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Enhancement of Thermal Contact Conductance: Effect of Metallic Coating

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Thermal contact resistance exists in any joint due to the imperfections of the surfaces. Several methods may be employed to enhance the thermal performance of joints. One of these methods is to coat the surfaces in contact with a layer of suitable metal. The coating material may have a low hardness, which increases the total contact area of the joint, and higher thermal conductivity, which enhances the heat transfer in the contact region. The described experimental investigation examined four coating materials: tin, copper, aluminum, and silver. Two methods of coating were used: electroplating and filtered arc vapor deposition. It was confirmed that all four coating materials enhanced thermal contact conductance. However, the optimum coating thickness varied with the coating material used. It was the hardness of the coating material that determined the optimum coating thickness. The higher the hardness of coating material, the thicker the coating needs to be for better performance. It was also found that the methods of coating affected the enhancement factor.

Nomenclature

H = hardness of the material, MPa
k = thermal conductivity of materials, $W/m \cdot K$
R = resistance
R_{cb} = bulk resistance of coating layer of a coated joint
R_{co} = minimum solid contact resistance in a coated joint
R_{cs} = solid contact resistance of a coated joint
R_q = rms radius of curvature, μm
R_t = total contact resistance of a coated joint, $R_{cb} + R_{cs}$
t = coating thickness, μm
t_o = optimum coating thickness
λ_a = mean slope
σ_q = rms roughness, μm

Subscripts

m = substrate
c = coating

Superscript

$*$ = filtered arc vapor deposition coating

I. Introduction

NO matter how smooth a surface may be, there exists a large number of microscopic peaks and valleys due to the imperfection of the machining process. When two nominally flat surfaces are brought into contact, the real contact area comprises numerous small contact spots and is only a small fraction of the apparent contact area (typically less than 1%).

When heat flows through the contact interface, the heat flow is constrained to the discrete contact spots. This constriction causes an additional resistance to the heat flow, namely, thermal contact resistance. It is defined as the temperature drop between two contact surfaces divided by the heat flux passing through the joint. The thermal contact conductance, by definition, is the reciprocal of thermal contact resistance.

Thermal contact conductance plays an important role in many engineering applications, including microelectronics, spacecraft, and nuclear reactors.[1,2] A large number of experimental investigations and theoretical analyses[3–5] have been conducted in the past. Sridhar and Yovanovich[6] reviewed those theoretical analyses on thermal contact conductance and made comparisons with experimental results. In general, it is understood that thermal contact resistance varies with the surface topological condition and surface microhardness. Contact pressure, thermal conductivity of the materials, and the mean junction temperature also affect thermal contact conductance.

Enhancement of thermal contact conductance has been an interesting topic for several decades.[7–9] One technique to improve the thermal performance of the joint is to introduce foreign materials of high thermal conductivity and low hardness, such as thermal grease, metallic coating, or foil, into the joint. The soft layer of foreign material generates more contact area and, therefore, reduces the overall thermal contact resistance.

Thermal grease, due to the possibility of evaporation and contamination, may not be suitable in many critical electronic assemblies. Soft metal foil offers excellent enhancement on the thermal contact conductance.[9] However, thin foil tends to wrinkle, which results in increasing of contact resistance rather than reducing it. Furthermore, metallic foils are often thin and weak, which makes them difficult to handle and apply.[9] Metallic coatings, on the other hand, are free of the contamination problem associated with the thermal grease. Also the application of coating is well developed and understood.

The current experimental program investigates the use of metallic coatings to enhance the thermal contact conductance, with particular reference to the selection of coating material and optimum coating thickness.

II. Literature Review

There have been a number of investigations dealing with the use of metallic coatings to enhance the thermal performance of joints. Lambert and Fletcher[9] presented an extensive review on the current state of knowledge in this field. They examined a large range of candidate coating materials and concluded that, of those coating materials, the most suitable ones for enhancing contact conductance were silver, copper, and gold.

The theoretical model of Mikic and Carnasciali[7] was used to analyze contact conductance of an elemental heat channel. They considered that the elemental model could be used for the evaluation of the contact resistance for multiple contacts between nominally flat and rough surfaces. They concluded that the coating material of

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higher thermal conductivity might significantly reduce the overall contact resistance of the joint. They also pointed out that plating only one end of the contact surface may have limited effect on reducing the contact resistance because the constriction of the heat flow still occurred in the low conductivity end. The better way to improve the conductance was to coat both ends of contact. An experimental verification of the theory was also conducted on a single constriction. The results were identical to the theoretical prediction.

Yovanovich[10] showed experimental results of lead, tin, aluminum, and copper foils on the reduction of thermal resistance. The results were obtained in an Armco iron joint. One of the surfaces was lathe turned and the other optically flat. The thickness of foils ranged from 10 to 500 μm and the contact pressure from 2 to 10 MPa. The introduction of foils reduced the contact resistance in every case. He concluded from the results that there was an optimum foil thickness for which the joint resistance was minimum. The ratio of the optimum foil thickness to the surface roughness varied with the foils used. He proposed that the effectiveness of the foil may be ranked by the ratio of its thermal conductivity to hardness; the larger the ratio, the greater will be the reduction of the joint resistance.

The thermomechanical model developed by Antonetti and Yovanovich[8] has been the most extensive analysis performed for a coated joint so far. The correlation developed for bare joints by Yovanovich[6] was used as the basis for the theory of coated joint. The contact conductance of coated joints was presented as a function of 1) bare contact conductance, 2) microhardnesses of coated and bare surface, and 3) a thermal multiplication factor that accounts for the effect of the metallic coating on the constriction. Experiments conducted on a silver-coated nickel specimen in contact with a bare nickel specimen confirmed the validity of the theory. The conductance of the coated joint was reported to be as much as an order of magnitude greater than that of the bare joint. They also noticed that, for a given coating thickness, the enhancement was greater for a smoother surface than for a coarser surface.

