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Experimental evaluation of the interface heat conductance between roughened beryllium and stainless steel surfaces

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Abstract

The interface heat conductance between non-conforming stainless steel and roughened beryllium disks of 1-inch diameter has been measured as a function of surface roughness, interstitial gas pressure, contact pressure and heat flux. Helium was used as the interstitial gas. Based on experimental findings, the interface conductance between non-conforming surfaces was found to be degraded by up to 32% relative to that between conforming surfaces due to the effects of differential thermal deformations. Whereas increasing the contact pressure was found to increase the interface conductance, increasing the surface roughness or decreasing the interstitial gas pressure was found to significantly decrease the interface conductance.

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1. Introduction

Solid to solid contact, in one form or another, is common in almost every engineering system. In most cases, the possibility that one of the solids may have different thermomechanical properties and hence different thermal performance relative to the other is of little or no consequence. However, in systems designed with high heat flux components such as nuclear power plants and, more recently, fusion systems, it is important that the thermal behavior of the solid–solid interface be precisely known. Beryllium has been proposed in a number of recent blanket designs as a neutron multiplier and/or thermal barrier region between the breeder and the coolant and, in one design, the beryllium is used as solid blocks within a steel cladding material [1]. Heat transfer between the beryllium and the steel cladding is dependent upon the interface conductance across the two surfaces, which is in turn dependent upon applied contact pressure, interstitial gas pressure and gas composition, heat flux, and a host of surface and material properties. In cases where both surfaces are composed of the same material or two different materials with similar thermomechanical properties, [2–4], the effect of thermal expansion has little or no effect on interface conductance since both surfaces deform in a similar manner. Hence the surfaces are said to be conforming in that contact is continually maintained between the two surfaces regardless of the degree of thermal deformation, Fig. 1a. In the case where the two surfaces are composed of materials with widely differing thermomechanical properties, beryllium and stainless steel for example, there exists the possibility that one surface will thermally deform to a greater extent than the other, resulting in gaps opening up within the interface, Fig. 1b. These surfaces are then said to be non-conforming [5,6]. Under high heat flux loads, small deformations could open up large enough gaps between the surfaces to significantly degrade heat transfer across the interface.

In the present work, interface conductance was measured between 1-inch diameter beryllium and stainless steel disks as a function of rms surface roughness, applied contact pressure, interstitial gas pressure, and applied heat flux. A 500 W heater with variable output was used to produce values of heat flux as high as 190 kW/m^2. The beryllium surfaces were either grit-blasted with Al$_2$O$_3$ powder or bead blasted with 25 μm glass beads to produce

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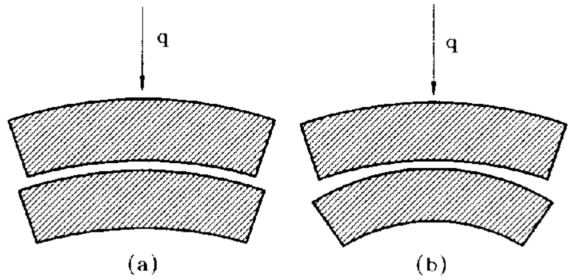

Fig. 1. Illustration of the types of thermal deformation: (a) conforming surfaces, (b) non-conforming surfaces.

microscopic surface roughnesses ranging from 0.56 to 2.46 μm based on profilometry measurements. Helium was used as the interstitial gas, and its pressure was varied between 1 atm and 14 kPa. A hydraulic ram was utilized to provide contact pressures ranging from 0 to 9 MPa.

Several models currently exist to predict the interface conductance between conforming surfaces, but none were found that would take differential thermal deformations into account. Therefore, a new model that would take into account the varying geometry of the non-conforming surface and the resulting changes in interface conductance was developed. A description of this non-conforming surfaces model, along with predictions of the experimental data presented in this paper, is presented in [6].

