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Technical Note

Thermal contact conductance: effect of overloading and load cycling

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Abstract

An experimental investigation is carried out to study the effects on joint conductance of progressive loading and unloading, cyclic loading and overloading to a predetermined value. The test pair used is AISI 304 stainless steel, bead blasted to an effective rms surface roughness of 7.55 μm and a slope of 0.36 rad. In all cases a hysteresis loop is seen to exist for the loading unloading cycle and is seen to decrease with increasing number of cycles. The conductance values eventually appear to settle down to values higher than those obtained during first loading. Enhancement of contact conductance by cyclic loading is found to be rather small. On the other hand overloading the test pairs to a predetermined contact pressure is found to be promising.

Keywords: Contact conductance; Load cycle; Overloading

1. Introduction

Engineering surfaces are never absolutely smooth and surface irregularities are apparent when observed under a microscope. As a result, when two solids are pressed together, contact is made only at a few discrete spots separated by relatively large gaps. Therefore, the heat flow through a joint in a vacuum environment and in the absence of radiation would be through the contact spots. The temperature difference, which occurs at the interface of the two solids as a result of the resistance to heat flux, is used as a basis for defining thermal conductance. The thermal conductance is defined as

$$h = \frac{Q/A}{\Delta T} \tag{1}$$

where h is the total joint conductance, Q is the total heat transfer across the interface and A is the apparent area and ΔT is the temperature drop.

Ways of increasing thermal conductance have been sought for situations where maximum heat dissipation is required. Heat transfer through a joint in vacuum generally depends on surface roughness and slope, surface flatness, thermal conductivity, contact pressure at the interface and hardness of the softer material in contact. Common approaches for improving thermal conductance at the interface involve loading/overloading of test materials, insertion of suitable interfacial material at the interface, a suitable coating at the interface, filling the voids at the interface with a high conductivity gas.

The present work aims to analyse enhancement of joint conductance by loading/overloading of the test materials and a brief review of work carried out by the past investigators in this important area of thermal management is given below.

Mikic [1] conducted a theoretical analysis. His analysis assumed that the contact asperities undergo plastic deformation in the initial loading process and elastic deformation in the unloading process. Thus the contact

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Nomenclature

A	apparent area	Rq	effective rms surface roughness, $\sqrt{(Rq_1^2 + Rq_2^2)}$
h	thermal conductance across the interface	T	interfacial temperature
Q	total heat transfer across the interface		

mechanism is different for loading process than that of the corresponding unloading process. Therefore the actual contact area is larger for unloading process than initial loading process resulting a higher value of conductance during unloading.

Williamson and Majumdar [2] conducted experimental analysis to find out the effect of surface roughness on hysterises effect. Their test specimens were aluminium/stainless steel specimens. Both smooth surface (effective rms 0.54 μm) and rough surface (effective rms 8.72 μm) were used in the analysis. Their results indicated that hysterises effect is significant for rough surfaces suggesting that effective rms roughness is a dominant factor in evaluating hysteresis effect. This is in agreement with the experimental works of Pullen and Williamson [3], Madhusudana and Williams [4] and William and Idrus [5].

McWaid and Marshall [6] reported the existence of hysteresis effect and recommended subsequent unloading and reloading will yield a value of conductance, which would be higher than that which would be expected if the contact was not preloaded.

Li et al. [7] investigated the effect of loading history (i.e hysteresis effect, cyclic loading and overloading beyond the normal operating pressure) on contact conductance. The authors reported that in all cases significant enhancement of contact conductance was noticed with their test pairs of AISI 304 stainless steel having an effective rms roughness of 2.9 μm.

2. Test specimens

2.1. Surface preparation of test specimens

The test specimens of AISI 304 stainless steel were cut from cylindrical rods and machined to a size of 45 mm in length and 25 mm in diameter. The specimens were fine turned on both end faces. Each specimen has four holes of 1.6 mm diameter at 9 mm intervals. Each of the holes is 12.5 mm deep for locating thermocouples. All the contacting faces were than lapped in guard holders on a standard lapping machine using diamond paste. The specimens were polished to within 0.2 μm rms roughness. The test specimens were then divided into a number of groups; each group was covered with masking tape except the top part that would be grit blasted. The surfaces were blasted randomly from a nozzle at an angle of 90° to the top of the exposed surfaces from a distance of approximately 100 mm. A range of blasting pressures and materials were employed to get different surface topographies for the test specimens.

