
Thermal Contact Conductance

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Summary

The performance of cryogenic instruments is often a function of their operating temperature. Thus, designers of cryogenic instruments often are required to predict the operating temperature of each instrument they design. This requires accurate thermal models of cryogenic components which include the properties of the materials and assembly techniques used. When components are bolted or otherwise pressed together, a knowledge of the thermal performance of such joints are also needed. In some cases, the temperature drop across these joints represents a significant fraction of the total temperature difference between the instrument and its cooler. While extensive databases exist on the thermal properties of bulk materials, similar databases for pressed contacts do not. This has often lead to instrument designs that avoid pressed contacts or to the over-design of such joints at unnecessary expense. Although many people have made measurements of contact conductances at cryogenic temperatures, this data is often very narrow in scope and even more often it has not been published in an easily retrievable fashion, if published at all. This paper presents a summary of the limited pressed contact data available in the literature.

Introduction

The performance of cryogenic instruments is often a function of their operating temperature. For example, the sensitivity of infrared bolometers is a function of $T^{-5/3}$; similarly the performance of photoconductive detectors deteriorates rapidly when the temperature reaches or exceeds their band gap, and superconducting components must operate below their transition temperatures. Thus, designers of cryogenic instruments often are required to predict the operating temperature of each instrument they design. This requires accurate thermal models of cryogenic components which include the properties of the materials and assembly techniques used. When components are bolted or otherwise pressed together, a knowledge of the thermal performance of such joints are also needed. In some cases, the temperature drop across these joints represent a significant fraction of the total temperature difference between the instrument and its cooler.

While extensive databases exist on the thermal properties of bulk materials, similar databases for pressed contacts do not. This has often lead to instrument designs that avoid pressed contacts or to the over-design of such joints at unnecessary expense. These are not always viable options. Although many people have made measurements of contact conductances at cryogenic temperatures, this data is often very narrow in scope and even more often it has not been published in an easily retrievable fashion, if published at all. This work presents a summary of the limited pressed contact data available in the literature.

Nomenclature

α	Proportionality constant
A	Overall contact surface area
A_L	Area of lower sample
A_U	Area of upper sample
d	Sample diameter
dT	Incremental temperature difference
F	Applied force
k	Effective thermal contact conductance
L	Length from thermometer to contact interface
n	Exponent
Q	Applied heater power
Q_0	Offset (parasitic) heater power
T_L	Lower sample temperature
T_U	Upper sample temperature
ΔT	Temperature difference across boundary
ΔT_L	Temperature drop across bulk material of lower sample
ΔT_U	Temperature drop across bulk material of upper sample

Theory of Thermal Contact Conductance and Review of Work

Thermal contact resistance is attributable to several factors, the most notable being that contact between two surfaces is made only at a few discrete locations rather than over the entire surface area. A close examination of even the smoothest surfaces reveals an asperity which limits the actual area of contact to as few as three discrete locations, irrespective of the dimensions of the sample. This is supported empirically by findings that the thermal conductance of pressed contacts is dependent upon the applied force and not on the area of contact nor on the apparent contact pressure (ref. 1).

As the applied force is increased, surface deformation of the material occurs. The initial area of contact increases and, as the material deforms further, contact occurs at new locations. The heat flow is constricted in the vicinity of the contact locations because of the narrowness of the effective areas of contact, as represented in figure 1. This constriction is, in large part, responsible for contact resistance.

Additionally, the presence of surface films or oxides contribute to the phenomenon. The thickness of these layers adds an additional variable to the conductance. In the case of oxides, since the oxide layer generally has high thermal resistance, it must be penetrated to obtain a consistent measure of the thermal resistance of the actual contacts. At low temperatures, each oxide layer acts as an additional boundary resistance, and the problem is compounded because of the acoustic mismatch between the layers (Kapitza resistance). Further, the thickness of the oxide layer is often a function of time.

Estimates of the constriction resistance have been made for specific assumed contact geometries by modeling the contacts as individual elements. By arranging the elements in groups of varying heights, the asperity can be accounted for as well. Although contact pressure and material hardness can be used to determine the ratio of the sample surface area to the actual contact area, the equivalent radius of the contact spot must be well known and a probability distribution of the spots must be calculated. Since each sample represents a new problem, estimation of the contact resistance from theoretical models is not a trivial task (refs. 18 and 19), and most data in the field are empirical. Table 1 presents a summary of low temperature thermal contact data available in the literature.

Experimental data has shown (refs. 1, 9–12) that the thermal conductance of metallic pressed contacts increases according to a simple power law function of temperature, and can be described by the relation:

$$k(T) = \alpha T^n$$

where n typically ranges from 0.75 to 2.5.

Thermal conductance also increases asymptotically with increasing applied force. As the applied force increases, the actual area of contact approaches the apparent area. For uncoated samples of aluminum, brass, copper, and stainless steel at liquid helium temperature, it has also been found that thermal conductance is related to the surface finish of the samples. Except in the case of aluminum, for lapped sample pairs with finishes of 0.1, 0.2, 0.4, 0.8, and 1.6 μm , the maximum observed contact conductance at 4.2 K was exhibited by the 0.4 μm surface finish. For aluminum samples, the conductance was lowest for the 0.4 μm surface finish, and peaked at 0.2 μm . Although several mechanisms were postulated to account for this effect, no causal relationship has been established, and the possibility of a systematic anomaly in sample pair preparation cannot be excluded.

Since constriction resistance plays a major role in limiting thermal transfer, increasing the effective contact area by applying a conforming coating can significantly enhance contact conductance, even if the coating material is of relatively low thermal conductivity. The reason for this is that ideally, a conforming coating allows the entire contact surface to transfer heat, rather than a few narrow areas. In reality, although the ideal condition is unattainable, considerable improvement in thermal contact conductance is possible by applying conforming coatings. Several methods have been reported (refs. 3, 13, and 14) such as gold plating the contact surfaces, coating the surfaces with low-temperature grease, or inserting a thin sheet of Indium metal between the contact surfaces. Of the methods reported, a thin layer of low-temperature grease appears to offer the best enhancement of thermal conductance.

