THE EFFECT OF SOFT-METAL COATINGS AND LININGS ON CONTACT THERMAL RESISTANCE

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UDC 531.212

The article presents the results of an experimental investigation of the thermal resistance of contacts with coatings and linings of soft metals (silver, copper) at compressive stresses of up to $56 \cdot 10^5$ N/m^2 over a temperature range of 250-600°C. The specimens were made of different kinds of stainless steel or of a molybdenum alloy.

One of the major problems in the manufacture of some types of systems for the conversion of thermal energy to electrical energy is the reduction in the thermal resistance of contacts that results from the discrete nature of the actual contact between the matched surfaces of machine components.

It is frequently impossible, for various reasons, to solder or weld two components into an inseparable junction, for which the contact thermal resistance is practically zero, and in such cases the thermal energy is transmitted by means of pressure contact.

The thermal conductivity of a contact between machined metal surfaces can be calculated from the formulas of [1], which were obtained by generalizing the experimental data of various authors. For contact heat exchange in a vacuum (disregarding the contribution of thermal radiation, the effect of which may be neglected in most cases), the following expression was obtained in [1]:

$$\alpha_{\mathrm{c}} = 8 \cdot 10^3 \bar{\lambda}_{\mathrm{m}} \left(\frac{P_{\mathrm{c}}}{3\sigma_{\mathrm{B}}} k \right)^{0.86},$$

where σ_{B} is the ultimate strength of the weaker material of the contact pair; k is a coefficient which reflects the effects of the actual microgeometry and which increases as the degree of smoothness of the surface becomes higher [1]. The conductivity of the contact increases as the height of the microscopic projections of the surfaces decreases, but for many important design materials the value of α_{c} in a vacuum remains very low even when the surfaces have a high degree of smoothness. In this case the thermal conductivity of the contact can be increased by adding to the contact some material with higher conductivity and lower hardness

TABLE 1. Physical Properties of Some Metals Compared with Kh18N9T Stainless Steel

Material	Melting point, °C	Brinell hardness at normal temperature (HB, N/mm^2)	Coefficient of thermal conductivity, W/m·deg at various temperatures, °C		
			0	250	500
Lead	327	40–70	35	31	–
Aluminum	660	250–320	209	222	–
Silver	960	250	412	370	361
Copper	1083	800	394	375	360
Nickel	1453	1200–1500	67	56.8	50
Kh18N9T steel		1350–1850	15	18.2	21.7

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 17, No. 5, pp. 871-879, November, 1969. Original article submitted November 18, 1968.

TABLE 2. Geometric Characteristics of Contact Surfaces of Experimental Specimens

No. of specimen	Material of specimen	Type of treatment	Coating material and thickness, μ	Treatment of coating	Average height of microscopic irregularities, μ	Smoothness grade	Maximum nonplanarity, μ
1	Kh18N9T	Turning	–	–	1.8–2.0	∇8	3–7
2	Kh18N9T	The same	Silver, 25	–	1.8–1.9	∇8	20–40
3	Kh18N9T	"	Nickel, 25	–	1.7	∇8	5–12
4	Kh18N9T	Turning, lapping	–	–	0.6	∇10	0–1
5	Kh18N9T	Turning	Silver, 25	Lapping	1–1.15	∇9	8–11
6	Kh18N9T	The same	Copper, 25	Lapping	0.85–1	∇9	5–12
7	Kh18N9T	Grinding	–	–	1.20	∇9	0–1
8	VM-1	The same	–	–	1.08	∇9	2
9	Kh18N10T	Polishing	–	–	0.95–1	∇9	5–10
10	Kh18N10T	The same	Silver, 45	–	1.1	∇9	20–30
11	KhN78T	"	–	–	0.25–0.3	∇11	10–15
12	VM-1	Grinding	–	–	1.05	∇9	5

Note: 1. The average height of the microscopic irregularities and the nonplanarity for each specimen number are obtained from the results of measurements of four surfaces. 2. The contact area in specimens 1-8 is a circle of diameter 35 mm, while in specimens 9-12 it is a square measuring 43 × 43 mm.

than the materials of the bodies in contact. The results of investigations [2-4] indicate that such a method of reducing the contact thermal resistance is effective. Table 1 shows the physical properties of some materials that may be used as coatings and linings in order to reduce the contact thermal resistance.

