THERMAL RESISTANCE OF CONTACTS COATED WITH LOW CONDUCTIVITY MATERIALS

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Results are presented of an experimental study of thermal resistance in contacts with a ceramic coating in a vacuum and a gaseous medium. Thermal resistance of contact is determined as a function of coating thickness and thermal conductivity.

In construction of energy devices one often meets the problem of producing high values of contact thermal resistance, particularly in the construction of heat insulating devices for various purposes. Contacts with a ceramic coating are of great interest in this connection, since they may be utilized at high temperatures. The present study will investigate such coatings.

The experimental apparatus used in the study consisted of a vacuum chamber with a model for study of contact heat transfer, vacuum pumps, gas cylinders, a lever system to generate compressive loads, and the measurement equipment.

The experimental specimens were cylinders 35 mm in diameter and 20 mm high, or parallelopipeds $43 \times 43 \times 20$ mm. Some specimens were prepared from sheet material 0.5-3.0 mm in thickness.

Experiments were conducted in a vacuum with absolute pressure 10^{-4} mm Hg and in helium at a pressure of about 1300 mm Hg. Maximum contact pressure was 30×10^5 N/m^2.

Both thermal flux and temperature drop over the contact were determined by three or four groups of thermocouples, producing more reliable values of contact thermal resistance R_c, calculated from the formula

$$R_c = \frac{\Delta t_c}{q}.$$

The error in calculation of R_c comprised about 12%.

Experiments were performed with the following pairs of materials: molybdenum–graphite, molybdenum–graphite with coating of aluminum oxide (Al_2O_3), molybdenum–graphite with coating of ceramic alloy 85% BeO + 15% Al_2O_3 (by weight). The mean height of surface microinhomogeneities on the contact surfaces of the molybdenum, graphite, aluminum oxide, and ceramic specimens was 1.07, 62, 55, and 57 μ respectively (calculated from profilogram).

The experimental data are presented in Fig. 1 in the form of R_c as a function of contact pressure at constant temperature in the contact zone, 580 ±10°C.

The low R_c values for the molybdenum–graphite pair are explained by the high conductivities of the two materials and the relatively low hardness of the graphite.

Coatings of aluminum oxide and ceramic alloy were placed on the graphite surface by vacuum sputtering.

The thermal resistance R_c of the molybdenum–graphite pair with Al_2O_3 coating in a vacuum is approximately 8-10 times higher than that of the uncoated pair, because of the low conductivity and greater hardness of the aluminum oxide in comparison to the graphite.

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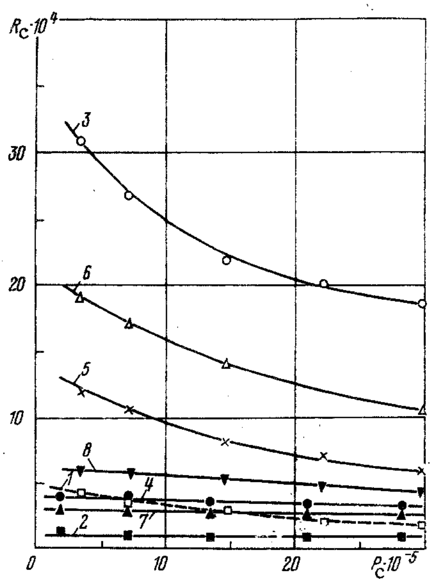

