EFFECTS OF PRESSURE AND TEMPERATURE ON THERMAL CONTACT RESISTANCE BETWEEN DIFFERENT MATERIALS

by

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To explore whether pressure and temperature can affect thermal contact resistance, we have proposed a new experimental approach for measurement of the thermal contact resistance. Taking the thermal contact resistance between phenolic resin and carbon-carbon composites, cuprum, and aluminum as the examples, the influence of the thermal contact resistance between specimens under pressure is tested by experiment. Two groups of experiments are performed and then an analysis on influencing factors of the thermal contact resistance is presented in this paper. The experimental results reveal that the thermal contact resistance depends not only on the thermal conductivity coefficient of materials, but on the interfacial temperature and pressure. Furthermore, the thermal contact resistance between cuprum and aluminum is more sensitive to pressure and temperature than that between phenolic resin and carbon-carbon composites.

Key words: *thermal contact resistance, interfacial temperature, pressure, experiment*

Introduction

Thermal protection systems are essential for the safety of vehicles subjected to severe aerodynamic heating [1]. A lot of researches have been performed on this subject [2-4]. Thermal contact resistance (TCR) is the most common quantity characterizing interfacial heat transfer and is also an open issue in the thermal protection system of multi-layer structures. The process of heat transfer across an interface is a complex thermal problem which depends on not only the thermal physical properties of the contact materials, but also the interfacial conditions. Owing to the rough nature of mechanical surfaces, the actual contact area is a small fraction of the nominal contact area. Gas or another fluid fills the interstitial area where the surfaces may not contact directly and completely. Sometimes interstices may be in a vacuum, and when heat flux conducts through two adjacent contact surfaces, an additional thermal resistance appears in the contact regions. Huang *et al.* [5] presented a procedure to determine the TCR between a smooth surface of a film and a rough surface of a metal specimen. Akinyemi *et al.* [6] investigated the effects of heat sink compounds with high or low-conductivity on thermal conductivity. However, few records have considered the effect of interfacial pressure and temperature on the thermal contact resistance between different materials at middle and high temperatures [7]. In this study, it will be explored whether pressure and temperature can affect thermal contact resistance between phenolic resin and carbon-carbon composites, cuprum, and aluminum.

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Experimental approach

The apparatus for the TCR measurements consists of a heating block, upper and lower specimens, an electronic tension-compression testing machine, and a heating chamber in which the highest temperature is up to 650 °C, fig. 1. The mechanical load is applied by an electronic tension-compression testing machine, in which the contact pressure is measured with a pressure sensor and recorded by computer. Thermocouples of 8·0.75 mm in diameter are installed into the holes of the specimens with grease so as to enhance the contact between sensors and specimen. In order to stabilize the heat flux of the contact surfaces, the voltage of the heating block must be kept constant. In fig. 1, 1 to 8, respectively, represents water trough, integrated digital collection tester, computer, thermocouples, cuprum, steel, asbestos, electronic tension-compression testing machine, 9I and 9II are two specimens, 10 is insulating layer, 11 is resistance wire, and I and II are heating device and dashpot damper device, respectively.

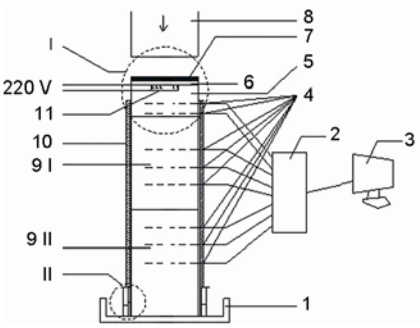

Figure 1. Apparatus for the TCR measurements

The TCR is measured using the static heat flow method. Two cylindrical cross-section specimens under a certain pressure are maintained in the axial contact, and then the upper one is heated. By utilizing the insulation in contact with the lateral side of both specimens, these surfaces are kept in approximate adiabatic conditions, so the heat conducts mainly along the axial direction. Actually, the heat flow in the vicinity of the contact interface is 3-D, but the lateral heat flow is much less than the axial one, so it can be regarded as a 1-D heat conduction problem. By measuring the temperature at different positions of the specimen along the axial direction, the axial heat flux and the interface temperature difference can be obtained, and then the values of TCR can be computed.

