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EXPERIMENTAL INVESTIGATION OF HIGH TEMPERATURE THERMAL CONTACT RESISTANCE WITH INTERFACE MATERIAL

Zheng X.P.[1]*, Liu D.H.[2] and Feng J.L[1].
*Author for correspondence
[1] Applied Mechanics Laboratory, Department of Engineering Mechanics,
Tsinghua University, Beijing 100084, China
E-mail: zhengxp@mail.tsinghua.edu.cn
[2] Department of Applied Mechanics, University of Science & Technology Beijing, Beijing 100083, China

ABSTRACT

Thermal contact resistance plays a very important role in heat transfer efficiency and thermomechanical coupling response between two materials, and a common method to reduce the thermal contact resistance is to fill a soft interface material between these two materials. A testing system of high temperature thermal contact resistance based on INSTRON 8874 is established in the present paper, which can achieve 600 Celsius degree at the interface. Based on this system, the thermal contact resistance between superalloy GH600 material and three-dimensional braid C/C composite material are experimentally investigated, under different interface pressures, interface roughness and temperatures, respectively. At the same time, the mechanism of reducing the thermal contact resistance with carbon fiber sheet as interface material is experimentally investigated. Results show that the present testing system is feasible in the experimental research of high temperature thermal contact resistance.

INTRODUCTION

Thermal contact resistance plays a very important role in many fields including aerospace structures1, microelectronics2, internal combustion engineering and nuclear plants3. Thermal contact resistance is primarily caused by the imperfect contact between two surfaces due to the presence of microscopic asperities characteristic of engineering surfaces, and it has been widely studied by using the theory, computation and experiment method recently. A predictive model for estimating thermal contact resistance between two nominal flat metallic rough surfaces had been developed and experimentally validated by Singhal et al.4. Fieberg and Kneer developed an approach to derive the thermal contact resistance under high temperature and high pressure conditions based on transient infrared temperature measurements5. Shojaefard et al. proposed a numerical estimation technique of thermal contact resistance in contacting surfaces6. Temizer and Wiggers developed a computational contact homogenization technique at the finite deformation regime to predict the macroscopic thermal response of contact interfaces between rough surface topographies7. Bahrami et al. reviewed the thermal contact resistance in a vacuum8, they divided the problem into three different parts: geometrical, mechanical, and thermal. Each problem includes a macro- and microscale subproblem, and existing theories and models for each part are also reviewed.

It should be mentioned that former researches always focus on low or intermediate temperatures, in order to study high-temperature thermal contact resistance, a testing system is established here, and this system can achieve 600 Celsius degree at the interface. Based on this test system, the thermal contact resistance between superalloy GH600 material and three-dimensional braid C/C composite material are experimentally investigated, under different interface pressures, interface roughness and temperatures, respectively, and the effect of carbon fiber sheet as the interface material is also investigated here.

NOMENCLATURE

k	[W/mK]	Thermal conductivity
q_n	[W/m^2]	Heat flux normal
R	[m^{2}K/W]	Interfacial thermal resistance
T	[K]	Temperature

TEST EQUIPMENT

A steady-state, one-dimensional axial heat flow measurement approach was used to determine thermal contact resistance experimentally under different interface pressures, interface roughness and temperatures.

The facility is based on INSTRON 8874 high-temperature material testing machine and consists of a test column, a loading system, a heating and cooling unit and a temperature measurement system, as shown in **Figure 1**. The test column is composed of five components: a heat source, heat and force transfer bar, fourteen thermal couples, two test specimens, and a heat sink, as shown in Fig.2. A radiation shield made of Zirconia (ZrO2) is placed around the column to minimize the radial heat losses from the test specimens. For the tests conducted in the present work, the heat flow direction was from bottom to top. Heat generation is accomplished by means of electrical heaters which can achieve 1500 K in 10 minutes. Heat is extracted from the top of the test specimen via the forced cooling system of INSTRON 8874.

