DETERMINING CONTACT THERMAL RESISTANCE FOR UNSTEADY HEAT TRANSFER BETWEEN TOUCHING BODIES

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A procedure for determining the contact heat transfer coefficient from the amount of heat received by a body during the transient state between touching bodies is proposed. The results obtained by way of experimental verification agree with data obtained under steady-state heat transfer conditions.

The contact heat transfer coefficient is usually determined by the procedure of [1, 2] based on measuring the temperature drop in the specimens under investigation during a steady-state thermal process.

Graphic linear extrapolation is employed to find the temperature head in the contact zone, after which the heat transfer coefficient is determined from the relation

$$\alpha = \frac{q}{\Delta t}. \tag{1}$$

Engineers often need to investigate heat exchange between touching bodies for short periods of contact and considerable specific pressures (as in pressure working of metals, cutting, etc.). In this case the touching bodies experience an unsteady thermal process, which precludes the use of the above procedure for estimating heat transfer.

The brevity of contact (whose duration may range from hundredths of a second to several seconds) as well as the high values of the contact heat transfer coefficient enable us to regard the touching bodies as semi-infinite.

The amount of heat received by the cooler body during the period of contact with thermal resistance in the contact plane is given by the following relation obtained by Ivantsov [3]:

$$Q_1 = \alpha F \tau (t_2 - t_1) \left[\frac{2}{\sqrt{\pi}\sqrt{a_1 h_1^2 \tau}} - \frac{1}{a_1 h_1^2 \tau} \left(1 - \exp a_1 h_1^2 \tau \operatorname{erfc} \sqrt{a_1 h_1^2 \tau}\right) \right],$$

$$Q_1 = \alpha F \tau (t_2 - t_1) f(a_1 h_1^2 \tau); \tag{2}$$

$$h_1 = \frac{\alpha (1 + k_\varepsilon)}{\lambda_1}; \tag{3}$$

$$k_\varepsilon = \sqrt{\frac{\lambda_1 \gamma_1 c_1}{\lambda_2 \gamma_2 c_2}}. \tag{4}$$

Substituting (3) into (2) and carrying out some transformations, we obtain

$$Q_1 = \alpha F \tau (t_2 - t_1) f(A \alpha^2), \tag{5}$$

where

$$A = \frac{a_1 (1 + k_\varepsilon)^2 \tau}{\lambda_1^2}. \tag{6}$$

Equation (5) yields the value of the nominal heat transfer coefficient during the contact period,

$$\alpha_{\text{nom}} = \alpha f(A\alpha^2) = \frac{Q_1}{F \tau (t_2 - t_1)}. \tag{7}$$

In fact, it is the temperature difference $(t_2 - t_1)$ which varies during the contact period, while the contact heat transfer coefficient α remains constant. However, the computed result is not affected if we combine the function $f(A\alpha^2)$ with the heat transfer coefficient and denote their product by α_{nom} as in (7).

Having determined calorimetrically the amount of heat received by the cooler body, we can use Eq. (7) to find α_{nom}.

In order to find α we plotted α_{nom} as a function of α for several values of A.

The quantity A is readily computable, since the quantities appearing in (6) are known from the experimental conditions.

Thus, α can be computed from the amount of heat received by the body by using relations (6) and (7) and a graph (Fig. 1).

POSSIBLE SOURCES OF ERROR

1. Equation (2) was derived under the assumption that the two bodies are semi-infinite. In reality, the touching bodies have a finite side surface, which makes it necessary to allow for the cooling of the calorimetrized body from the side surface during the periods of contact and transportation to the calorimeter. The magnitudes of these losses can be determined by computation and then added to the quantity Q_1 in expression (7).

2. If the calorimetrized body is subjected to plastic deformation at the instant of contact, it is necessary in using (7) to subtract in advance from Q_1 the amount of heat generated in the body as a result of conversion of the energy of plastic deformation into heat.

3. The initial temperatures of the bodies should be measured directly before the start of contact. If this is not feasible, a correction must be introduced to allow for the cooling of the body from the instant of measurement to the start of contact.

4. The contact duration should not exceed several seconds, since the curvature of the curves in Fig. 1 decreases with increasing time (i.e., with increasing values of A), especially for large α, and this reduces the accuracy of determining α.

