[Article ID] 1003- 6326(2002)03- 0489- 05

Modeling for thermal contact resistance of frictional interface under high temperature and high pressure①

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[Abstract] According to the thermodynamic characteristics in the work interface of the plastic forming of metals, a set of TCR (thermal contact resistance) experimental system under the conditions of high temperature and high pressure has been designed. The interrelations between the thermal contact resistance (TCR) and its influence factors such as contact pressure etc, are obtained. A modified coefficient E is introduced to consider the relative slide in the contact interface. Then the interfacial TCR calculating model, which suits to the special conditions of 'high temperature+ plastic rheology' and frictional contact such as continuous roll casting process, is established.

[Key words] continuous roll casting; thermal contact resistance; plastic rheology; frictional contact
[CLC number] TG 111.3 **[Document code]** A

1 INTRODUCTION

The phenomenon that the interface of two specimens contact under the effect of mechanic load is seen everywhere[1], while what is the action when heat flows across the interface has not been understood, especially the interface with friction contact and 'high temperature + plastic rheology' conditions such as continuous roll casting process. Because the conditions of the contact surfaces are complex and all the factors related to the contact surfaces are interactive, heat transfer mechanism in the interface has not been completely understood also till now. The imperfect contact in the interface, which results in heat flux constriction in the process of heat transfer, is usually regarded as the primary cause of thermal contact resistance[2, 3]. Thermal contact resistance plays an important role in all thermal systems where the mechanical contact is involved. This paper mainly aims at the contact interface with high temperature, high pressure and relative slide conditions such as continuous roll casting process to find the interrelations between thermal contact resistance and its influence factors such as contact pressure etc, and to bring forward the idea of divided thermal resistance to consider the sliding contact condition in the interface. Thermal contact resistance model considering the friction contact and 'high temperature+ plastic rheology' conditions in the interface is set up.

2 MECHANISM OF ENGENDERING OF THERMAL CONTACT RESISTANCE

When heat flows across the interface of two solids pressed together, a temperature difference ΔT (as shown in Fig. 1) is produced, then thermal contact resistance is defined as the ratio of the jump of temperature ΔT and the mean heat flux q in the interface:

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

Hence thermal contact conductance is

$$h_c = \frac{1}{R} = \frac{q}{\Delta T} \tag{2}$$

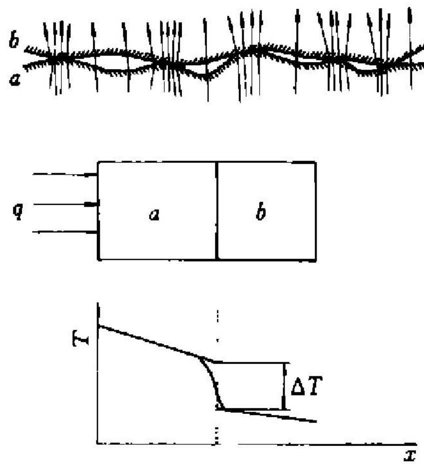

Fig. 1 Mechanism of interfacial heat transfer

The modes of heat transfer across the interface are

1) Most part of heat flows through the true contact areas by heat conduction;

2) Small part of heat flows through the interfacial fluid by conductive, convective and radiation heat transfer.

① **[Foundation item]** Project (G199906496) supported by the National Key Foundamental Research and Development Program; project (99JJY20052) supported by the National Natural Science Foundation of Hunan Province
[Received date] 2001- 07- 18; **[Accepted date]** 2001- 10- 22

For most of the contact conditions, the height of gap is relative small compared to its contact dimension. Meanwhile, there is usually vacuum or some gas in the gap, their thermal conductivity is very small, so it is suitable to neglect the conductive and convective heat transfer. Radiative heat transfer can be neglect too[4]. But a modified thermal conductivity of the gas in voids considering the effect of radiative heat transfer will be included under extremely high temperature condition.

Numerous factors influence interfacial heat transfer, most of them are nonlinear. Working conditions of the interface are diversified, thermal distortion and contact conditions are interactive and coupled. All of the factors make the problem of thermal contact resistance complex. The factors are as follows.