It should be noted that in order to calculate the thermal resistance of contacts with coatings or thin linings, some correction must be made in the formulas for contact heat exchange that are proposed in [1] and other studies, since the deformation of dense coatings and linings is different in nature from the deformation of microscopic projections of machined surfaces. It should also be noted that when the contact surface has a coating of a different material, the region of contraction of the lines of thermal current to the spots of actual contact consists of two segments with different values of thermal conductivity, and consequently the thermal resistance of the contact will depend on the thermal conductivities of the base material and the coating material and on the ratio of the coating thickness to the radius of the contact spot.

The authors have conducted an experimental investigation of contact heat exchange on specimens of Kh18N9T stainless steel whose contact surfaces were coated with silver, copper, or nickel. In addition, we investigated contacts in which copper foil had been placed. The specimens were made of VM-1 molybdenum alloy, Kh18N9T stainless steel, and KhN78T stainless steel. Table 2 lists the specimens investigated and gives the most important data concerning them.

The experiments were carried out on a contact heat-exchange testing apparatus consisting of a vacuum operating chamber, vacuum pumps, a spring system for producing the compressive loading on the contact under investigation, cylinders of inert gases, regulating transformers, and measuring instruments.

The heat flux through the contact was produced by means of an electric heater and a water cooler. The lateral surfaces of the specimens were nearly adiabatic; this was achieved by means of shields and a compensation-heating electric heater positioned on one of the shields. The temperature in the various experiments ranged from 250-600°C. Chromel–Alumel thermocouples with an electrode diameter of 0.2 mm were used for measuring the temperature. The ends of the thermocouples were taken out of the operating chamber between rubber-lined flanged joints.

The compressive loading was produced by means of a spring system. The plunger used for transmitting the stress from the spring to the operating chamber was sealed with a Sylphon bellows which had a low degree of rigidity. In order to prevent the occurrence of a bending moment, the stress was transmitted from the plunger to the cooler through a small sphere of ShKh15 steel. The maximum contact pressure in the experiment was $56 \cdot 10^5$ N/m^2.

