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Summary

The thermal conductance of pressed contacts which have been augmented with Indium foil or Apiezon-N™ grease has been measured over the temperature range of 1.6 to 6.0 K, with applied forces from 22 N to 670 N. The sample pairs were fabricated from OFHC copper, 6061-T6 aluminum, free-machining brass, and 304 stainless steel. Although the thermal conductance was found to increase with increasing applied contact force, the force dependence was less than in earlier work. The addition of Indium foil or Apiezon-N™ grease between the contact surfaces resulted in an improvement over uncoated surfaces ranging from a factor of approximately 3 for stainless steel to an order of magnitude for copper contacts.

Introduction

Previous work (refs. 16) has shown that the thermal conductance of pressed contacts may be increased by gold plating the contact surfaces. In many instances, however, a further improvement in thermal conductance is desired. In these instances, a thin layer of Indium foil or vacuum grease between the contact surfaces may augment the thermal performance. This paper presents the results of a series of measurements of the thermal conductance of uncoated matched sample pairs fabricated of OFHC copper, 6061-T6 aluminum, free-machining brass, and 304 stainless steel having a thin layer of Indium foil or Apiezon-N™ (ref. 7) grease between the contact surfaces. Apiezon-N™ was selected as being a representative general purpose laboratory grease commonly used in cryogenic work.

Method

A detailed description of the apparatus and the experimental method has been described previously (ref. 1), and is summarized here. The measurements were made with the lower contact linked to a liquid helium bath held at between 1.6 and 4.2 K. A range of forces from 22 N to 670 N was applied to the contact pair by a rocker arm lever pulled by a wire connected to an external motor drive. The wire and the rocker arm assembly are thermally anchored to the cold plate, which is immersed in liquid helium. Between the lever and the sample pair is a stack of insulators. A heater is placed between the insulators and the upper sample. Thermometers are placed in the upper and lower samples, in the upper insulator, and in the cold plate. The upper and lower samples are maintained in a vacuum.

Overall dimensions of the sample pairs were 12.7 mm diameter and 8.89 mm height for the upper sample and 10.2 mm diameter and 15.2 mm height for the lower sample. All contact surfaces on the sample pairs were lapped to a 0.8 μm finish. For the Indium data, a sheet of Indium foil (99.9% purity) of diameter 12.7 mm and thickness 0.13 mm (0.005 in.) was cut using the upper sample as a template, and was placed on the lower sample and formed around it to prevent slippage. For the Apiezon-N™ data, Apiezon-N™ grease was applied to both contact surfaces.

For each sample pair, data were taken at 8 forces (22, 44, 112, 224, 336, 448, 560, and 670 N), 9 heater powers (0, 0.1, 0.2, 0.5, 0.75, 1, 2, 5, and 10 mW; for the copper 0, 1, 2, 5, 10, 20, 50, and 75 mW were used) and bath temperatures from approximately 1.6 to 4.2 K. The 22 N aluminum data were not obtained for the Apiezon-N™. For the Indium, contact was made at room temperature, and the samples were cooled with a small force (22 N) applied. For the Apiezon-N™, the samples were cooled with maximum force applied. The reasoning behind the amounts of force are given in the Discussion below. For each force the resulting data set of upper (T_h) and lower (T_c) sample temperatures, and heater powers (Q) was fit to the function:

$$Q + Q_o = \int_{T_c}^{T_h} \alpha T^n \, dT \qquad (1)$$

where Q_o is the parasitic heat flux. The parameters to be fit are Q_o, α, and n. Q_o was found to be ~0.1 mW. The thermal conductance is

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$$k = \alpha T^n \tag{2}$$

Results

The fitted thermal conductances are shown in figures 1–4 for the aluminum, brass, copper, and stainless steel sample pairs having Indium foil between the contact surfaces. The fitted thermal conductances are shown in figures 5–8 for the aluminum, brass, copper, and stainless steel sample pairs having Apiezon-N™ grease between the contact surfaces. The fitted α and n are also listed in tables 1 and 2, for both Indium and Apiezon-N™ augmented sample pairs, respectively.