In practice, measuring such enhanced contacts is not as straightforward as it might appear. Ordinarily, the contribution of the bulk material thermal conductivity to the thermal contact conductance is negligible, however the high thermal conductance of Indium or ApiezonTM coated contacts require 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 2 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:

$$\Delta T_C = (T_U - \Delta T_U) - (T_L + \Delta T_L)$$

The ΔT_U and ΔT_L are found for each data point, from:

$$Q = A_U / L \int_{T_U - \Delta T_U}^{T_U} k dT$$

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.

$$Q = A_L / L \int_{T_L}^{T_L + \Delta T_L} k dT$$

Table 1. Summary of Thermal Contact Literature

Researcher (Reference)	Year	Material	Temp (K)	Applied Force (N)	Conductance (W/K)
Berman (1)	1956	Copper	4.2	223	5.5 x 10 ⁻³
		"	"	446	1.02 x10 ⁻²
		"	"	670	1.46 x 10 ⁻²
		"	"	892	1.9 x 10 ⁻²
		"	"	1115	2.3 x 10 ⁻²
Deutsch (12)	1979	Copper	4.2	1004	0.34
Kittel et al (8, 15)	1992	Au-plated:	1.6-4.2	22-670	1.3 x 10 ⁻⁴
		Aluminum			to
		Brass			3.3 x 10 ⁻²
		Copper			
		Stainless steel			
	1994	Bimetallic:	77	9-267	9 x 10 ⁻³
		Alum & Stainless			to
		Steel			2.1 x 10 ⁻²
Manninen & Zimmerman (13)	1977	Copper	4.2	1004	0.34
Mian et al (15)	1979	Mild steel	300	981	*0.825
					†1.25
					*optically flat
					†roughness < 3μm

Table 1. Summary of Thermal Contact Literature (continued)

Researcher (Reference)	Year	Material	Temp (K)	Applied Force (N)	Conductance (W/K)		
Nilles and Van Sciver (11)	1988	Copper	4-290	129	4×10^{-3}		
		-oxidation treatment			1.4×10^{-2}		
					2.0×10^{-2}		
		-normal			8.0×10^{-2}		
					1.3×10^{-1}		
					1.4×10^{-1}		
Radebaugh et al (17)	1977	Copper	4.2	490	10^{-2}		
		Polished Ag			4.2	490	1.1
		Stainless Stl			300	490	10^{-2}
Salerno et al (4, 5, 6, 7)	1984	Aluminum	1.6-4.2	22-670	1×10^{-4}		
	1985	Brass			to		
	1986	Copper Stainless Stl			2.0×10^{-2}		
Salerno et al (9, 10)	1993	Augmented: Aluminum	1.6-4.2	22-670	3.6×10^{-5}		
		Brass			to		
		Copper			1.0×10^{-2} (Au-plated Washer)		
		Stainless Steel			5.0×10^{-4}		
	1994				to 0.28 (In, Ap)		
Suomi et al (18)	1968	Copper	0.02-0.2	?	10^{-2}		
Thomas & Probert (19)	1970	Stainless Steel	88-95	446	0.36		
				892	0.5		
Wanner (20)	1981	Aluminum	1-4	4683	**0.2		
				9366	**0.6		
				12488	**1.5		
**at 4.2 K							

Summary of Experimental Data

Data is shown in figure 3 for thermal conductance vs. temperature at 670 N applied force for uncoated contact surfaces, gold coated contact surfaces, contacts with a gold coated aluminum washer placed between the surfaces, contacts having a thin sheet of indium foil between the surfaces, and contact surfaces coated with a layer of Apiezon-N™ grease. Although only copper is shown for clarity, similar trends are observed for aluminum, brass, and stainless steel. Depending upon the sample bulk material and the thickness of the coating, improvement of thermal conductance ranges from a factor of 2 for gold coating to an order of magnitude for Indium foil. The improvement gained by insertion of the gold-coated aluminum washer between the contact surfaces was essentially offset by the addition of two extra contact interfaces.

In figure 4, thermal conductance of copper contact pairs at 4.2 K is plotted vs. applied force, for several of the references in Table 1. Nilles and Van Sciver (ref. 7) prepared both rigorously cleaned copper samples and oxidized copper samples which were heated in laboratory air. Deutsch (ref. 2) and Manninen and Zimmerman (ref. 5) derived thermal conductance from measurements of the electrical conductance, using the Weidemann-Franz law. It appears that the room temperature Lorenz number was used. At low temperatures, the Lorenz number is known to decrease by an order of magnitude (ref. 20). If their data is corrected for this effect, it then lies within the range of the other data plotted.

In figures 5–8 thermal conductance at an applied force of 670 N is plotted against temperature with surface finish as a parameter, for uncoated aluminum, brass, and copper sample pairs. For stainless steel, only results for the 0.8 μm finish are presented. Both the aluminum and copper sample pairs exhibit a temperature dependent crossover of specific finishes.

Figures 9–12 present thermal conductance vs. applied force for several 0.8 μm finish sample pairs, with surface coating as a parameter. In figure 13, thermal conductance of bimetallic contact pairs (5052 aluminum/304L stainless steel; 5083 aluminum/304L stainless steel) is plotted against applied force at 77 K (ref. 4).

Discussion

It is apparent that conforming coatings offer significant enhancement to the thermal contact conductance, with Indium and Apiezon™ exhibiting the most significant enhancement.

In principle, the same result should be realizable with any conforming coating. Previous work with gold coating 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. As a side note, although the superconducting transition temperature of Indium is 3.4 K, no measurable effects of the transition on the thermal conductance were noted.

Although the insertion of Indium foil between the contact surfaces greatly improved the conductance, a significant improvement over Indium was realized with Apiezon™ in the cases of aluminum, brass, and copper. Early data taken where only a moderate contact force was applied at room temperature before cooling of the sample pair was problematic and, in many cases, impossible to analyze. This can be attributed to the fact that, unlike Indium foil which flows, the Apiezon™ grease becomes rigid at cryogenic temperatures. If good contact is not made at room temperature the resultant thick, non-deforming layer of Apiezon™ separates from the contact surfaces at liquid 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 minimum contribution to the resistance.

It can be seen from figure 3 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. If the improvement in thermal conductance over uncoated surfaces by the addition of Apiezon-N™ grease and Indium foil is plotted versus the bulk thermal conductivity of the sample material, 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.

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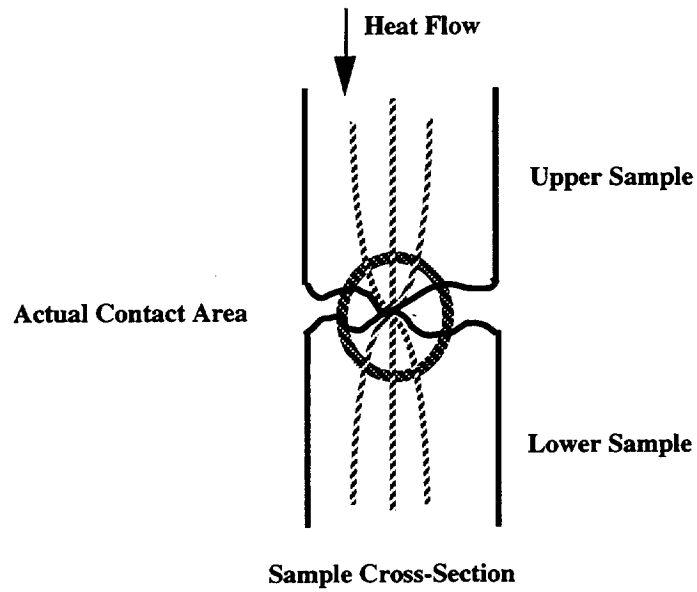


Figure 1. Heat Flow Constriction.