Kang et al.[11] conducted an experimental investigation to determine the degree to which thermal contact conductance may be enhanced by the application of a metallic coating. They used vapor deposition to coat aluminum specimens with lead, tin, and indium. Four different thicknesses were coated onto the specimens in an attempt to determine the optimum coating thickness for each coating material. The results confirmed that there exists an optimum coating thickness at which the contact conductance may be most enhanced. It appeared that different coating materials may yield different optimum thickness values. They concluded from experimental results that the hardness of coating material is the most influential parameter in the selection of a coating material. They also found that an increase in the contact pressure might result in a decrease in the enhancement of the contact conductance. The thermomechanical model of Antonetti and Yovanovich[8] was applied to predict the experimental results. Kang et al.[11] suggested that the poor agreement between the predictions and experimental results was due to the model being inappropriate for all material and surface combinations.

Lambert and Fletcher[12] conducted experiments using silver as the coating material. Three coating methods, vapor deposition, electroplating, and flame spraying, were employed. The experiments were conducted on the silver-coated aluminum A356 in contact with an anodized aluminum 6101-T6 and electroless nickel-plated C11000-H03. The coating thicknesses for the vapor deposition were 1, 2, and 3 μm and for the electroplating and flame spraying were 12.7, 25.4, 50.8, and 76.2 μm. The experimental program demonstrated that electroplating silver, apart from its qualities of high adherence, wear resistance, and imperviousness to corrosion in a marine environment, was also the best for thermal enhancement. They defined an enhancement factor, the contact conductance of the coated joint divided by that of bare joint at identical load, to measure the effectiveness of the coating. It was noticed that for the contact between silver-coated A356 and anodized-aluminum 6101, the enhancement factor reduced from 15.5 for 12.5-μm coating to 2.5 for 76.2-μm coating at the contact pressure of 200 kPa. It was also noticed that the contact conductance of flame-sprayed silver on A356 aluminum in contact with electroless nickel-plated copper actually reduced by as much as 50% as the result of coating, irrespective of the coating thickness. The authors did not offer an explanation for the reduction in contact conductance. The results were compared to those of the thermomechanical model of Antonetti and Yovanovich.[8] Because of significant flatness deviation of the test specimens, the theoretical prediction appeared to be an upper bound, rather than an accurate estimate, of the experimental results.

Experimental work conducted by Lambert and Fletcher[13] used vapor-deposited silver and gold as the coating material on A356 aluminum. The coating thicknesses were selected as 1, 2, and 3 μm for both materials. The enhancement factor for the contact of anodized-aluminum 6101 to aluminum A356 with 3-μm silver coating ranged from 1.79 to 2.14, depending on the contact pressure. No definite dependence of the conductance ratio on mean junction temperature was found in the experimental investigation. For the 3-μm gold coating, the enhancement factor was found to range from 2.53 to 3.41, depending on the contact pressure applied.

The investigation conducted by Howard et al.[14] studied the effects of the multiple-layered coating and the interstitial coating thickness on the contact conductance. The coating material used was indium, and the coating process was vapor deposition. Their results indicated that 1) due to the oxidation and thermal cycling the enhancement factors of the coated joint was significantly less for multiple-layered coating than that of single-layered coating and 2) the enhancement factor might reach a maximum theoretical limit as the coating thickness increased. An optimum coating thickness was not observed in their investigation, even though the ratio of coating thickness to rms roughness varied from 0.1 to 12.

O'Callaghan et al.[15] presented a theory to predict the optimum thickness of a metallic coating for maximum enhancement. Their analysis suggested that if the coating material is softer than the base material, the real contact area will be increased at a given load; therefore, the contact conductance will be increased. The degree of improvement depended on the conductivity of coating material and the base material, and the optimum coating thickness is expected to be on the order of the surface roughness. The experiments conducted on the stainless steel coated with ion-deposited tin coating confirmed their theoretical prediction.

Snaith et al.[16] proposed a selection criterion to determine the suitability of a coating material to reduce the overall contact resistance:

$$H_m k_c / H_c k_m > 1$$

The optimum coating thickness was found to be on the order of the rms surface roughness. This result was identical to that of O'Callaghan et al.[15] For coating thickness much larger than the rms roughness of the surface, the bulk resistance of the coating tended to exceed the reduction in contact resistance offered by the coating.

It is evident from the literature review that no general agreement has been reached regarding the optimum coating thickness. The experimental investigations conducted by previous researchers found that the optimum coating thickness varied with the material coated on the surfaces, whereas the theoretical considerations suggested that the optimum coating thickness is on the order of surface rms roughness.

III. Experimental Procedure

The present experimental program was designed to conduct thermal contact conductance test in a vacuum environment. The aim of this series of tests was to determine the relationship of coating material and thickness in enhancing the thermal contact conductance. In particular, attention was focused on the optimum coating thickness for different materials and coating methods. The coating methods applied were electroplating and filtered arc vapor deposition (FAD). The coating materials were tin, silver, copper, and aluminum.