Discussion

The high thermal conductance of the Indium or Apiezon-N™-augmented contacts required that a correction be made to the experimental data to account for the bulk thermal conductivity of the sample material between the thermometers and the contact interfaces. Figure 9 represents the situation schematically. The upper sample temperature, T_u, and lower sample temperature, T_l, are measured 3.17 mm from the interface, resulting in a ΔT across the bulk material of the samples. These are denoted by ΔT_u and ΔT_l in the figure. The ΔT of interest, across the interface, ΔT_c, is:

$$\Delta T_c = (T_u - \Delta T_u) - (T_l + \Delta T_l) \tag{3}$$

The ΔT_u and ΔT_l are found for each data point, from

$$Q + A_u / L = \int_{T_u - \Delta T_u}^{T_u} k dT \tag{4}$$

and

$$Q + A_l / L = \int_{T_l}^{T_l + \Delta T_l} k dT \tag{5}$$

where the quantities A_u and A_l denote the areas of the upper and lower samples, respectively, and L denotes the length from the thermometer to the contact interface.

In the previous work (refs. 1–6), the contact conductance had been so low as to render the contribution to the conductance by the thermal conductivity within the bulk material insignificant for all cases except stainless steel. Therefore, only the stainless steel data had been corrected. In this case, however, due to the high conductance of the Indium or Apiezon-N™ augmented contacts, correcting for the bulk conductivity of aluminum, brass, and copper affected the results on the order of 10%.

The published bulk thermal conductivity of 6061-T6 aluminum, OFHC copper, 304 stainless steel were used (refs. 8 and 9) in calculating the correction. The conductivity of free-machining brass was not available. For the brass, the bulk conductivity was obtained from prior measurements of a one piece, solid brass sample used for check-out of the apparatus. The sample consisted of a circular rod attached to a rectangular base. The rod was 10.1 mm in diameter and 24.1 mm in height, with two germanium resistance thermometers located 12.7 mm apart, in 3.17-mm-diameter holes drilled through the sample diameter. The upper thermometer was located 3.17 mm from the top of the sample. The base was bolted to the cold plate of the apparatus. The data points obtained were fit to a power function. The thermal conductivity over the range of 4.2 to 5.0 K was $0.00511\ T^{1.32}$ W/cm K. The data were extrapolated to cover the entire range of 1.6 to 6.0 K.

From figures 1–4 it is seen that, as in earlier work (refs. 1–6), the thermal conductance increases with increasing applied force, although for the Indium augmented contacts, the sensitivity to force is much less. Figures 5–8 show that for the Apiezon-N™ augmented contacts, the sensitivity to force is reduced even further.

Figures 10–13 compare the conductances of the Indium foil and Apiezon-N™ sandwiches to the conductances of the previously measured uncoated contacts (refs. 1–4), the previously measured gold coated contacts (ref. 5), and the previously measured augmented contacts employing a gold coated aluminum washer (ref. 6). Comparisons were made at the highest force, 670 N, although the effect is much greater at lower forces, due to the much lower force dependence of the present work.

It can be seen that addition of the Indium foil or Apiezon-N™ grease dramatically improves the contact conductance of all the materials. For stainless steel, the material least affected, the conductance is tripled, while for copper, an order-of-magnitude improvement is realized. Since for two surfaces pressed together, the heat flow occurs at a few contact points, materials such as Indium or Apiezon-N™ which readily conform to the contact surfaces will increase the actual contact area, thereby decreasing the resistance due to constriction of the heat flow.

Because of the softness of Indium, this decrease in constriction can be realized at even low applied forces. In principle, the same result should be realizable with any conforming coating. Previous work with gold coating (ref. 5) showed that although the conductances were improved as the result of gold coating the surfaces, the improvement was nowhere near the magnitude of that realized with Indium. There are two reasons for this. Firstly, gold, although soft compared to the sample materials, is still much harder than Indium, especially at low temperatures, where Indium remains pliable. Secondly, the thickness of the gold coating was 2 μm per sample, a total of 4 μm. The thickness of Indium was 0.13 mm, over thirty times that of the gold. Note that although the superconducting transition temperature of Indium is 3.4 K, no measurable effects of the transition on the thermal conductance were found.