2. Experimental

Fig. 2 is an illustration of the test apparatus in which all measurements were made. A Pyrex bell jar was used to isolate the test article from the surrounding environment, allowing test runs to be conducted in helium gas at pressures as low as 14 kPa. Gas pressure measurements were made via a mercury-filled manometer. Loads as high as 9 MPa were applied to the test surfaces via a Carver 20-ton hydraulic press. A machined copper heating block, wound with heating wire, provided heat fluxes as high as 190 kW/m^2 and temperatures in excess of 200°C. The test specimens were arranged as illustrated in Fig. 2, with heat flowing from the heater block down through the beryllium disk, then through the steel disk, and finally to a heat sink. A water-cooled heat exchanger, wrapped around the lower heat flux meter, was utilized as the heat sink and control of the bottom-end temperature. The coolant temperature was 15°C.

The stainless steel, AISI 304, specimen was manufactured from 1-inch diameter stock, machined to 0.25 inch thickness, and then polished with a diamond paste. The microscopic surface roughness of the steel surface was 0.29 μm as measured by an Alphastep surface profilometer connected to a PC computer. However, during the course of taking experimental measurements, there was an onset of some degree of permanent macroscopic thermal

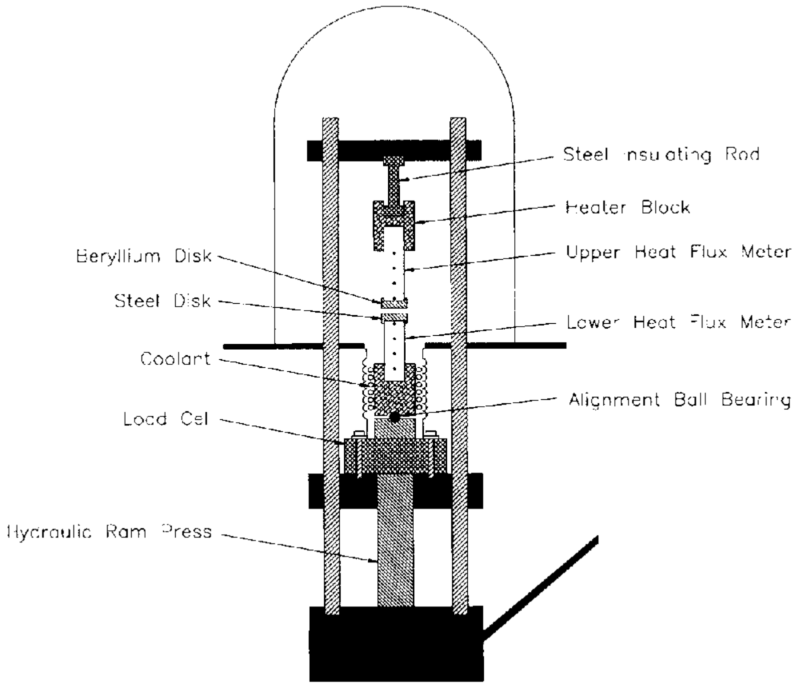

Fig. 2. Test apparatus used in the interface conductance experiments.

deformation. Though the microscopic surface roughness remained unaffected, the steel surface became bowed, increasing the effective surface roughness to 3.51 μm [6]. The three beryllium specimens, numbered Be#1, Be#6 and Be#7, were first polished flat, and then either sand blasted with Al_2O_3 grit or bead blasted with 25 μm glass beads. The microscopic surface roughnesses of these three beryllium surfaces were measured to be 0.56, 1.31 and 2.46 μm, respectively. Only the smoothest beryllium specimen, Be#1, experienced any measurable degree of permanent thermal deformation, increasing its effective surface roughness to 1.06 μm.

The interface heat conductance measurements could not be made directly, and had to be computed from those quantities which were directly measurable, namely temperature and length. Six K-type thermocouples were placed along the axial length of the test article at precisely measured spacings. Two copper heat flux meters, one placed above the Be/steel interface and the other placed below, allowed for the computation of the average heat flux passing across the test interface. Thermocouples positioned inside the beryllium and steel specimens allowed for the computation of the respective interfacial-surface temperatures. Knowing the average heat flux and temperature difference across the Be/steel interface, Fourier's law was used to compute the interface heat conductance of the system.

