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Technical Notes

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Thermal Contact Conductance of Molybdenum-Sulphide-Coated Joints at Low Temperature

K. Ramamurthi*
Indian Institute of Technology Madras, Chennai 600 036, India
and
S. Sunil Kumar† and P. M. Abilash†
Liquid Propulsion Systems Centre, Trivandrum 695 547, India

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Nomenclature

h	=	contact conductance, W/m^2K
q	=	heat flux, W/m^2
R_a	=	average surface roughness, μm
t	=	thickness of MoS_2 coating, μm
ΔT	=	temperature difference across the interface

Introduction

JOINTS used for cryogenic structural supports and satellite deployment mechanisms are often exposed to very low temperatures. These joints, unlike those for ground applications, do not use metal-to-metal contact. A conducting or insulating interstitial medium is introduced at the interface for controlling the contact conductance. When gold and silver plating and the use of thermal grease is adopted for enhancing the contact conductance, a reduction in contact conductance is achieved by providing a nonmetallic coating at the interfaces. Molybdenum sulphide (MoS_2) is widely used as the nonmetallic coating in cryogenic structural joints, because it not only reduces the joint conductance but also provides dry lubrication at the joint. A precise knowledge of the contact conductance of the coated joint is essential, especially at the low temperatures at which it is used for estimating the parasitic heat-conduction loads through the cryogenic structural supports.

A variety of nonmetallic coatings such as manganese dioxide, silicon elastomer, carbon black, and polyethylene have been evaluated over a range of interface temperatures and pressures [1,2]. The temperatures considered in the preceding studies are essentially above the ambient. A general model for computing the conductance in multilayered contacts was developed by Muzychka et al. [3] for a flux tube having two applied coatings. The need remains to determine contact conductance of nonmetallic coating [4] such as MoS_2 at low temperatures. In this paper, the effectiveness of MoS_2 coating on aluminum and stainless steel contacts at different interface temperatures and loads is determined. Experiments are carried out over a range of low temperatures.

Experiments

Eleven pairs of specimens were made of aluminum (Al) and stainless steel (SS). Each sample pair was 25 mm in diameter and either 25 or 5 mm in height, respectively. They were prepared with varying levels of surface finish, with values of average roughness R_a between 0.2 and 2 μm and the average slope of asperities varying from 0.09 to 0.15. The measured flatness values were well within 0.2 μm.

One side of each of the aluminum samples was anodized to prevent atmospheric oxidation of the surface and to obtain better retentivity of the MoS_2 coating on the surface. The thickness of anodization was typically 0.2 μm. MoS_2 was sprayed on both the anodized and bare metal surfaces and thermally cured at 80°C between 3 and 6 h for proper bonding. Different coating thicknesses of 1, 5, and 10 μm were used. The samples were stored in airtight bags to prevent contamination of the surfaces by the atmosphere.

All measurements were carried out in a closed-loop cryostat. The schematic of the experimental setup used for the measurement is similar to the one reported in [5]. A solid-state flat-type heat flux transducer was placed above the upper sample to measure the heat transfer rate directly. The surfaces of the transducer were in contact with a special miniature high-temperature thermopile that generates a dc signal from the temperature difference between the two sides of the transducer plate. The signal is directly proportional to the heat flux through the meter, which is calibrated using ASTM C177-76 and is accurate within 0.1%. Two T-type thermocouples were connected to the bottom sample and six were connected to the larger sample at the top. The thermocouples were placed 5 mm apart. All thermocouples were calibrated before their use.

Each sample pair was tested over a range of temperatures between 50 and 300 K and loads between 0 and 700 kPa. The heat flux through the specimen was measured directly using a heat flux transducer. Typical transient times in the experiments varied between 70 min and 3 h. The criterion for steady state was taken to correspond to a maximum rate of change of 1.0 K in 10 min. The heat flux through the specimen q was also determined using the measured temperature gradients in the sample and a one-dimensional heat-conduction analysis using the thermal conductivity of samples at that temperature [6]. The estimated values of heat flux were about the same as those measured by the heat flux meter, indicating that transverse and axial heat flow through the loading mechanism was negligibly small. The maximum value of the measured total heat loss was within 5%. For each set value of cold head temperature, the contact conductance h at the interface was determined by the relation $h = q/\Delta T$.

After each set of measurements, the contact force was enhanced. Data were generated for both ascending and descending values of the applied load to determine hysteresis associated with the mechanical loading of the joint.

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*Professor, Mechanical Engineering Department. Associate Fellow AIAA.

†Engineer, Propulsion Research and Studies.

Uncertainty in Measurements

All thermocouples were calibrated between 200 and 300 K using a high-accuracy, dual-temperature, dry-block calibrator traceable to National Institute of Standards and Technology standards. Below 200 K and up to 40 K, the thermocouples were calibrated against the cold head temperature using the cold head resistance temperature detectors (RTD) output with an accuracy of 0.05 K. The T-type thermocouple has an uncertainty of $\pm 1.5\%$ over the cryogenic range of temperatures. The maximum uncertainty in differential temperature would therefore correspond to an uncertainty of 3% in the estimated values of surface contact conductance.