A. Experimental Apparatus and Specimen Preparation

Thermal contact conductance experiments were conducted in an axial heat flow cut bar apparatus. Details of the experimental apparatus has been described by Li et al.[17]

Table 1 Comparison of surface roughness parameters with metallic coating

Coating specification			Bare surface			Coated surface		
Specimen	Coating	T	σ_q	λ_a	R_q	σ_q	λ_a	R_q
MS 27	Ag	2	3.626	0.343	2.883	3.193	0.322	3.051
MS 35	Ag	2	3.350	0.334	3.000	3.082	0.308	3.030
MS 36	Ag	2	3.425	0.340	2.926	3.424	0.323	2.945
MS 1	Ag	5	2.904	0.324	2.831	3.253	0.311	3.103
MS 11	Ag	5	3.390	0.339	2.900	3.237	0.320	3.100
MS 8	Ag	9	3.325	0.335	2.918	3.349	0.287	3.170
MS 9	Ag	9	3.261	0.331	2.962	3.302	0.289	3.301
MS 40	Ag	20	3.067	0.329	2.842	3.344	0.264	3.296
MS 41	Ag	20	3.353	0.339	2.822	3.242	0.269	3.208
MS 25	Cu	2	4.251	0.355	2.868	4.533	0.361	2.697
MS 34	Cu	2	4.313	0.654	1.028	4.199	0.344	2.708
MS 22	Cu	4	4.634	0.362	2.792	4.826	0.358	2.878
MS 42	Cu	4	4.168	0.361	2.951	4.22	0.336	2.871
MS 21	Cu	7	3.993	0.333	2.810	4.504	0.343	2.945
MS 30	Cu	7	4.213	0.349	2.895	4.610	0.351	2.954
MS 3	Cu	12	4.278	0.348	2.922	4.507	0.344	2.963
MS 38	Cu	12	4.088	0.344	2.823	4.486	0.352	2.948
MS 17	Sn	5	4.577	0.360	2.869	3.452	0.197	3.418
MS 49	Sn	5	4.265	0.364	2.630	3.238	0.181	3.476
MS 20	Sn	12	4.304	0.357	2.891	2.586	0.134	3.405
MS 26	Sn	12	4.536	0.366	2.808	2.424	0.124	3.408
MS 23	Sn	21	4.244	0.354	2.967	1.738	0.092	3.390
MS 28	Sn	21	4.181	0.345	2.601	1.719	0.109	3.300
MS 29	Sn	41	4.657	0.347	2.754	1.514	0.086	3.438
MS 37	Sn	41	4.055	0.336	2.985	1.452	0.078	3.337
SS 2	Al*	3	3.001	0.337	1.977	3.219	0.284	3.070
SS 116	Al*	3	3.398	0.335	2.026	3.425	0.298	3.058
SS 118	Al*	3	3.601	0.342	1.924	3.392	0.295	3.187
SS 31	Al*	5	3.922	0.338	1.980	3.537	0.299	3.266
SS 32	Al*	5	3.652	0.352	1.995	3.264	0.302	2.960
SS 11	Al*	10	3.91	0.344	2.014	3.278	0.283	3.322
SS 15	Al*	10	3.428	0.352	2.107	3.357	0.285	3.143
SS 27	Al*	20	3.358	0.315	2.007	3.267	0.262	3.437
SS149	Al*	20	3.591	0.349	1.997	2.915	0.241	3.516

Test specimens were made of American Iron and Steel Institute (AISI) 304 stainless steel (SS) and AISI1020 mild steel (MS) rods. The specimens were 45 mm long and 25 mm in diameter. Four thermocouple holes (ϕ1.6 mm × 19 mm) were drilled along the axis of the specimen at a spacing of 9 mm.

The two flat ends of the specimen were machined, ground, and mechanically polished to rms 0.075 μm. One end of each specimen was bead blasted to obtain a uniform surface. Surface roughness measurements for the original bead-blasted and coated surfaces were made on a Talysurf 4 surface roughness tester, an RTI^{TM}-815 A/D convert card, and a 386 personal computer. Results of the surface roughness data are listed in Table 1.

After the bead blasting process, the SS specimens were cleaned using Shellite solvent made by Shell Company in a Sanophon ultrasonic cleaning bath for 15 min to remove dirt and soil. The MS specimens were lightly coated with grease to protect them from oxidation. The specimens were then stored in the laboratory ready for testing and/or coating.

B. Metallic Coating

Four coating materials were selected in this investigation: tin, silver, and copper for electroplating and aluminum for FAD. Tin was selected as one of the coating materials because of its extremely low hardness. Silver has low hardness and excellent thermal conductivity. Copper presents moderate hardness and high thermal conductivity and so does aluminum. The selection of coating thickness was based on recommendations of previous researchers and consultations with the industry.

The process of electroplating is well understood and advanced in the industry. Nine of the MS specimens were coated with silver according to Australian Standard (AS) 1856-1991, "Electroplated Coating—Silver." Each of the eight MS specimens were coated with copper and tin according to MIL-C-1455OB "Copper Plating, (Electroplated)," and AS 4169-1994 "Electroplated Coating—Tin and Tin Alloys." Nine SS specimens were coated with aluminum, using FAD, at the Surface Research Center, University of Wollongong, Australia. FAD is a new technique developed recently by the Commonwealth Scientific and Industrial Research Organisation, Division of Applied Physics, Australia. It is a physics vapor deposition process, with the advantage of a magnetic filter to remove the macroparticles from being deposited on to the surface. In the FAD process, the ions produced from the cathode are focused and steered into a plasma duct, and the macroparticles are separated from the ionized cathode material in the magnetic field. The beam of filtered ions is guided to the substrate and deposited in a uniform, dense, macroparticles-free coating.[18]

The coating thickness was measured using a Deltascope magnetic thickness tester. The original bare specimens were bead blasted at one end and mechanically polished at the other end. The thickness and microhardness measurements for electroplated coatings were conducted on the coated specimens, at the previously polished ends. The magnetic tester cannot measure the thickness of FAD aluminum coating on SS specimens. To overcome this problem, an MS specimen was placed in the vacuum chamber to be coated with aluminum coating at the same time as the SS specimen. The MS specimen was used to measure the coating thickness and the microhardness.

