Plastic Set of Smooth Large Radii of Curvature Thermal Conductance Specimens at Light Loads

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Theme

SMOOTH metal surfaces joined together (e.g., by rivets, bolts, etc.) are commonly encountered in spacecraft. To predict the heat-transfer rates for high-vacuum conditions across such surfaces, the macroscopic elastic deformation theories of A. M. Clausing and B. T. Chao[1] and B. B. Mikic and W. M. Rohsenow[2] are often used. This paper presents thermal contact conductance test data obtained from two 1-in.-diam Armco iron cylindrical specimens having smooth, convex, one-half wave length contacting surfaces with large radii of curvature. The conductance data were gathered during two loading and unloading sequences of each specimen in the light to moderate pressure range of 0.45×10^6 to 3.5×10^6 N/m^2 at a constant interface temperature (369°K) under high vacuum conditions (1.2×10^{-7} torr). The test results obtained during the first loading of each specimen are compared with the theories of Clausing and Chao, Mikic and Rohsenow, and also an empirical expression proposed by L. S. Fletcher and D. A. Gyorog.[3]

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Experimental cyclic test data are presented for two Armco iron cylindrical specimens having smooth, convex, spherical, one-half wave length contacting surfaces which show the variation of the coefficient of thermal contact conductance with apparent joint contact pressure in the light to moderate range. The conductance tests were performed by varying the interface contact pressures of the specimens in a monotonic increasing then decreasing manner through two complete cycles from approximately 4.5×10^5 to 3.5×10^6 N/m^2 (65–500 psi) while maintaining their mean interface temperatures nearly constant at approximately 367°K. The test specimens were exposed to steady-state test conditions for periods ranging from 50 to 180 hr between each point while monitoring the variation of the conductance with time. Results from this procedure indicated a minimum of 50 hr was required to reach a stable condition between pressure changes. The surface texture quantities were determined by using a Brush surfanalyzer 1200 system.

The test data are compared with the theoretical predictions of Clausing and Chao[1] and Mikic and Rohsenow.[2] In addition, the data are compared with the empirical solution of Fletcher and Gyorog.[3] The calculations were made using the solutions taken from Refs. 1–3 which are presented in Table 1.

In Table 1, b = radius of cylindrical specimen; $f(x_L)$ = function representing the effect of neighboring contact points on the flow of heat through a point contact; h = coefficient of thermal contact conductance; k = harmonic mean of the coefficient of thermal conductivity; L_s = one-half the spherical surface wave length; P = apparent contact pressure; T_m = temperature at interface of contact; x_L = the constriction ratio; β = coefficient of thermal expansion; δ_0 = effective surface parameter representing the gap between the contacting surfaces at no load; ε^2 = ratio of real to apparent contact area; λ_{eff} = effective diameter of the contour area; $\phi(\varepsilon)$, $\phi(\lambda_{\text{eff}})$ = functions which represent approximate finite series solutions of the temperature field at the contact plane; and the subscript m = mean.

Table 1 Calculations using solutions from Refs. 1–3

Reference	Equation
1	$hb/k = 2x_L/\pi f(x_L)$
2	$h = \dfrac{1}{\dfrac{8\phi(\varepsilon)}{k\varepsilon\sqrt{\pi n}} + \dfrac{4\phi(\lambda_{\text{eff}})L_s}{k\lambda_{\text{eff}}}}$
3	$h = \dfrac{k_m e^{170(P\beta T_m b)/(E\delta_0)}}{\delta_0}\left[5.22 \times 10^{-6}\dfrac{\delta_0}{b} + 0.036\dfrac{P\beta T_m}{E}\right]^{0.56}$

Figure 1 presents the experimental test data obtained from specimen 1. Its mean interface temperature was kept constant during the test at 369°K with one exception noted at the end of the first loading where it was raised at constant pressure (350 N/m^2) to 477°K. The interface remained at this temperature for 50 hr. Then while maintaining constant pressure it was lowered to 369°K and the pressure cycling was continued. The data obtained for the first loading followed the generally recognized trend exhibited when macroscopic elastic deformation of contacting surfaces takes place. All data following the first loading fell on a single curve having a slope slightly greater than one which is characteristic after moderate loading pressures have been applied.[4] For the smallest apparent contact pressures, the measured thermal conductances were consistently

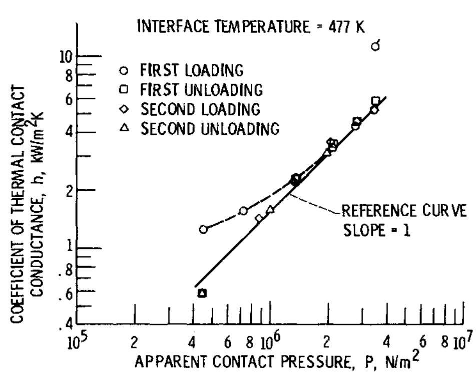

Fig. 1 Coefficient of thermal contact conductance vs apparent contact pressure for Armco Iron specimen 1. Interface temperature = 369°K.