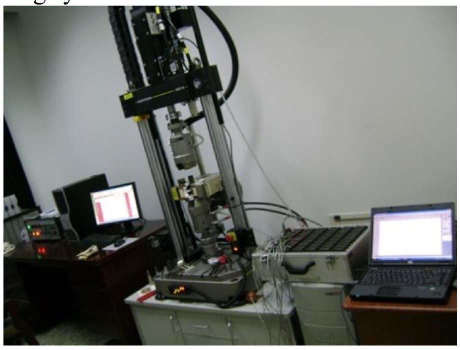


Figure 1 High-temperature thermal contact resistance test system

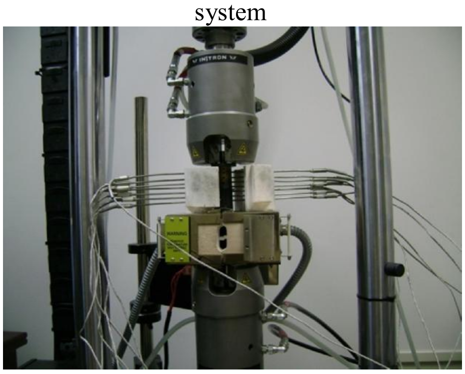


Figure 2 High-temperature thermal contact resistance test system

A compressive load was applied on the specimens by a simple hydraumatic system, and the temperature of the specimens are controlled by using circulating cooling water overhead the top specimen and a heater at the bottom specimen. The K-Type thermocouples were mounted in holes drilled perpendicular to the axis of symmetry of the specimens. All the thermocouples were connected to a Data Acquisition system, which was composed of 32 channels and interfaced to a notebook computer. The Data Acquisition system can output the temperature history of each thermocouple.

TEST SPECIMENS

Cylindrical specimens (30 mm diameter and 40 cm length) were made from GH600 and three-dimensional braid C/C composite, as shown in **Figure 3**.

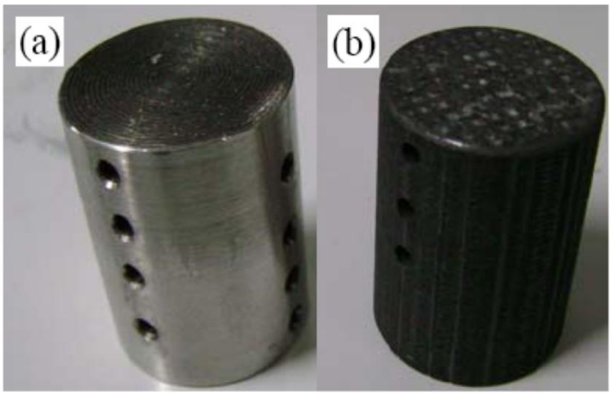


Figure 3 Test specimens: a) superalloy GH600; b) C/C composite material

The conductivity of C/C composite material is assumed to be a constant value of 66.1Wm-1K-1, and the conductivity of superalloy GH600 varies with temperature9. The surface roughness of the specimen is tested by Talysurf 5P-120 surface topography instrument made by Rank Taylor Hobson Company. The surface roughness of the C/C specimen used in the present investigation is 26.3 m, and the surface roughness of the GH600 specimens used are 49.7 m, 36.2 m and 0.532 m respectively.

TEST PROCEDURE

Locate the test specimens accurately on the setup;

Activate the cooling system, loading system and temperature measurement system;

Set the interface pressure at the loading control software, and activate the heating system. Then Data Acquisition system will gather the temperature of each thermocouple every 30 second until the interface temperature achieve 900 K;

Shut down the heating system, after the specimen is cooled to room temperature, then change the interface pressure to the next level and repeat step 3, until all of the interface pressure is covered;

Save all the temperature history data, unloading the system, cut down the power.

It is also noted that using interface material is a common method to decrease the interface thermal contact resistance. In the present research the interface temperature can reach to 900 K, so ordinary interface materials such as thermal greases and phase-change materials are no more valid here. Instead, the carbon fiber sheet is used as the interface material in the present experiment, as shown in **Figure 4**.

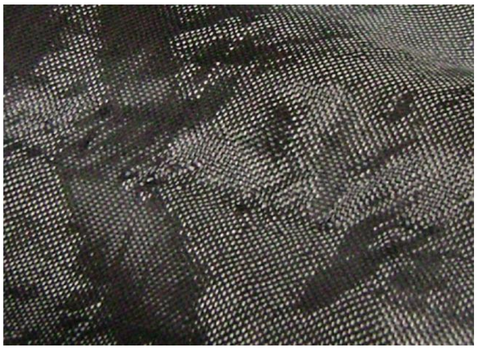


Figure 4 Carbon fiber sheet interface material

In the present research, different layers of interface material under different interface pressure and interface temperature are investigated compared with no interface material.