1) Geometrical topographies in the interface:
- surface roughness;
- surface waviness;
- surface deviation;
- asperity shape, size and quality.

2) Load conditions:
- contact pressure;
- loading history.

3) Temperature conditions:
- mean interfacial temperature;
- heat flux and direction of heat flow;
- heating history.

4) Material properties:
- thermophysical properties of contact solid materials;
- thermophysical properties of interstitial materials.

5) Interfacial contact conditions:
- sliding contact in the interface or not;
- other mediums in the contact surface or not.

3 EXPERIMENTAL

3.1 Experimental system of thermal contact resistance

A set of TCR(thermal contact resistance) experimental system under high-temperature and high-pressure conditions is designed, which aims at the interfacial characteristics of continuous roll casting process, as shown in Fig. 2. First, the heater heats the pure aluminum bar, and then heat flows across the interface to steel bar, so thermal contact resistance is formed in the interface. The variation ranges of experimental parameters are approximately as following: heating voltage ranges from 0 V to 220 V, contact pressure ranges from 0 MPa to 118.4 MPa, average surface temperature ranges from 50 ℃ to 300 ℃, the total error about the experimental system is approximately ±4.5%.

Voltage adjustor is used to control output voltage to obtain different contacting surface temperatures. The signals are collected by thermocouples and then are conveyed through thermo-switch apparatus to data gathering instrument, whereafter the signals are stored in the personal computer, so the temperature distribution conditions of every points in the specimens at different interfacial temperatures are obtained. The load can be changed by adjusting the hydraulic pressure device, then the data are gathered when steady state reaches, so the temperature distribution conditions of every points of the specimens at different contact pressure are obtained.

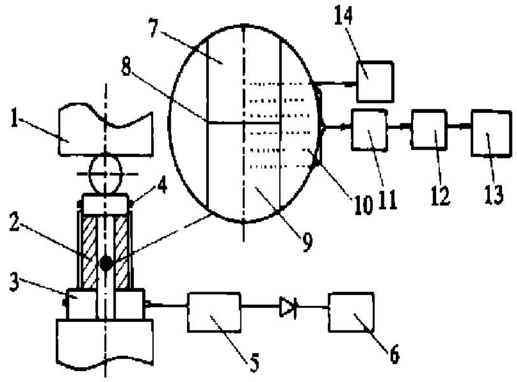

Fig. 2 Experimental system of thermal contact resistance

1—Hydraulic pressure device (with pressure monitor); 2—Insulator; 3—Heater; 4—Cooler; 5—D. C. stabilizer; 6—A. C. power supply; 7—Specimen 1; 8—Interface; 9—Specimen 2; 10—Thermocouples; 11—Thermograph; 12—Data gathering instrument; 13—Personal computer; 14—UJ33 voltameter

3.2 Specimen preparation and relative thermophysical parameters measurement

Materials of specimens are steel (specimen 2) and pure aluminum (specimen 1). All of the specimens are 86 mm long by 25.4 mm in diameter. In order to obtain different surface roughness of specimens, the samples underwent different machining technologies. All surfaces were characterized utilizing a JB-1C profilometer. By assuming a Gaussian distribution of the surface heights[5], R_a value is provided for the surfaces, root-mean-square (RMS) surface roughness is used to represent the surface topography and the RMS value is determined by R_a as

$$\sigma = \sqrt{\frac{\pi}{2}} R_a \tag{3}$$

Three kinds of surface topographies were obtained. The RMS surface roughness of series A is 9.49 μm, series B is 10.85 μm and series C is 12.65 μm. The Brinell microhardness of softer specimen is measured using a HW187.5 sclerometer and the mean HB of aluminum is 80.1.

3.3 Results of experiments

1) Keeping the input voltage constant, the com-

bined RMS surface roughness of contact specimens belongs to series B, that is $\sigma = 10.85\ \mu m$, the experimental results with the variation of interfacial contact pressures are shown in Figs. 3 and 4.