3. Results

Two different sets of experiments were performed which were designed to measure the dependence of the interface conductance of the Be/steel pair on various environmental parameters. The first set of experiments was designed to measure how the interface heat conductance varied as a function of the applied contact pressure for a given gas pressure and heat flux. The second set of runs measured interface conductance as a function of applied heat flux for a given gas pressure and set of contact pressures. All measurements were made using helium as the interstitial gas.

3.1. Interface conductance vs. contact pressure, Be#1/SS304 and Be#6/SS304

The experimental results for the Be#1 system, under a constant heat flux of 118 kW/m^2, are presented in Fig. 3. From the figure, it is observed that the interface conductance, h, is a function of the magnitude of both the applied contact pressure and the interstitial gas pressure. Increasing the contact pressure of the system was found to increase the interface conductance by an amount dependent upon the magnitude of the interstitial gas pressure. For example, in 1 atm of helium gas, the Be#1 system experienced an increase in h of 5500 W/m^2 K over the 0 to 6 MPa range of contact pressures. In 13 kPa of helium, over the same contact pressure range, the Be#1 system experienced an increase in h of only 2500 W/m^2 K. Thus, by increasing the gas pressure from 13 kPa to 1 atm, not only did the absolute value of h increase for a given value of contact pressure, but so did its sensitivity to changes in contact pressure. When the interstitial gas pressure was varied for a given contact pressure, the interface conductance of the Be#1 system was changed by an amount dependent upon the current magnitude of the contact pressure. For example, at a fixed value of zero contact pressure, the measured value of h was found to increase from 3750 to 9500 W/m^2 K, a change of 5750 W/m^2 K, when the gas pressure was increased from 13 kPa to 1 atm. When the contact pressure was increased to 6 MPa, the magnitude of h increased from 6250 to 15000 W/m^2 K, for a change of 8750 W/m^2 K, over the same increase in gas pressure. Thus, by increasing the contact pressure acting on the interface, both the absolute value of h and the sensitivity of h to changes in gas pressure were increased.

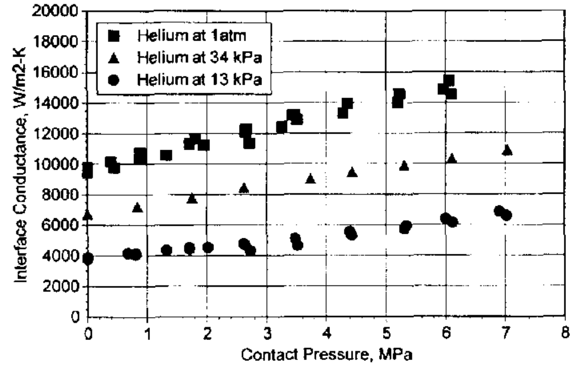

Fig. 3. Interface conductance vs. contact pressure for the Be#1/SS304 system.

Experimental results for the rougher Be#6/SS304 system are presented in Fig. 4, along with the previous Be#1/SS304 results for comparison. It will be observed

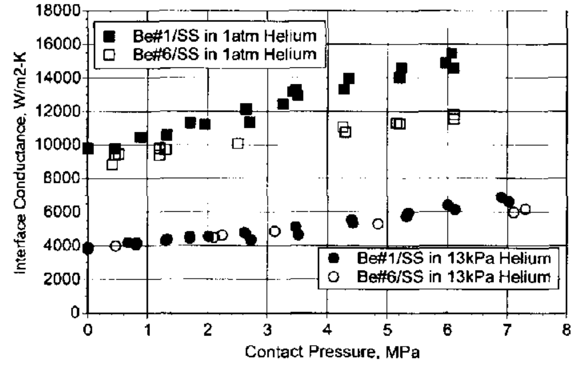

Fig. 4. Interface conductance vs. contact pressure for the Be#1/SS304 and Be#6/SS304 systems.

