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Effect of Surface Deformations on Thermal Contact Conductance of Coated Junctions

Kee-Chiang Chung*
National Yunlin Institute of Technology, Touliu City, Yunlin 640, Taiwan, Republic of China

Thermal contact conductance is normally a significant contribution to the total thermal conductance of electronic packages. Extensive work has been done to predict thermal contact conductance using coating techniques, however, only limited research has been conducted on the effect of surface deformations of coatings. The nature of the deformations of surface asperities had strong influence on the thermal contact conductance. Based on classical theories of contact mechanics, the surface deformations could be either plastic or elastic. How the different coating materials, coating thickness, and surface roughness influence the surface deformation is still not clear. Hence, the aim of the present work is to present the effect of coatings on surface deformations. Various surface treatment samples are used in this study including one-surface, two-surface, and phase-mixture coatings upon aluminum substrates. Five different coating materials are employed in this investigation under low contact pressures where little experimental data exist. Results showed that coating interfaces deform plastically during the first loading–unloading process under light load.

Nomenclature

C = constriction parameter correction factor
H = Vickers microhardness, Pa
h = uncoated thermal contact conductance, W/m^{2}K
h_c = coated thermal contact conductance, W/m^{2}K
k = thermal conductivity, W/mK
P = contact pressure, Pa
S = asperity slope
t = coating thickness, μm
σ = surface roughness, μm

Superscript
$'$ = effective

Introduction

WITH the recent trend toward increased miniaturization and component density, thermal management within these packages has become the primary factor that limits the physical size of both individual components and multichip modules. Therefore, in many electronic packages the thermal conductance across a particular interface must be improved for the thermal design to meet its performance objective.[1,2] As a consequence, there is an increasing interest in enhancing the heat transfer at interfaces within electronic systems. One of the most promising methods for enhancing heat transfer at the interface involves the use of contacting surface treatments. These treatments include surface preparation as well as chemical vapor deposition (CVD). For thermal enhancement, metallic or nonmetallic (e.g., ceramic) coatings are generally the most successful surface treatment.[3,4] Kang et al.[5] conducted an experimental investigation to determine the degree to which the thermal contact conductance of an aluminum 6061-T6 junction could be enhanced through the use of vapor-deposited lead, tin, and indium coatings. Results of this investigation indicated that the thermal contact conductance enhancement effect was greater at low contact pressures and decreased significantly with respect to increases in the contact pressure. Also, the enhancement for the thermal contact conductance was found to be in the range from 50–700%. Lambert and Fletcher[6] reviewed the published thermal contact conductance data for metallic coated metals. Using 654 data chosen from 99 separate contact conductance experiments, they presented a regression analysis that utilized expressions for dimensionless thermal contact conductance and relative pressure developed for optically flat surfaces. The dimensionless contact conductance relationship is

$$h_c\sigma/sk' = 0.00977(P/H')^{0.52} \tag{1}$$

A theoretical development and experimental verification of the plastic thermal contact conductance model can be found in Antonetti.[7] The general expression for the contact conductance of the pure coated joint is

$$h_c = h\left(\frac{H}{H'}\right)^{0.93}\left(\frac{k_1 + k_2}{C_1k_1 + C_2k_2}\right) \tag{2}$$

where H is the hardness of the softer of two substrates, H' is the effective hardness of the layer-substrate combination, C_1 and C_2 are the constriction parameter correction factors that relate to the surface roughness and asperity slope, and k_1 and k_2 are the thermal conductivities of the base substrates. Four different materials, 1) stainless steel 304, 2) aluminum, 3) nickel–iron alloy, and 4) beryllium were examined by Maddren and Marschall[8] to investigate the temperature dependence of the hardness and elastic constants from liquid nitrogen to room temperature. They indicated that the use of available correlations to extrapolate the contact conductance measured at room temperature to predict the conductance at cryogenic temperatures would lead to large errors. An experimental investigation was conducted to evaluate the enhancements in the thermal conductance of silver and gold coatings on aluminum A356-T61 by Lambert and Fletcher.[9] Results of the experimental investigation showed that the thermal conductance values of silver- and gold-coated aluminum A356-T61 were greater than conductance values for the uncoated A356 by factors of 1.25–2.19 for the electroless nickel-plated copper junctions and 1.79–3.41 for the anodized aluminum junctions. Sridhar and Yovanovich[10] compared most of the elastic and plastic models available in the literature with experimental data. They concluded that smoother test samples deform elastically and rougher test samples deform