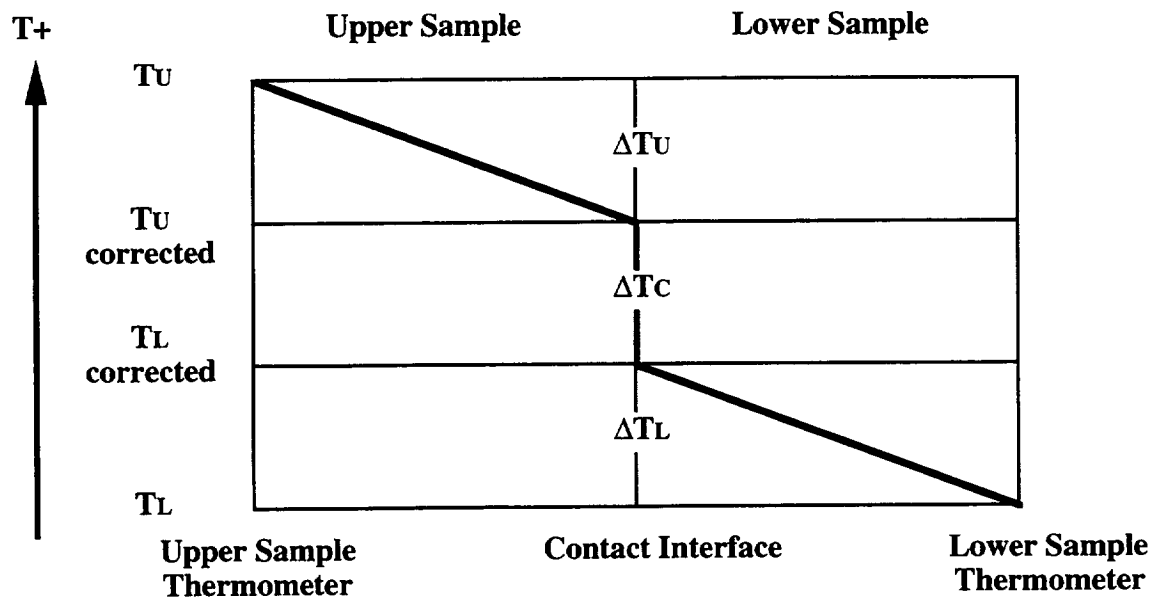


Figure 2. Schematic representation of temperature drop across samples and contact area.

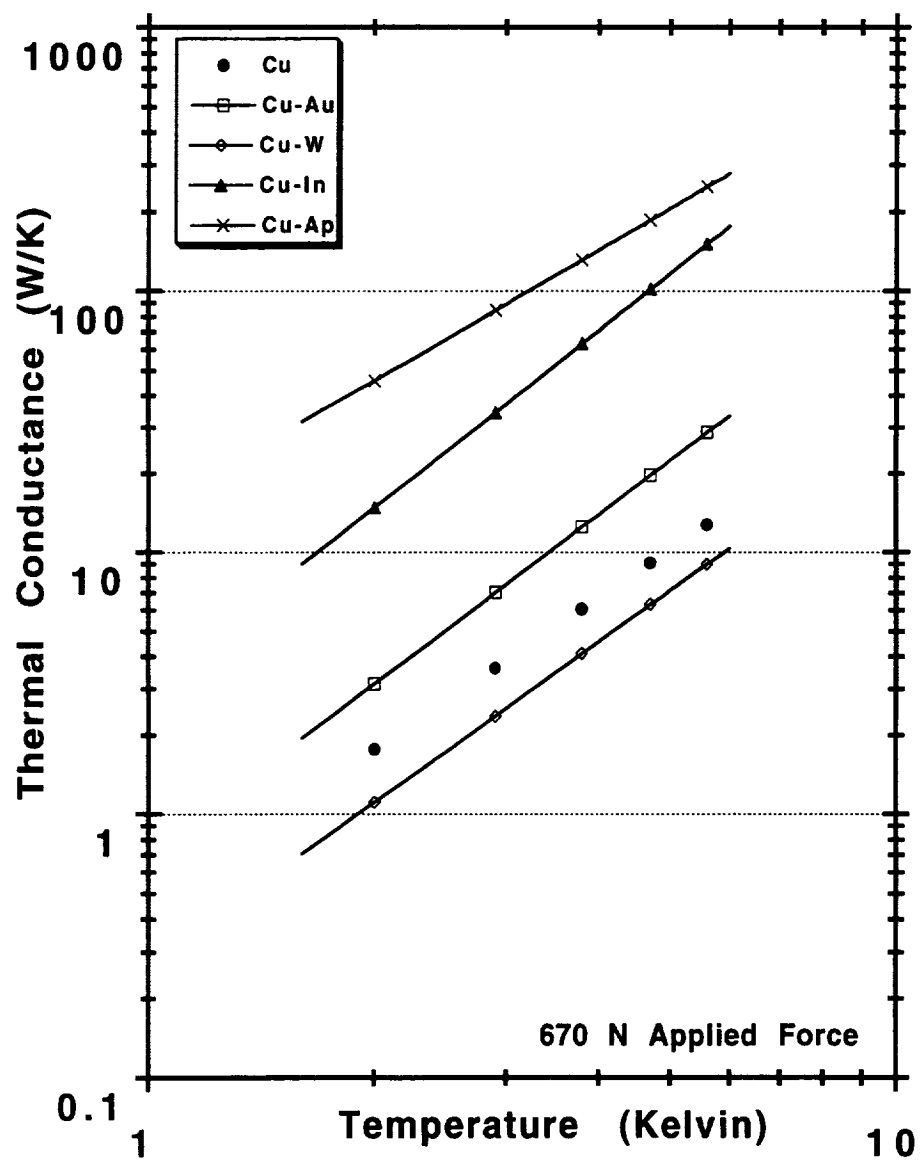


Figure 3. Surface Coating Comparison Au:Gold plated; W:Alum Washer; In:Indium Foil; Ap:Apiezon™ grease.