2) Experiment data of thermal contact resistance at different RMS surface roughness are as shown in Figs. 5 and 6.

3.4 Analysis of experimental results

Based on the experimental data, a method of parameter estimate, in which a mean heat transfer coefficient is introduced, is utilized to handle the experimental data, then the calculating results are shown in Figs. 7 and 8.

Fig. 7 shows the interrelation between thermal contact conductance and contact pressure. An hysteresis loop is formed when the contact pressure is decreased following an increase. The conductance values under the process of decreasing pressure are higher

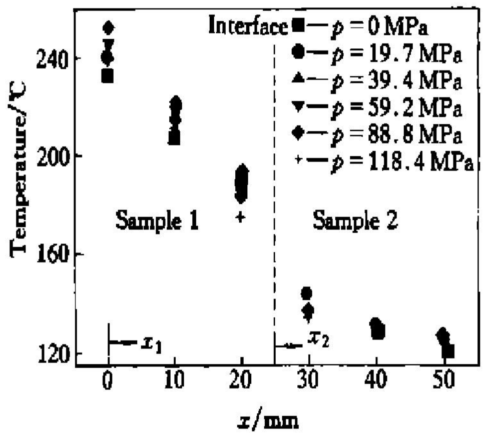

Fig. 3 Experimental results during loading

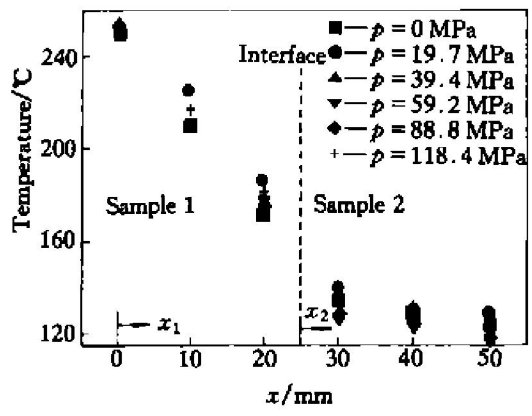

Fig. 4 Experimental results during unloading

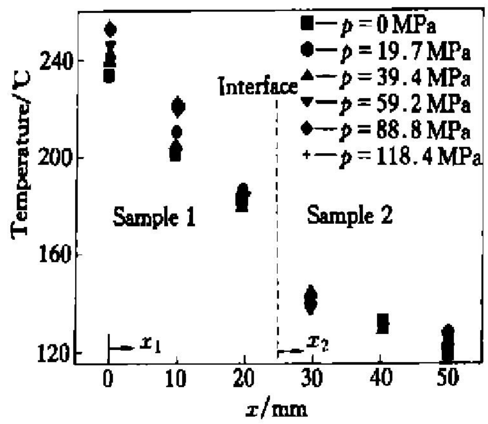

Fig. 5 Experimental results at $\sigma = 9.49\ \mu m$

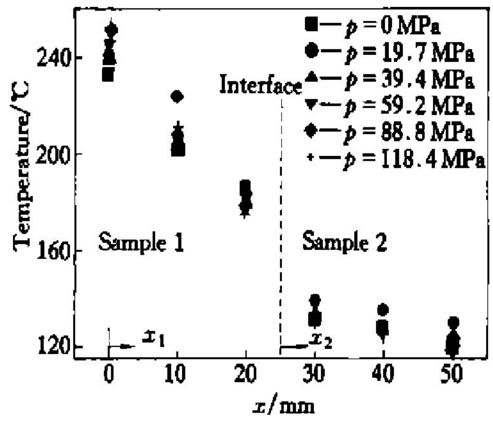

Fig. 6 Experimental results at $\sigma = 12.65\ \mu m$

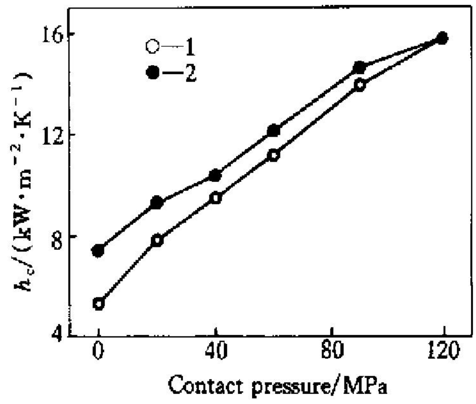

Fig. 7 Interrelation between thermal contact conductance and contact pressure

1—Loading; 2—Unloading

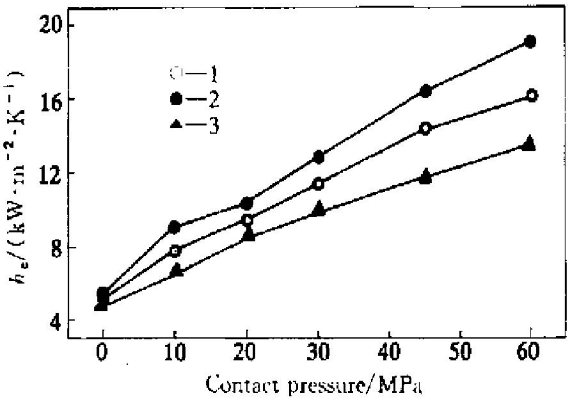

Fig. 8 Interrelation between thermal contact conductance and RMS surface roughness

1—$\sigma = 9.49\ \mu m$; 2—$\sigma = 10.85\ \mu m$; 3—$\sigma = 12.65\ \mu m$

than increasing one.

The interrelation between thermal contact conductance and combined RMS surface roughness of two contact specimens is shown in Fig. 8. It can be seen that RMS values of roughness will influence thermal contact conductance at a certain extend. Thermal contact conductance will increase with the decrease of RMS surface roughness.

4 MODELING FOR THERMAL CONTACT RESISTANCE

Madhusudana and Fletcher[4, 6, 7] proposed the following correlation for thermal contact conductance:

$$\frac{h_c\sigma}{k_m} = c\left(\frac{p}{h}\right)^n \tag{4}$$