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*Associate Professor of Mechanical Engineering.

plastically. Five different contacting surfaces were investigated by Williamson and Majumdar,[11] with test samples of different surface roughness combinations using aluminum, stainless steel, and copper. From their report, the surface in contact can deform elastically or plastically, dependent on various contacting surface combinations. Hence, no concrete conclusion of conductance hysteresis effect on contacting surfaces was made. However, no surface deformation of coating layers was investigated in the previous studies. In order to successfully model the thermal contact conductance of coatings it is first necessary to understand how contact mechanics and surface deformation apply to coated joints.

Experiments

In order to determine the effect of surface deformations on thermal contact conductance of coated junctions, an experimental investigation was conducted with three different coating techniques. Thirty-two specimen pairs with five different coating materials varying in thickness from 0.18 to 50.8 μm were tested.

Test Specimens

To get a wide range of material properties, three basic coating types were studied using five different materials in this investigation. As illustrated in Fig. 1, these were 1) one-surface coatings, 2) two-surface coatings, and 3) phase-mixture coatings. Also, a fairly broad range of surface roughness and coating thickness was adopted. The one- and two-surface coating samples were prepared with three different coating materials; aluminum, lead and indium upon aluminum 6061-T6 substrates. These substrates were prepared on the surfaces of 2.54 cm diam by 2.54 cm long cylindrical aluminum 6061-T6 specimens that were fabricated from a commercial bar taken from stock. Three different coating thicknesses, 12.7, 25.4, and 50.8 μm, and two surface roughnesses 1.6 and 3.2 μm were employed to evaluate the thermal contact conductance for each coating material. The copper–carbon and silver–carbon coating materials were coated on aluminum 6061-T6 substrates for the phase-mixture coating specimens. The graded phase-mixture coatings were layered onto an aluminum 6061-T6 substrate by glow discharge plasma. A capacitively coupled bell-jar type reactor operating at a frequency of 10 kHz was used for plasma creation. Either a single- or double-diode magnetron electrode system was used to create a plasma. Two copper/silver plates (18 × 18 cm) were used as the electrodes for a single electrode system, and two titanium plates were added as the second set of electrodes for a double electrode system. A sample mounting disk was located in the middle of the diode and rotated at 50 rpm for uniform plasma coatings. The composition of the graded coating layers, which changes from 100% carbon to copper/silver metallic over the thickness of the coating layer, eliminates sudden changes in physical and chemical structures between two dissimilar materials and assists in establishing a stronger, more durable interface. Four surface roughnesses ranging from 0.23 to 3.87 μm were used for aluminum bare contacting surfaces. Two coating thicknesses, 0.25 and 0.45 μm of the copper–carbon coatings and 0.18 and 0.39 μm of silver–carbon coatings were conducted for phase mixture coating layers. All detailed data are listed in Table 1.

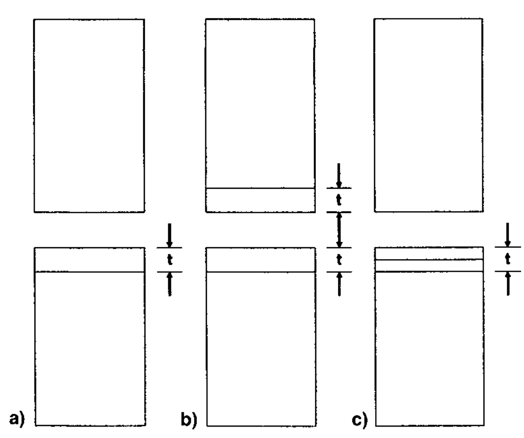

Fig. 1 Different types of joint contacts: a) one-surface coatings, b) two-surface coatings, and c) phase-mixture coatings.

