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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed six manuscript pages and three figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Experimental Thermal Contact Conductance of Bead-Blasted SS 304 at Light Loads

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Nomenclature

c_1	=	Vickers microhardness correlation coefficient, Pa
c_2	=	Vickers microhardness correlation coefficient
E	=	Young's modulus, Pa
H	=	microhardness, Pa
h_c	=	contact conductance, $W/m^2 \cdot K$
k_s	=	harmonic mean thermal conductivity, $2k_A k_B/(k_A + k_B)$, W/mK
m	=	combined mean absolute slope, $\sqrt{(m_A^2 + m_B^2)}$, rad
P	=	contact pressure, Pa
q	=	heat flux, W/m^2
T	=	temperature, K
ΔT	=	temperature drop, K
ν	=	Poisson's ratio
σ	=	combined rms roughness, $\sqrt{(\sigma_A^2 + \sigma_B^2)}$, m

Subscripts

A, B	=	contacting bodies
c	=	contact
v	=	Vickers microhardness

Introduction

CONTACT heat transfer has many applications in engineering, such as ball bearings, spacecraft thermal control, microelectronic chips, and nuclear fuel heat dissipation. Several models to predict thermal contact resistance/conductance are available in the literature. Sridhar and Yovanovich[1] presented an extensive survey of the most accepted thermal contact conductance models available. They compared the models against stainless steel (SS) 304, Ni 200, Al 6061, Zr–Nb, and Zr-4 data collected by other researchers and concluded that the Cooper et al.[2] plastic model and the Mikic[3] elastic model are accurate to predict the experimental data, especially for high contact pressures. At light contact pressures, the theoretical models tend to underpredict experiments. The main objective of this work is to verify the deviation between experiments and theory at light loads.

To compare experiments and elastic or plastic models, it is convenient to know what is the deformation mode experienced by the contacting asperities. Mikic[3] proposed an index to predict if the deformation is either elastic or plastic. According to the author, the deformation mode depends on the geometry of the asperities and the mechanical properties of the contacting solids and does not depend on the magnitude of the contact pressure. In this work, the deformation mode of the contacting asperities is tested experimentally by measuring the contact conductance both in ascending and descending levels of contact pressures. It is well known that when the deformation is plastic, the thermal contact conductance measured in descending levels of contact pressure is always larger than in ascending levels because of the hysteresis effect (Mikic,[4] McWaid,[5] and Li et al.,[6] among others). The plastic deformation generated during the first loading is not recovered during the unloading; therefore, the contact spots are larger than during the first loading.

Review of Thermal Contact Conductance Models

The Cooper et al.[2] plastic model and the Mikic[3] elastic model are used here. These models were developed for isotropic surfaces (such as bead blasted). Yovanovich,[7] presented the following simple correlation for the Cooper et al.[2] plastic model:

$$h_c\sigma/k_s m = 1.25(P/H_c)^{0.95} \tag{1}$$

where P/H_c, the dimensionless contact pressure, is computed using the model proposed by Song and Yovanovich[8]:

$$P/H_c = \left[P\big/c_1(1.62\sigma/m)^{c_2}\right]^{1/(1+0.071c_2)} \tag{2}$$

Mikic[3] presented the following correlation for his elastic model:

$$h_c\sigma/k_s m = 1.55\left(\sqrt{2}P\big/mE'\right)^{0.94} \tag{3}$$

where

$$E' = \left[\left(1-\upsilon_A^2\right)\big/E_A + \left(1-\upsilon_B^2\right)\big/E_B\right]^{-1} \tag{4}$$

is the effective Young's modulus of the contacting bodies (A and B).

Experimental Study

The experimental study consists of measuring the thermal contact conductance between two SS 304 specimens under vacuum environment. The two specimens are nominally flat, with one of the contacting specimens smooth (lapped) and the other rough (bead blasted). The experimental setup and procedure used here is basically the same as employed by other researchers (McWaid[5] and Li et al.,[6] among others). It consists basically of a cold plate, testing column (two contacting samples), load cell, electrical heater, and loading

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mechanism. Heat is dissipated in the electrical heater, crosses the test column, and is absorbed by the cold plate. The contact pressure is read by means of a load cell.

The temperature distribution of the testing column is measured by means of six number 36 type-T thermocouples positioned 5 mm apart from each other along the longitudinal direction in each sample. A computational code uses the least-square method to find the best linear fit for the temperature distribution inside each test specimen. The heat fluxes of each sample are obtained by multiplying the slope of the temperature distributions by the conductivity of the SS 304, which is a function of the temperature and is given by the following expression:

$$k_{SS304} = 10.05 + 0.028T, \qquad 277 < T < 360\,\mathrm{K} \tag{5}$$

This correlation was obtained in a previous conductivity test using calibrated ARMCO fluxmeters.