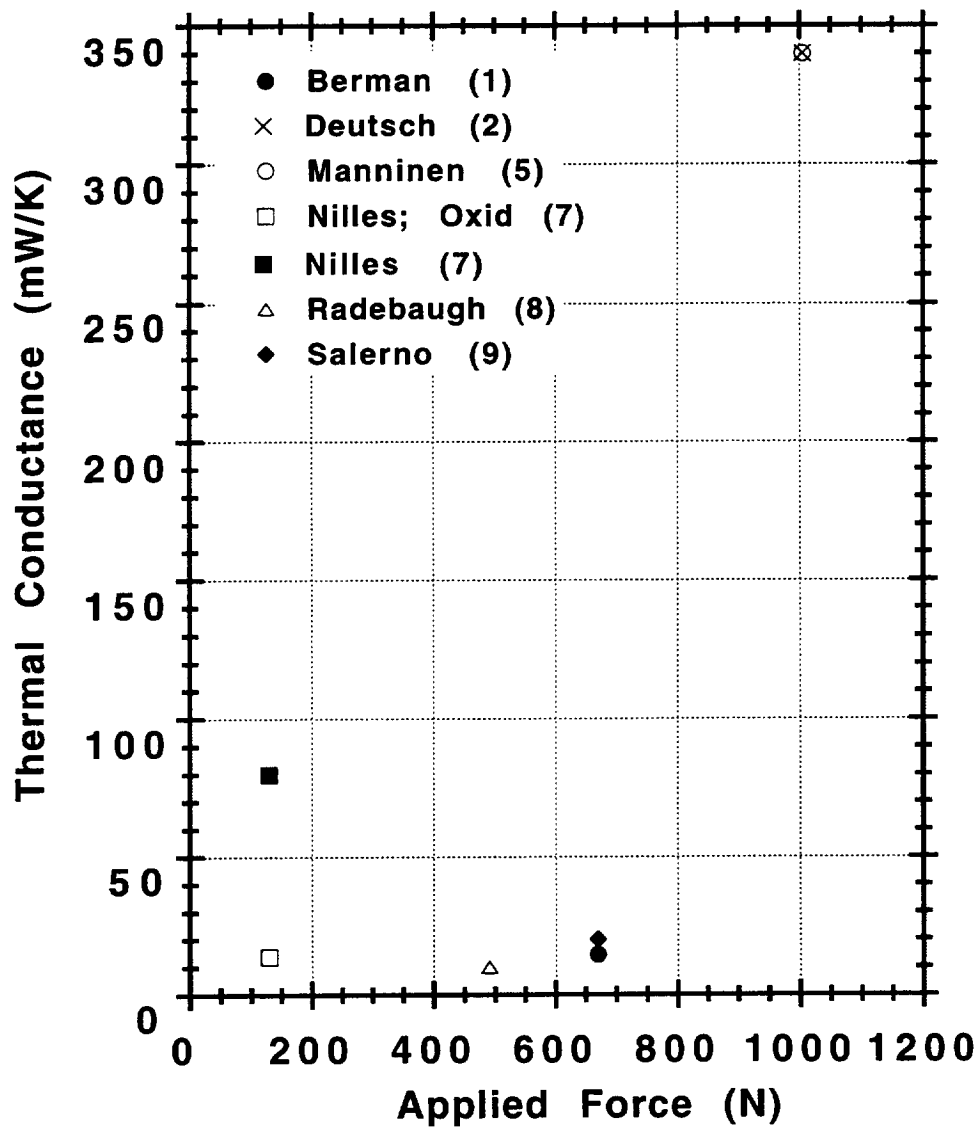


Figure 4. Thermal conductance of Copper Sample Pairs at 4.2 K vs. Applied force (References from Table 1).

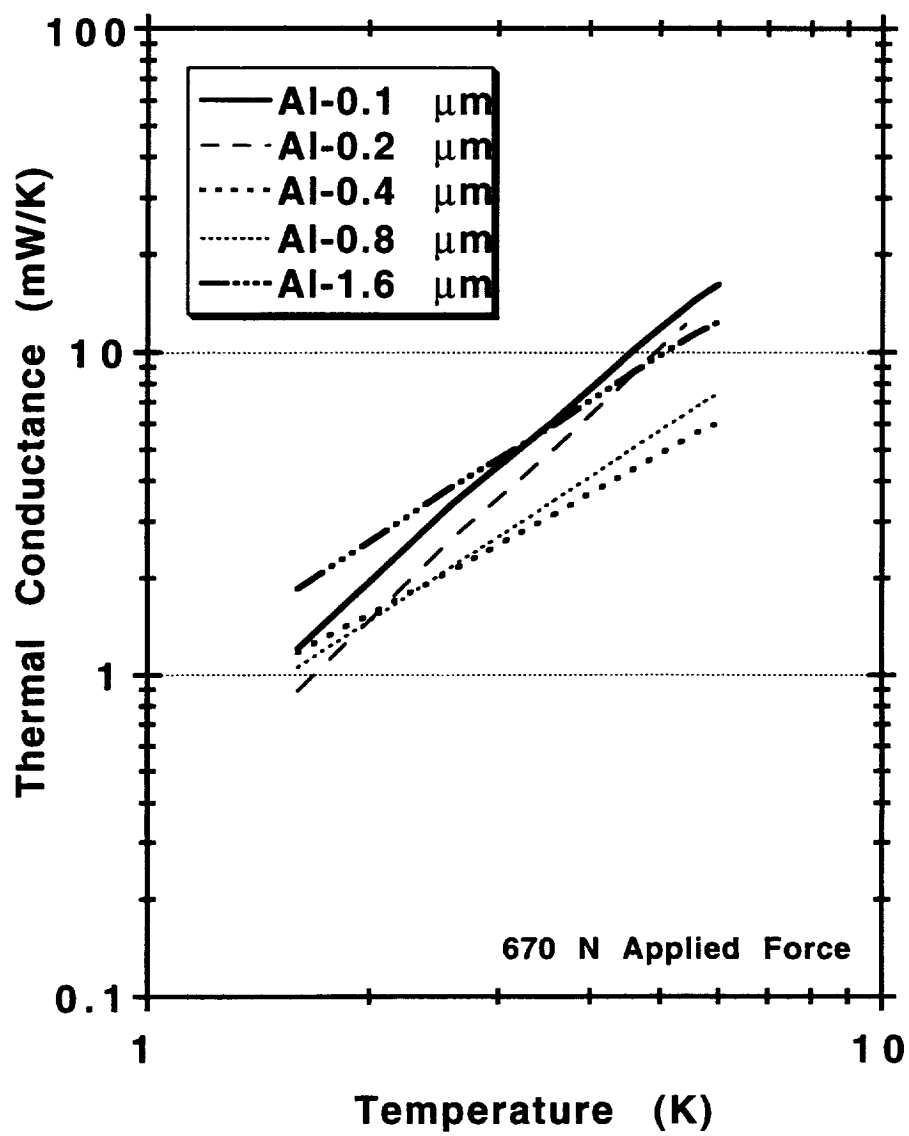


Figure 5. Thermal conductance of uncoated Aluminum for various surface finishes.