Fig. 1

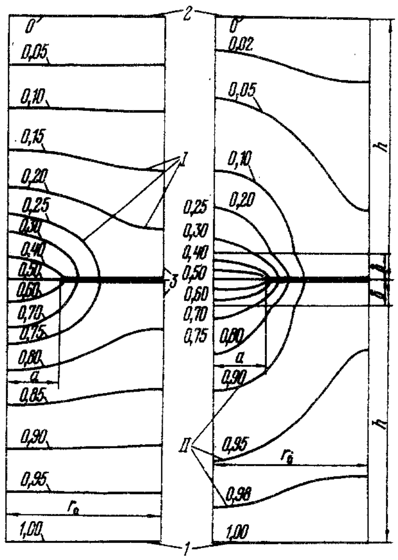

Fig. 2

Fig. 1. Contact thermal resistance versus compression for molybdenum—graphite without and with coverings at constant temperature in contact zone t_c = 580°C: 1, 2) molybdenum—graphite in vacuum and helium, respectively; 3-5) molybdenum—graphite with Al_2O_3 coating, δ = 300 μ; 3) in vacuum; 4) in helium; 5) in vacuum with copper foil in contact; 6-8) molybdenum—graphite with ceramic alloy, δ = 300 μ; 6) in vacuum; 7) in helium; 8) in vacuum with copper foil in contact. R_c, $m^2 \cdot deg/W$, P_c, N/m^2.

Fig. 2. Isotherms in surface contact zone of elementary thermal channel with r_0/a = 3.0; h/a = 5.0, where r_0 is radius of equivalent cylinder; a, contact spot radius, and δ, coating thickness. 1) Surface with temperature t_{max}; 2) t_{min}; 3) adiabatic surfaces; I) isotherms for surface contact without coating; II) isotherms with coating, m = 0.5, Λ = 5.0. Numbers on curves are dimensionless temperature; abscissa, r; ordinate, z.

The R_c values for the coated pairs (curves 3-8, Fig. 1) include the thermal resistance of the 300 μ coating, which can be determined from the known heat conductivity coefficient. Taking the coefficient values presented in [1], we find the thermal resistance of the contact is (0.25-0.30) $\times 10^{-4}$ $m^2 \cdot deg/W$, approximately 1% of the value of R_c in vacuum and 6-10% of R_c in helium. It should be noted that the thermophysical properties of coatings obtained by the vacuum sputtering method [2] may differ significantly from the results of other studies [3] and the data presented in [4].

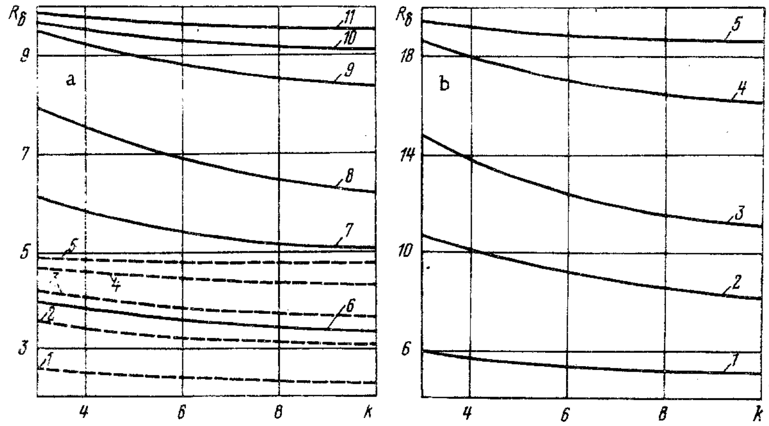

Fig. 3. Effect of contact geometry on R_δ: a) at Λ = 5.0 and Λ = 10 (1, 2, 3, 4, 5—Λ = 5.0; m = 0.10, 0.25; 0.50; 1.0 and 2.0; 6-11) Λ = 10; m = 0.10; 0.25; 0.50; 1.0; 1.50 and 2.0); b) at Λ = 20 (1, 2, 3, 4 and 5—m = 0.10, 0.25; 0.50; 1.0 and 2.0).

For the molybdenum—graphite pair with the ceramic alloy coating the thermal contact resistance in vacuum is approximately 75% lower than that of the pair with aluminum oxide coating, which is explained by the higher conductivity of the ceramic alloy in comparison to aluminum oxide.

