Using Metallic Coatings to Enhance Thermal Contact Conductance of Electronic Packages

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Recently a new thermomechanical model for coated contacts has been developed and shown to be quite accurate. After a brief overview of the theory, this paper concentrates on illustrating the utility of the new model by applying it to a common electronics packaging problem: heat transfer across an aluminum joint. Several soft metallic coatings are considered, and the thermomechanical model is used to predict the improvement in the contact conductance over that for a bare aluminum-to-aluminum joint. For each coating material, heat transfer performance is presented as a function of the coating thickness, the surface roughness, and the applied pressure. Finally, a parameter is proposed that allows candidate coating materials to be ranked.

INTRODUCTION

In many electronics packages the thermal conductance across a particular interface must be improved for the thermal design to meet its performance objective. If the joint cannot be made permanent because of servicing or other considerations, the contact heat transfer coefficient can be enhanced—that is, improved over the bare joint situation—utilizing one of the following well-known techniques: application of a thermal grease, insertion of a soft metal foil, or coating one or both of the contacting surfaces with a relatively soft metal.

Thermal greases, however, cannot be employed in many critical electronic assemblies because of the possibility of the grease evaporating and contaminating nearby sensitive components. Foils are attractive from a theoretical point of view, but in practice they are not used very often. This is because soft foils tend to wrinkle, which can result in an increase rather than a decrease in the contact resistance. Furthermore, soft foils are flimsy, often deflecting under their own weight, which makes them difficult to handle and apply effectively.

Metallic coatings are free of the contamination problems associated with thermal greases and the handling problems associated with soft foils. In addition, when one of the contacting surfaces of a joint is coated, a number of workers [1–3] have reported as much as an order-of-magnitude improvement in the conduct conductance, depending on the materials involved, the texture of the contacting surfaces, and the metallic layer thickness.

Recently, a new thermomechanical predictive model for coated contacts has been developed and

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shown to accurately predict the thermal contact conductance data obtained from experiments performed on nominally flat, rough, nickel specimens put in contact with nominally flat, smooth, nickel specimens coated with a silver layer [4]. The purpose of the present work is to illustrate the utility of this new model by using it to analyze a common electronics packaging problem, heat transfer across an aluminum joint operating in a vacuum or in a gaseous environment.

THEORETICAL BACKGROUND

A comprehensive treatment of the theoretical development and experimental verification of the thermomechanical model can be found in [4]. In the following discussion, therefore, only those portions of the theory needed to apply the model to a thermal design problem will be presented. From [4] the general expression for the contact conductance of the coated joint (shown in Fig. 1) operating in a vacuum is

$$h_c' = h_c \left(\frac{H}{H'}\right)^{0.93} \left(\frac{k_1 + k_2}{C_2 k_1 + k_2}\right) \tag{1}$$

where h_c is the uncoated contact conductance, H is the hardness of the softer of the two substrates, H' is the effective hardness of the layer-substrate combination, C_2 is the constriction parameter correction factor, which accounts for heat spreading in the coated substrate, and k_1 and k_2 are the thermal conductivities of the base metals (substrates).

As can be seen from Eq. (1), the coated contact conductance is the product of three quantities: the uncoated contact conductance h_c; a mechanical multiplication factor $(H/H')^{0.93}$; and the thermal multiplication factor in brackets.

The uncoated contact conductance can be readily calculated from a correlation by Yovanovich [5]:

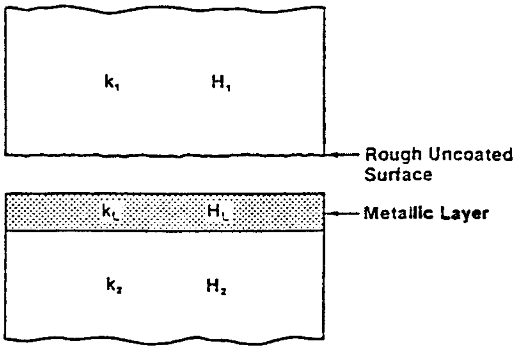

Figure 1 Representation of the coated joint.

$$h_c = 1.25\left(\frac{m}{\sigma}\right)\left(\frac{2k_1k_2}{k_1 + k_2}\right)\left(\frac{P}{H}\right)^{0.95} \tag{2}$$

where H is the hardness of the softer substrate (H_1 or H_2), m is the combined average absolute asperity slope for the two contacting surfaces, and σ is the combined rms surface roughness. Both surface parameters are obtained from profilmeter measurements.

