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An experimental study on thermal contact conductance across the SS316L/CuCrZr interface

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Abstract. A vacuum apparatus to measure thermal contact conductance (TCC) was introduced. A TCC test method and procedure was presented. By monitoring the temperature distribution on the test specimen, the heat flux and temperature drop of the contact interface were calculated, and then the TCC was obtained. The experimental research was conducted with pressed pairs SS316L/CuCrZr contacts in a range of 100~300°C and 1~10MP. The experimental data analysis results show that the TCC increases with the increase of contact temperature and the TCC also grows with the growth of contact pressure. The TCC appears as a linear relationship with the change trend of pressure at a given temperature. By uncertainty analysis, the measurement error of TCC decreases with the increase of contact pressure at a given temperature. And the variation rate of measurement error increases with the rise in contact temperature.

1. Introduction

Thermal contact conductance (TCC) is the ratio between the average heat flux and the temperature drop across the interface. The reciprocal of TCC is thermal contact resistance (TCR). Thermal contact resistance (TCR) is the ratio between the temperature drop and the average heat flux across the interface. TCC is a vital heat transfer property in many engineering applications, such as aerospace technologies [1], electronics [2] and nuclear reactors [3]. Thermal contact conductance depends on a lot of factors such as pressure, temperature, material properties, contact interface topography [4]. The factors affecting the thermal conductivity can be divided into macro-influence factors and micro-influence factors. Macroscopic factors include thermal properties, elastoplasticity, surface hardness and surface shape of materials. Microscopic factors include asperity, micro-morphology and elastoplastic deformation of contact peak. Therefore, the research on TCC involves three underlying problems: geometry, mechanics and thermal. And there are three kinds of contact mechanics problems: pure elastic contact, pure plastic contact and more complex elastoplastic contact [4]. To investigate TCC quantitatively, researches have carried out a lot of experimental and theoretical research work [5-7].

Contact thermal conductivity is a multidisciplinary field of geometry, heat, and machinery. Many scholars have conducted extensive and in-depth research on it. In recent decades, many researchers have proposed contact interface model based on experimental data and mathematical analysis to calculate TCC [8-10]. Yovanovich [11] introduced a plastic contact thermal resistance model with an average height Gaussian distribution of contact interface. Leung [12] compared the asperity of contact interface with the particles in statistical thermodynamics to investigate the thermal contact resistance. Many pieces of research applied the fractal theory to examine the contact surface morphology, and then obtained the relationship model between surface morphology and interface thermal resistance [13,14]. Based on the fractal theory TCR analysis method, the researches also established a multi-scale TCR model considering the scale effect and the material thermal properties [15]. Unfortunately, so far, there is no satisfactory theoretical model and no reliable empirical formula for experimental research.

In this paper, based on the TCC model proposed by Yovanovich, the experimental method was designed to calculate the TCC of pressed pairs SS316L/CuCrZr. Furthermore, the influence of temperature and pressure on the TCC of pressed couples SS316L/CuCrZr was analyzed to provide experimental data and method basis for the investigation of TCC.

2. Method and procedure

2.1. Test principle

A temperature drop is observed when two solid interfaces come into physical contact. Thermal contact conductance (TCC) is the ratio between the average heat flux and the temperature drop across the interface. The TCC of the contact interface can be expressed as

$$h_s = \frac{q}{\Delta T} = \frac{q}{T_{C1} - T_{C2}} \tag{1}$$

where h_s is the thermal contact conductance, ΔT is the interface temperature drop, q is the heat flux, T_{C1} and T_{C2} denote the temperature of different sides of the contact surface, respectively[11].

In this paper, the steady heat transfer method is used to test the TCC between the pressed pairs SS316L/CuCrZr contacts. As is shown in figure 1, the contact surface temperature of specimen 1 T_{C1} is calculated by the linear fitting of the temperature of four points on the specimen 1. In the same way, T_{C2} is obtained, and ΔT is derived as $\Delta T = T_{C1} - T_{C2}$. According to the heat conduction theory, the heat flux q is derived via the heat flux meter. As is shown in Fig. 1, it can be expressed as

$$q = \lambda \frac{T_i - T_{i+1}}{\delta} \tag{2}$$

where λ is the thermal conductivity coefficient of the heat flux meter specimen, T_i, T_{i+1} is the temperature measured by thermocouples of the heat flux meter ($i = 1, 2, 3, 5, 6$), δ is the distance of the adjacent thermocouples hole on the heat flux meter.