C. Microhardness Measurements

A series of microhardness measurements was conducted to investigate the influence of the metallic coating on the contact surfaces. The tester used was a Leco M-400-H1 desk top microhardness tester. It has a Vickers diamond pyramid indenter and can apply a maximum of 1000-g load to the test specimen. The optical objective employed produces a total magnification of 400. Minimum display is 0.1 μm, and uncertainty related to load is 2%. Specimens tested included the MS substrate and tin-, silver-, copper-, aluminum-, and metallic-coated specimens at various coating thicknesses. The results of silver, copper, and aluminum coating are plotted in Figs. 1–3.

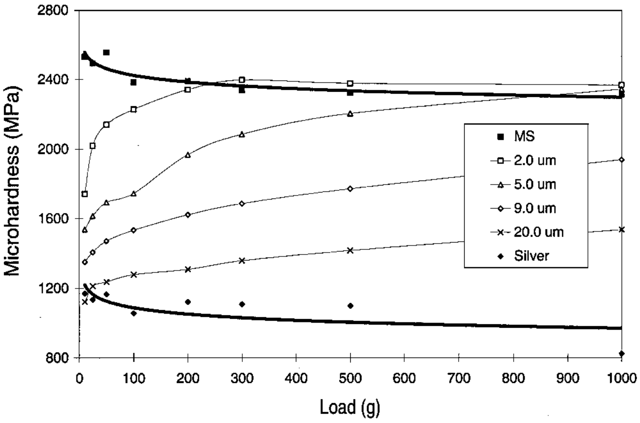

Fig. 1 Microhardness of electroplated silver-coated MS specimens.

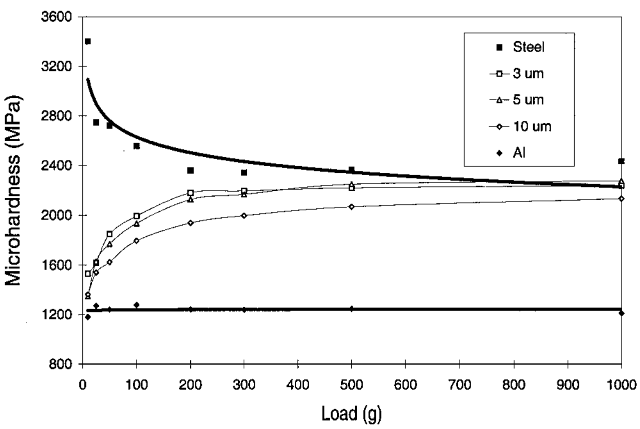

Fig. 2 Microhardness of FAD aluminum-coated MS specimens.

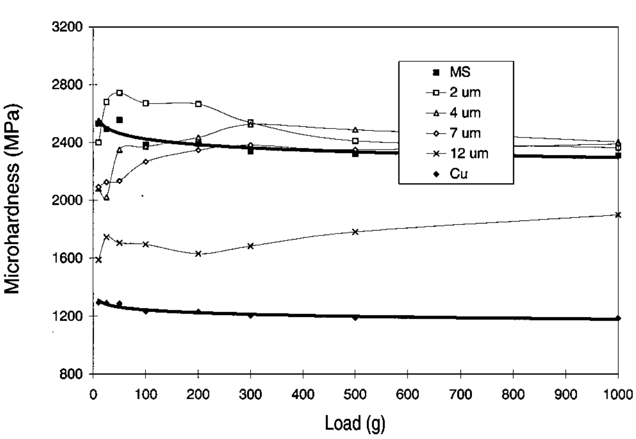

Fig. 3 Microhardness of electroplated copper-coated MS specimens.

All test specimens were lapped to a roughness around 0.08-μm rms prior to the coating process. Load was applied at a speed of 10 μm/s and maintained for 15 s. Six indentations were made under each load. Microhardness values were calculated as the load over the projected area of indentation.

The maximum uncertainty of the microhardness measurement was estimated at 3.28% for MS steel at the smallest load of 10 g.

D. Test Procedure

The test specimens were cleaned with acetone prior to assembly. A light load of 100 kPa was applied to the test column to secure the alignment. The chamber was sealed, and the vacuum pump switched on. The system was left to degassing over 12 h before the heater was switched on. The system was considered to reach steady state based on two observations: 1) Temperature measurement did not vary by 0.2°C over a period of 15 min for each thermocouple. 2) The heat fluxes in the two test specimens differed by less than 3%. Load was gradually increased in the loading process. The mean junction temperatures for all tests conducted were maintained at 353 ± 2 K throughout the test.

E. Data Reduction

When the test system reached steady state, a program was used to smooth temperature readings of test specimens using the least-squares method. The temperature drop between the two contact surfaces was calculated using the extrapolated temperature of the two contact ends. The heat flux passing through the junction was taken as the average value of top and bottom specimens. The value of contact conductance was calculated from the value of the heat flux and the temperature drop across the joint.

F. Uncertainty of the System

It can be shown that, at the vacuum level of 2×10^{-2} mbar, the conduction and convection heat loss from the metallic test specimens is less than 0.4% of the total heat input. Therefore, the vacuum level of the experimental setup induces little additional uncertainty to the experimental system.

Surface measurement showed that the waviness of the test specimens were on the same order or lower than the roughness. Therefore, the waviness of the surfaces induced little uncertainty in the test system.

The uncertainty of the system contained three major parts: the uncertainty in the loading system (5%), uncertainty in the thermal conductivity of the SS heat flux meter (3%), and uncertainty in the thermocouples due to the uncertainty in their location (3%). The maximum experimental uncertainty was, thus, estimated to be 10.72%.

IV. Results and Discussion

The results of this experimental investigation are presented and discussed in terms of the surface profile, surface microhardness, and enhancement of metallic coating and optimum coating thickness. A comparison of the coating materials and corresponding enhancement factors is discussed at the end of this section.