For a given joint, then, the only unknowns in Eq. (1) are the effective hardness H' and the constriction parameter correction factor C_2. Thus the key to solving a coated contact problem is in the determination of these two quantities.

Mechanical Problem

Strictly speaking, the effective hardness must be obtained empirically for the particular layer-substrate combination being considered. This requires a series of Vickers hardness measurements, which will result in an effective hardness plot similar to that shown in Fig. 2 (which is for a silver layer on a nickel substrate). If the materials and facility required to generate the required effective hardness curve are not available, then to a first approximation it can be assumed that the general form of the curve for the particular layer-substrate combination being considered is the same as that shown in Fig. 2, and the following equations can be used to estimate the effective hardness. In the region $t/d < 1.0$:

$$H' = H_2\left(1 - \frac{t}{d}\right) + 1.81 H_L\left(\frac{t}{d}\right) \tag{3a}$$

where H_L is the hardness of the layer and H_2 is the hardness of the substrate, with both values being obtained from a Vickers test. Similarly, in the region $1.0 \le t/d \le 4.90$:

$$H' = 1.81 H_L - 0.21 H_L\left(\frac{t}{d} - 1\right) \tag{3b}$$

where the relative thickness t/d is determined from

$$\frac{t}{d} = 1.04\,\frac{t}{\sigma}\left(\frac{P}{H'}\right)^{-0.097} \tag{4}$$

When $t/d > 4.90$, the effective hardness equals the layer hardness H_L.

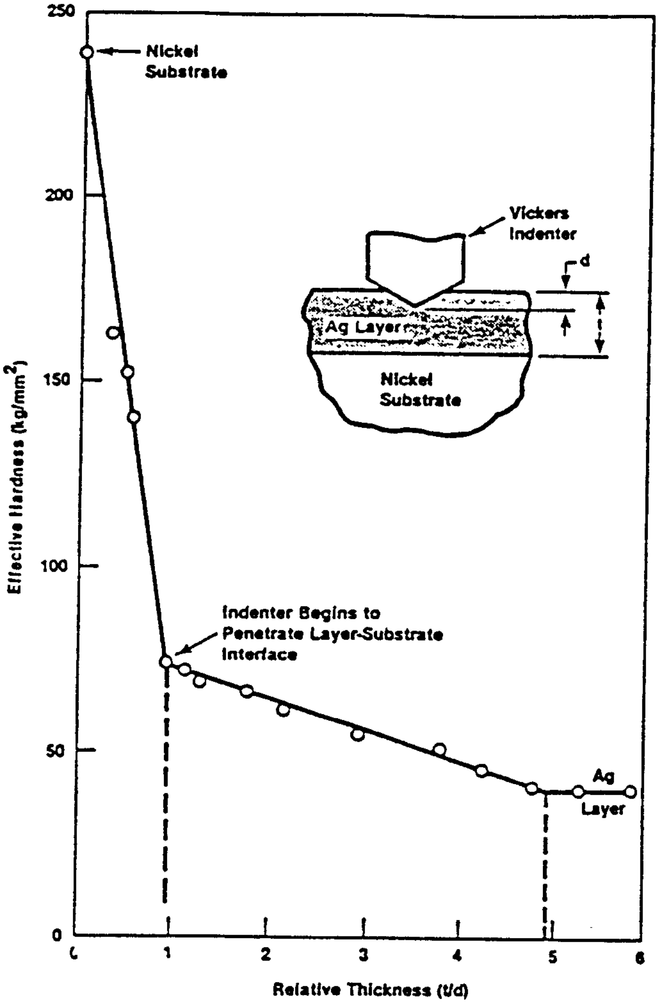

Figure 2 Effective hardness of silver layer on nickel substrate [4].