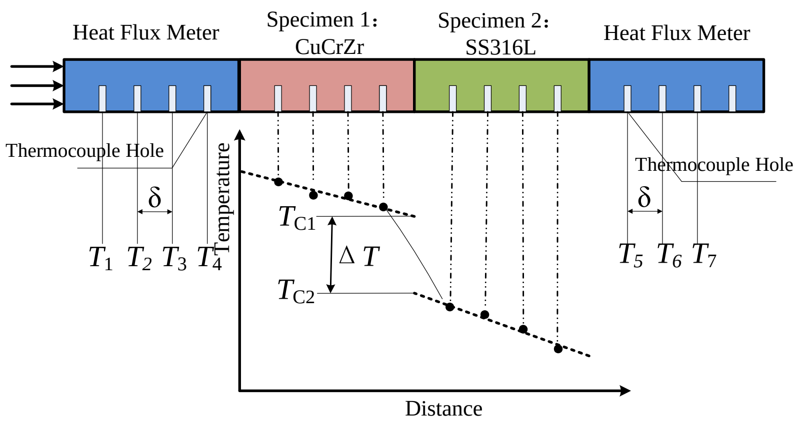
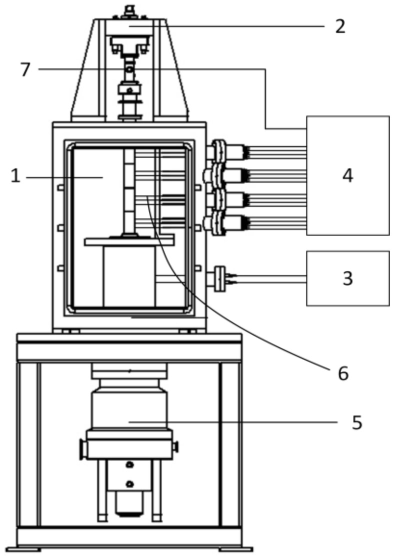


Figure 1. Schematic of thermal contact conductance test

2.2. Test setup

The schematic of TCC experimental apparatus is shown in figure 2, which mainly consists of a vacuum chamber, loading system, heating system, temperature, and pressure data acquisition system and molecular pump.



1—vacuum chamber; 2—loading system; 3—heating system; 4—temperature and pressure data acquisition system; 5—molecular pump; 6—thermocouple; 7—pressure sensor

Figure 2. Schematic of TCC experimental apparatus

The pressed pairs SS316L/CuCrZr specimens are cylindrical with 30mm diam and 65mm height. Four holes have been drilled into the specimens along the radial direction with a depth of 15mm for placing thermocouples. The TCC measurement device consists of two brass heat flux meters and pressed pairs SS316L/CuCrZr specimens (as is shown in figure 1). Sixteen thermocouples are mounted in the holes of specimens and heat flux meter to measure and collect the temperature data of the specimens. According to formula (1), the TCC of pressed pairs SS316L/CuCrZr is calculated based on the temperature data collected. By controlling thyristor voltage regulator of heating system, the TCC at different temperatures of the specimens can be obtained. Meanwhile, the TCC at different pressure values in specimens can be obtained by controlling the loading system.

3. Results and Discussion

Based on the TCC test principle and TCC experimental apparatus setup, the pressed pairs SS316L/CuCrZr specimens were used to verify the feasibility of the TCC test method. The TCC between pressed pairs SS316L/CuCrZr specimens were tested with the interface pressure from 1MP to 10MP at 100°C, 200°C and 300°C respectively.

3.1. Test results

Table 1 shows the TCC of pressed pairs SS316L/CuCrZr at different temperatures and pressures. For three different interface temperatures, the TCC results under pressures of 1, 2.5, 5, 7.5, and 10MP were calculated. As the temperature and pressure of the contact surface affect each other, the temperature cannot be accurately adjusted to 100, 200, and 300 ℃, and the pressure also cannot be carefully adjusted to 1, 2.5, 5, 7.5, and 10MP at the thermal equilibrium state of the test process.

Table 1. TCC of specimens at different temperatures and pressures

102.87℃	201.98℃	300.9℃

Pressure, MPa	TCC, W·°C^{-1}·m^{-2}	Pressure, MPa	TCC, W·°C^{-1}·m^{-2}	Pressure, MPa	TCC, W·°C^{-1}·m^{-2}
1.06	2865	1.01	6934	1.04	14804
2.43	3424	2.66	10044	2.65	19954
5.01	5185	5.02	14055	4.93	30300
7.55	6527	7.43	17818	7.40	37793
9.96	7689	9.99	22532	9.97	45018

The TCC results listed in table 1 were fitted to reveal the tendency of TCC versus pressures at different temperatures. The fitting results shown in figure 3 reveal that the TCC of pressed pairs SS316L/CuCrZr gradually increases with pressure and exhibits a good linearity. All data fall in the range $10^{-4} \le P/H_e \le 10^{-2}$ (where P is the contact pressure, H_e is the effective contact micro-hardness)[11], whereas the dimensionless conductance and dimensionless contact pressure appear as a straight line according to CMY model. Contact pressure at 1~10MP and temperature at 100~300℃, the effective contact micro-hardness can be considered constant. Therefore, the TCC has a linear relationship with the change trend of contact pressure.