For the Apiezon-N™ grease, the same arguments can be made; however, there are two additional considerations. Firstly, a significant improvement in thermal conductance over Indium was realized with Apiezon-N™ in the cases of aluminum, brass, and copper. Secondly, earlier data taken with only a moderate contact force applied at room temperature and then cooled down was problematic and, in many cases, impossible to analyze. This can be attributed to the fact that , unlike Indium foil which flows, the Apiezon-N™ grease becomes rigid at cryogenic temperatures. If good contact is not made at room temperature the resultant thick, non-deforming layer of Apiezon-N™ separates from the contact surfaces at helium temperatures, and the thermal resistance across the contact area actually increases. To be effective, a large force must be applied at room temperature. This also assures that the layer of grease is thin, providing the minimum contribution to the resistance.

Although the precise mechanism by which the conductance is enhanced by a conforming layer is not known, the following observations are offered. Firstly, as mentioned earlier, the number of actual contact areas would greatly increase with a conforming layer, providing additional avenues for thermal transfer, and minimizing the constriction resistance. Secondly, it can be seen from figures 10–13 that the improvement in conductance at 670 N and 6 K is far greater for aluminum, brass, and copper, being over an order of magnitude, than for stainless steel, which improves by roughly a factor of three. This suggests that the thermal conductivity of the bulk material may play a role. To explore this possibility further, the improvement in thermal conductance over uncoated surfaces by the addition of Apiezon-N™ grease and Indium foil are plotted versus the bulk thermal conductivity of the sample material in figures 14 and 15, respectively. The error bars were determined by means of an extensive analysis, and reflect the uncertainty in fitting the data points. They do not include any systematic errors, or any errors associated with the data collection procedure. Nevertheless, it appears that conductance increases in a roughly logarithmic manner with increasing thermal conductivity of the bulk material. The asymptotic leveling of the conductance with increasing thermal conductivity of the material seems reasonable, since the conductivity of the bulk material would serve as an upper limit to the augmentation possible with enhancement of the contact surfaces.

Conclusion

From an applications point of view, either Indium foil or Apiezon-N™ grease can easily be applied to contact surfaces, therefore providing a simple and effective increase in thermal contact conductance at liquid helium temperatures.

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Table 1. Results for sample pairs with Indium foil

Force	Aluminum		Brass		Copper		Stainless steel	
(N)	α	n	α	n	α	n	α	n
22	2.09 ±0.049	1.70 ±0.039	3.81 ±0.026	1.23 ±0.018	2.29 ±0.19	2.17 ±0.070	0.321 ±0.004	1.08 ±0.009
44	2.19 ±0.043	1.67 ±0.033	3.86 ±0.026	1.22 ±0.017	2.35 ±0.21	2.16 ±0.075	0.323 ±0.004	1.08 ±0.008
112	2.29 ±0.046	1.65 ±0.034	4.05 ±0.030	1.19 ±0.020	2.38 ±0.21	2.18 ±0.076	0.337 ±0.004	1.10 ±0.007
224	2.44 ±0.044	1.67 ±0.032	4.00 ±0.027	1.24 ±0.018	2.46 ±0.21	2.21 ±0.076	0.355 ±0.004	1.11 ±0.007
336	2.45 ±0.040	1.71 ±0.029	4.08 ±0.017	1.29 ±0.011	2.59 ±0.23	2.22 ±0.079	0.365 ±0.006	1.12 ±0.010
448	2.52 ±0.044	1.75 ±0.033	4.35 ±0.017	1.30 ±0.011	2.77 ±0.24	2.23 ±0.080	0.374 ±0.005	1.12 ±0.009
560	2.63 ±0.049	1.76 ±0.035	4.53 ±0.017	1.31 ±0.011	2.92 ±0.26	2.24 ±0.081	0.379 ±0.003	1.13 ±0.005
670	2.76 ±0.048	1.76 ±0.034	4.47 ±0.018	1.35 ±0.012	3.13 ±0.27	2.25 ±0.081	0.387 ±0.003	1.13 ±0.005