Because t/d depends on the effective hardness and t/d must be known to determine the effective hardness, an iterative approach is required. Convergence is very rapid, however, due to the fact that t/d is a weak function of the effective hardness. It is recommended that the arithmetic average of the layer and substrate hardnesses be used as the initial guess for the effective hardness.

Moreover, it is important to realize that very often the substrate surfaces may have been work-hardened, particularly if finished by a lapping process. In this case, it is inappropriate to use the bulk hardness of the substrate for H_2. Rather, the reader is referred to [6] for the technique to be used to determine a proper effective substrate hardness value.

Thermal Problem

The thermal portion of the analysis involves the solution of Laplace's equation for heat flow from a concentric circular hot spot on the end of an infinite right circular cylinder with adiabatic walls. If the dimensionless constriction parameter is defined as

$$\psi(\epsilon', \phi_n) = 4k_2 a' R_c' \qquad (5)$$

then, after determining the constriction resistance R_c' from the thermal analysis, the constriction parameter with a layer present at the contact is shown in [4] to be

$$\psi(\epsilon',\phi_n) = \frac{16}{\pi\epsilon'} \sum_{n=1}^{\infty} \frac{J_1^2(\delta_n'\epsilon')}{(\delta_n')^3 J_0^2(\delta_n')} \cdot \phi_n \cdot \gamma_n \cdot \rho_n \qquad (6)$$

Equation (6) is nothing more than the expression for the dimensionless constriction parameter for an uncoated contact (with a uniform heat flux prescribed at the contact and where the resistance is calculated on an average contact temperature basis) multiplied by three modification factors.

The first of these, ϕ_n, accounts for the influence of the layer; the second, γ_n, accounts for the contact temperature basis used to determine the constriction resistance; and the third, ρ_n, accounts for the contact spot heat flux distribution assumed. For abutting surfaces, it is usual to assume that the contact spots are isothermal. The modification factors in this case are $\gamma_n = 1.0$, and

$$\phi_n = K\left[\frac{(1+K) + (1-K)e^{-2\delta_n'\epsilon'\tau'}}{(1+K) - (1-K)e^{-2\delta_n'\epsilon'\tau'}}\right] \qquad (7)$$

$$\rho_n = \frac{\sin(\delta_n'\epsilon')}{2J_1(\delta_n'\epsilon')} \qquad (8)$$

The constriction parameter correction factor is now defined as the ratio of the constriction parameter with a layer to that without a layer, for the same value of the relative contact spot radius:

$$C = \frac{\psi(\epsilon',\phi_n)}{\psi(\epsilon')} \qquad (9)$$

Table 1 presents, in abridged form, numerical values for the constriction parameter correction factor for an isothermal contact spot on a layer. The reader is referred to [4] for a more complete tabulation.

Alternative Analysis

It should be noted that the following expression for the contact conductance of a coated joint can also be derived using an alternative analysis technique [4]:

Table 1 Constriction Parameter Correction Factor
- Isothermal Contact Temperature