Computational considerations

Thermal contact resistance arises in the contact region of two solids because the real contact area is only a small fraction of the nominal or apparent area. The thermal contact resistance is calculated as the ratio of the temperature jump across the interface to the heat flow through:

$$R = \frac{\Delta T}{q_n} \tag{1}$$

Where ΔT denotes the temperature jump in the contact region and q_n denotes the heat flux normal to the interface.

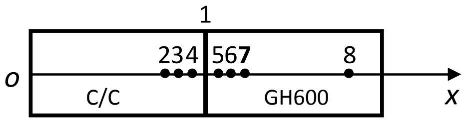


Figure 5 Location of the thermocouples

Thermal contact conductance is the reciprocal of the thermal contact resistance. The temperatures along the specimens, measured along their axis by 14 K-Type thermocouples, as shown in Fig.5, were used to calculate the heat flux and temperature difference at the interface. The temperature of each point Ti (i=2,3,⋯,8) can be experimentally obtained by thermocouples, and the interface is set to be point 1, with T_1^+ and T_1^- stand for temperature of each side. Heat flux between point i and j can be obtained from Fourier's law:

$$q_{ij} = k_{ij}\frac{T_i - T_j}{x_j - x_i} \tag{2}$$

Where k_{ij}(i, j=2, 3, ⋯ , 8) means average thermal conductivity between point i and j, xi means coordinate of point i, as shown in Table 1.

Table 1. Coordinates of temperature points

No	1	2	3	4	5	6	8	8
Coordinate/mm	40	20	28	36	44	52	60	70

As heat loss is inevitable along the specimens, the heat flow through the interface is determined as the average of the heat flow through the two specimens:

$$q_n = \frac{1}{2}\left(q_{34} + q_{56}\right) \tag{3}$$

We also mentioned that:

$$q_{41} = q_{34} = k_{34}\frac{T_3 - T_4}{x_4 - x_3} = k_{44}\frac{T_4 - T_1^+}{x_1 - x_4} \tag{4}$$

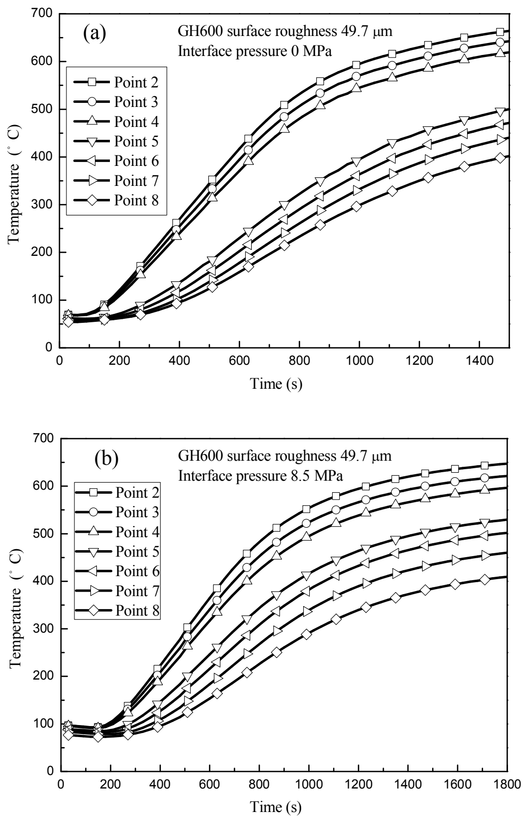
Then we can deduce the temperature at the both side of the interface:

$$\begin{aligned} T_1^+ &= T_4 - \frac{k_{34}}{k_{44}}\frac{x_1 - x_4}{x_4 - x_3}\left(T_3 - T_4\right) \\ T_1^- &= T_5 + \frac{k_{56}}{k_{55}}\frac{x_5 - x_1}{x_6 - x_5}\left(T_5 - T_6\right) \end{aligned} \tag{5}$$

The temperature jump ΔT is defined as $\Delta T = T_1^+ - T_1^-$, then the thermal contact resistance can be experimentally determined by Eq.(1)

EXPERIMENTAL RESULTS

Temperature variations with time were shown in **Figure 6**. Also, **Figure 7** shows the variation of thermal contact resistance with interface average temperature and interface pressure.