Table 1 Specimen surface characteristics and coating types

Coating material	One-surface coatings, μm		Two-surface coatings, μm		Phase mixture coatings, μm	
	σ	t	σ	t	σ	t
Al	1.6	25.4	1.6	12.7	—	—
	1.6	50.8	1.6	25.4	—	—
	3.2	25.4	3.2	12.7	—	—
	3.2	50.8	3.2	25.4	—	—
Pb	1.6	25.4	1.6	12.7	—	—
	1.6	50.8	1.6	25.4	—	—
	3.2	25.4	3.2	12.7	—	—
	3.2	50.8	3.2	25.4	—	—
In	1.6	25.4	1.6	12.7	—	—
	1.6	50.8	1.6	25.4	—	—
	3.2	25.4	3.2	12.7	—	—
	3.2	50.8	3.2	25.4	—	—
Cu-C	—	—	—	—	0.23	0.25
	—	—	—	—	0.39	0.45
	—	—	—	—	2.52	0.45
	—	—	—	—	3.87	0.25
Ag-C	—	—	—	—	0.31	0.18
	—	—	—	—	0.35	0.18
	—	—	—	—	2.89	0.39
	—	—	—	—	3.22	0.39

Apparatus

The detailed description of the experimental apparatus has been previously reported by Chung.[12] The apparatus consists of a test pneumatic pressure cylinder, a data acquisition system, and a vacuum chamber containing a test column. The test column consists of a load bellow, heating and cooling systems, two heat-flow meters, and pairs of test specimens. In order to reduce natural and forced convection, a vacuum environment is required. The operating vacuum pressure is less than 0.2 torr and the operating interface temperature is 60 ± 2°C. The temperature gradient through the specimens and the subsequent temperature jump across the interface were measured using 28-gauge copper/constantan thermocouples. The thermocouples were inserted in holes of 1.59 mm diam and 1.27 cm depth, drilled perpendicularly to the axes of the heat-flow meters.

Experimental Procedure and Uncertainty

Once the test specimens had been prepared and the surface characterized, the test specimen pairs were cleaned with acetone and a lint-free cloth. These pairs were carefully placed between heat-flow meters and test alignment of the vertical stack. The bell jar was put on the vacuum plate. The specimens were allowed to out-gas for approximately five to six hours and were then evacuated to a stable vacuum level.

The temperature gradients in each sample, computed from a linear least-squares regression of the individual thermocouple readings, are used to calculate the heat flux through each specimen. The temperature profiles in the specimens are extrapolated to the interface to obtain the temperature discontinuity across the interface. The contact conductance is computed as the quotient of the mean heat flux across the junction and the temperature discontinuity. To determine whether elastic or plastic deformation was dominant at the coated joints, the contact pressure was increased from approximately 125 to 500 kPa and back to 125 in 125-kPa increments. If plastic deformation of the coating interface occurred, one would expect to observe an increase in the conductance during unloading over that during initial loading. The uncertainty in the temperature drop across the coating interface is the result of the uncertainties associated with the thermocouple readings and the extrapolated temperature. An estimate of the total uncertainty for one- and two-surface coating samples was approximately ±12.5 and ±8% for phase-mixture coating samples.

Results and Discussion

The contact conductance results of one-surface aluminum coatings during the first load–unload cycle are shown in Fig. 2. All the test data clearly show an increase in thermal contact conductance with increasing interface pressure. The contact conductance during the first unloading was greater than that for the initial loading for the same applied contact pressures. This seems to indicate that the deformation is predominantly plastic during the initial loading. Figure 3 shows the results of two-surface aluminum coatings of load–unload first cycle. The experimental data of this contact conductance were similar to those for the one-surface aluminum coating test. Comparing the results of the one- and two-surface aluminum coating tests shows that there is more of a hysteresis effect in two-surface coatings than in one-surface coatings. This is to be expected due to the fact that two-surface coatings can produce lower microhardness values than one-surface coatings at the interface. At the same surface roughness junctions of aluminum coatings (Figs. 2 and 3), no definite dependence of the coating thickness on hysteresis effects is observed. Regardless of the coating thicknesses (Figs. 2 and 3), the rougher substrate surfaces can obtain higher hysteresis effects than smoother substrate surfaces.

Figures 4 and 5 show the lead coatings on aluminum substrate using the one- and the two-surface coating techniques, respectively. Similar to the previous figures, the thermal contact conductances are plotted vs increasing pressure for four different combinations of surface roughness and coating thickness. The two-surface coating interface also can create a higher