Number of Layers Above Substrate = 1
Substrate/Layer Conductivity = K

		Relative Layer Thickness (t/a)					
ϵ	$1/K$	0.01	0.05	0.10	0.50	2.00	10.0
0.020	50.0	0.6928	0.3657	0.2441	0.0762	0.0301	0.0206
0.020	10.0	0.9058	0.6962	0.5602	0.2630	0.1362	0.1024
0.020	5.0	0.9498	0.8141	0.7069	0.4092	0.2514	0.2038
0.020	2.0	0.9831	0.9292	0.8781	0.6868	0.5515	0.5044
0.020	0.5	1.0178	1.0814	1.1508	1.5003	1.8455	1.9837
0.020	0.1	1.1191	1.5690	2.0796	4.9932	8.3735	9.8188
0.040	50.0	0.6842	0.3503	0.2281	0.0666	0.0269	0.0202
0.040	10.0	0.9029	0.6878	0.5485	0.2476	0.1266	0.1007
0.040	5.0	0.9841	0.8087	0.6987	0.3951	0.2397	0.2012
0.040	2.0	0.9825	0.9270	0.8746	0.6786	0.5422	0.5015
0.040	0.5	1.0186	1.0840	1.1553	1.5142	1.8662	1.9938
0.040	0.1	1.1246	1.5880	2.1128	5.1060	8.5623	9.9310
0.060	50.0	0.6757	0.3362	0.2145	0.0602	0.0251	0.0201
0.060	10.0	0.9001	0.6795	0.5372	0.2345	0.1203	0.1002
0.060	5.0	0.9466	0.8035	0.6907	0.3822	0.2312	0.2003
0.060	2.0	0.9819	0.9250	0.8711	0.6707	0.5346	0.5004
0.060	0.5	1.0192	1.0869	1.1597	1.5280	1.8850	1.9978
0.060	0.1	1.1288	1.6054	2.1449	5.2189	8.7405	9.9777
0.080	50.0	0.6674	0.3233	0.2028	0.0555	0.0239	0.0200
0.080	10.0	0.8973	0.6712	0.5261	0.2232	0.1159	0.1000
0.080	5.0	0.9451	0.7982	0.6828	0.3703	0.2247	0.2001
0.080	2.0	0.9814	0.9229	0.8676	0.6630	0.5283	0.5001
0.080	0.5	1.0198	1.0894	1.1642	1.5419	1.9020	1.9990
0.080	1.0	1.1329	1.6229	2.1775	5.3329	8.9075	9.9934
0.100	50.0	0.6590	0.3112	0.1924	0.0517	0.0230	0.0200
0.100	10.0	0.8945	0.6629	0.5154	0.2134	0.1125	0.1000
0.100	5.0	0.9435	0.7928	0.6748	0.3594	0.2197	0.2000
0.100	2.0	0.9808	0.9207	0.8641	0.6556	0.5231	0.5000
0.100	0.5	1.0203	1.0920	1.1689	1.5557	1.9173	1.9994
0.100	0.1	1.1373	1.6407	2.2107	5.4481	9.0624	9.9980
0.200	50.0	0.6173	0.2615	0.1540	0.0401	0.0209	0.0200
0.200	10.0	0.8793	0.6218	0.4651	0.1776	0.1040	0.1000
0.200	5.0	0.9351	0.7650	0.6352	0.3155	0.2064	0.2000
0.200	2.0	0.9779	0.9094	0.8455	0.6218	0.5079	0.5000
0.200	0.5	1.0235	1.1058	1.1941	1.6251	1.9869	1.9997
0.200	0.1	1.1588	1.7383	2.3920	6.0455	9.6298	9.9998

$$h'_c = \frac{2a'k'}{\psi(\epsilon')}\left(\frac{N'}{A_a}\right) \tag{10}$$

where the effective thermal conductivity k' is defined as

$$k' = \frac{2k_1k_2}{C_2k_1 + k_2} \tag{11}$$

and the constriction parameter can be found from

$$\psi(\epsilon') = (1 - \epsilon')^{1.5} = \left(1 - \sqrt{\frac{P}{H'}}\right)^{1.5} \tag{12}$$

The average contact spot radius is given by

$$a' = 0.77\left(\frac{\sigma}{m}\right)\left(\frac{P}{H'}\right)^{0.097} \tag{13}$$

From a force balance at the contact, the total number of contacts per unit area for the joint can be determined from

$$\frac{N'}{A_a} = \frac{1}{\pi(a')^2}\left(\frac{P}{H'}\right) \tag{14}$$

It is interesting to note that, although quite different algebraically, Eq. (10) yields numerical results that are identical to Eq. (1). The advantage of Eq. (10) is that it allows one to appreciate how the parameters that contribute to the coated contact conductance change as the coating thickness is increased.

It should be understood that the preceding theory is for nominally flat, rough surfaces. There is no model, as yet, that handles out-of-flat surfaces, although in most situations the conduct conductance predicted by Eq. (1) and Eq. (10) can be used as an upper bound.