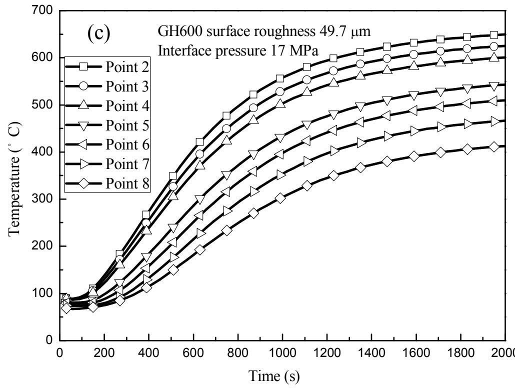


Figure 6 Temperature history of each measurement point under different interface pressure: (a) 0 MPa; (b) 8.5 MPa; (c) 17 MPa

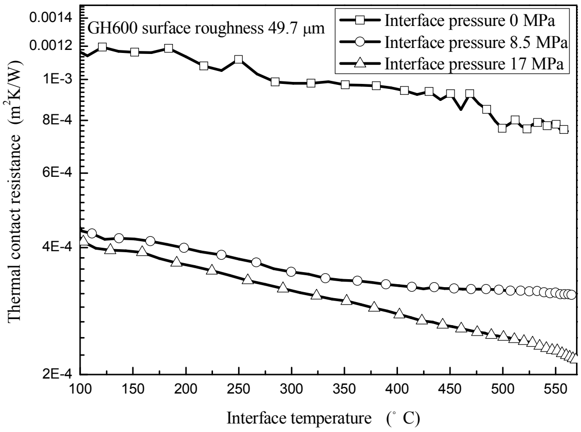


Figure 7 Variation of thermal contact resistance with average interface temperature under different interface pressure

As can be seen from the results in **Figure 7**, thermal contact resistance decreases with increasing interface pressure. As the contact pressure at the interface is increased, the contact asperities deform further in addition to new asperities coming into contact, which increases the amount of actual contact area. The solid spot contribution to thermal contact conductance correspondingly increases. At the same time, with the increment of the interface temperature, thermal contact resistance decreased because of the rapid increment of interface radiation heat transfer.

In order to investigate the effect of surface roughness to the thermal contact resistance, three GH600 specimens with different surface roughness under a constant interface pressure of 17 MPa are tested, and variation of thermal contact resistance with average interface temperature under different surface roughness is given in **Figure 8**.

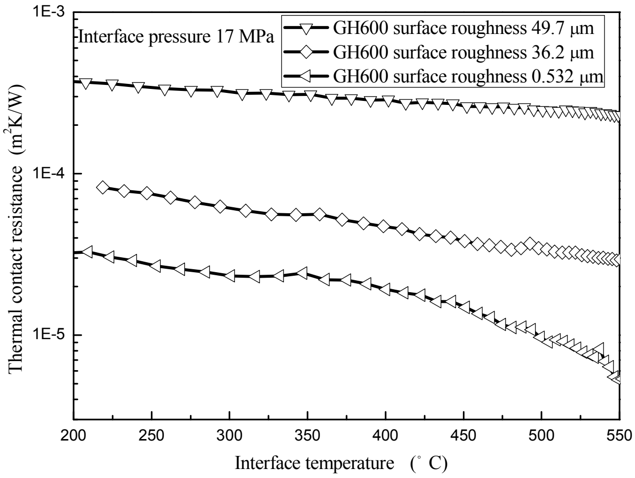
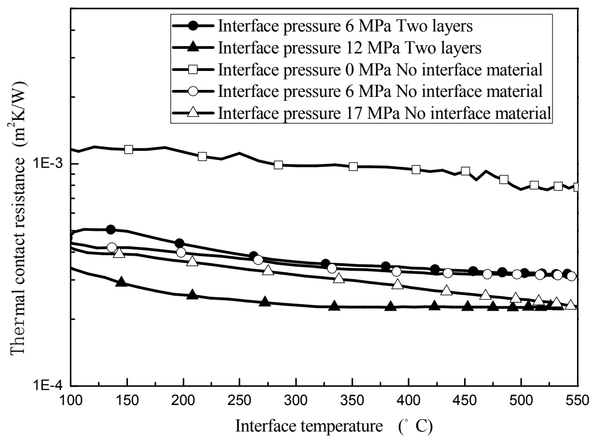


Figure 8 Variation of thermal contact resistance with average interface temperature under different surface roughness

As expected, thermal contact resistance was found to increase as surface roughness increased. As the surface roughness increases, the number of contact spots and the real area of contact decreases, thus allowing for less solid spot conductance across the interface. The thermal contact resistance is seen decrease with a 97% drop for a decrease in the nominal surface roughness from 49.7 m to 0.532 m at 550 ℃ under 17 MPa.

