joint. Mirmira et al.[62] presented experimental data on contact conductance of room-temperature vulcanization silicones and epoxy adhesives. They indicated that the thermal conductance of the majority of these adhesives did not change significantly with variations of temperature and apparent pressure (300–3000 kPa). It was concluded that for a given thickness of applied adhesive, thermal conductivity may play the main role in decreasing the thermal resistance.

Summary

The present review of previously published thermal contact conductance and resistance models for joints incorporating enhancement materials reveals that there are many thermophysical models because the joints are quite different and complex. Numerous micro and macro surface characteristics and surface microhardness are required to characterize properly the mechanical and thermal response of the joints to loads and heat transfer. The enhancement materials used included gases, liquids, greases, greases loaded with small particles, phase change materials, and metallic and non-metallic inserts. The accuracy of many of the reviewed models were validated by extensive testing.

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