EXPERIMENTAL VERIFICATION OF THE METHOD

Determination of thermal contact resistance by the calorimetric method was tested with Kh18N10T and

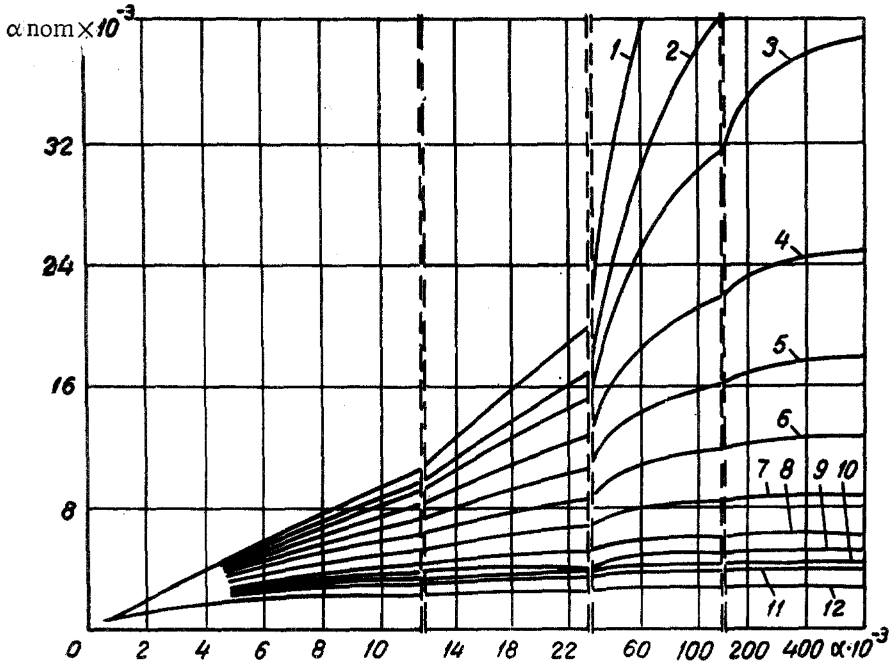

Fig. 1. The nominal heat transfer coefficient α_{nom} (W/m^2 · °K) as a function of the contact heat transfer coefficient α (W/m^2 · °K) for several values of A (m^4 · degrees^2/W^2): 1) $A \cdot 10^8 = 0.74 \cdot 10^{-2}$; 2) 0.037; 3) 0.074; 4) 0.185; 5) 0.37; 6) 0.74; 7) 1.5; 8) 3; 9) 4.5; 10) 5.9; 11) 7.4; 12) 15.

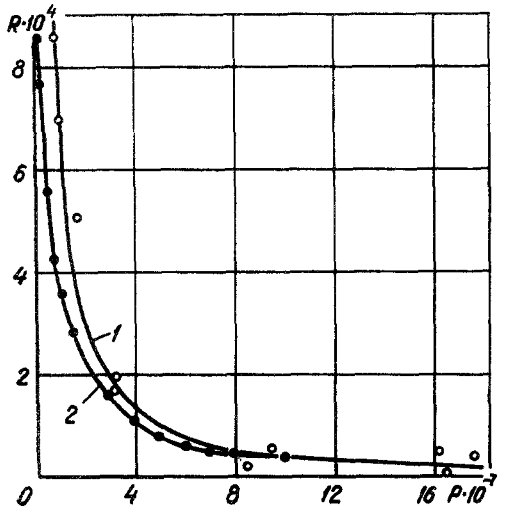

Fig. 2. Thermal resistance R_t (m^2 · °K/W as a function of the compressing force P (N/m^2): 1) calorimetric method; contact materials: Kh18N10T steel-Kh18N10T steel; surfaces: ∇^3-∇^3; 2) steady-state method according to the data of [1]; contact materials: 1Kh13 steel-1Kh13 steel; surfaces: ∇^3-∇^3.