A. Surface Profile

Table 1 lists the coating material and its thickness for each specimen used in the tests, along with the roughness measurement results for bare and coated surfaces. It is evident from Table 1 that the surface profiles of the coated specimens were different from bare specimens. It was found that the modification to surface profile due to metallic coating varied with the coating materials and the coating thickness. For the aluminum FAD coating, the asperity slopes were reduced, the radius of curvature was increased, and the surface rms roughness did not change. Electroplating silver caused a reduction in surface asperity slope and an increase in radius of curvature. The trend was clearer on the electroplated tin. The results showed not only the reduced asperity slope and enlarged radius of curvature, but also reduced rms roughness. In the case of electroplated copper, modification to the surface profile was not significant.

In general, the modification to the surface profiles was more evident when the coatings were thicker, that is, 20 μm of silver, 41 μm of tin, and 20 μm of aluminum, than for thin coatings, that is, 2 μm of silver, 5 μm of tin, and 3 μm for aluminum. These results agreed with the experimental investigation conducted by Madhusudana et al.,[19] in which they stated that the assumption that the coated surface maintains the surface profile as that of bare surface may not be valid.

B. Microhardness of Coated Surface

Microhardness measurements were conducted for each coated specimen, as well as the coating material and substrate involved. The results are plotted in Figs. 1–3. In general, microhardness values for all specimens tested varied with the load. For substrate and coating material, the microhardness value decreased with the increasing of load. For coated surfaces, however, the value of microhardness increased with the load applied. The variation of the microhardness was particularly large at small loads.

Figure 1 shows the values of microhardness on the silver-coated MS specimen. It is clear that the value lies in between that of the substrate and coating material. The coating thickness determined the reduction in the value of the microhardness. Thicker coating, such as 12-μm silver coating, created a surface layer that was much softer than the base material, and resulted in a larger reduction in the microhardness. It may be seen from Fig. 1 that the microhardness of the coated surfaces drops dramatically in the low-load range.

As shown in Fig. 2, the FAD aluminum coating shows a tendency similar to the electroplated silver. The measured microhardness of the coated surfaces lies between that of the aluminum and the MS substrate. The coating thickness was again the predominant factor that determined the magnitude of the reduction in the value of the microhardness on the coated surfaces. The thicker coating, such as 15 μm, was seen to be softer than the thin coating, such as 5 μm. The reduction of microhardness in the low-load range was also evident.

As shown in Fig. 3, the microhardness result for the copper-coated specimens was somewhat unexpected. The microhardness of the coated surface reduced as the result of increasing in coating thickness at the same load. The reduction in the low-load range is more evident than in the high-load range. However, the microhardness of 2-, 4-, and 7-μm coated specimen was higher than the MS substrate, especially with 2-μm coating. The reasons for the increased microhardness may be 1) oxidation had occurred on the surface and/or 2) the solution of electroplating was contaminated with other metals.

C. Thermal Contact Conductance

The values of bare joint thermal contact conductance of MS and SS specimens were experimentally determined, using the bare specimens that have surface profiles similar to the coated specimens. Those values were set as the basis for comparison of the coated-surface conductance in the later section.

Two metallic coatings, electroplated silver and FAD aluminum, were selected to compare the effect of metallic coating on a single end or both ends. The purpose of this test was to verify whether the enhancement of the contact conductance when both ends are coated is significantly higher than that of a joint, in which only one end is coated.

Figure 4 shows test results for silver-coated specimens. The tests were conducted using three separated pairs of specimen. The first pair had one contact end electroplated with 2-μm silver coating. The second pair had both contact ends electroplated with 2-μm silver, and the third pair was a bare joint. Three pairs of specimens went through a similar loading process, as indicated in Fig. 4. The results plotted were for the first loading.

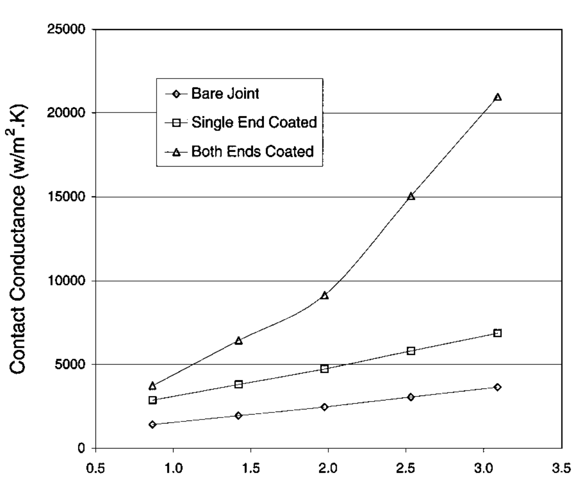

Fig. 4 Comparison of thermal contact conductance: bare joint, one-end-electroplated 2-θm silver and both-ends-electroplated 2-θm silver.

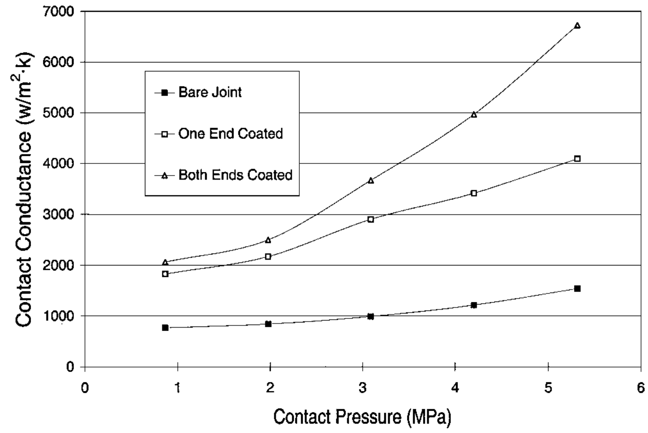

Fig. 5 Comparison of thermal contact conductance: bare joint, one-end FAD 3-θm aluminum and both-ends FAD 3-θm aluminum.