For contact operation in a helium atmosphere the major portion of the thermal flux flows through the gas layers filling the spaces between microprojections of the contacting surfaces. Since the sum $H_1 + H_2$ of the mean height of microprojections of the roughness of the contacting surfaces for both pairs with coatings is practically identical (the indices 1 and 2 refer to the two contacting surfaces), the R_c values are also similar.

Also studied were coated pairs with a copper foil 50 μ in thickness introduced into the contact. Introduction of the foil reduced R_c in vacuum by a factor of 2.5-3.0.

It must be noted that the relationship between R_c for pairs with the graphite coated and uncoated is determined not only by the values of the thermal conductivity coefficients, but also by various mechanical properties of the materials.

In theoretical studies of contact heat transfer it is usually assumed that the actual surface contact is formed by individual spots of circular shape, uniformly distributed over either the entire surface or over individual so-called contour areas [5, 6]. In this case the problem reduces to determination of the thermal resistance of a single contact, which may be calculated for surfaces without coatings from the formulas of [5]. The geometric parameters of the contact are calculated with the formulas of [7].

If discrete segments of actual surface tangency form a two-dimensional periodic contact, the thermal resistance of an individual contact may be calculated with the formulas of [8, 9].

In the presence of a coating of some other material on the contact surfaces the contact thermal resistance will depend on the coating thickness and the coefficient of thermal conductivity of its material.

We will consider an elementary cylindrical thermal channel (Fig. 2) with contact spot radius a and equivalent cylinder radius r_0, on the contact surfaces of which there exists a coating of thickness δ. The coefficient of thermal conductivity of the basic material is λ_1, that of the coating, λ_2.

It is assumed that there is no heat conductive material between the contact surface (vacuum conditions) and that the effect of thermal radiation is negligibly small.

We assume that the thermal flux is directed from surface 1 at a temperature of t_{max} to surface 2 at a temperature of t_{min}. If the coefficients λ_1 and λ_2 are independent of temperature, the problem of determining the stationary temperature field reduces to solution of the Laplace equation

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial z^2} = 0 \tag{1}$$

with the following boundary conditions (indices 1 and 2 on t refer to basic material and coating, respectively):

$$\begin{aligned}
&1)\ \text{at}\ z=0\quad t=t_{\max}\ \text{for all}\ r\ \text{from}\ 0\ \text{to}\ r=r_0;\\
&2)\ \text{at}\ z=h-\delta\quad t_1=t_2\ \text{and}\ \lambda_1\frac{\partial t_1}{\partial z}=\lambda_2\frac{\partial t_2}{\partial z}\ \text{for all}\ r\ \text{from}\ 0\ \text{to}\ r=r_0;\\
&3)\ \text{at}\ z=h\ \text{and}\ a<r<r_0\quad \frac{\partial t_2}{\partial z}=0;\\
&4)\ \text{at}\ z=h+\delta\quad t_2=t_1\ \text{and}\ \lambda_2\frac{\partial t_2}{\partial z}=\lambda_1\frac{\partial t_1}{\partial z}\ \text{for all}\ r\ \text{from}\ 0\ \text{to}\ r=r_0;\\
&5)\ \text{at}\ z=2h\quad t=t_{\min}\ \text{for all}\ r\ \text{from}\ 0\ \text{to}\ r=r_0;\\
&6)\ \text{at}\ r=0\quad \frac{\partial t_1}{\partial r}=0\ \text{and}\ \frac{\partial t_2}{\partial r}=0\ \text{for all}\ z;\\
&7)\ \text{at}\ r=r_0\quad \frac{\partial t_1}{\partial r}=0\ \text{and}\ \frac{\partial r_2}{\partial r}=0\ \text{for all}\ z;
\end{aligned} \tag{2}$$

8) in the plane of tangency (z = h) of the surfaces at $0 \leq r \leq a$ ideal contact is assumed, i.e., the thermal channel is considered to be a continuous body.