from the figure that, for measurements made in 1 atm of helium, the rougher specimen has consistently lower values of h relative to the smoother specimen for any given value of contact pressure. Furthermore, the rougher Be#6 specimen is observed to be less sensitive to changes in contact pressure relative to the smoother Be#1 specimen pair. For example, in 1 atm of helium and over the contact pressure range of 0.5 to 6 MPa, the rougher Be#6 system is seen to experience an increase in h of 2500 W/m^2 K, or 28%. This may be compared with a 5500 W/m^2 K, or 58%, increase in h for the smoother Be#1 system. For measurements made in 13 kPa of helium, the rougher specimen is observed to possess nearly identical values of interface conductance as the smoother specimen for contact pressures less than 4 MPa. Above 4 MPa contact pressure, the smoother specimen is seen to experience a slightly higher value of interface conductance relative to the rougher Be#6 specimen, with a maximum difference of 12.5% at a contact pressure of 7 MPa.

It is surmised that the dependence of the interface conductance upon the magnitude of the contact pressure is twofold: first, applying contact pressure to the interface forces the softer stainless steel surface to elastically and plastically deform against the harder and rougher beryllium surface. This decreases the mean separation distance between the two surfaces which results in decreased interface resistance. Second, due to the large difference in thermomechanical properties between stainless steel and beryllium, the steel specimen will thermally deform to a different degree than the beryllium specimen. This can result in large gaps within the interface which would increase the resistance to heat flow between the two surfaces. Application of an external load pushes the two surfaces flat against each other, decreasing the mean separation distance between the two specimens, and hence increasing the net value of h across the interface.

It is postulated that the strong dependence of interface conductance upon the interstitial gas pressure is due to the dominant role of heat transfer across pockets and layers of interstitial gas, rather than through the points of solid–solid contact between the beryllium and steel surfaces. Consider that, due to the roughened nature of the test specimens, numerous cavities will exist within the interface which will trap the helium test gas. Additionally, as the beryllium and steel surfaces are heated, non-conforming thermal deformations will open up large gaps within the interface, resulting in large areas where the only mechanism for heat transfer will be conduction across gas layers. It is surmised that the majority of the surface areas of the two test surfaces will not be in contact with each other, and that, at atmospheric gas pressures, heat conduction across those relatively few points of solid–solid contact will be negligible relative to the heat conduction across the numerous gas-filled layers and cavities. The only time when heat conduction across the points of solid–solid contact would dominate would be in near vacuum conditions, when the gas conductance contribution would be reduced to near zero levels.

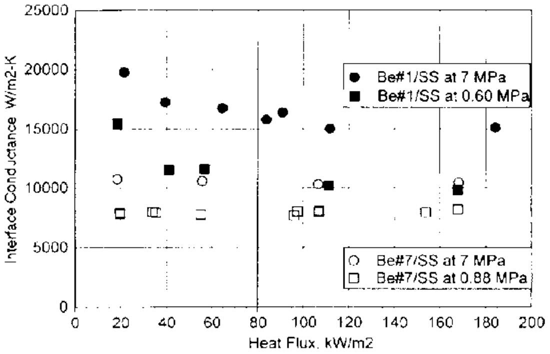

Fig. 5. Interface conductance vs. heat flux for the Be#1/SS304 and Be#7/SS304 systems.