Gaseous Environments

If the joint in question operates in air, or any other gaseous environment, an estimate of the conductance across the gas in the interstitial spaces of the joint can be made using a model proposed in [5]:

$$h_g' = \frac{k_g}{Y' + M} \tag{15}$$

where the distance between the mean planes of the contracting surfaces is obtained from [4],

$$Y' = 1.53\sigma\left(\frac{P}{H'}\right)^{-0.097} \tag{16}$$

and the gas parameter M is determined from

$$M = \alpha\beta\Lambda \tag{17}$$

For air at 377 K and 1 atm, $M = 0.81$ and the thermal conductivity is $k_g = 0.0305$ W/m K.

Now the total thermal conductance across a coated joint is determined by adding the contact and gas conductances: $h_j' = h_c' + h_g'$.

APPLICATION

The theory outlined in the previous section will now be applied to a common problem in electronics packaging: heat transfer across an aluminum joint. Assume that the joint in question has an apparent contact area of 6.41×10^{-4} m^2 (approximately 1 in.^{2}), and that the range of contacting surface finishes being considered is as given in Table 2. What is desired is a parametric study showing the variation in joint contact conductance as a function of metallic coating type and thickness, surface finish, and the pressure on the joint.

Table 2 Assumed Surface Characteristics of Joints

(σ) rms roughness	(m) avg. absolute asperity slope
Uncoated Side of Contact	
1.0 μm	0.10 radian
4.0	0.20
8.0	0.30
Coated Side of Contact	
0.20	0.02

The thermophysical properties of the coatings to be considered (lead, tin, and silver), as well as the aluminum substrate material, are presented in Table 3.

Figure 3 shows the effect of the layer thickness on the contact conductance. As seen from Fig. 3, except for a very thin layer (about 1μm), the performance curves are arranged according to layer hardness. Lead, with the lowest hardness, has the highest contact conductance: and silver, with the highest hardness, has the lowest conductance. The thermal conductivity of the coating appears to play a minor role. The unusual shape of the curves is attributable to the fact that the assumed effective hardness curve (Fig. 2) has three distinct zones. Moreover, because the hardness of silver is much closer to aluminum than are the hardnesses of lead and tin, the transition from one region to the next is not abrupt in the silver-on-aluminum effective hardness curve, and this is reflected in the smoother contact conductance plot for the silver layer curve shown in Fig. 3.

Figure 4 was generated by drawing a curve through three points computed for each layer material using the surface characteristics in Table 2. From Fig. 4, it can be seen that the smoother the finish of the

Table 3 Assumed Properties of Materials

	k (W/m K)	H (kg/mm^2)
Lead	32.4	3.0
Tin	58.4	8.5
Silver	406.0	40.0
Aluminum	190.0	85.0

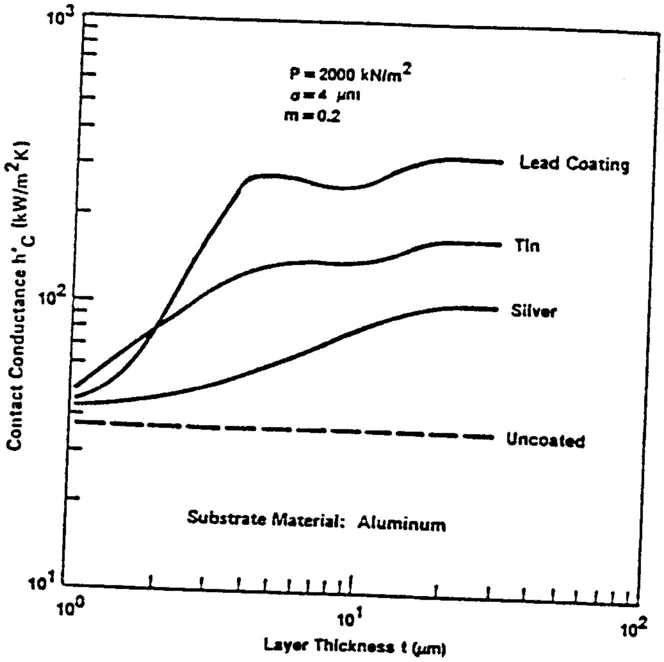

Figure 3 Effect of layer thickness on contact conductance (in a vacuum).

uncoated surface, the higher is the joint conductance.

Figure 5 shows the effect of joint pressure on the contact conductance. It should be noted that the load is assumed to be uniformly applied over the apparent contact area.