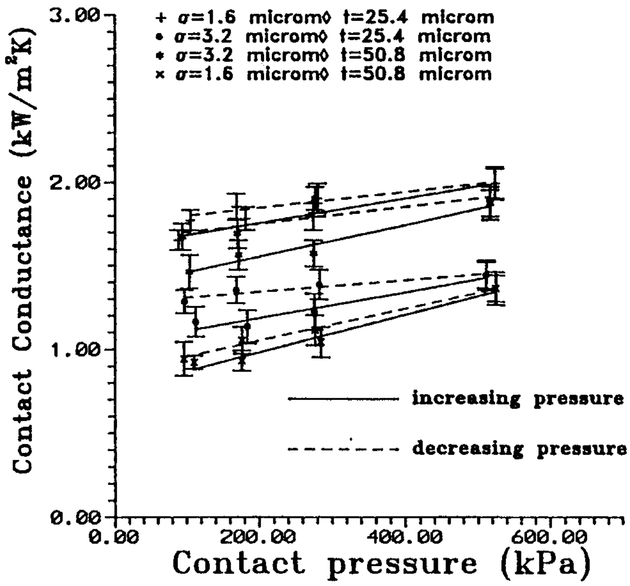

Fig. 2 Contact conductance for one-surface aluminum coating with different surface characteristics during first loading and unloading.

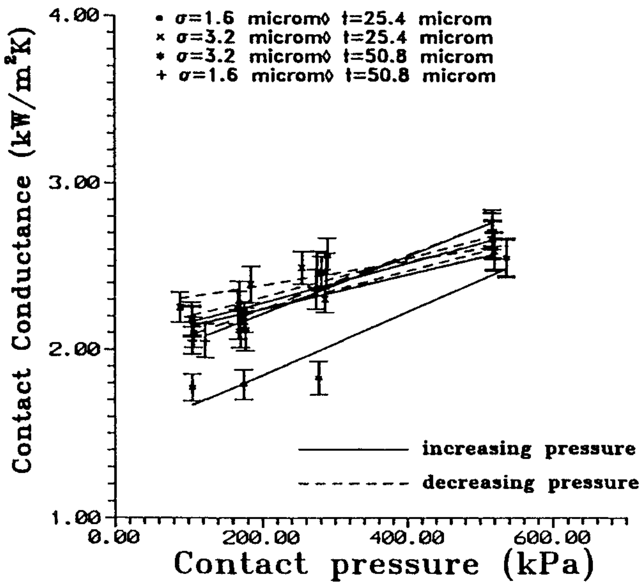

Fig. 4 Contact conductance for one-surface lead coating with different surface characteristics during first loading and unloading.

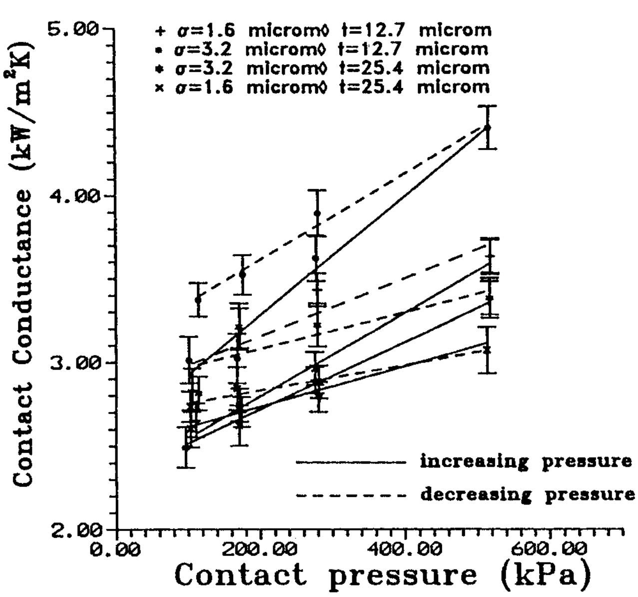

Fig. 3 Contact conductance for two-surface aluminum coating with different surface characteristics during first loading and unloading.

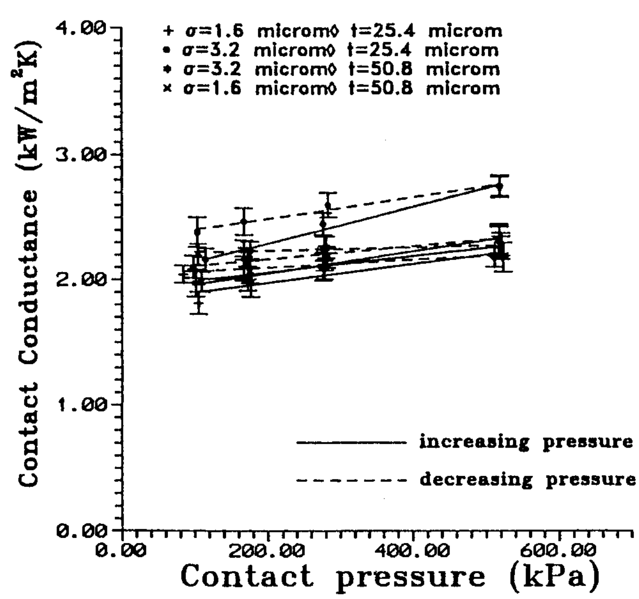

Fig. 5 Contact conductance for two-surface lead coating with different surface characteristics during first loading and unloading.