All four SS 304 specimens were machined from the same bar stock to cylinders of 25 mm diameter by 45 mm long. The specimens were then ground flat, lapped by means of a mechanical lapping machine, and further hand lapped to obtain maximum flatness. The flatness deviations of the lapped surfaces were checked using a monochromatic light source and an optical flat and did not exceed 0.5 μm. Two specimens remained flat, and the other two specimens were bead blasted to two different roughness levels (0.72 and 1.31 μm). The roughnesses were measured with a stylus profilometer both before and after the tests, and the differences were negligible. A Vickers microhardness test was performed on one of the flat specimens, and the Vickers microhardness correlation coefficients obtained using this procedure were $c_1 = 10.6$ GPa and $c_2 = -0.40$.

The test procedure consisted of assembling the testing pair (one flat lapped and one bead-blasted sample) inside the vacuum chamber. The chamber was closed, and a vacuum was drawn using a mechanical pump connected in series with a diffusion punp. The vacuum inside the chamber was 10^{-6} torr. The electrical heater was turned "on," and the system was left for at least 16 h to achieve steady state. The thermal contact conductance was computed by means of the following expression:

$$h_c = q/\Delta T \tag{6}$$

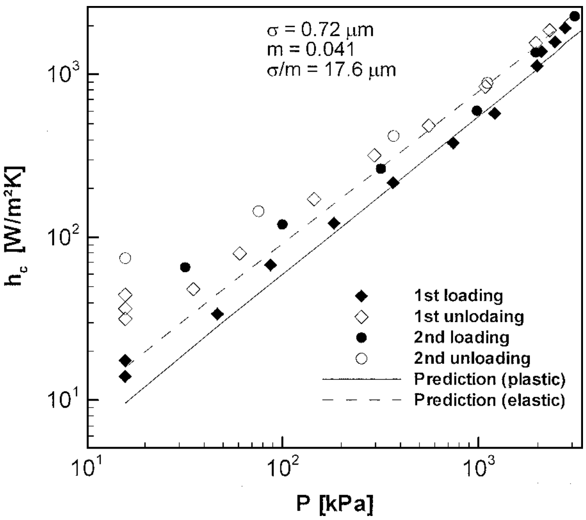
where q is the average of the heat fluxes of the two contacting specimens. The temperature drop ΔT is computed by extrapolating the temperature profiles of each contacting specimen to the interface. For comparison between the experiment and theory, the thermal conductivity of SS 304 [k_s appearing in Eqs. (1) and (3)] is evaluated at the mean temperature of the contact, which is the average of the two extrapolated temperatures.

This procedure was repeated for each contact pressure level tested. The pressure levels varied from 15.8 to approximately 3000 kPa in both ascending and descending levels. Two loading/unloading cycles were measured for each pair. The system was considered to be in steady state when the thermal contact conductance between the specimens did not vary more than 1% in 1 h. As the contact pressure was increased between each pressure step, the power level of the electrical heater was increased to maintain a reasonable temperature drop (8–40°C) between the samples. The mean temperature of the interface ranged from 15 to 60°C.

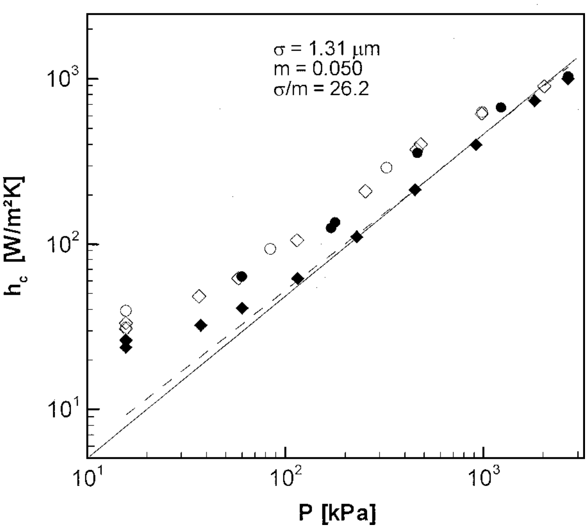
For light contact pressures, the uncertainty of heat flux measurement is ±5%, and the uncertainty of the temperature drop across the interface is ±1%. When the methodology of error propagation[9] is used, the uncertainty of the thermal contact conductance measurements is ±5% for the lightest contact pressure. For the highest contact pressure, the uncertainties of the heat flux and of the temperature drop were both ±2%, and the thermal contact conductance uncertainty is also ±5%.

Experimental Results and Comparison with Theory

Figure 1a shows the results for the smoothest of the two pairs tested, $\sigma = 0.72$ μm. It can be clearly seen that the hysteresis loop appears during both the first and second loading/unloading cycles.



a)



b)

Fig. 1 SS 304 bead-blasted/lapped contact conductance results.