3.2. Interface conductance vs. heat flux, Be#1/SS and Be#7/SS

Interface heat conductance was measured as a function of applied heat flux for a given set of contact pressures. Fig. 5 presents the experimental results for both the Be#1 and Be#7 systems. It will be recognized from the figure that, for surfaces of sufficient roughness, there appears to be virtual independence of h to the magnitude of the applied heat flux. For surfaces smoother than this critical roughness, i.e. the Be#1/steel specimen pair, there is maximized heat conductance at low values of heat flux and a steady decrease in the magnitude of h with increasing values of heat flux until a limiting value is reached. At this point, further increases in heat flux had little or no effect on the interface conductance. For the Be#1 system under a 7 MPa external load, the maximum measured interface conductance was found to be 19 800 W/m^2 K at the lowest measured heat flux setting of 21 kW/m^2. At a heat flux of 110 kW/m^2, the measured value of h reached a minimum value of 15 000 W/m^2 K, whereupon it became insensitive to further increases in heat flux. For the Be#1 system under a 0.60 MPa external load, the maximum value of h was 15 500 W/m^2 K at a heat flux of 20 kW/m^2. While the limiting, or minimum, value of h was not observed over the heat flux interval of 20 to 190 kW/m^2, the general trend of the data suggests that this limiting point would exist at a heat flux of approximately 200 kW/m^2, with a minimum interface conductance value of 9500 W/m^2 K.

For the Be#7 system, there appeared to be near independence of the interface conductance with respect to the magnitude of the applied heat flux, regardless of the amount of contact pressure applied. For the case of the Be#7 system under at 7 MPa external load, the measured value of h was 10 700 W/m^2 K at a contact pressure of 18.5 kW/m^2. This value of h varied by less than 5% over the 18.5 to 170 kW/m^2 range of explored heat fluxes, and is well within the range of uncertainty associated with the interface conductance measurements. For data taken under a contact pressure of 0.88 MPa, the measured value of h was 7800 W/m^2 K at 20 kW/m^2, and varied less than 3% over the entire range of explored heat fluxes.

It is postulated that the reason why there is near independence of h with respect to the magnitude of the heat flux for the Be#7/SS304 system is the following: due to the roughness of the Be#7 surface, the absolute value of the interface conductance is expected to be small, even in the absence of any thermal deformations. Since the interface of this rougher specimen pair is already filled with numerous gaps and cavities, the effect of the thermal deformation is minimal. The Be#1/SS304 system, on the other hand, has surfaces which are relatively smooth and in close contact. Thus, without any thermal deflection, the interface conductance of this system is initially high. However, as soon as any degree of thermal expansion is encountered, large gaps form in the interface and the interface conductance of the system rapidly decreases. It is not understood why the interface conductance reaches a saturation level at some critical value of heat flux and then becomes independent of further increases in the applied heat flux. Further studies must be made to elucidate this phenomena.

4. Summary

The experimental data indicate that contact pressure, interstitial gas pressure, surface roughness and applied heat flux are important parameters in determining the interface conductance across a beryllium-steel interface. Increasing contact pressures increased the magnitude of the interface conductance by an amount dependent upon the surface roughness and interstitial gas pressure. Interstitial gas pressure played a dominant role in determining the interface conductance, raising the magnitude of h by as much as 153%. Surface roughness was found to vary not only the magnitude of the interface conductance, but also its sensitivity to changes in other environmental parameters. The data suggest that, for surfaces of sufficient roughness, the interface conductance can be made nearly independent of contact pressure and heat flux. The effect of heat flux on h was found to be dependent upon surface roughness of the Be/steel interface. Smoother surfaces encountered greater maximum values of interface conductance, but experienced large drops in h over a relatively small heat flux range. Beyond a certain value of heat flux, the interface conductance was seen to saturate to a minimum value, becoming insensitive to further increases in heat flux. Rougher surfaces were found to be nearly independent of heat flux over the complete range of explored values.

References

[1] G.E. Shatalov, M.A. Abdou, A. Antipenkov, W. Daenner, Y. Gohar et al., Fusion Eng. Design 16 (1991) 85.
[2] M.M. Yovanovich, Proc. 8th Int. Heat Transfer Conf., 1 (1986) 35.
[3] S. Seaho, PhD Dissertation, Department of Mechanical Engineering, University of Waterloo, 1988.
[4] Z.R. Gorbis, A.R. Raffray and M.A. Abdou, Fusion Technol. 19 (3) 2B (1991) 1519.
[5] M.S. Tillack and R.D. Abelson, 3rd Int. Symp. Nucl. Fusion Technol., June 1994.
[6] R.D. Abelson, Masters Thesis, Department of Nuclear, Mechanical and Aerospace Engineering, UCLA, 1995.