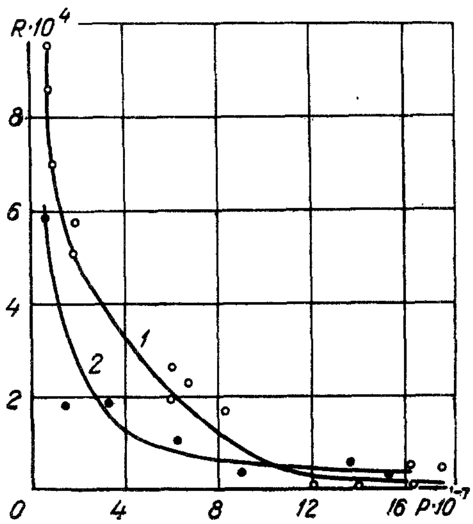

Fig. 3. Effect of contact temperature on the dependence of the thermal resistance R_t (m^2 · °K/W) on the compressing force P (N/m^2). 1) Contact temperature = 100°; 2) 200°.

St. 3 steel specimens 40 mm in diameter and 60 mm long, with class 3 surfaces.

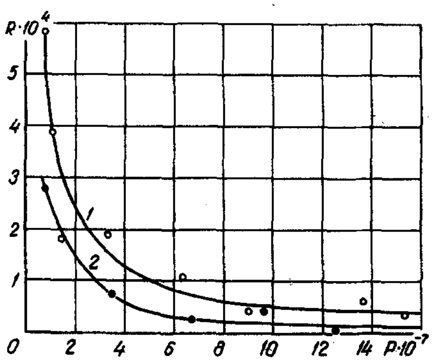

Fig. 4. Thermal resistance R_t ($m^2 \cdot {}^\circ K/W$) as a function of the compressing force P (N/m^2) for a Kh18N10T steel-Kh18N10T steel contact: (1) in the absence of and (2) with a lubricant in the contact cavity.

One of the specimens was heated to the required temperature in an electrical tube furnace; the other ("cold") specimen was at the temperature of the water in the calorimeter vessel.

The specimens were then brought in contact and pressed together in an IMCh-30 testing machine.

When the required time had elapsed, the "cold" specimen was placed in the calorimeter. The change in the calorimeter water temperature was measured with a metastatic thermometer to within 0.001° K with allowance for the appropriate corrections. The total force used to compress the specimens was recorded during the contact period.

Because of the inherent lag of the testing machine, the prescribed pressure was established 5–8 sec after the start of compression. Hence, in order to obtain a stable compressing force we extended the total contact duration to 15–18 sec. In treating the experimental data we computed the total force as the mean integral force over the time. The heat flux through the side surface of the calorimetrized specimen during the periods of contact and transportation to the calorimeter were determined by computation. In our case it turned out to be 1–1.5% of the amount of heat received by the specimen.

Comparison of our results (Fig. 2) with previously published data [1] obtained under conditions of steady-state heat exchange indicated a similar dependence and close values of the thermal contact resistance. The thermal resistance was somewhat higher in our case due to the lower thermal conductivity of Kh18N10T steel as compared with that of 1Kh13 steel.

Figure 3 shows the effect of junction temperature on the dependence of the thermal resistance on contact pressure for Kh18N10T steel. We see from this that within a certain range of pressures, increases in the junction temperature tend to decrease the contact thermal resistance. However, with further increases in pressure the effect of junction temperature on thermal resistance decreases, and is practically nonexistent at higher pressures. A similar picture was noted in the case of the St. 3 steel specimens.

We also investigated the effect of a liquid lubricant containing graphite, lime, and sodium nitrate on contact conduction. The results (Fig. 4) indicate that the presence of a liquid lubricant over the contact area reduces contact thermal resistance markedly.

Our results on thermal resistance are in good agreement with those of [1, 2] obtained under steady-state heat transfer conditions. We therefore recommend our procedure for investigating heat exchange under short-term contact conditions.

NOTATION

α is the contact heat transfer coefficient: q is the steady-state heat flux in the specimen; Δt is the temperature head at the junction; Q_1 is the amount of heat acquired by the body; t_1 and t_2 are the initial temperatures of the first and second body; λ, γ and c are the coefficient of thermal conductivity, the specific weight, and the specific heat of the body material; a is the thermal diffusivity; τ is the duration of contact; F is the geometric area of the contact junction; k_ε is the criterion of thermal activity of one body relative to that of the other.

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