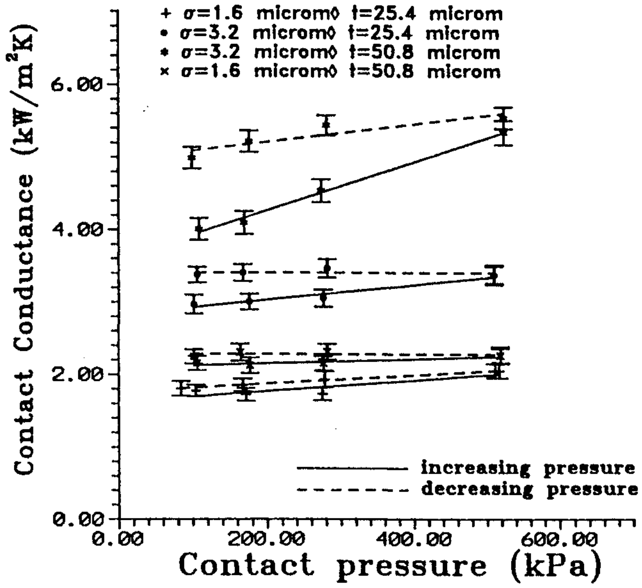

Fig. 6 Contact conductance for one-surface indium coating with different surface characteristics during first loading and unloading.

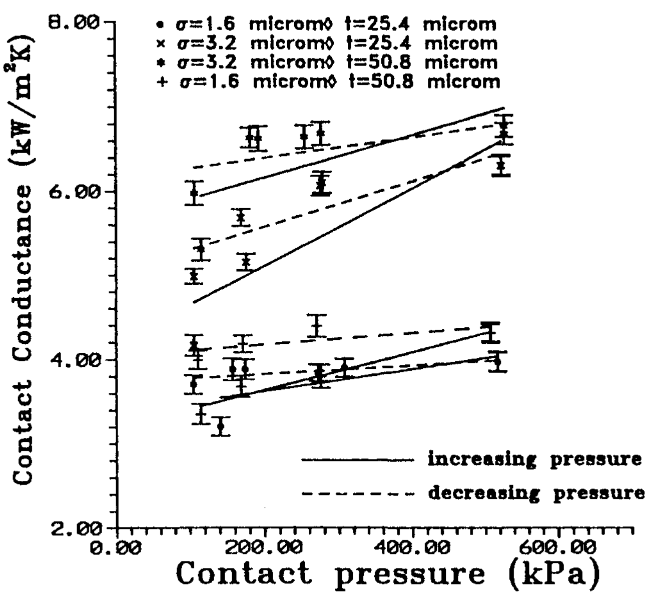

Fig. 7 Contact conductance for two-surface indium coating with different surface characteristics during first loading and unloading.

hysteresis effect than the one-surface coating interface. Because the data of lead coatings show a large scatter, one cannot be very certain that the rougher substrate surfaces were able to produce greater hysteresis effects. Investigation of the influence of coating thickness on hysteresis effects of lead coatings in Figs. 4 and 5 showed again that no solid results were obtained.

As shown in Figs. 6 and 7, the contact conductance during the first unloading is greater than that for the initial loading. This implies that there was some plastic deformation on the indium coating interface as well. An interesting feature of coating thickness was observed in Figs. 6 and 7. Both of the 1.6- and 3.2-μm surface roughness cases exhibited that the thicker coating layer can obtain a larger hysteresis effect. The same phenomenon was not found in other coating materials. The reason may be due to the extremely soft surface characteristic of indium. It is evident that rougher substrate surfaces (3.2 μm) provide more significant hysteresis effects than smoother substrate surfaces (1.6 μm). However, the same conclusion is not valid for some of the test pairs of one- and two-surface lead coating interfaces. Therefore, it is important to compare the hysteresis effect of different coating materials at the same surface roughness and coating thickness.