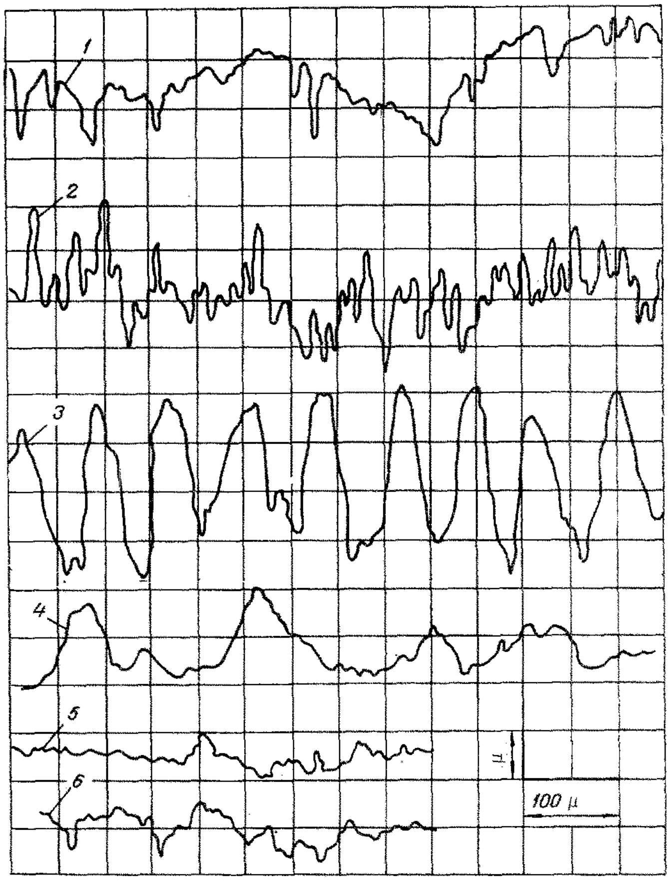

Fig. 1. Typical profilograms of contact surfaces of steel specimens without coatings and with unlapped coatings. 1) Turning, ∇8; 2) turning, ∇8, plus 25-μ silver coating; 3) turning, ∇8, plus 25-μ copper coating; 4) turning, ∇8, plus 25-μ nickel coating; 5) polishing, ∇9; 6) polishing, ∇9, plus 45-μ silver coating.

The experiments were conducted in a vacuum at a pressure of 10^{-4} mm Hg, with a surrounding medium of inert gas (helium) at a pressure of $1.8 \cdot 10^5$ N/m^2.

The value of the heat flux was determined from the temperature gradients on the measurement intervals of the cooler and the heater. The temperature drop at the contact was determined from the readings of four differential thermocouples whose junctions were fixed in special openings in the specimens at a distance of 2 mm from the contact plane. The thermal resistance of the contact was calculated from the formula

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

The experimental specimens were cylinders with a diameter of 35 mm and a height of 20 mm or parallelepipeds measuring 43 × 43 × 20 mm. In some experiments we used specimens of sheet steel (Kh18N10T) 0.6-0.8 mm thick. The contact surfaces of the specimens were worked by turning, grinding, and polishing.

Soft-metal coatings were applied to the contact surfaces of the stainless steel specimen by an electrochemical method, which ensured firm adhesion to the deposit to the underlying metal and made it easy to regulate the thickness of the coating.

When the coating is applied, the thickness must be kept uniform. The calculated value of the coating thickness gives an idea only of its average value. Actually, the coating is usually much thicker at the edges and corners of components than at the center of the surface [5]. The reason for the nonuniformity of the coating is the nonuniform distribution of current over the cross section of the specimen, which depends on