It is evident from Fig. 4 that 1) the silver-coated joints had a higher contact conductance than the bare joint, 2) a both-ends-coated joint offered much higher enhancement of contact conductance, 3) the values of contact conductance increased with the contact pressure, and 4) the load effect was more obvious on both-ends-coated contact. The enhancement factor for the single-end- and both-ends-coated joint were 1.89 and 5.75, respectively, at contact pressure of 3.089 MPa, whereas at a lower contact pressure of 0.865 MPa, that factor dropped to 2.03 and 2.64, respectively.

Figure 5 shows the results for aluminum FAD coating. Three pairs of specimens were involved in the test. The two bare joint SS specimens had surface profiles similar to the coated specimen. Contact conductance between the two increased with the load. The second pair had one contact end coated with 3-μm FAD aluminum coating; the contact conductance increased with the load as expected. The third pair had both contact ends coated with 3-μm aluminum FAD coating, which resulted in further increase in contact conductance compared to the single-end-coated joint. As with silver coating, the effect of load was more evident at higher load on the both-ends-coated specimen pair. The enhancement factor for single-end- and both-ends-coated specimens were 2.66 and 4.37, respectively, at a contact pressure of 5.313 MPa, whereas at a lower contact pressure of 0.865 MPa, those value dropped to 2.37 and 2.67, respectively.

For the six pairs of specimens tested in this section, it is clear that metallic coating may have more effect on enhancing the contact conductance when both contact ends were coated. The effect of load also tends to be more striking in joints where both contacting surfaces were coated.

We believe there were two reasons for the effect of load to be more striking at larger load:

1) The metallic coating enhanced the contact conductance by two means: one through the reduced microhardness and another through the increased thermal conductivity. The reduction in the value of surface microhardness caused an increased contact area, which resulted an increase in the contact conductance. On the other hand, the increased thermal conductivity may also work on the enlarged contact area, which resulted in further increase in the contact conductance. At larger load, the effective thermal conductivity of the joint may have increased due to an enlarged contact area, which resulted the effect of load to be more striking at larger load.

2) Although there were no physical evidence to prove that flatness deviation existed on thin coating, the application of coating may introduce some flatness deviation into the contact surface, particularly in the edge of the contact surface. The possible flatness deviation may reduce the effect of metallic coating at small loading. However, when the loads were large enough to overcome the flatness deviation, the enhancement of metallic coating was fully achieved.

D. Optimum Coating Thickness

A total of four coating materials involving 21 pairs of specimens were tested. Each pair had both contact ends coated with metallic

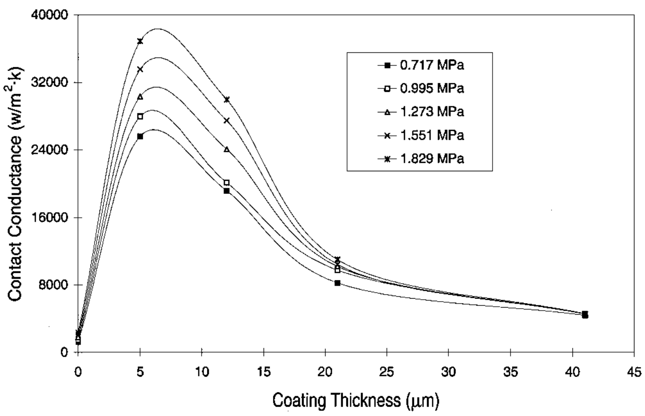

Fig. 6 Comparison of thermal contact conductance: MS specimens bare joint electroplated with 5-, 12-, 21-, and 41-θm tin coating.

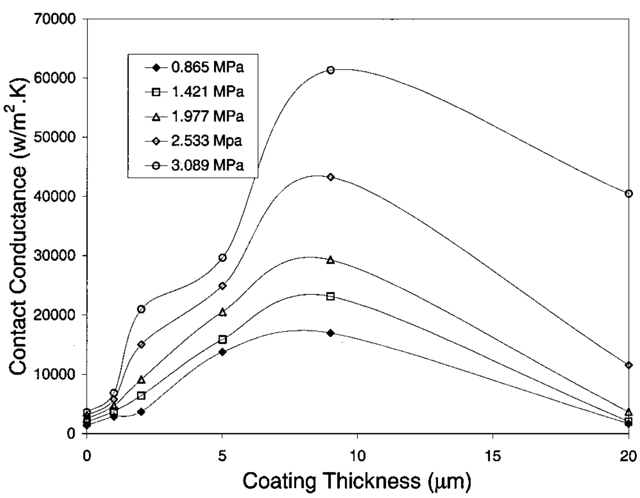

Fig. 7 Comparison of thermal contact conductance: MS specimens electroplated with 2-, 5-, 9-, and 20-θm silver coating.

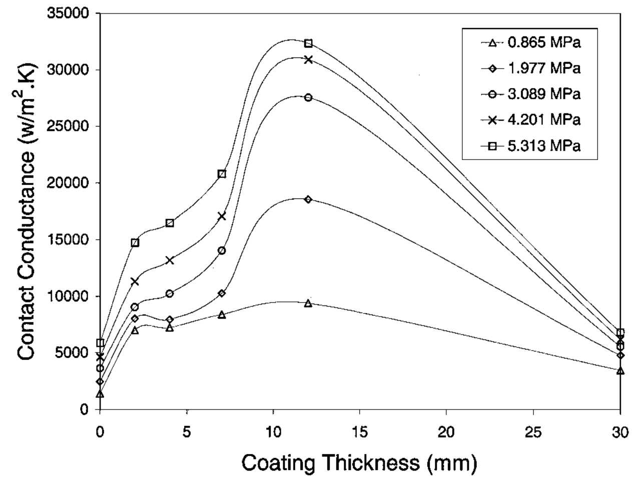

Fig. 8 Comparison of thermal contact conductance: MS specimens electroplated with 2-, 4-, 7-, 12-, and 30-θm copper coating.