One group of specimens are made from phenolic resin or carbon-carbon composite, while the other specimens consist of cuprum or aluminum. There are five pairs of specimens in each group. Each specimen is manufactured to a cylinder of 90 mm in length and 30 mm in diameter. The roughness of specimen surface must be very small. Each specimen has three internal cylindrical screw holes, which are 8·0.75 mm and 20 mm in depth for the placement of thermocouples, and the distance between every two holes is 37 mm.

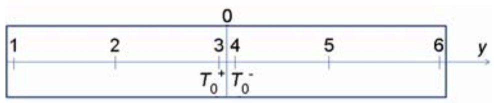

Figure 2. Locations of sensing temperature points

Each specimen contains three temperature sensing points and their locations are illustrated in fig. 2. Temperatures T_i (i = 1, 2, 3, 4, 5, and 6) are measured by utilizing the thermocouples.

The location of the interface is marked 0 in fig. 2. The temperatures at the interface of the right and left specimen are defined respectively as T_0^- and T_0^+. Based on the Fourier heat equation, the axial heat flux q_{ij} between any two adjacent points can be calculated, in the case of 1-D heat flux, from:

$$q_{ij} = k_{ij} \frac{T_i - T_j}{y_j - y_i} \tag{1}$$

where $k_{ij}(i,j$ = 1, 2, 3, 4, 5, and 6) is the thermal conductivity between point i and j, y_i – the position co-ordinates of the sensing temperature points, which are 0.008, 0.045, 0.082, 0.09, 0.098, 0.135, and 0.172 m, respectively.

As the interfacial temperatures cannot be measured directly, an inverse method is used to deduce the temperatures T_0^- and T_0^+. Approximately, if the axial heat flux is constant along the specimen, *i. e.*, $q_{23} \approx q_{30}$, from eq. (1) we can obtain:

$$T_0^+ \approx T_3 - \frac{k_{23}}{k_{30}} \frac{y_0 - y_3}{y_3 - y_2} (T_2 - T_3) \tag{2}$$

$$T_0^- \approx T_4 - \frac{k_{45}}{k_{40}} \frac{y_4 - y_0}{y_5 - y_4} (T_4 - T_5) \tag{3}$$

As the heat loss inevitably exists around the specimen, the calculated heat flow is not the same according to two adjacent temperatures. In order to correct for lateral heat losses, the arithmetic mean of the heat flow through the interface on both sides is considered as the axial heat flux of the interface, namely:

$$q \approx \frac{1}{2}\left[q_{23} + q_{45} - \frac{8}{37}(q_{12} - q_{23}) + \frac{8}{37}(q_{45} - q_{56}) \right] \tag{4}$$

From eq. (1) to eq. (4), we can get the TCR in the form:

$$R = \frac{T_0^+ - T_0^-}{q} \approx 2\,\frac{T_3 - T_4 - \dfrac{k_{23}(y_0 - y_3)}{k_{30}(y_3 - y_2)}(T_2 - T_3) - \dfrac{k_{45}(y_4 - y_0)}{k_{40}(y_5 - y_4)}(T_4 - T_5)}{q_{23} + q_{45} - \dfrac{8}{37}(q_{12} - q_{23}) + \dfrac{8}{37}(q_{45} - q_{56})} \tag{5}$$

where the thermal conductivity of carbon-carbon composites in the axial direction is approximately taken as 70 W/m°C, of phenolic resin as 0.55 W/m°C, of aluminum as 239 W/m°C, and of cuprum as 395 W/m°C on the basis of the thermal conductivity tested previously.

Results

Carbon/carbon composite and phenolic resin are placed at 9I and 9II in fig. 1, respectively. The heat flux conducts from the carbon-carbon composite, through the contact interface, to the phenolic resin. The TCR can be calculated using eq. (5) after the measurement. Figure 3 shows that the TCR does not fluctuate much when interfacial temperatures range between 50 °C and 250 °C, no matter what pressure is applied. In other words, the interfacial temperature does not influence the TCR significantly. However, the TCR decreases slowly as contact pressure increases.