where h_c is thermal contact conductance in kW/(m^2·K); σ is the combined RMS surface roughness of two surfaces in μm and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_1 and σ_2 are the RMS surface roughness of specimens 1 and 2, separately; k_m is harmonic mean of the thermal conductivities of the two contacting specimens in W/(m·K), $k_m = 2k_1k_2/(k_1 + k_2)$, k_1, k_2 is thermal conductivity of specimen 1 and 2 in W/(m·K), separately; p is contact pressure in MPa; h is microhardness of the softer material in MPa; c, n can be obtained from experiment.

When there is no external pressure exerted on the samples, there is only the weight of the upper sample in the interface, which is usually a constant. Considering the above condition, a surplus thermal contact conductance h_0 is introduced into Eqn. (4), that is

$$\frac{h_c\sigma}{k_m} = c\left(\frac{p}{h}\right)^n + \frac{h_0\sigma}{k_m} \tag{5}$$

In order to simplify the calculate process, Eqn. (5) is changed into the following form under the hypothesis that the thermophysical parameters k_m and h of specimens keep constant during contact heat transfer procedure.

$$y = f(x_1, x_2; b_1, b_2, b_3) = \frac{b_1}{x_1}\left(\frac{x_2}{h}\right)^{b_2} + \frac{b_3}{x_1} \tag{6}$$

where y represents thermal contact conductance h_c; x_1, x_2 delegate RMS surface roughness σ and contact pressure p, respectively; b_1, b_2, b_3 are the pending coefficients, separately.

As for this nonlinear problem, direct solution is impossible to get. A method of gradually draw near is adopted in numerical computation[8]. According to experimental data, initial value $b_{01} = 10^{-4}$, $b_{02} = 1$, $b_{03} = 5$ of pending coefficients b_1, b_2, b_3 are taken, respectively. At last $b_1 = 9.42 \times 10^{-5}$, $b_2 = 0.84$, $b_3 = 5.84$ are obtained through computation[9]. Then the following correlation is got:

$$y = \frac{9.42 \times 10^{-5}}{x_1}\left(\frac{x_2}{h}\right)^{0.84} + \frac{5.84}{x_1} \tag{7}$$

Transform it into a general form, that is

$$\frac{h_c\sigma}{k_m} = 1.57 \times 10^{-3}\left(\frac{p}{h}\right)^{0.84} + 0.92 \times 10^{-3} \tag{8}$$

The calculating results are compared to the experimental data, as shown in Fig. 9, they in general agree with each other. So the model is reliable to the experimental conditions.