Figure 8 shows the comparison of the one-surface coating interface data with uncoated substrate data during a complete load–unload cycle for a surface roughness of 3.2 μm and coating thickness of 50.8 μm. A hysteresis effect was observed for all coating test specimens, but the uncoated substrate did not seem to deform plastically. The experimental results on indium coatings clearly showed hysteresis, suggesting that plastic deformation in the indium coating interface was very significant. This is probably due to the fact that indium can produce a softer coating layer than aluminum and lead can. Based upon the earlier test data, the microhardness of the coating material seems to be the most indicative parameter in the ranking of the surface deformation.

Another experiment was conducted using phase-mixed coatings, which are typically a two-phase mixture of copper and carbon or silver and carbon. The relative ratio of carbon to copper or carbon to silver can be varied by altering the deposition parameters, giving the desired chemical concentration gradient through the coatings. All the phase-mixture coating interfaces, including copper/carbon and silver/carbon, show the hysteresis effect in Fig. 9. One interesting observation in Fig. 9 is that the silver coatings obtain larger hysteresis effects than do copper coatings disregarding the influence of surface roughness. Similar to the previous results, the softer coating material (silver) had a greater surface hysteresis effect at the interface neglecting the surface roughness effect.

The previous experimental results clearly show that the coating interfaces were predominantly plastic deformation for the first loading of a fresh surface. Hence, a linear regression correlation [Eq. (1)] and a theoretical plastic contact conductance model of coatings [Eq. (2)] were applied to compare with the test data. Thermal contact conductance and apparent contact pressure values are reduced to dimensionless terms in order to facilitate comparison of data from different coating surfaces involving various coating materials, surface profiles, and contact pressures. A comparison of the dimensionless thermal contact conductance values obtained from present study and other coated surfaces with an existing plastic contact conductance model of coatings and a linear regression correlation is shown in Fig. 10. The experimental results of 18 pairs of samples using vapor deposited lead, tin, and indium coatings on aluminum 6061-T6 with the coating thickness range

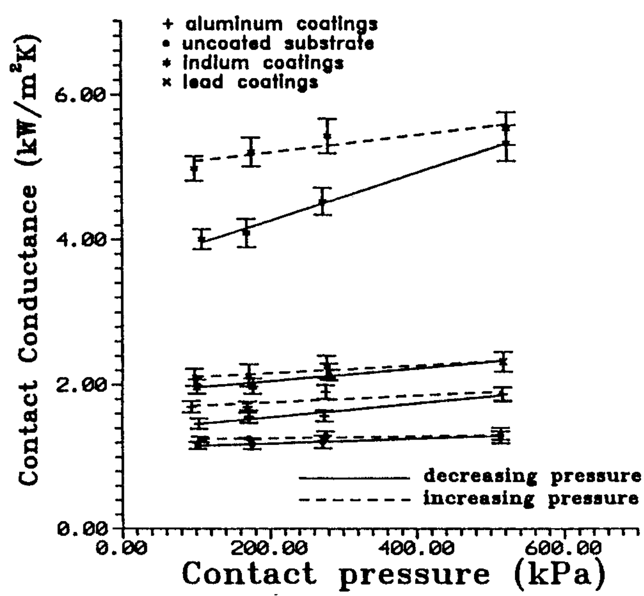

Fig. 8 Comparison of one-surface coating interface using different coating materials at 3.2-μm surface roughness and 50.8-μm coating thickness.

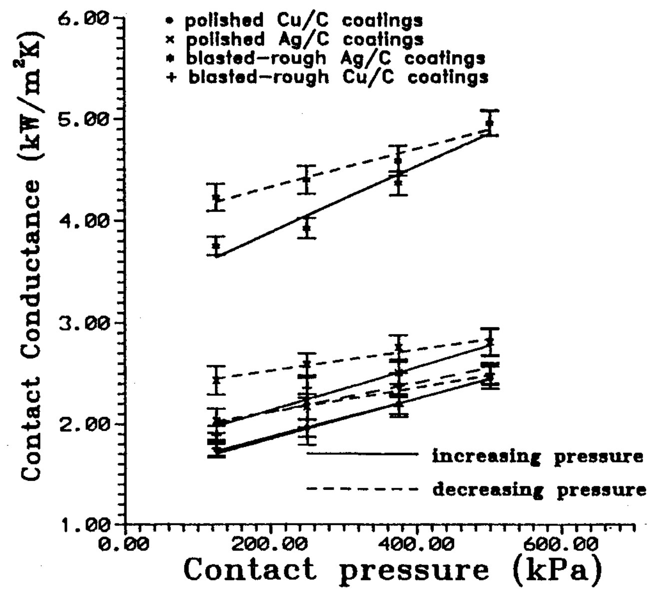

Fig. 9 Contact conductance for phase-mixture coatings during first loading and unloading.