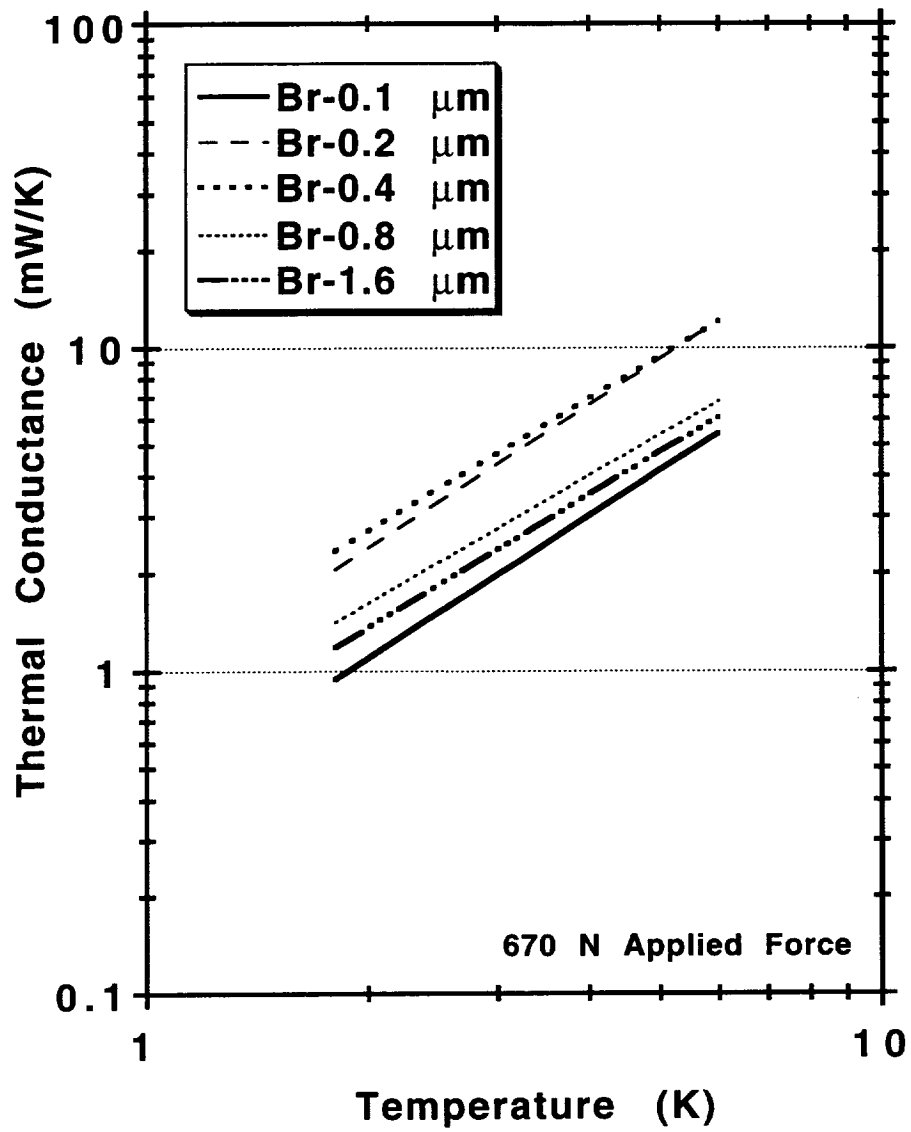


Figure 6. Thermal conductance of uncoated Brass for various surface finishes.

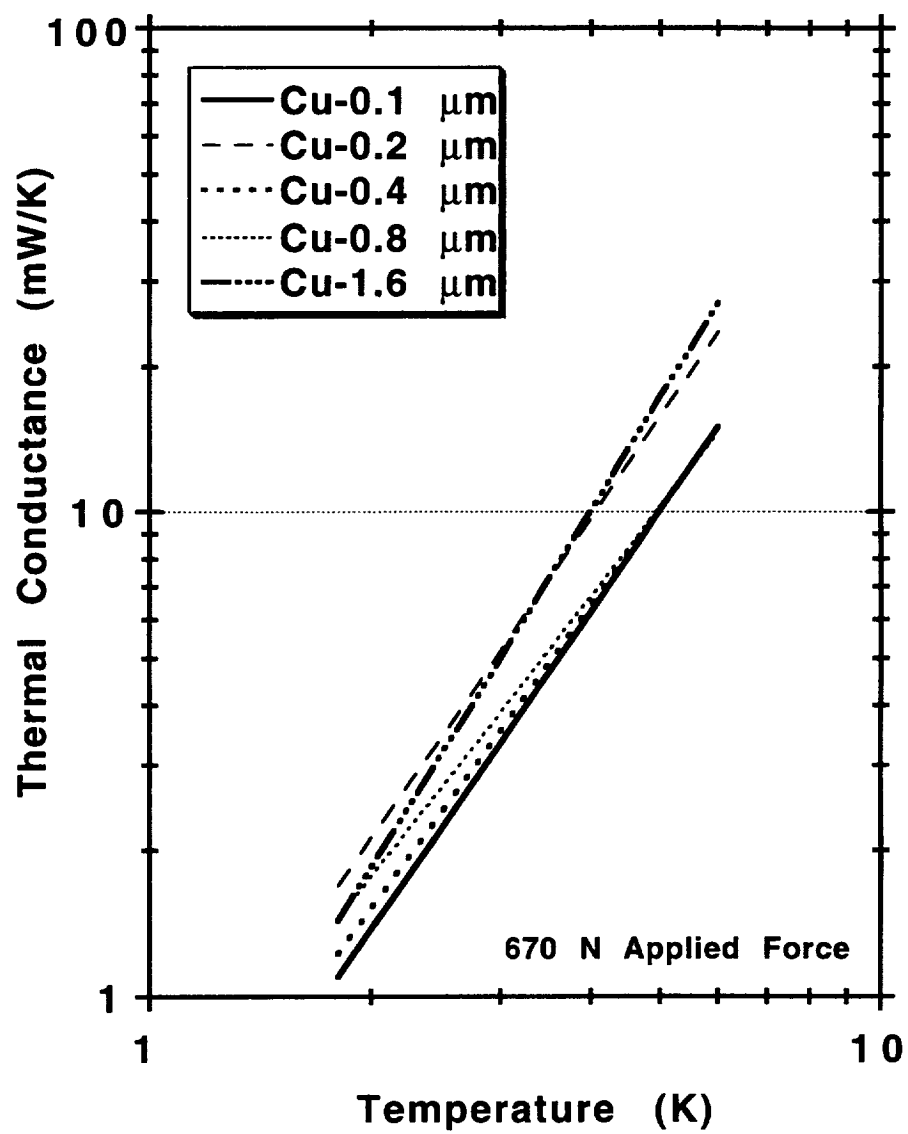


Figure 7. Thermal conductance of uncoated Copper for various surface finishes.