Table 2. Results for sample pairs with Apiezon-N™ grease

Force (N)	Aluminum α	Aluminum n	Brass α	Brass n	Copper α	Copper n	Stainless steel α	Stainless steel n
22	—	—	24.6	0.710	15.1	1.54	0.103	1.01
	—	—	±0.682	±0.031	±0.10	±0.032	±0.004	±0.02
44	14.5	1.14	25.2	0.673	14.8	1.57	0.101	1.09
	±0.200	±0.043	±0.768	±0.032	±0.10	±0.034	±0.002	±0.01
112	14.5	1.16	21.5	0.766	14.9	1.55	0.321	0.930
	±0.198	±0.044	±0.493	±0.030	±0.10	±0.032	±0.007	±0.014
224	15.0	1.11	24.9	0.690	14.9	1.55	0.396	1.02
	±0.200	±0.040	±0.728	±0.032	±0.10	±0.034	±0.004	±0.007
336	14.2	1.20	19.3	0.827	15.1	1.54	0.434	1.03
	±0.168	±0.042	±0.414	±0.032	±0.12	±0.037	±0.003	±0.004
448	15.6	1.24	18.0	0.847	14.8	1.57	0.468	1.02
	±0.194	±0.039	±0.392	±0.035	±0.11	±0.036	±0.002	±0.004
560	17.0	1.20	17.9	0.855	15.0	1.57	0.486	1.03
	±0.263	±0.043	±0.377	±0.034	±0.11	±0.036	±0.002	±0.003
670	18.0	1.24	21.7	0.768	14.6	1.64	0.501	1.03
	±0.331	±0.051	±0.579	±0.034	±0.13	±0.037	±0.002	±0.003

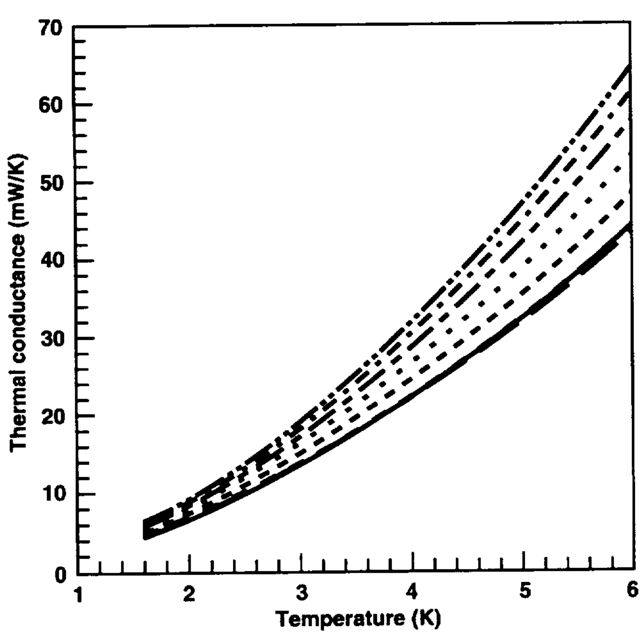

Figure 1. 0.8 μm Aluminum with Indium foil.

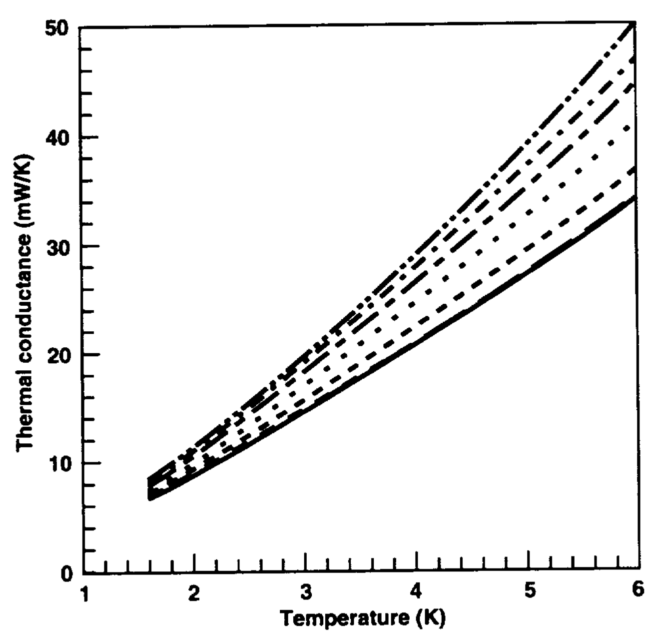

Figure 2. 0.8 μm Brass with Indium foil.

