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Measurements of interfacial thermal contact conductance between pressed alloys at low temperatures

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ABSTRACT

Interfacial thermal contact conductance is the primary factor limiting the heat transfer in many cryogenic engineering applications. This paper presents an experimental apparatus to measure interfacial thermal contact conductance between pressed alloys in a vacuum environment at low temperatures. The measurements of thermal contact conductance between pressed alloys are conducted by using the developed apparatus. The results show that the contact conductance increases with the decrease of surface roughness, the increase of interface temperature and contact pressure. The temperature dependence of thermal conductivity and mechanical properties is analyzed to explain the results. Thermal contact conductance of a pair of stainless steel specimens is obtained in the interface temperature range of 135–245 K and in the contact pressure range of 1–9 MPa. The results are regressed as a power function of temperature and load. Thermal conductance is also obtained between aluminums as well as between stainless steel and aluminum. The load exponents of the regressed relations for different contacts are compared. Existing theoretical models (the Cooper-Mikic-Yovanovich plastic model, the Mikic elastic model and the improved Kimura model) are reviewed and compared with the experimental results. The Cooper-Mikic-Yovanovich model predictions are found to be in good agreement with experimental results, especially with measurements between aluminums.

1. Introduction

Contact heat transfer is important in many cryogenic engineering applications such as superconducting magnet, plate-fin heat exchangers and spacecraft electronic components. In these cases, thermal contact conductance is sometimes the primary factor limiting the heat transfer along conduction paths. The thermal designs about these cases require experimental and theoretical investigations of the thermal contact conductance. Engineering surfaces of solid materials are not perfectly smooth due to consisting of microscopic asperities. When heat flows across contact surfaces, the real solid-solid contact area takes a very small fraction of the nominal contact area and most of the heat flows through the actual contact spots. Therefore, additional resistances are produced on account of the constrictions of the heat flux lines across the contact surfaces. This affects the thermal contact conductance of the contact interface. Overall, Thermal contact conductance can be used to characterize heat transfer across interfaces in contact.

As early researchers, Thomas and Probert [1] measured the thermal contact conductance of stainless steel (SS) contacts at 90–300 K, as well as SS/aluminum (Al) contacts at 150–300 K. They gave a semi-quantitative explanation for the directional effect on the contact conductance. Maddren and Marschall [2] measured the contact conductance of several metals near room temperature and at cryogenic temperatures (110–144 K). They found the SS data were in good agreement with the elastic contact model and the Al data do not agree well with either the elastic or the plastic contact model. And the beryllium results in their measurements indicated that the contact conductance may not always be directly proportional to the bulk thermal conductivity. Up to 1999, Gmelin et al. [3] reviewed the experimental results of the thermal contact conductance at sub-ambient temperature. They also presented new data in 4–300 K for SS/SS contacts and concluded that the steady-state experiments (similar to American National Standard ASTM D5470-12 [4]) had a smaller degree of error than the transient experiments. They hinted a few problematic points in steady-state experiments. For example, in temperature gradient measurements, errors would be small if the sample length is approximately twice its diameter and the temperature measuring points are not too close to the contact interface. Kumar and

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Nomenclature

A	area (m^2); fitted coefficient
a	mean radius of contact spot (m)
B	roughness exponent
C	temperature exponent
C_1	micro hardness coefficient (GPa)
C_2	dimensionless micro hardness coefficient
D	load exponent
d	locations of the thermal couples (m)
E	Young's modulus (Pa)
E'	effective Young's modulus (Pa)
H	hardness (Pa)
h	thermal contact conductance ($W/m^2/K$)
k	thermal conductivity (W/m/K)
k_s	harmonic mean thermal conductivity (W/m/K)
l	length of specimen (m)
m	mean absolute slope of surface
n	contact spot density (m^{-2})
P	contact pressure (Pa)
Q'	heat loss (W)
q	heat flux (W/m^2)
s	number of thermocouples in a specimen
T	temperature (K)
ΔT	temperature drop (K)
δT	temperature difference (K)
u	thermocouple separation (m)