The maximum difference between loading and unloading is 100% for the first cycle and 75% for the second cycle. Therefore, during both first and second loading/unloading cycles the asperities undergo plastic deformation. The comparison between the experimental results and the plastic model [Eq. (1)] for the first loading is reasonably good, especially for large contact pressures. At the lightest contact pressure, the plastic model underpredicts the first loading data by approximately 40%. The elastic model [Eq. (3)] predicts larger values of thermal contact conductance than the plastic model and is in fairly good agreement with the first unloading and the second loading/unloading cycle for high contact pressures despite that the asperities had already been plastically deformed during the first loading.

The results for the roughest test pair, $\sigma = 1.31$ μm, and the comparison against both the elastic and the plastic models are shown in Fig. 1b. The hysteresis loop is evident during the first loading/unloading cycle but not during the second cycle. The second loading/unloading cycle data points lie approximately over the same curve as the first unloading. These observations lead to the conclusion that the deformation is plastic during the first loading and elastic during the subsequent unloading/loading/unloading cycles. The plastic model predicts the first loading data very well for high contact pressures, similar to the smoother pair. For light contact pressures, the plastic model underpredicts the experimental data by a maximum difference of 70% for the lightest contact pressure.

The elastic and the plastic models predict similar values of contact conductance for this pair, and the elastic model predicts the first loading very well, especially at high contact pressures. However, the appearance of the hysteresis loop clearly shows that the deformation is plastic during the first loading. If one simply compares first loading data with the elastic model, the good agreement could suggest that the deformation of the asperities is elastic, which is not true. On the other hand, when a complete loading/unloading cycle is measured, it is easy to verify that the deformation mode of the contacting asperities is plastic in this case. The data points for first unloading and second loading/unloading cycle lie well above the models, as expected, due to the plastic deformation experienced by the asperities during first loading.

The plastic model presents the same behavior when compared with both test pairs: For the first loading, it underpredicts the experimental data at light loads, but as the pressure increases, the theoretical prediction gets closer to the measured values. This observation is in agreement with the experimental data compiled by Sridhar and Yovanovich.[1] Because this phenomenon has been consistently detected by different researchers employing different setups, it does not seem to be a weakness of the experimental program adopted here. The present authors believe that this is a weakness of the theoretical models. The theoretical models assume a Gaussian asperity height distribution, but the authors believe that the highest asperities of the real surfaces are truncated. At light contact pressures, only the higher asperities come into contact, and the truncation of the highest asperities makes the mean separation between the contacting surfaces smaller than predicted by the Gaussian model. Because the actual separation is smaller than predicted, the actual thermal contact conductance is higher than predicted by the Gaussian model, especially at light contact pressures. As the contact pressure increases, more and more asperities come into contact, and the effect of the few truncated asperities becomes negligible. A new thermal contact conductance model that takes the effect of the truncation of the contacting asperities into account is needed.

Conclusions

The appearance of the hysteresis loop indicated that the contact between bead-blasted/lapped SS 304 is plastic during the first loading/unloading cycle for both roughness levels tested, 0.72 and 1.31 μm. The plastic model of Cooper et al.[2] predicted first loading data points very well for high contact pressures. For light contact pressures, the model underpredicts the experiments. Other researchers employing different experimental setups have systematically noticed this unexpected behavior, indicating that this is a weakness of the theoretical models. The present authors believe that the models underpredict the experiments at light loads due to the truncation of the highest asperities; the highest asperities are shorter than predicted by the models. A new model is needed for the light contact pressure range.

Acknowledgments

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Cooling Fin Design

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Nomenclature

A	=	area of the fin cross section, m^2
b	=	q/kT_a, m^{-1}
h	=	heat transfer coefficient, W/Km^2
L	=	fin length, m
k	=	thermal conductivity, W/Km
m	=	fin parameter, m^{-1}
P	=	perimeter of the fin cross section, m
q	=	heat flux at the fin root, W/m^2
T	=	fin temperature, K
T_a	=	ambient temperature, K
T_L	=	tip temperature, K
T_0	=	temperature at the fin root, K
x	=	dimensionless position along the fin
z	=	position along the fin, m
θ	=	dimensionless temperature, $(T - T_a)/T_a$
θ_L	=	dimensionless temperature at the tip, $(T_L - T_a)/T_a$
θ_0	=	dimensionless temperature at the fin root, $(T_0 - T_a)/T_a$

Introduction

RECENT advances in high-performance designs for everything from electronic components at the submicron scale to equipment used in aircraft and space vehicles have increased the need for enhanced heat transfer devices. The design and analysis of fin structures for extended surface heat transfer are at the forefront of this technology. Although the basics of the heat conduction process in straight fins are extensively discussed in standard heat transfer textbooks,[1] the design of specific applications often requires a more detailed analysis leading to a broad range of surface types and operating conditions.[2]

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