The thermal flux passing through the contact for any z within the basic material may be written as

$$Q = \int_0^{r_0} \lambda_1 \frac{\partial t_1}{\partial z} 2\pi r dr. \tag{3}$$

We define the thermal resistance of an individual contact without and with coating as

$$R_1 = R_{1max} - R_{1min},\ R_2 = R_{2max} - R_{2min}, \tag{4}$$

where R_{1max} and R_{2max} are the total thermal resistances of the channel without and with coating; R_{1min} and R_{2min} are the total thermal resistance of the channel with ideal contact ($a = r_0$) without and with coating.

In expanded form the expressions for R_1 and R_2 may be written as:

$$R_1 = \frac{t_{max} - t_{min}}{Q_1} - \frac{1}{\pi r_0^2} \cdot \frac{2h}{\lambda_1},$$
$$R_2 = \frac{t_{max} - t_{min}}{Q_2} - \frac{1}{\pi r_0^2} \left(\frac{2h - 2\delta}{\lambda_1} + \frac{2\delta}{\lambda_2} \right), \tag{5}$$

where Q_1 and Q_2 are the thermal fluxes for the channel without and with coating.

We introduce the following dimensionless variables:

$$m = \frac{\delta}{a},\ n = \frac{h}{a};\ k = \frac{r_0}{a};\ \Lambda = \frac{\lambda_1}{\lambda_2};\ T = \frac{t - t_{min}}{t_{max} - t_{min}};$$
$$q_1 = \frac{Q_1}{(t_{max} - t_{min}) \lambda_1 a};\ q_2 = \frac{Q_2}{(t_{max} - t_{min}) \lambda_1 a};\ R_\delta = \frac{R_2}{R_1}. \tag{6}$$

Using Eq. (5) and the dimensionless variables of Eq. (6), the quantity R_δ may be represented by

$$R_\delta = \frac{q_1}{q_2} \cdot \frac{1 - [n + m(\Lambda - 1)] q_2 \dfrac{2}{\pi k^2}}{1 - \dfrac{2n}{\pi k^2}}. \tag{7}$$

This problem was solved numerically by the method of [10] on an electronic computer. The temperature distribution for the thermal channel presented in Fig. 2 was found as the solution of the thermal conductivity equation for which the condition is approximately fulfilled that the derivative of temperature with respect to time is equal to zero for all elementary volumes of the thermal channel.

The increments Δr in r and Δz in z were set equal. The relationship between increments in coordinates and time was chosen to satisfy the condition of stability of the finite difference system in cylindrical coordinates.

Calculations of the temperature field, thermal flux, and values R_1, R_2 and R_δ were made for four different ratios Λ of the conductivity coefficients of base material and coating: $\Lambda = 2$, 5, 10, and 20. For each Λ value R_δ was determined as a function of relative radius $k = r_0/a$ of the equivalent cylinder for various values of relative coating thickness. The geometric parameters m and k were varied within the limits $m = 0.1$-2.0; $k = 3$-10.

For each thermal channel variant the stationary temperature field and the thermal flux through the contact were calculated. As an example, Fig. 2 shows isotherms of surfaces without and with coatings ($\Lambda = 5.0$; $m = 0.5$) for a thermal channel with geometric parameters $k = 3.0$, $n = 5.0$.

Introduction into the contact zone of material with a low coefficient of thermal conductivity leads to increase in temperature gradient and increased contact thermal resistance. On the boundary between base material and coating the isotherms have a characteristic break, produced by change in the value of the coefficient of thermal conductivity.

Figure 3a, b shows the dimensionless contact thermal resistance R_δ as a function of the geometric parameter k for various values of relative coating thickness. With increase in k the thermal resistance of the coated contact increases somewhat more slowly than that of the uncoated contact, because of the different character of the contraction of the flux lines into the actual contact spot. A decrease in R_δ with growth in k occurs basically at small values of k.

With increase in relative coating thickness the effect of the parameter m on the value of R_δ decreases, since the contribution of the basic material to the value R_2 becomes insignificant and consequently, the value of R_δ is determined mainly by the ratio of the conductivities Λ.