The effect of interface material is also investigated herein, Fig.9 shows a comparison of thermal contact resistance with vs. without interface material under different interface temperatures and interface pressures.



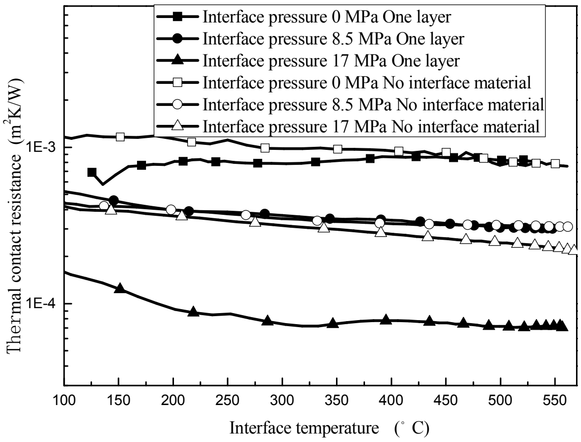


Figure 9 Comparison of thermal contact resistance with vs. without interface material

It was found that for two layer carbon fiber sheet interface material, interface material has almost nothing to do with thermal contact resistance if interface pressure is less than 17 MPa. As two layer carbon fiber sheet means an extra interface between the two layers, which may counteract the effect of decrease the thermal contact resistance itself, and this is the reason why we use multi-layer materials for heat insulation. At the same time, for one layer carbon fiber sheet interface material, if interface pressure is more than 17 MPa, then the thermal contact resistance can greatly decreased from 2×10^{-4} m^2K/W to 7×10^{-5} m^2K/W at 550 ℃.

CONCLUSION

This study provides experimental data which can not only be used to determine the thermal contact resistance of superalloy GH600 and three-dimensional braid C/C composite material with interface material under different circumstances, but also provides additional information for use in identifying the important parameters that govern the thermal contact resistance in the presence of carbon fiber sheet. Based upon the experimental results presented here, several conclusions can be made. First, the present test system is feasible in the experimental research of high temperature thermal contact resistance. Second, if an optimum interface material is used, the thermal contact resistance will decrease. Third, as there is presently inadequate experimental evidence, it would be interesting to test additional specimens to get more and better results on this subject.

In conclusion, although the carbon fiber sheet used were shown to be significantly decrease the thermal contact resistance, the thickness and interface pressure must be carefully determined to be effective. Experience gained from this investigation demonstrated that as a result, in several instances, when the interface material is not properly applied, it actually results in increases in the thermal contact resistance.

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REFERENCES

[1] L. S. Fletcher, J. Heat Transfer, **110**, 1059 (1988)
[2] M. Grujicic, C. L. Zhao and E.C. Dusel, **246**, 290 (2005)
[3] M. A. Lambert and L. S. Fletcher,gh metals. J. Heat Transfer, **119**, 648 (1997)
[4] V. Singhal, P. J. Litke, A. F. Black and S. V. Garimella, Int. J. Heat Mass Transfer, **48**, 5446 (2005)
[5] C. Fieberg and R. Kneer, Int. J. Heat Mass Transfer, **51**, 1017 (2008)
[6] M. H. Shojaefard and K. Goudarzi, Am. J. Appl. Sci., **5**, 1566 (2008)
[7] I. Temizer and P. Wriggers, Int. J. Numer. Meth. Eng, **83**, 27 (2010).
[8] M. Bahrami, J. R. Culham, M. M. Yananovich and G. E. Schneider, Appl. Mech. Rev., **59**, 1 (2006)
[9] D. H. Liu, X. P. Zheng, F. Wang, et al., Acta. Mater. Compos. Sin., **27**, 43 (2010)