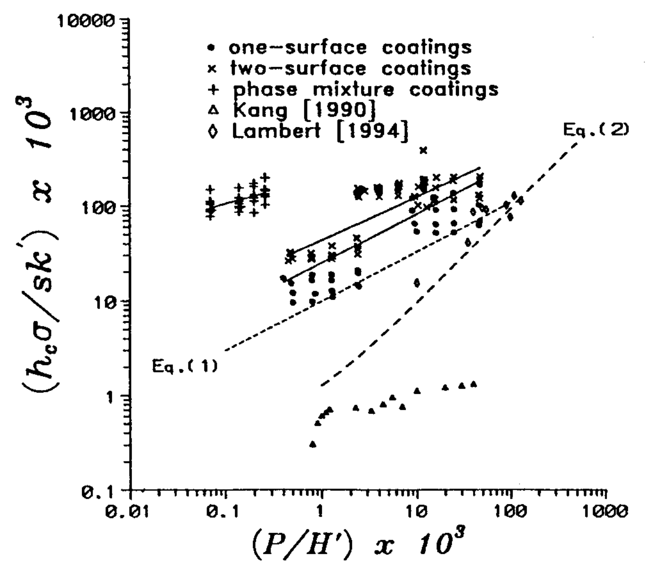

Fig. 10 Comparison of the dimensionless contact conductance of the different coating techniques.

of 0.25–5 μm and the surface roughness range of 0.37–0.86 μm were provided by Kang et al.[6] Also shown in Fig. 10 are the dimensionless thermal contact conductance data obtained by Lambert and Fletcher[9] for vapor-deposited silver and gold coatings on one surface of aluminum A356-T61 contact pairs with the coating thickness range of 1–3 μm and the surface roughness range of 0.15–0.69 μm. For all test data of coated joints, both the theoretical model and regression correlation overpredicted the test data of Kang et al.[6] and underpredicted the other data. It is clear that a unique theoretical model that can correlate all the various experimental data from this investigation does not apply at low contact pressures. However, excluding the dimensionless thermal contact conductance data from Kang et al.,[6] different coated junctions test results converge when the contact pressure continues to increase. Significant light load deviation of data sets is observed in Fig. 10. This apparently shows the need for development of a much improved plastic model for prediction of the contact conductance of coatings. The higher contact pressures experimental data and multiple-load cycle tests also need to be investigated.

Conclusions

Over recent years, the power densities at the component level within electronic packages have increased dramatically. To improve performance, cost, and reliability by packaging greater numbers of circuits in ever smaller space is the greatest challenge for a thermal design engineer. Deformations at the coated interface have a strong influence on the thermal contact conductance. It is therefore critical to study the effect of load and deformation on the thermal contact conductance of coated interfaces.

In this investigation, 128 data points were used to evaluate the effect of coating techniques on thermal contact conductance. One complete load cycle was undertaken for one- and two-surface coatings contacts using aluminum, lead, and indium, three different coating materials as well as phase-mixture coatings contacts using copper/carbon and silver/carbon. For each test specimen pair, the contact loading pressure was increased from approximately 125 to 500 kPa and back to 125 kPa in 125-kPa increments. The results show qualitative analysis of the hysteresis effect of coated joints using one- and two-surface and phase-mixture coating techniques. From the experimental data, the softer the coatings, the greater the hysteresis effect at interface. The microhardness of the coating material seems to be the most significant parameter in predicting the surface hysteresis effect. Comparing the experimental data of the same coating materials at the same surface roughnesses, it is apparent that no definite dependence of the coating thickness on hysteresis effects is evident. Also, it is not certain as to whether the rougher surfaces can have a larger hysteresis effect than the smoother surfaces. Hence, further experimental data is needed to substantiate this result. Also, the effect of the surface roughness and coating thickness combinations on the surface deformation needs to be examined from an experimental as well as analytical point of view.

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