It is necessary to stress that the basic contribution to thermal resistance is given by the material located near the contact spot. Thus even a coating of low thickness may significantly change the thermal resistance.

We note that high effectiveness of coatings with thickness several times smaller than the actual contact spot radius also occurs in the case where $\Lambda < 1.0$ ($\lambda_1 < \lambda_2$), i.e., for deposition of coatings to reduce thermal resistance. This case has been considered in [11].

Calculations have shown that R_δ as a function of Λ in logarithmic coordinates may be approximated with sufficient accuracy by straight lines whose slope is dependent on the geometric parameters m and k. In connection with this, an approximate value of R_δ for any value of Λ and given m, k can be obtained from the condition

$$R_\delta = \Lambda^{\frac{\lg R_\delta^*}{\lg \Lambda^*}},$$

where R_δ^* is the known value of R_δ for a given thermal conductivity ratio Λ. For the value R_δ^* the values of R_δ presented in Fig. 3 for $\Lambda^* = 5$, 10, 20 may be used.

With known R_δ for a thermal channel with given geometric parameters m and k the thermal resistance of a single coated contact is determined by the product

$$R_2 = R_\delta R_1,$$

where R_1 may be calculated by the formulas of [5].

According to the results of this present study the thermal resistance R_1 of a single uncoated contact proved to be 5-7% higher than indicated by the formulas of [5], which were obtained for a thermal channel of infinite dimensions in the directions z and $-z$.

The author's studies were performed at $h = (1.0\text{-}1.5)\, r_0$. Calculations show that further increase in h has practically no effect on R_1. For example, for a change in the dimensionless parameter h/a from 3 to 7 at $r_0/a = 3$ the value of R_1 changed less than 1%. Such a weak effect of the parameter h/a also affects the thermal resistance R_2 of a single coated contact and consequently, the value of R_δ.

In connection with this, it may be assumed that the values of R_δ presented here for a thermal channel of finite dimensions in the directions z and $-Z$ do not differ in practice from those for a channel with infinite z dimension.

The values R_1 and R_2 determine the thermal resistance of the contact in a vacuum. If a heat conducting medium is present in the contact gap its effect may be considered with the formulas of [5].

NOTATION

P_c	is the specific compressive load (contact pressure);
t_c	is the temperature at contact zone;
H	is the mean height of microinhomogeneities of contact surfaces;
λ_1, λ_2	are the coefficients of thermal conductivity of contact and coating materials;
r and z	are the coordinate axes;
a, r_0	are the actual contact spot radius and equivalent cylinder radius;
δ	is the coating thickness;
h	is the cylinder height;
t	is the temperature;
t_{max}, t_{min},	are the maximum and minimum temperatures of thermal channel;
$k = r_0/a$	is the relative equivalent cylinder radius;
$n = h/a$	is the relative cylinder height;
$m = \delta/a$	is the relative coating thickness;
$\Lambda = \lambda_1/\lambda_2$	is the ratio of contact material conductivity to coating conductivity;
$T = \frac{t - t_{min}}{t_{max} - t_{min}}$	is the dimensionless temperature;
Q	is the thermal flux;
R_c	is the thermal resistance of contact per unit area of surface in contact;
R_{1max}, R_{2max}	are the total thermal resistance of channel;
R_{1min}, R_{2min}	are the total thermal resistance of channel for ideal contact ($a = r_0$);

R_1, R_2	are the thermal resistances of individual contact;
$q_1 = Q_1/(t_{max}-t_{min})\lambda_1 a$;	
$q_2 = Q_2/(t_{max}-t_{min})\lambda_1 a$	is the dimensionless thermal flux;
$R_\delta = R_2/R_1$	is the dimensionless contact thermal resistance;

Subscripts

values with index 1	for the channel without coating,
index 2	for the channel with coating.

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