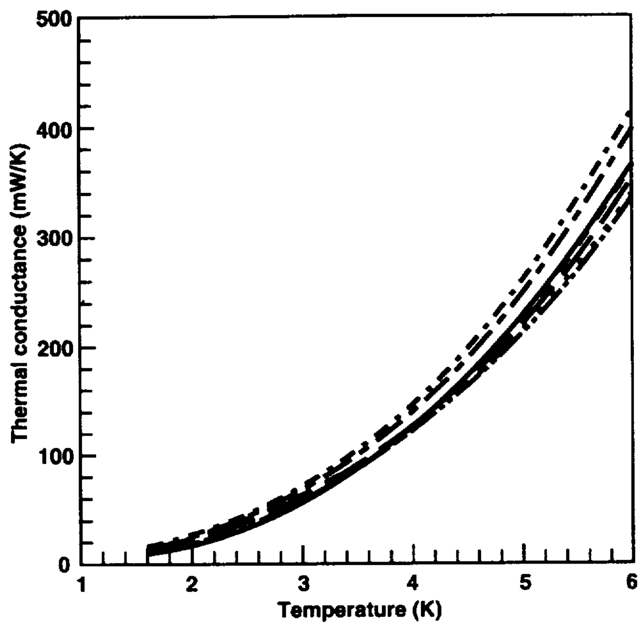

Figure 3. 0.8 μm Copper with Indium foil.

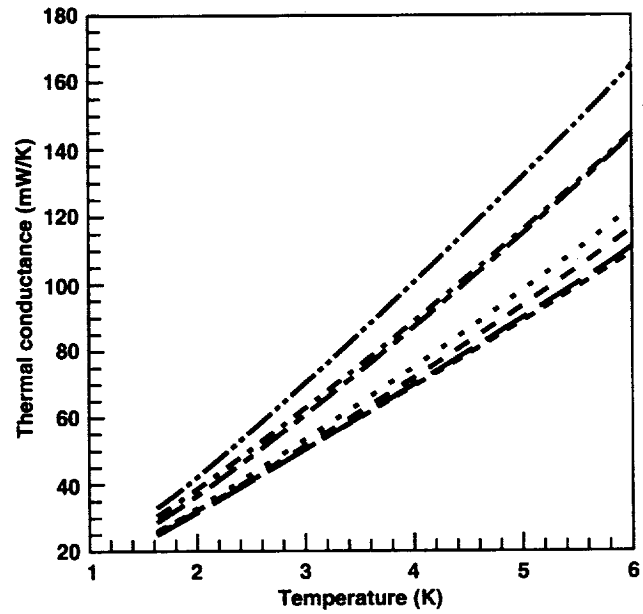

Figure 5. 0.8 μm Aluminum with Apiezon-N™ grease.

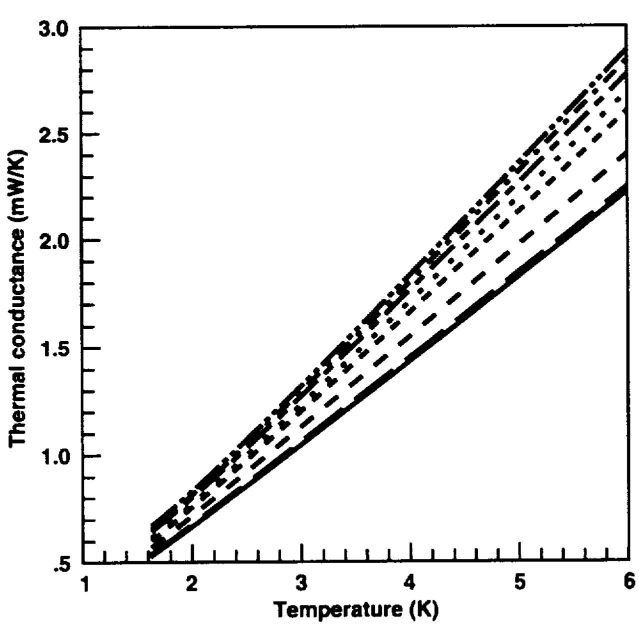

Figure 4. 0.8 μm Stainless steel with Indium foil.