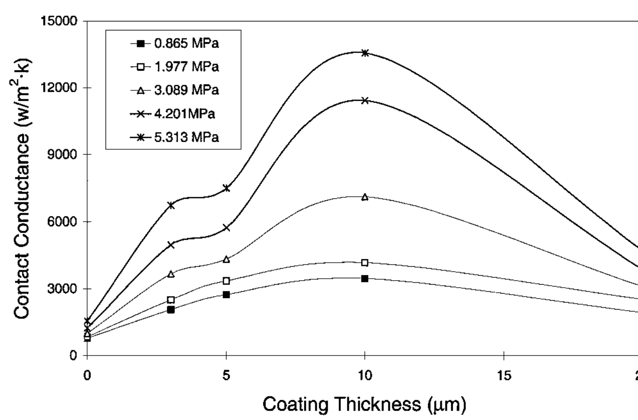

Fig. 9 Comparison of thermal contact conductance: SS specimens FAD with 3-, 5-, 10-, and 20-θm aluminum coating.

coating at uniform thickness. The coating materials were tin, silver, copper, and aluminum.

1. Tin Coating

Four coating thicknesses, 5, 12, 21, and 41 μm, were coated to the test specimens with tin. For all pairs tested, the contact conductance increased with the contact pressure, as shown in Fig. 6. It is clear that the optimum coating thickness exists within the range of thickness applied. Coating of 5 μm thickness offered the best enhancement for contact conductance. The enhancement factor reduced as the coating thickness increased. Coating of 41 μm thickness did not significantly enhance contact conductance. The optimum coating thickness appeared to be around 5 μm for the tin coating.

The experiments conducted by Kang et al.[11] showed that tin, when coated to one end of contact, may enhance the contact conductance by as much as 50% at its optimum coating thickness. In the present work, both ends of contact were coated, which resulted in a much higher enhancement factor for the tin coating. For example, when a 5-μm-thick coating was present in each side of the joint, the value of contact conductance was enhanced by 2100%.

2. Silver Coating

The thickness of silver coating applied to the specimens were 2, 5, 9, and 20 μm. Results are plotted in Fig. 7. Compared to the bare joint, contact conductance increased for all four pairs tested. It is demonstrated in Fig. 7 that contact conductance increased with the contact pressure for all test pairs, and the effect of contact pressure was more evident with the thicker coating at higher loading. The contact conductance increased with the coating thickness at 2, 5, and 9 μm and then decreased at 20 μm thickness. It is clear that there existed an optimum coating thickness that enhanced contact conductance more effectively. The optimum coating thickness appeared to be around 9 μm.

3. Copper Coating

The coating thickness for copper were 2, 4, 7, 12, and 30 μm. Results are plotted in Fig. 8. It is apparent in Fig. 8 that the optimum coating thickness exists in the range of the thickness applied in this investigation. For each the coating thickness applied, the contact conductance has been enhanced. The 12-μm coating offered the best enhancement for the contact conductance. The enhancement initially increased with the coating thickness. When the thickness reached 12 μm, contact conductance started to reduce sharply. The 30-μm coating enhanced contact conductance at the low-load range, without much effect at high load.

4. Aluminum Coating

Figure 9 shows the results of FAD aluminum coating on SS specimens. It is clear that the optimum coating thickness existed in the range of coating thickness applied. For each coating thickness, the contact conductance has been enhanced. The enhancement factor increased with coating thickness for 3-, 5-, and 10-μm coating and reduced with the further increasing of coating thickness. The optimum coating thickness for this contact set appeared to be around 10 μm.

An interesting downward trend in Figs. 6–9 was observed. Figures 6–9 revealed that the contact conductance data may converge to a single datum if the coating thickness were allowed to increase. We believe that the contact conductance may eventually asymptote

Table 2 Rank of coating materials by their thermal conductivity and microhardness

Material	k_c [a]	H_c [b]	k_c/H_c	$H_m{}^b k_c/(H_c k_m)$
Tin	66.6	103	0.65	34.65
Silver	427	1055	0.40	21.20
Copper	398	1230	0.32	16.96
Aluminum	237	1277	0.19	10.07

[a]Thermal conductivity value at 27°C.
[b]Microhardness value at load of 100 g.

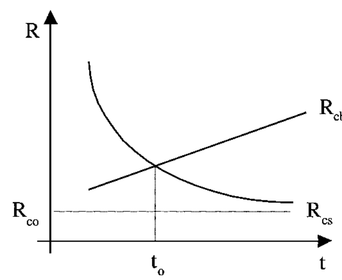

Fig. 10 Solid contact resistance and bulk coating resistance vs coating thickness in a coated joint.

to zero. The value of total contact resistance of a coated joint R_t (or contact conductance as presented in Figs. 6–9), by the method used to calculate it, is made of two parts. One is the solid contact resistance at the interface R_{cs} and the other is the bulk resistance of the coating material R_{cb}, as diagramed in Fig. 10. If the coating thickness t was allowed to increase to such a point that all of the microconstriction took place in the coating layer only, the solid contact resistance R_{cs} at the interface will reach a minimum value of R_{co}. This value is determined by the thermal conductivity and microhardness of the coating material only. On the other hand, the bulk resistance R_{cb} increases with the coating thickness t. As the coating thickness t increases, the total contact resistance of the coated joint may initially decrease. A minimum total contact resistance (or maximum contact conductance as in Figs. 6–9) may reach at an optimum coating thickness t_o, where the bulk resistance is close to the solid contact resistance. The total contact resistance then increases with the coating thickness. If the coating thicknesses were allowed to increase, the bulk coating resistance would dominate the total contact resistance. The total contact resistance may increase to infinity as the coating thickness increases, which in return will asymptote the total contact conductance of the coated joint to zero. However, for the purpose of enhancing the thermal contact conductance, any increase beyond the optimum coating thickness is not desirable.