The alternative analysis technique was used to generate Table 4. Here the change in the parameters influencing the contact conductance can be appreciated as the tin coating thickness increases. Table 4 clearly shows that as the layer thickness is increased, the primary reason for the corresponding increase in the contact conductance is the dramatic increase in the total number of microcontacts.

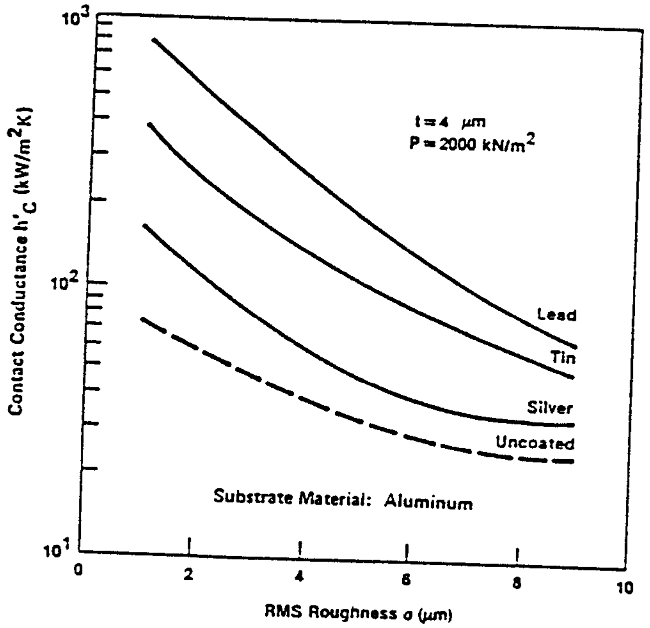

Figure 4 Effect of surface finish on contact conductance (in a vacuum).

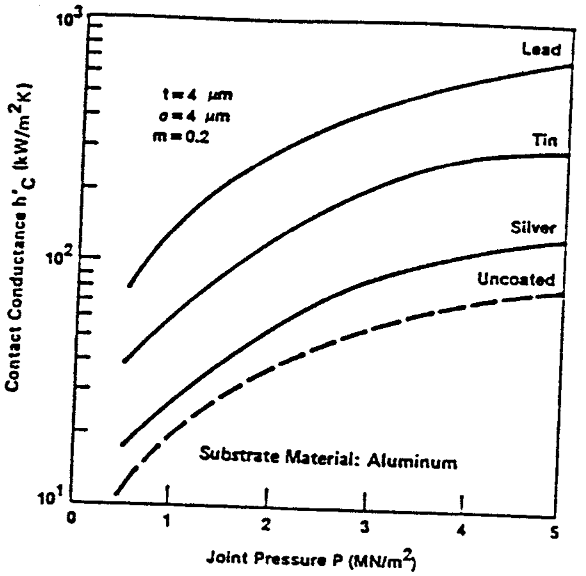

Figure 5 Effect of joint pressure on contact conductance (in a vacuum).

At this point, it is interesting to determine the conductance across the interstitial spaces if the joint described in Table 4 is operated in air at 377 K. Using Eq. (15), it can be shown that when the tin layer thickness is zero, h_g = 2150 W/m^2 K, or 5.5% of the total joint conductance. Furthermore, when the tin layer thickness is 16 μm, the heat transfer rate across the air increases very little to 2450 W/m^2 K, which amounts to only 1.4% of the total joint conductance.

Ranking Coating Performance

Yovanovich [7], studying the effect of soft foils on joint conductance, proposed that the performance of different foil materials could be ranked according to the parameter (k/H), using the properties of the foil material. He showed empirically that the higher the value of this parameter, the greater was the improvement in the contact conductance over a bare joint. Following this thought, what is proposed here, though not proven experimentally, is that the performance of coated joints can be ranked by the parameter $k'/(H')^{0.93}$. Table 5 shows the variation in this parameter as the layer thickness is increased. Table 5 suggest as well that even if the effective hardnesses of the layer-substrate combinations being considered are not known, the relative performance of coating candidates can be estimated by assuming an infinitely thick coating