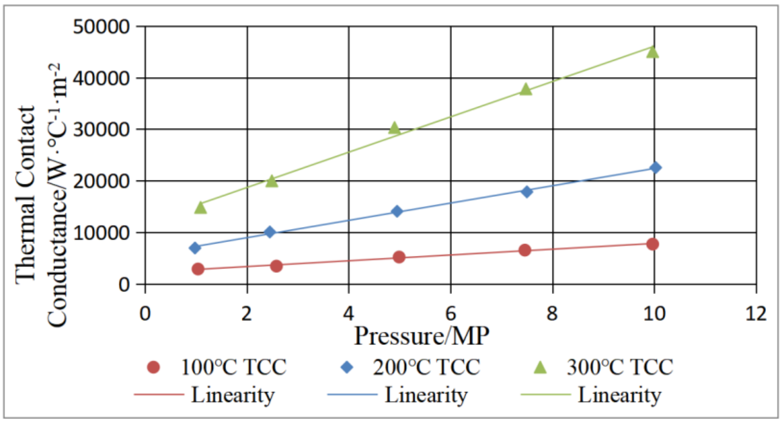


Figure 3. TCC curve of SS316L/CuCrZr with pressure at different temperatures

3.2. Uncertainty analysis

The errors in the test can be divided into systematic error and accidental error. The system error is mainly caused by the test equipment. According to the equipment parameters provided by the TCC experimental apparatus manufacturer, the uncertainty of temperature and pressure control system, temperature and pressure measurement system are 1.8 and 0.6%, respectively. The system error can be written as

$$error(h_s) = \sqrt{(1.8\%)^2 + (0.6\%)^2} = 1.9\% \tag{3}$$

and in the experiment, the random error comes from heat loss. According to error propagation law [16] and equation (1), the accidental error can be expressed as

$$error(h_a) = \frac{\Delta h}{h} = \frac{\sqrt{\left(\frac{\partial h}{\partial q}\right)^2 \Delta q^2 + \left(\frac{\partial h}{\partial t}\right)^2 \Delta t^2}}{h} = \frac{\sqrt{\left(\frac{1}{t}\right)^2 \Delta q^2 + \left(\frac{q}{t^2}\right)^2 \Delta t^2}}{h} \tag{4}$$

where h is the TCC of the contact interface, t is the temperature drop, q is the heat flux, Δt is the accident error of temperature drop and Δq is the random error of heat flux. According to figure 1, the accident error of temperature drop can be expressed as

$$\Delta t = \sqrt{\frac{T_{C1}^2 + T_{C2}^2}{2}}. \tag{5}$$

And according to Equation (2), the accident error of heat flux can be expressed as

$$\Delta q = \sqrt{\frac{q_1^2 + q_2^2 + q_3^2 + q_4^2 + q_5^2}{5}}. \tag{6}$$

The total error of TCC is written as

$$error(h) = \sqrt{error(h_s)^2 + error(h_a)^2} \tag{7}$$

According to Equations (3-7), the measurement errors of TCC at different temperature and pressure are shown in figure 4.

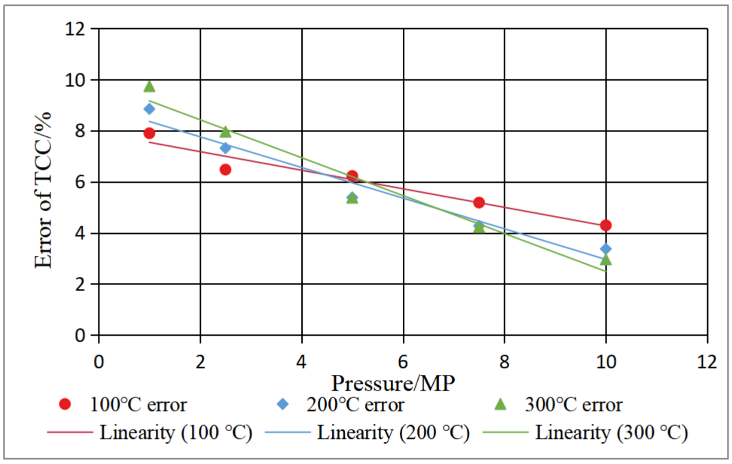


Figure 4. Measurement errors of SS316L/CuCrZr TCC versus pressure at different temperatures

As is shown in figure 4, all measurement errors are less than 10%. Meanwhile, as the contact pressure increases, the measurement error decreases. And the variation rate of measurement error increases with the increases of contact interface temperature.

4. Conclusions

- ✓ An accurate method was proposed to calculate the TCC between two contact interface. An experimental vacuum apparatus to test the TCC was introduced, and the TCC between pressed pairs SS316L/CuCrZr materials at different pressure and temperature was tested.
- ✓ It can be seen in figure 3 that the TCC is increasing as the temperature and pressure increase. And at a given temperature, the TCC appears as a linear relationship with the change trend of pressure. As shown in figure 4, the measurement error of TCC is decreasing as the pressure increases at a given temperature. And the variation rate of measurement error increases with the rise in contact interface temperature.
- ✓ In this paper, the effect of pressure and temperature on TCC was investigated quantitatively. The obtained results are consistent with the theoretical analysis of TCC and verify the feasibility of the designed TCC test method.

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