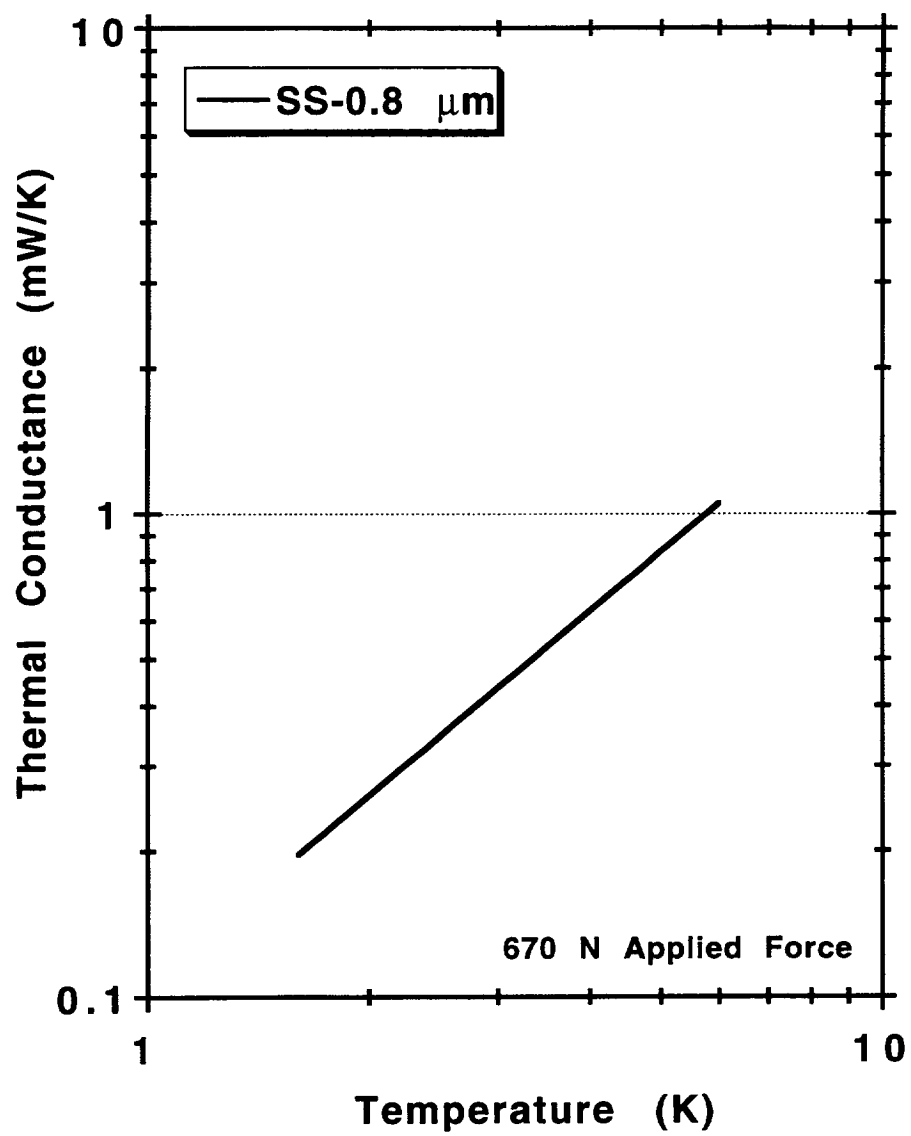


Figure 8. Thermal conductance of uncoated Stainless Steel for 0.8 μm surface finish.

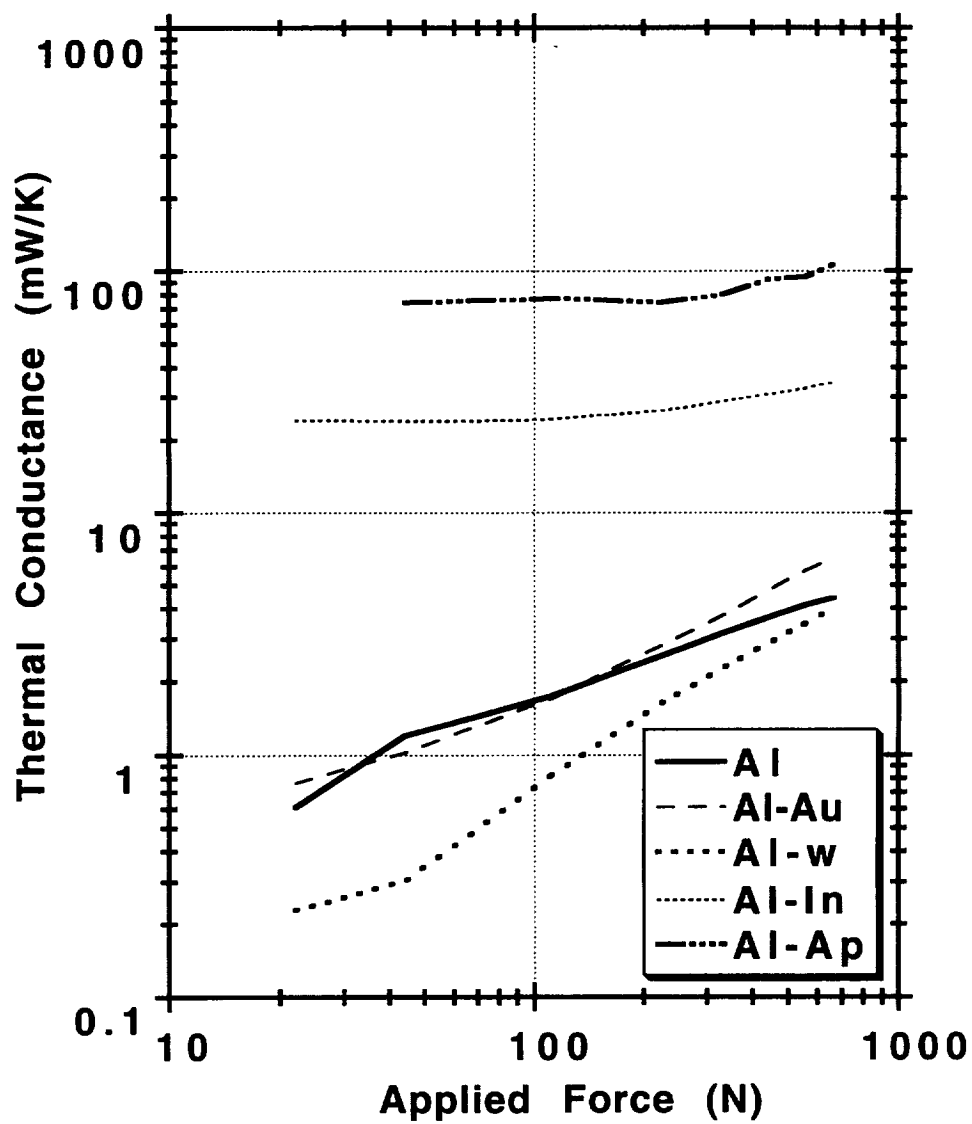


Figure 9. Thermal conductance vs. applied force for 0.8 μm Aluminum at 4.2 K.