Table 4 Summary of Calculated Theoretical Parameters for a Tin Layer on an Aluminum Substrate (in a vacuum)
($\sigma = 4\ \mu$m, $m = 0.20$)

P	t	t/d	H'	$\psi(\epsilon')$	C	k'	a'	N'	h_c'
2000	0.0	0.00	85.0	0.927	1.000	190.0	8.6	6700	36,600
2000	1.0	0.45	53.8	0.909	1.355	161.4	8.9	9700	47,900
2000	2.0	0.84	26.8	0.872	1.627	144.7	9.6	17,000	84,300
2000	4.0	1.58	14.4	0.827	2.046	124.7	10.2	28,100	134,000
2000	8.0	3.09	11.7	0.809	2.566	106.6	10.4	33,200	141,000
2000	16.0	6.66	8.5	0.777	3.015	94.6	10.7	42,900	174,000
2000	∞	—	8.5	0.777	3.253	89.3	10.7	42,900	165,000

P = pressure (kN/m^2); t = layer thickness (μm); t/d = relative layer thicknes; H' = effective hardness (kg/mm^2); $\psi(\epsilon')$ = constriction parameter; C = constriction parameter correction factor; k' = effective thermal conductivity (W/m K); a' = mean contact spot radius (μm); N' = total number of contact spots; h_c' = thermal contact conductance (W/m^2 K).

Table 5 Ranking the Effectiveness of Coatings $[k'/(H')^{0.93}]$

Coating thickness (μm)	Lead	Tin	Silver
0	3.05	3.05	3.05
1	3.72	3.96	3.53
2	7.05	6.81	3.98
4	19.6	10.5	4.68
8	18.0	10.8	6.24
16	21.0	12.9	8.16
∞	19.9	12.2	8.38

Assumes $P = 2000$ kN/m^2, $\sigma = 4.0\ \mu$m, $m = 0.20$ radian.

(where the effective hardness equals the layer hardness).

CONCLUDING REMARKS

This paper has shown how a newly developed thermomechanical model for coated contacts can be used to predict the enhancement in thermal contact conductance for a coated joint. For the particular case considered, an aluminum-to-aluminum joint, it was demonstrated that up to an order-of-magnitude improvement in the contact conductance is possible, depending on the choice of coating material and the thickness employed. It should also be noted that aluminum substrates are relatively soft and have a relatively high thermal conductivity, and if the joint in question had been, for example, steel against steel, the improvement in the contact conductance would have been even more impressive.

ACKNOWLEDGMENT

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NOMENCLATURE

a	contact spot radius
A	area
b	flux tube radius
C	constriction parameter correction factor
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
d	equivalent Vickers indentation depth
H	Vickers microhardness
H'	effective microhardness of soft layer on harder substrate
h	thermal contact conductance
J_n	Bessel function, first kind, order n
K	thermal conductivity ratio (substrate to layer)
k	thermal conductivity
k'	effective thermal conductivity
M	gas parameter ($= \alpha\beta\Lambda$)
m	combined average absolute asperity slope ($= \sqrt{m_1^2 + m_2^2}$)
N	number of contact spots in apparent area A_a
P	apparent contact pressure
Pr	Prandtl number
R	resistance
t	layer thickness
Y	separation distance of mean planes of contacting surfaces
α	accommodation coefficient
β	gas parameter $[= (2\theta/\theta + 1)/P_r]$
γ_n	constriction parameter modification factor attributable to heat flux distribution
δ_n	eigenvalue
ϵ	relative contact spot radius ($= a/b$)
θ	specific heat ratio ($= c_p/c_v$)

Λ	molecular mean free path
λ_n	eigenvalue
ρ_n	constriction parameter modification factor attributable to contact temperature basis
σ	combined rms roughness ($= \sqrt{\sigma_1^2 + \sigma_2^2}$)
τ	relative layer thickness ($= t/a$)
ϕ_n	constriction parameter modification factor attributable to the layer
$\psi(\epsilon)$	constriction parameter

Superscripts

In general, prime indicates the layer.

Subscripts

a	apparent
c	contact or constriction
g	gas
j	joint
L	layer
1	one side of contact
2	other side of contact

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