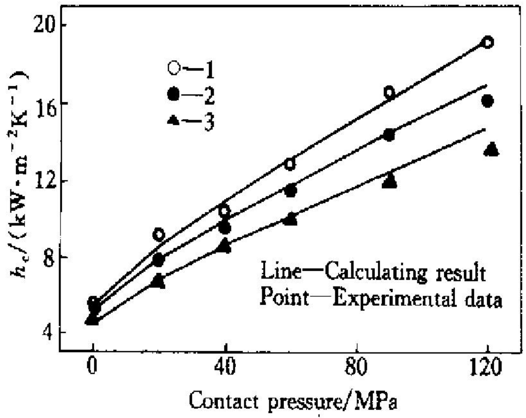

Fig. 9 Interrelation between thermal contact conductance and RMS surface roughness
1—σ = 9.49 μm; 2—σ = 10.85 μm; 3—σ = 12.65 μm

There is relative sliding in the interface between the shell of solidified metal and casting roller under the condition of solidification and plastic rheology during continuous roll casting. There is a neutral surface in the rolling zone, and the flow direction is changed at the front and back of neutral surface. And the sign of friction force is changed immediately, then a great break will be appeared. So there is not only thermal contact resistance but also friction heat in the interface (as shown in Fig. 10), and they are interactive.

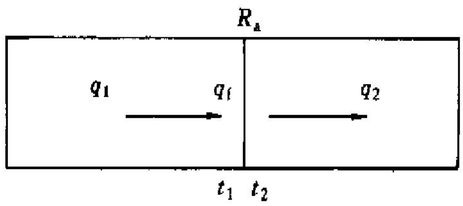

Fig. 10 Heat transfer in interface

Consequently thermal contact conductance needs to be modified. Considering frictional heat in per area is[10]:

$$q_f = F \cdot V \tag{9}$$

where F is friction force of the interface, $F = m\tau_k \cdot (2\tan^{-1}[V/c])/\pi$, here m is friction factor, usually takes 0.4; τ_k is the submit limit of shear; V is the relative sliding velocity between the interface; c is the transition speed from sliding friction state to adhesive friction state.

From Ref. [11], according to the idea of divided thermal contact resistance, so total thermal contact resistance is departed into two parts: one is determined by the thermophysical properties and surface states of sample 1, the other is determined by those of sample 2. There is a dummy temperature t_3 between the two parts and friction heat q_f is produced in the interface. A modified coefficient E is introduced as following:

$$E = \frac{h'_c}{h_c} = \frac{(q_1 + q_f)(t_1 - t_2)}{(t_1 - t_2)q_1 + (t_1 - t_3)q_f} = \frac{1 + q_1/q_f}{\frac{t_1 - t_3}{t_1 - t_2} + \frac{q_1}{q_f}} \quad (10)$$

where h'_c is thermal contact conductance considering friction heat in the interface.

5 CONCLUSIONS

1) A set of experimental systems for thermal contact resistance under the conditions of high temperature and high pressure is set up, in which contact pressure ranges from 0 MPa to 118.4 MPa, mean interface temperature ranges from 50 ℃ to 300 ℃.

2) The model of thermal contact conductance under the conditions of high temperature and high pressure is put forward by theoretical and experimental investigation. Because relative slip exists between solidification shell of the metal and the surface of the roller during continuous roll casting, the idea of divided thermal contact resistance is introduced to modify the proposed model, then the interfacial TCR model, which suits to the special conditions of ‘high temperature + plastic rheology’ and frictional contact such as in continuous roll casting, is established.

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(Edited by HE Xue-feng)