Greek symbols

η	distance of interface from d_0
λ	dimensionless mean plane separation (m)
v	Possion's ratio
σ	root mean square roughness (m)
Φ	$\Phi = \Phi(\varphi)$
φ	plasticity index
ψ	constriction alleviation factor
ω	experimental uncertainty

Subscripts

a	apparent
avg	average
B	Brinell (bulk hardness)
e	elastic (hardness)
i	surfaces; specimens; thermal couples
k	(uncertainty of) thermal conductivity
l	(uncertainty of) length
m	micro (hardness)
Q'	(uncertainty of) heat loss
q	(uncertainty of) heat flux
r	real
T	(uncertainty of) temperature
0	centroid
1, 2	surface 1, 2; specimen 1, 2

Abbreviations

Al	aluminum
CMY	Cooper, Mikic and Yovanovich
SS	stainless steel

Ramamurthi [5,6] investigated thermal contact conductance between Al and SS joints at 50–300 K in the contact pressure range 0.01–0.7 MPa. They used Monte-Carlo simulation to explain their data satisfactorily. The simulation based on the Gaussian distribution of asperity heights in the rough surface and considered both elastic and plastic deformation under load. Xiao et al. [7] measured the thermal contact conductance of SS/SS sets, SS/Al sets and Al/Al sets at 100–330 K. Their results were mainly smaller than other researchers' and were not explained with theoretical model. Xu et al. [8] studied thermal contact conductance of pressed SS at 125–210 K. The results were explained by a new theoretical model, which based on the Kimura's asperity distribution estimation. Wahid et al. [9] did a very similar derivation in their paper. According to the model, the deformations of the specimens are fully plastic for all experimental conditions involved in their measurements. It was noted that the theoretical predictions of the model were overestimated, especially under large contact pressures. Xu et al. [10] later carried measurements with SS/Al and found fractal model predicted well the measured values at low contact pressures. Shi and Wang [11] presented a photo thermal experimental apparatus to measure the thermal contact conductance between copper and stainless steel. The authors considered that the apparatus was suitable for measuring thermal contact conductance at low temperatures. With the similar apparatus, Bi et al. [12] measured the contact conductance of SS/SS and SS/copper in the temperature range of 20–290 K and in the contact pressure range of 0.2–0.7 MPa. Choi and Kim [13] designed a thermal contact conductance measurement system using a cryocooler as the heat sink instead of cryogen. At the same contact conditions, two same pairs of specimens were measured simultaneously to improve the accuracy in the experiments. The authors found the Cu/Cu contact conductance increased significantly small as the contact pressure changed from 14 MPa to 21 MPa. In general, the experimental investigations of thermal contact conductance between pressed alloys in the temperature range from liquid nitrogen to room temperature are limited. Moreover, some data from various researchers are obviously different for the similar contact sets.

Existing theoretical investigations of thermal contact conductance are based on elastic mechanics and plastic mechanics. When two real surfaces are placed in contact, direct contacts between solid spots occur only at discrete parts of the interfaces. The deformation of each contact spot will be assumed for predicting the real contact surface. There are two macroscopic material deformation mechanics: plastic and elastic. Corresponding to the deformation mechanics, two types of contact conductance models are proposed by researchers. Despite a number of theoretical models are available in the literature, there is still a lake of a satisfied analytical model to explain the experimental results over the temperatures range from liquid nitrogen to room temperature. As the earliest plastic model, the Cooper-Mikic-Yovanovich (CMY) model [14] is well-established and has been shown to yield reasonable predictions at room temperature. The model assumes that the surface asperity heights take Gaussian distribution and the contact spots have plastic deformation under pressure. The CMY model predictions had been compared to the measurements at low temperatures by Maddren and Marschall [2]. Mikic [15] proposed an elastic model, assuming all the micro contact spots had pure elastic deformation. Some comparisons in room temperature shows the Mikic model is more applicable for hard materials than for soft materials. The Mikic model has not been applied to explain the experimental results at low temperatures yet. Zheng et al. [16] introduced an improved thermal contact conductance model based