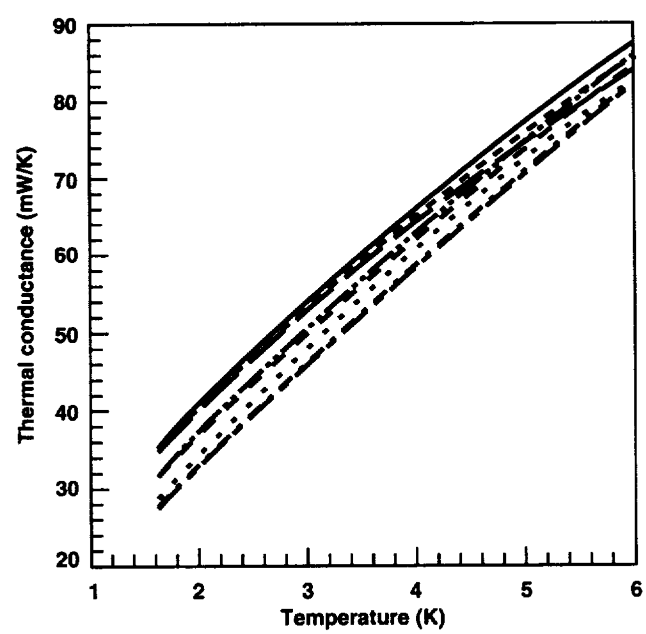

Figure 6. 0.8 μm Brass with Apiezon-N™ grease.

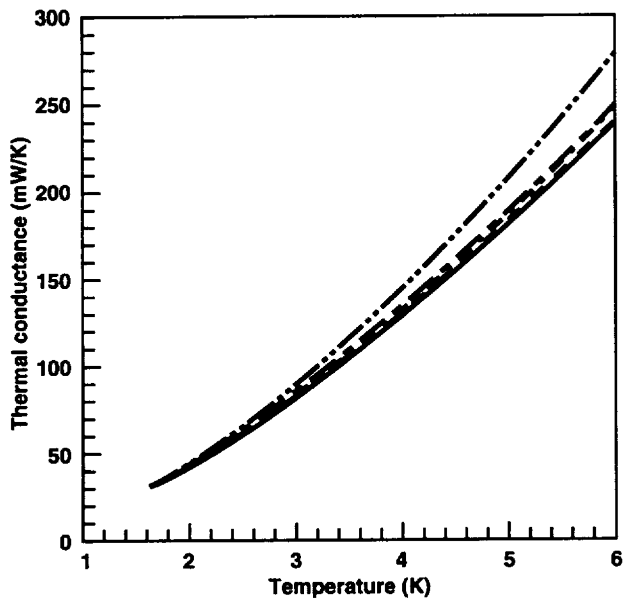

Figure 7. 0.8 µm Copper with Apiezon-N™ grease.

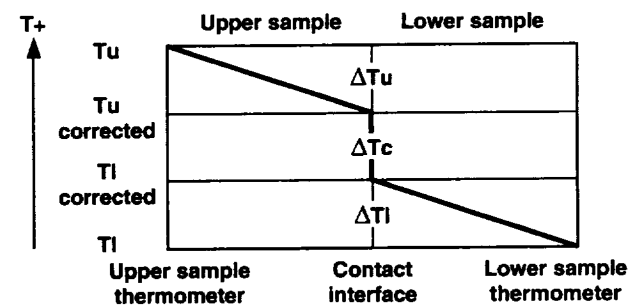

Figure 9. Schematic representation of temperature drop across samples and contact area.

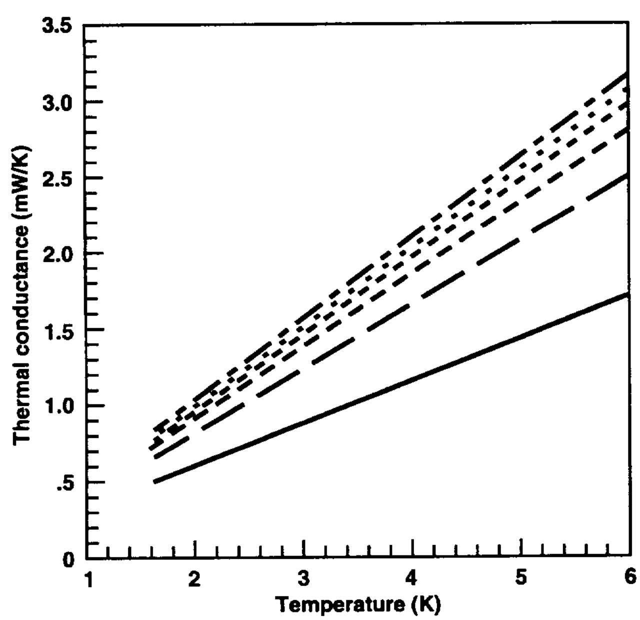

Figure 8. 0.8 µm Stainless steel with Apiezon-N™ grease.