However, as shown in fig. 4, the experiment on cuprum and aluminum with high thermal conductivities shows us different results. It can be found from fig. 4 that the TCR decreases when temperature rises. The TCR tends to decline gradually with pressure increases.

It is noticeable that the value of the TCR depends on interfacial temperature, contact pressure, and the materials thermal properties. With the increase of temperature and pressure, the TCR between cuprum and aluminum decreases more rapidly than the TCR between carbon-carbon composite and phenolic resin. Comparing the differences between them, we find that the TCR between materials with high thermal conductivity (*e. g.* cuprum) is more easily affected by pressure than that between materials with low thermal conductivity (*e. g.* phenolic resin).

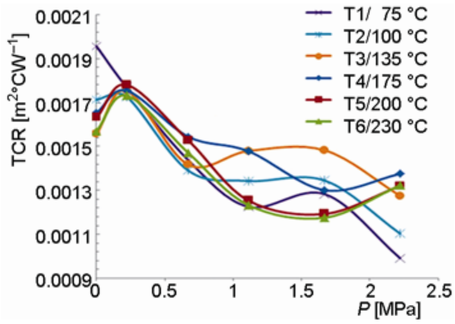

Figure 3. Variation of the TCR between phenolic resin and carbon-carbon with pressure

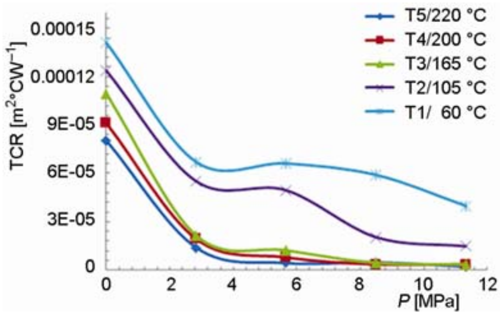

Figure 4. Variation of the TCR between cuprum and aluminum with pressure

Conclusions

This paper proposes a new experimental approach for measurements of the TCR on the basis of the Fourier thermal conductivity theory, and two groups of experiments of the TCR were performed. The results show that the TCR depends on not only the thermal conductivity coefficient of materials, but also interfacial temperature and pressure. However, its sensitivity is not the same; the TCR between cuprum and aluminum is more sensitive to pressure and temperature than that between phenolic resin and carbon-carbon composite.

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Nomenclature

k – thermal conductivity, [Wm^{-1}°C^{-1}]
P – pressure, [MPa]
q – axial heat flux, [Wm^{-2}]
R – thermal contact resistance, [m^2°CW^{-1}]
T – temperature, [°C]
y – co-ordinate, [m]

Subscripts

0^- – interface of right specimen
0^+ – interface of left specimen

References

[1] Li, W. J., ***et al.***, Nonlinear Analysis on Thermal Behavior of Charring Materials with Surface Ablation, *International Journal of Heat and Mass Transfer*, *84* (2015), May, pp. 245-252
[2] Li, W. J., ***et al.***, Thermochemical Ablation of Carbon/Carbon Composites with Nonlinear Thermal Conductivity, *Thermal Science*, *18* (2014), 5, pp. 1625-1629
[3] Huang, H. M., ***et al.***, Simulation of Co-Rotating Vortices Based on Compressible Vortex Method, *International Journal of Numerical Methods for Heat and Fluid Flow*, *24* (2014), 6, pp. 1290-1300
[4] Chen, Z., ***et al.***, Thermal Contact Resistance between Grapheme and Silicon Dioxide, *Applied Physics Letters*, *95* (2009), 16, pp. 161910.1-191910.3
[5] Huang, H. M., ***et al.***, Effect of Surface Morphology on Thermal Contact Resistance, *Thermal Science*, *15* (2011), Suppl. 1, pp. 33-38
[6] Akinyemi, O. D., ***et al.***, Effects of Heat Sink Compounds on Contact Resistance of Porous Media, *Thermal Science*, *11* (2007), 4, pp. 113-124
[7] Heichal, Y., ***et al.***, Predicting Thermal Contact Resistance between Molten Metal Droplets and a Solid Surface, *Journal of Heat Transfer*, *127* (2005), 11, pp. 1269-1276

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