Presented as Paper 72-20 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted June 22, 1972; synoptic received August 23, 1972; revision received October 19, 1972. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $1.00; hard copy, $5.00. **Order must be accompanied by remittance.**
Index categories: Heat Conduction; Thermal Surface Properties.

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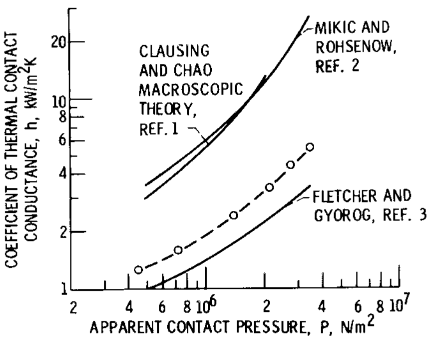

Fig. 2 Coefficient of thermal contact conductance vs apparent contact pressure for Armco Iron specimen 1, based on surface statistics obtained *before* the test was run. Interface temperature = 369°K.

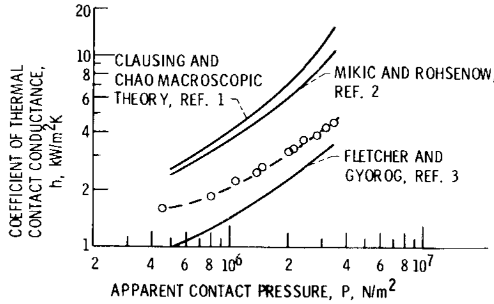

Fig. 3 The coefficient of thermal contact conductance vs apparent contact pressure for Armco Iron specimen 2, based on surface statistics obtained *before* the test was run. Interface temperature = 369°K.

lower than those obtained initially. Therefore, it may be surmised that the specimen took a permanent set after the initial loading.

The results from specimen 2 obtained under almost identical experimental conditions appear in Ref. 5 and will only be discussed here. Unlike specimen 1, specimen 2 was not exposed to a temperature excursion. The data of specimen 2 follow the accepted trend for elastic deformation. However, closer examination at the lowest loading pressure shows a consistent and reproducible decrease in the conductance perhaps indicating an increasing permanent set.

The contacting surfaces of each specimen were examined before and after each test with a Brush surfanalyzer. Both specimens deformed plastically with the attendant changes in the coefficient of thermal contact conductance noted in the test data. The interface temperature excursion apparently caused specimen 1 to deform more than specimen 2.

Figures 2 and 3 show the curves determined by applying the theories of Refs. 1 and 2 and the empirical expression of Ref. 3 to the test data obtained during the first loading of specimens 1 and 2, respectively. The calculations were made using the surface statistics obtained before the tests were conducted. The coefficients determined from both theories are approximately 3 and 1.5 factors larger than the test data obtained from specimens 1 and 2, respectively. The values determined from the empirical expression are approximately 35% lower than the test data obtained from the specimens. The disagreement between specimens 1 and 2 test results and the theories of Refs. 1 and 2 are similar to several cases discussed in Ref. 1.

As an explanation for the disagreement, Clausing and Chao suggest that visible oxide films were inhibiting the flow of heat across their specimens' contacting surfaces. No such oxide films were visible on the Armco iron specimens tested here, however. A discussion by Mikic and Rohsenow in Ref. 2 may serve as a second explanation for the large difference between theory and experiment noted here and in Ref. 1. Mikic and Rohsenow mention that their solution might have serious limitations on the accurate prediction of the conductance dependent on the degree of nonuniformity of the distribution of the contact spots over the apparent contact area. They conclude that if the distribution of the contact spots were nonuniform it would have the same effect on the conductance as an equivalent type of waviness. Like Ref. 2, it is assumed in Ref. 1 that microscopic contacts are distributed uniformly over the contacting surfaces. The surface statistics obtained from specimens 1 and 2, show that each contact surface had a small number of very tall asperities. As a result, it is probable that their distribution was not uniform over the contact surface, particularly at light loads. Thus as discussed by Mikic and Rohsenow and demonstrated by the test data of Clausing and Chao and the tests conducted here, the assumption that the contact spots are uniformly distributed over the contacting surfaces, made in both Refs. 1 and 2, may be too restrictive for smooth, convex, large radii of curvature surfaces.

In summary, the tests data showed major disagreement with calculations based on the theories of Clausing and Chao and Mikic and Rohsenow and fair agreement with the empirical expression of Fletcher and Gyorog. These calculations were made by using the specimens' surface statistics obtained before the tests were made. Plastic deformation of all the contacting surfaces was verified from a comparison of surface analyzer statistics obtained before and after the tests were made. Test results support the conclusions that a) the assumption of macroscopic elastic deformation made in both theories is inadequate for an accurate theoretical prediction of the variation of the thermal contact conductance with apparent contact pressure for the type of specimens which are described herein; b) a principle assumption in both theories specifying the distribution of the microscopic contact spots to be uniform over the contacting surfaces may be too restrictive for smooth, convex, large radii of curvature specimens; and c) the empirical expression of Fletcher and Gyorog correlates the test data to within 35% when the surface statistics obtained from both specimens before the test are used.

References

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