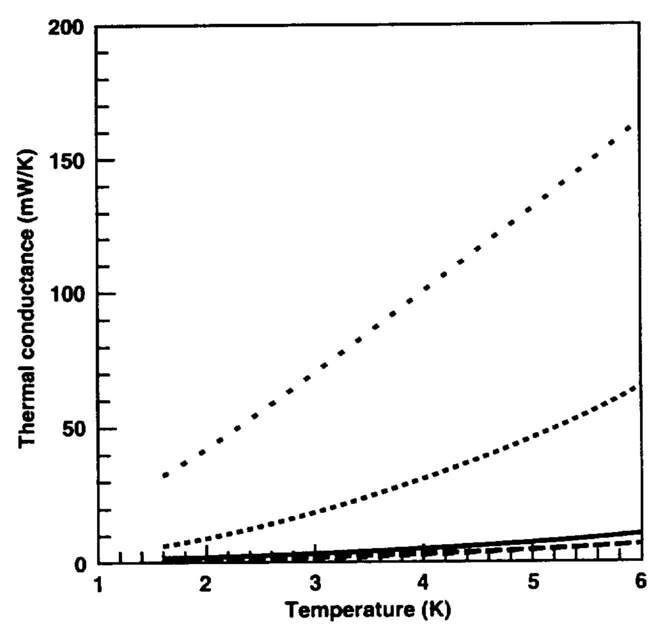

Figure 10. Comparison of conductances for 0.8 µm aluminum.

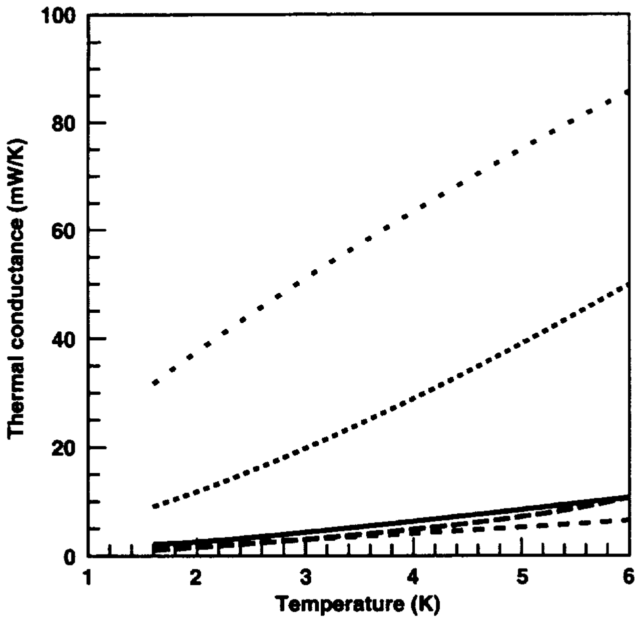

Figure 11. Comparison of conductances for 0.8 µm brass.

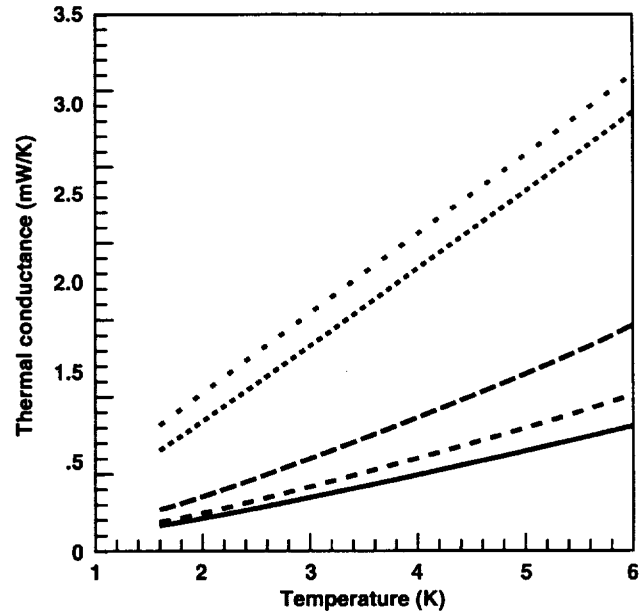

Figure 13. Comparison of conductances for 0.8 µm stainless steel.