Uncertainties in the heat flow through the test specimen were within 5%, considering the heat loss (5%) and the uncertainty in the transducer measurement (0.1%). In terms of the thermal contact conductance, the maximum uncertainty is $\sqrt{0.03^2 + 0.05^2} = 6\%$.

Results and Discussion

A total of 81 measurements were carried out. The initial experiments were done for a constant interface pressure of 10 kPa with bare SS and anodized aluminum samples with an average surface roughness of 0.8 μm. Measurements were done over a range of interface temperatures varying from 40 to 300 K. Subsequently, experiments were repeated for the contacting surfaces with MoS_2 coating for the same interface pressure with average coating thicknesses of 1, 5, and 10 μm.

The variation of contact conductance with temperature for MoS_2-coated samples of anodized aluminum and stainless steel is shown in Fig. 1. The coating thickness was 5 μm. Higher conductance is obtained with MoS_2 coated over aluminum than with MoS_2 coated over stainless steel. This arises from the high thermal conductivity of aluminum compared with stainless steel. It is also seen from Fig. 1 that the difference in contact conductance between aluminum and stainless steel joints decreases at lower temperature. Aluminium, being a softer material, deforms and flows better under pressure, filling a number of crevices between the asperities on the surface, leading to an increased area of contact, especially at higher temperatures. Further, the variation of the hardness between stainless steel and aluminum with respect to changes in temperature is smaller at the lower range of temperatures [6]. This gives rise to smaller changes in the difference of contact conductance between aluminum and stainless steel at the lower temperatures.

The values of contact conductance in the absence of MoS_2 coating (contact between bare surfaces of anodized aluminum and SS) is also shown in Fig. 1 by filled symbols. The variation with temperature for the bare joint is seen to be similar to those of the MoS_2-coated joint.

When the surface of the aluminum is not anodized, the variation of the contact conductance with temperature shows a similar trend for bare metal surfaces in contact and for MoS_2-coated joints. This is shown in Fig. 2, wherein the influence of varying thickness of MoS_2 coating is also given. It is seen that the bare joint has a larger value of conductance than the anodized uncoated joint, and further, the rate of change of contact conductance with temperature is also higher for the nonanodized joint. Figure 2 also shows that as the coating thickness increases, contact conductance not only reduces, but the sensitivity of the changes in conductance with temperature decreases.

Figure 3 gives the variation of contact conductance of MoS_2 coated on anodized and bare aluminum samples over a range of interface loads for an average surface roughness of the metal surface of 0.2 μm. The interface temperature is kept at 150 K. Measurements were made for two thickness levels of MoS_2 coating of 1 and 5 μm. The contact conductance increases with interface loads, the increase being more pronounced at smaller values of interfacial pressures. A

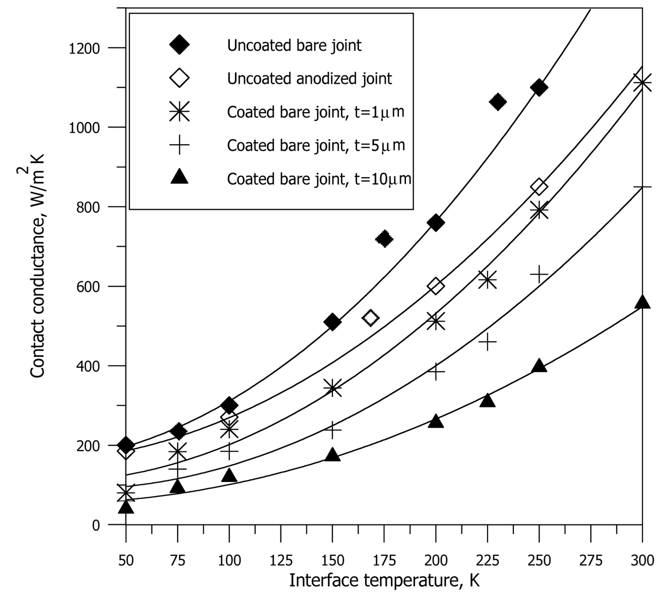

Fig. 2 Effect of anodization and coating thickness on thermal contact conductance at low temperature for aluminum with $R_a = 0.8$ μm at 10 kPa.

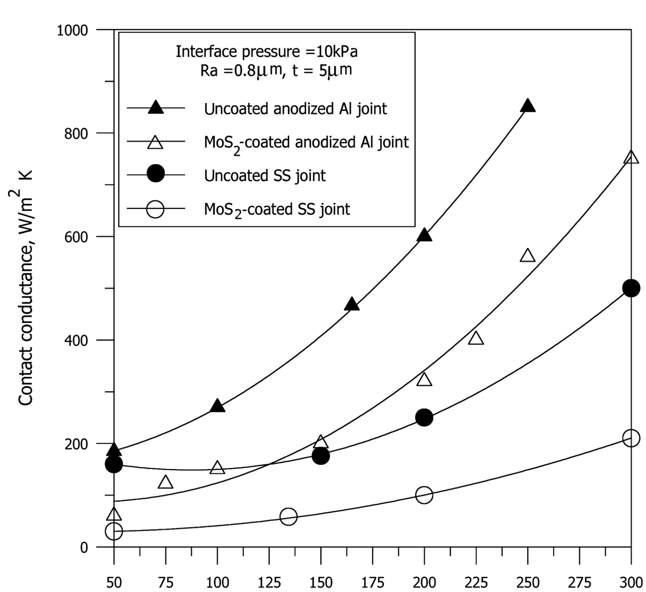

Fig. 1 The influence of MoS_2 coating at low temperature for different materials.