2.2. Analysis of test surface

Surface texture was quantified using Federal Surf Analyzer 5000 precision measuring instrument. A general-purpose diamond stylus of 10 μm radius was used for all the surface texture measurements of the test specimens. The system uses an IBM compatible, Hewlett-Packard Vectra computer with a VGA colour monitor, equipped with touch screen control and software, developed, for processing the data. It records the displacement of the stylus by acquiring the data in the form of electrical signals. The data is used to generate a surface profile that gives an overall view of the finish of the surface. The software also analyses the digitized data acquired to calculate various roughness parameters. It was ensured that all the test pieces were clean prior to the surface texture analysis. Acetone was used as a cleaning agent rather than ethyl sprit, which was used initially. This was because, it was found that in a few cases when the surface was cleaned with ethyl sprit, even after a long waiting period, signs of the solution on the test surface were still noticeable, This was not a problem with acetone. For each surface, typically around 3–7 traces were randomly selected.

3. Thermal contact conductance experiments

3.1. Procedure

The experiments were conducted in an axial heat flow cut bar apparatus described by Wahid et al. [8]. The experimental rig consists of a heater block, upper and lower specimens, the reference heat flux meter and the heat sink. A band type heater provides a maximum heat input of 250 W. The heat sink is a hollow copper cylinder. Cooling is accomplished by primary refrigerants circulating inside a coil absorbing heat from cooling water which in turn passes through the heat sink. The test column is enclosed inside a glass cylinder and sits on a stainless steel base plate. The top plate sits on the glass cylinder. Stainless steel bellows are used to facilitate vertical movement of the shaft. Load can be applied to the shaft by a lever and hanging weight arrangement. Two diaphragm type valves are provided in the rig. One could be connected to a mechanical pump for inducing vacuum and the other to facilitate gas introduction. Temperature measurements are made by 16 type T thermocouples.

The thermal conductivity of the AISI 304 stainless steel specimen was first obtained by comparing the heat flux through the specimens with that measured by the heat flux meters made of Austenitic Stainless Steel, SRM, supplied by National Institution of Standard Technology, USA. It was necessary to deduce the thermal conductivity of the specimen so that accurate prediction of heat flux can be achieved. The system was degassed for 24 h and the vacuum was maintained at 0.025 mbar. Heat flow obtained was the average heat flow across the reference materials. By varying the heat flow, the thermal conductivity was determined for known temperature differences and a correlation developed [8].

3.2. Uncertainty analysis

The maximum heat loss between the top and bottom heat flux meters during the test was 9%. Contact points of the thermocouples were ±0.5 mm of the nominal location, resulting an error of 6%. The convection heat loss was estimated to be less than 1%. According to the law of error propagation [9] total uncertainty in the measurement of thermal contact conductance is estimated to be 10.8%.

4. Results and discussion

The test specimen of AISI 304 stainless steel of effective rms roughness 7.55 μm, and a slope of 0.36 rad experienced a first loading in six steps to a maximum contact pressure of 6.4 MPa, followed by unloading of the loads in reverse order. The procedure was repeated for a second loading and unloading process. The results are plotted in Fig. 1. The existence of hysteresis effect is evident in the plot. The measured conductance is seen to be higher in the unloading process for a particular contact pressure than in the loading process. The largest difference of conductance is seen to have occurred at the end of the unloading process. At this pressure of 1.14 MPa, the conductance was 14.91% and 13.8% higher than the corresponding loading. The decrease in conductance in the second unloading process can be attributed to the fact that surface microasperities exhibit different behaviours during loading and unloading. Specifically, the deformation of the asperities is predominantly plastic on loading and predominantly elastic on unloading.

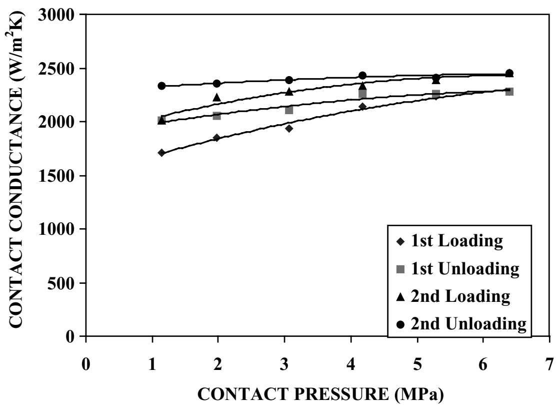

Fig. 1. Effect of loading and unloading on contact conductance.

Experiments were now conducted to investigate the load cycles on contact conductance. The test specimens were initially loaded to 6.4 MPa, and unloaded to the 0.865 MPa to a maximum of 40 load cycles and the plot is shown in Fig. 2. It can be seen that load cycles applied, does affect the contact conductance. Although the increase of the conductance is evident throughout the stated range, the main increase on conductance is seen to occur on the first 25 cycles, resulting an increase of 4.4%. At the end of 40 cycles an overall increase of 4.5% was achieved. The contact conductance pattern throughout the stated load cycles could be related to the deformation mode of the contact asperities. It is believed that at 25 load cycles asperities have completed their plastic deformation. At the next phase of load cycles due to elastic deformation it is seen that the conductance values have been stabilised.