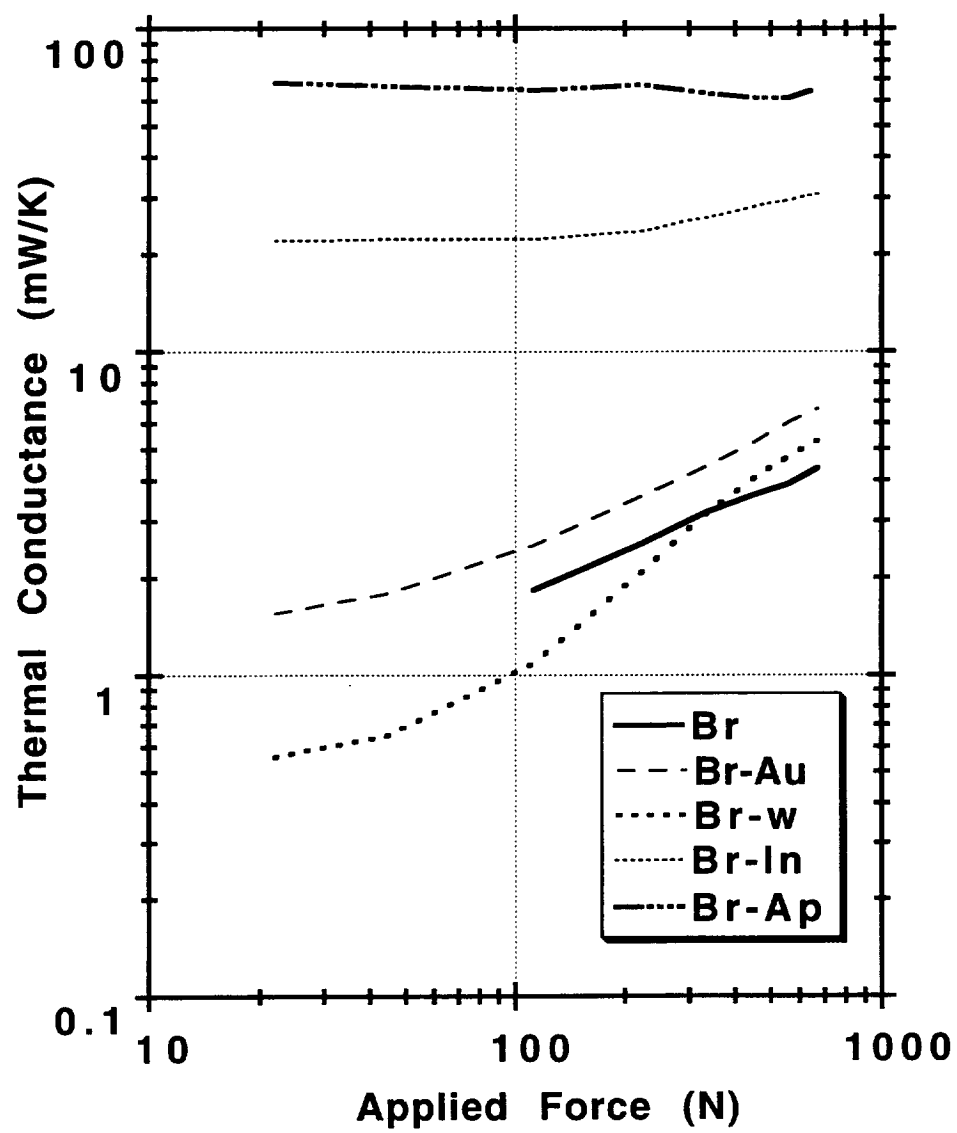


Figure 10. Thermal conductance vs. applied force for 0.8 μm Brass at 4.2 K.

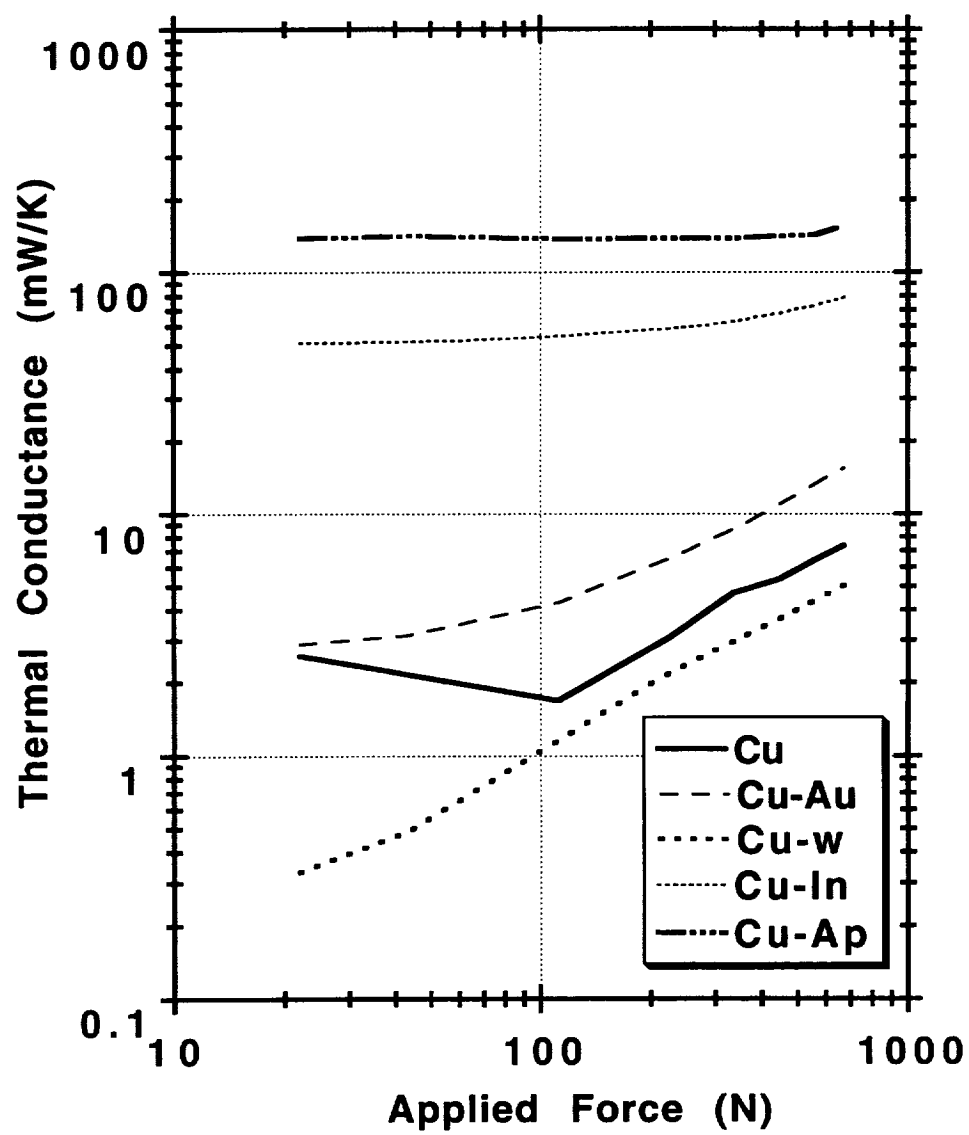


Figure 11. Thermal conductance vs. applied force for 0.8 μm Copper at 4.2 K.