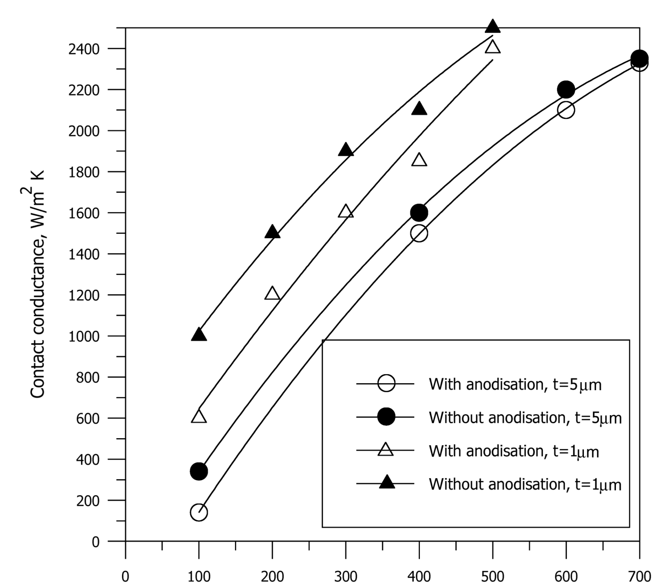

Fig. 3 Changes in contact conductance with interface load for different coating thickness of aluminum joint for $R_a = 0.2$ μm at 150 K.

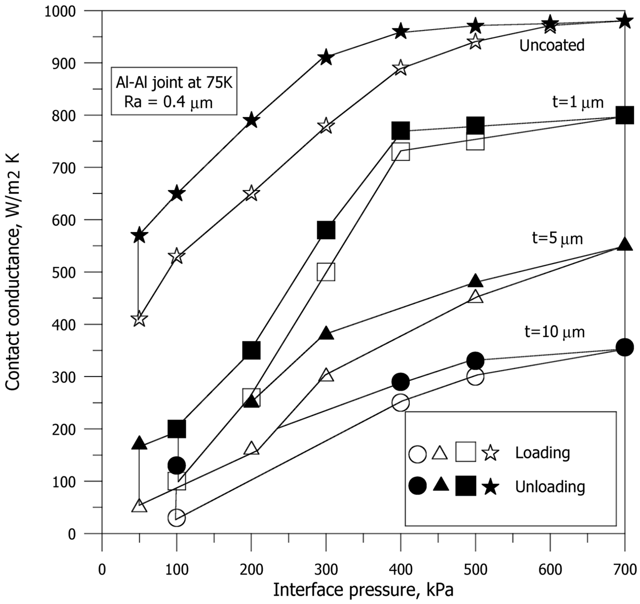

Fig. 4 Loading hysteresis of coated and uncoated joints.

reduction is also observed in the contact conductance for MoS_2 coated over anodized surfaces.

The effect of loading and unloading the interface on thermal contact conductance was also studied. Measurements were done for three different MoS_2 coating thicknesses (1, 5, and 10 μm) and are compared with measurements made using uncoated aluminized samples. Figure 4 illustrates the results during the ascending and descending phases of loading for an interface temperature of 75 K and a range of interface pressure between 0 and 700 kPa. The values of conductance for all three coating thicknesses is higher during the descending phase of loading. The thickness of the coating is not observed to significantly influence the hysteresis zone. For uncoated samples, however, the hysteresis zone is seen to be larger compared with MoS_2-coated samples. Hysteresis arises from the deviation of flow of materials from the elastic to plastic state under pressure [2]. Under plastic flow, the deformations that occur at high interface loads are more permanent and the contacting asperities do not regain their original shape even after releasing the interface pressure. This leads to the increased area of contact to be sustained even when the pressure is relieved, leading to higher contact conductance. The smaller values of hysteresis zone are suggestive of the smaller permanent deformations of the surfaces in the presence of coating.

Conclusions

MoS_2 coating over aluminum and stainless steel surfaces is shown to significantly reduce the thermal contact conductance at cryogenic temperatures. Anodization of surfaces before coating leads to a further reduction in thermal contact conductance. Changes in thermal contact conductance with interface loading is also influenced by the thickness of the coating used and the surface roughness. At lower values of coating thickness, the surface roughness values more significantly influence the contact conductance. The variation of thermal contact conductance with changes of interface pressure is smaller at higher values of coating thicknesses. The MoS_2-coated samples also show a reduction in the zone of hysteresis. The variations of the coating thickness, however, do not bring about any significant change in the zone of hysteresis.

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