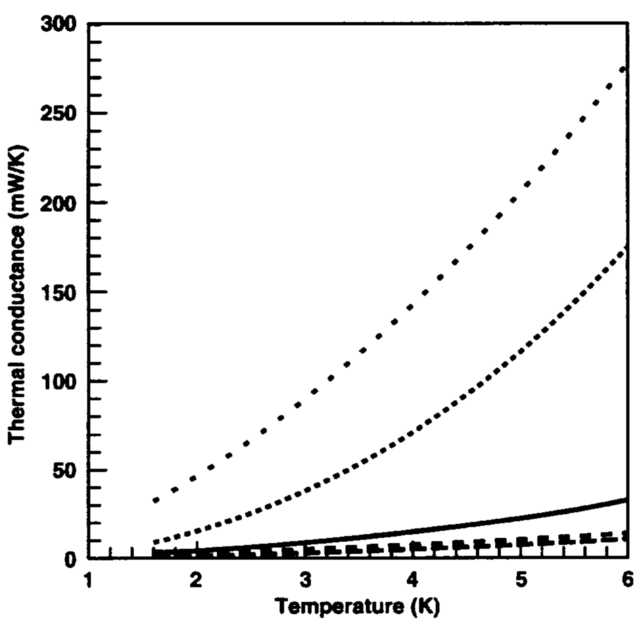

Figure 12. Comparison of conductances for 0.8 µm copper.

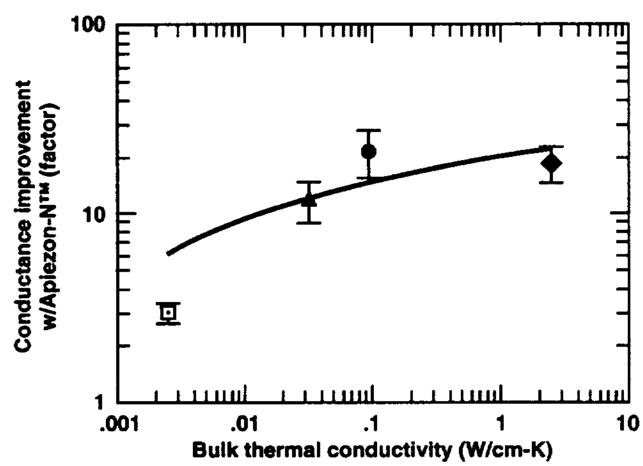

Figure 14. Thermal conductance improvement with Apiezon-N™ grease vs bulk thermal conductivity of sample material.

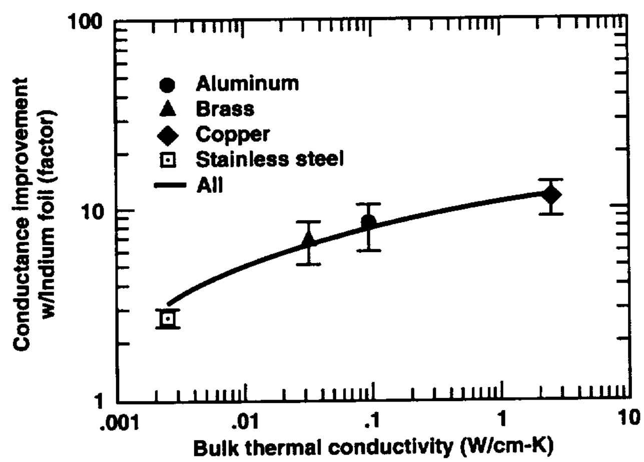

Figure 15. Thermal conductance improvement with Indium foil vs. bulk thermal conductivity of sample material.

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13. ABSTRACT *(Maximum 200 words)*

The thermal conductance of pressed contacts which have been augmented with Indium foil or Apiezon-N™ grease has been measured over the temperature range of 1.6 to 6.0 K, with applied forces from 22 N to 670 N. The sample pairs were fabricated from OFHC copper, 6061-T6 aluminum, free-machining brass, and 304 stainless steel. Although the thermal conductance was found to increase with increasing applied contact force, the force dependence was less than in earlier work. The addition of Indium foil or Apiezon-N™ grease between the contact surfaces resulted in an improvement over uncoated surfaces ranging from a factor of approximately 3 for stainless steel to an order of magnitude for copper contacts.

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