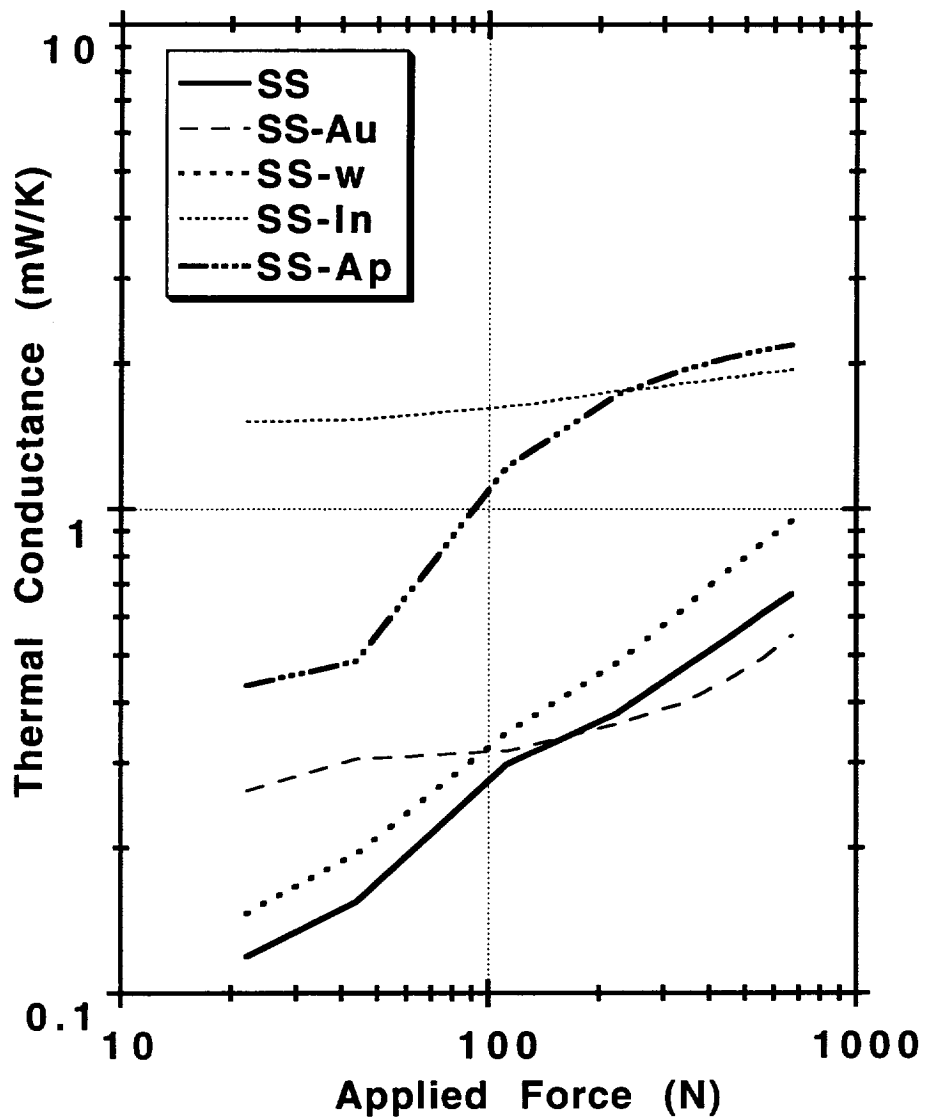


Figure 12. Thermal conductance vs. applied force for 0.8 μm Stainless Steel at 4.2 K.

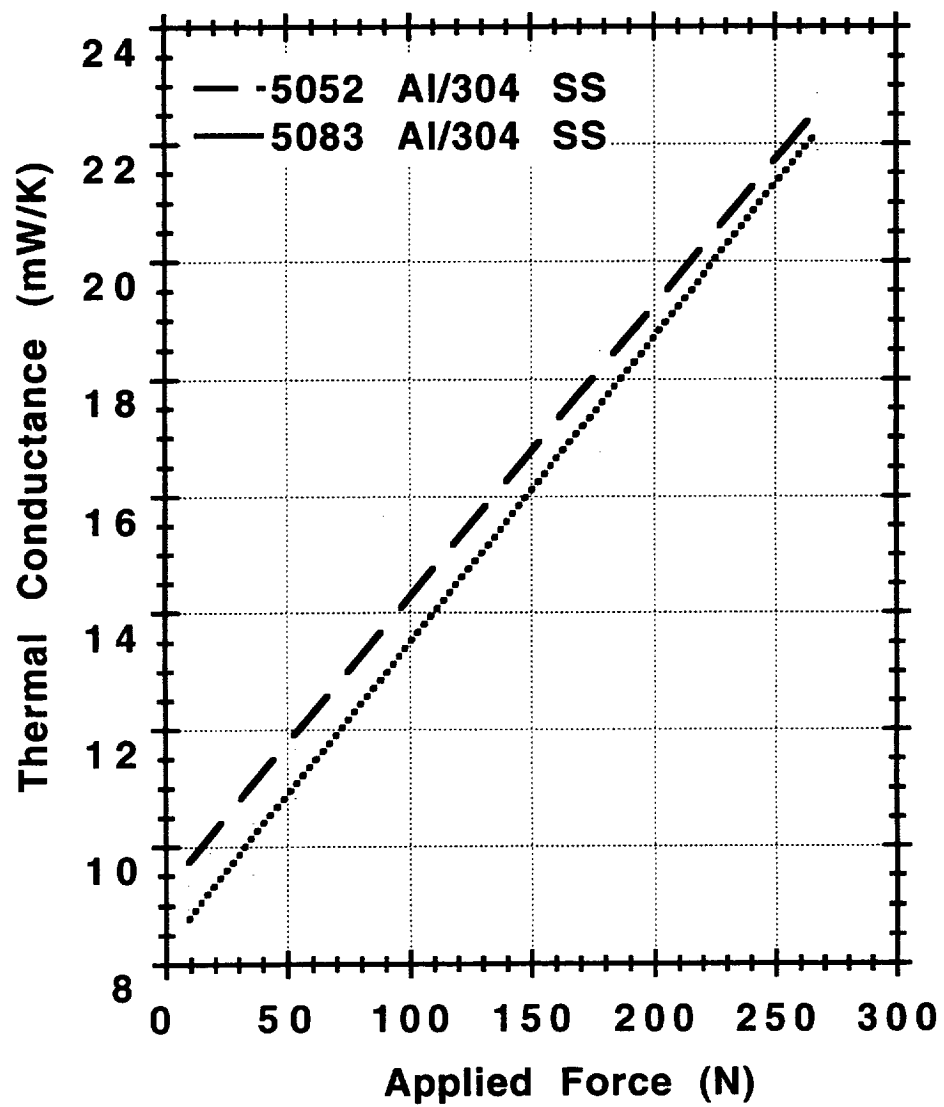


Figure 13. Thermal conductance vs. applied force for Aluminum/Stainless Steel at 77 K.

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