As an extension of the experimental investigation, the specimens were overloaded beyond the initial maximum pressure of 6.4 MPa. Overloading were carried out

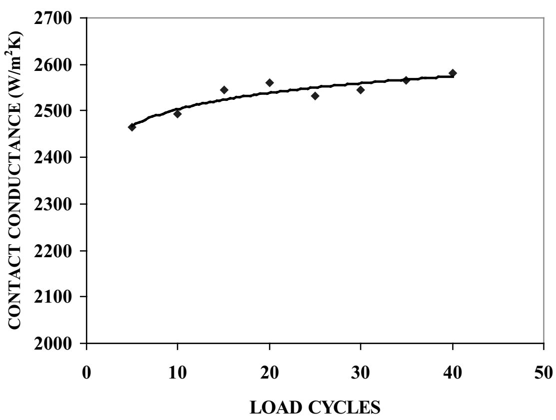

Fig. 2. Effect of load cycles on contact conductance.

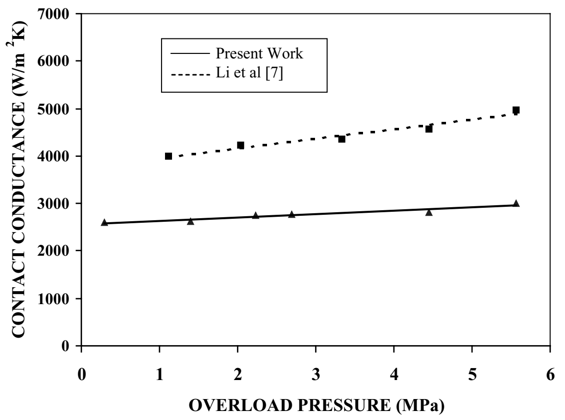

Fig. 3. Comparison of the results with that of previous worker.

Table 1
Surface parameters

	Effective surface roughness Rq (μm)	Slope (rad)
Present work	7.55	0.36
Li et al. [7]	2.9	0.47

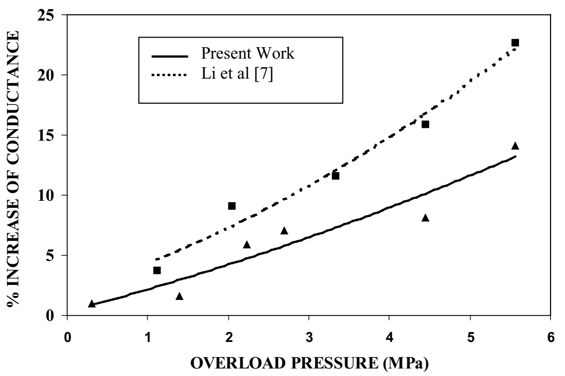

Fig. 4. Comparison of the percentage enhancements in conductance due to overloading with that of previous worker.

immediately after the first load cycling. The results are shown in Fig. 3. In this figure, the overloading pressure is defined as the difference between the actual applied pressure and the maximum initial pressure. Also plotted in Fig. 3 are the results of a previous work by Li et al. [7]. The surface parameters for the two sets of data are shown in Table 1.

The percentage enhancements in conductance are plotted against overloading pressure in Fig. 4. It is noted that the maximum enhancement obtained in the present work was about 14% whereas Li et al. [7] obtained an enhancement of about 23%. It is apparent that the degree of enhancement, for a given material, depends on the surface characteristics. In effect, the smoother pair has higher conductance and also exhibits higher rate of increase on overloading.

5. Conclusions and recommendations

1. It is demonstrated that enhancement of contact conductance can be achieved by repeatedly loading and unloading, stainless steel joints. Though each unloading process enhances conductance, it seems that the first unloading process yields highest increase in contact conductance (14.91%).
2. Considerable enhancement on contact conductance can be achieved by overloading process. For the present analysis an overloading of 5.56 MPa resulted an enhancement of contact conductance by as much as 14%.
3. Although cyclic loading does increase the thermal contact conductance, the effect is rather small. The experimental analysis also demonstrated that a maximum of 25 cyclic loading might be sufficient.

It is recommended that:

1. Further experimental investigation be conducted on loading/unloading and overloading processes, especially with other contact materials, such as copper and aluminium.
2. Effect of roughness on loading/unloading and overloading at different blasting process also needs to be addressed.
3. A comprehensive and convincing theory, to predict conductance on loading/unloading and overloading processes is yet to be developed.

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