It may be concluded from the four series of experiments that the optimum coating thickness to enhance the thermal performance, in fact, changes with the coating material applied and the contact pressure under which it operates. Table 2 lists a rank, proposed by Yovanovich,[10] in which he indicated that coating materials may be ranked by their thermal conductivity and hardness. For the four coating materials applied in this investigation, tin has the largest value of k/H, and it optimum coating thickness was the smallest, at 5 μm. The value of k/H of silver is lower than that of tin, and its optimum coating thickness was higher, at 9 μm. FAD aluminum coating has a k/H value less than that of the copper coating; however, its optimum coating thickness was lower, at 10 μm, than that of copper coating, at 12 μm. The reason for the reverse order in the rank may be because the substrate materials were different. FAD aluminum was coated on SS specimens, whereas copper was coated on MS substrate. Another possible reason may be that the two coatings were applied using different techniques.

E. Enhancement Factor at Optimum Coating Thickness

Figure 11 shows the enhancement factor of the four coating materials used in this investigation at their optimum coating thicknesses. Tin, being the softest material of all, offered best enhancement at low load; the enhancement factor of 21 was reached at a load of 0.717 MPa. However, silver, being the second softest material, reached a higher enhancement factor at a higher load of

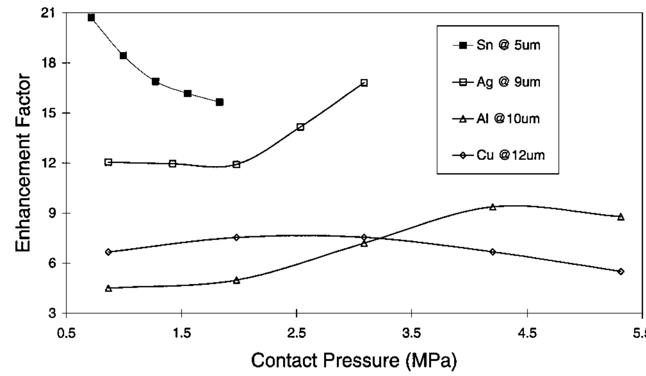

Fig. 11 Comparison of enhancement factor of four coatings: MS specimens electroplated with 5-θm tin, 9-θm silver, 12-θm copper, and SS specimens coated with 10-θm FAD aluminum.

3.089 MPa. The enhancement factors of electroplated copper and FAD aluminum were of the same order; the enhancement factors of FAD aluminum appeared to increase with the load applied and those of electroplated copper reduced with the load. It may be preferable to use copper coating when the contact pressure is low, whereas at higher contact pressure the aluminum coating may be more appropriate.

We believe that the value of enhancement factor for any particular metallic coating at a given coating thickness may initially increase with the contact pressure, reach a maximum value, and then reduce with the contact pressure, as shown in Fig. 11. Because tin has very low hardness, the maximum enhancement factor may have been reached even before the smallest load of 0.717 MPa. The contact pressure range in the present work may be in the decreasing part of the enhancement factor vs contact pressure curve. On the other hand, the enhancement factor for silver may still increase with the load. The enhancement factor curve of copper demonstrated that the maximum enhancement factor was reached at about 2 MPa. The maximum enhancement factor for aluminum was also reached within the contact pressure range we operated, at about 3.5 MPa.

V. Conclusions

An experimental investigation was conducted to examine the effect of metallic coatings on the enhancement of thermal contact conductance. Four coating materials, tin, silver, copper, and aluminum, were used. Two coating techniques were employed. A total of 23 pairs of specimens were tested. The following results were confirmed:

1) In general, the coated-surface profile was different from the original bare surface. The modification to the surface profile was more evident in thicker coatings than in thin coatings. Therefore, the assumption that the coated surface maintains the same surface profile as that of the bare surface may not be valid. It is suggested that the surface profiles of coated joints be reported when assessing the effectiveness of metallic coating on enhancement of thermal contact conductance.

2) The values of microhardness of coated surfaces lie between those of the substrate and the coating material, except for copper coating at certain thickness. The coating thickness determines the reduction in the value of microhardness. Thicker coatings resulted in the larger reduction in the value of microhardness. It was apparent that the microhardness value of the coated surfaces dropped dramatically in the low-load range. This is seen to be the predominant reason for the increase of thermal contact conductance. This conclusion applies to soft coating on a hard substrate.

3) To get maximum enhancement of contact conductance, it is necessary to coat both ends of contact. The effect of the load also tends to be more noticeable when both contacting surfaces are coated.

4) The optimum coating thickness for enhancing the thermal performance depended on the coating material used and the contact pressure under which it operated. For the coating materials used

in this investigation, it appeared that the microhardness of coating material dominated the extent of enhancement.

5) As the microhardness of coating materials increased, so did the optimum coating thickness. For tin, silver, aluminum, and copper, the optimum coating thickness on similar surface profiles increased with the hardness of the coating material. The value of k/H of the tested material may also be used to rank the coating material in term of enhancing the thermal contact conductance in a coated joint. It appears that the higher value of k/H may result in a thinner optimum coating thickness.

6) When the thickness of the coating was optimum, the enhancement factors varied with the contact pressure. The variation depended on the material coated. For tin and copper, the enhancement factor reduced as the contact pressure increased, whereas for silver and aluminum, it increased with the contact pressure.

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