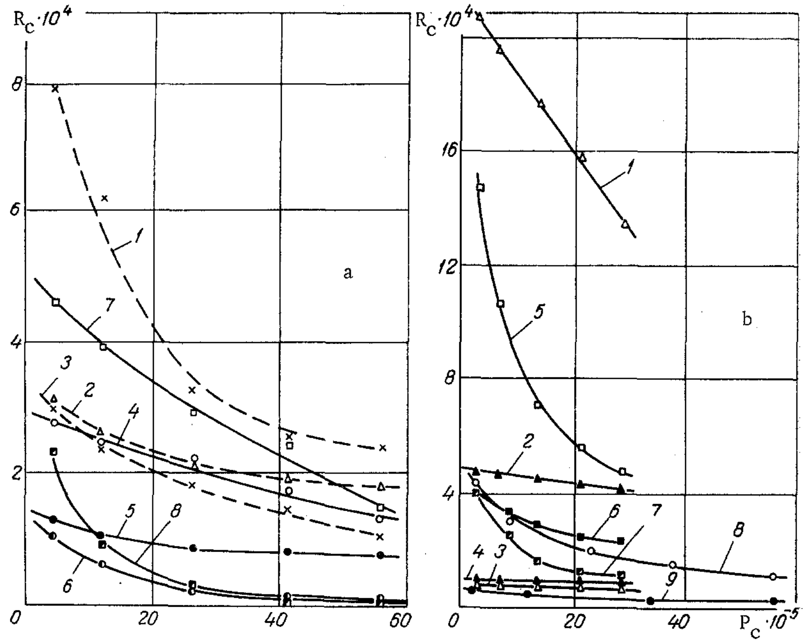

Fig. 2. Variation of R_c, $m^2 \cdot deg/W$, as a function of contact pressure (N/m^2) for pairs made of Kh18N9T steel (with and without coatings) in a vacuum at $t_c = 440\text{-}460$°C (Fig. 2a) and for different pairs (Fig. 2b): a: 1) Turning, ∇8; 2) turning, ∇8, plus nickel coating; 3) turning, ∇8, plus silver coating; 4) turning, ∇8, lapping; 5) turning, ∇8, plus silver coating, lapping; 6) turning, ∇8, plus copper coating, lapping; 7) grinding, ∇9; 8) the same, with copper foil in the contact; b: 1, 2, 3, 4) KhN78T – KhN78T, $t_c = 600$°C [1) in vacuum, without foil; 2) in vacuum, with copper foil; 3) in helium, without foil; 4) in helium, with copper foil]; 5) VM-1 – Kh18N10T, vacuum, $t_c = 500$°C; 6, 7) VM-1 – Kh18N10T, 45-μ silver coating, vacuum, $t_c = 500$°C [6) first variant of coating; 7) second variant of coating]; 8, 9) VM-1 – VM-1, vacuum; $t_c = 500$°C; [8) without foil; 9) with copper foil].

many factors, including the physicochemical properties of the electrolyte and the metal being deposited, as well as the conditions of the electrolysis.

The quality of the treatment of the surfaces was investigated with an M201 profilograph-profilometer. The average height of the microscopic irregularities was found by measurements within the limits of the basic length at three or four portions of the surface. Figure 1 shows typical profilograms for a number of surfaces with and without coatings.

From an analysis of the profilograms of the various surfaces, we can conclude that the microgeometry of the coating surface is determined to a large extent by the microgeometry of the underlying metal surface, but the height and shape of the microscopic irregularities may vary. It should also be noted that the various forms of coatings produce different effects on the microgeometry. Thus, for example, when a turned steel surface was coated with silver, the average height of the microscopic irregularities remained practically unchanged, although the thickness of the coating was 12-15 times the height of the microscopic irregularities. A similar result was obtained when the surface of a polished specimen of Kh18N9T steel (smoothness grade 9) was coated with silver. The surface was found to be somewhat less smooth when a copper coating was used, and better when a nickel coating was used.

The results of the experimental investigations are shown in Fig. 2 and Fig. 3 in the form of curves of contact thermal resistance as a function of the specific compressive loading and the contact temperature. As can be seen from Fig. 2a, a soft-metal coating on the contact surfaces of the stainless steel specimens results in a considerable reduction of the contact thermal resistance in every case. In the range of parameter values investigated – i.e., $t_c = 250\text{-}500$°C and $P_c = (4.8\text{-}56) \cdot 10^5$ N/m^2 – the value of R_c for the coated

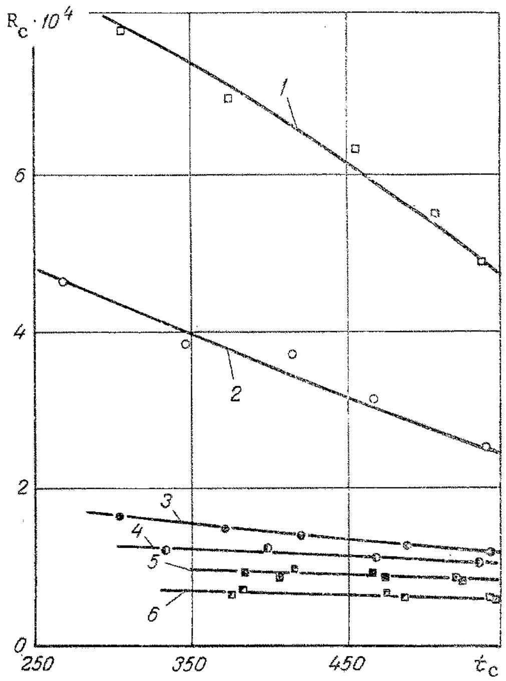

Fig. 3. Variation of R_c, $m^2 \cdot deg/W$, as a function of contact temperature, °C, at constant contact pressure: 1, 2, 3, 4) Kh18N9T – Kh18N9T, vacuum, $P_c = 4.8 \cdot 10^5$ N/m² [1) grinding, ∇9; 2) turning, ∇8, lapping; 3) turning, ∇8, silver coating, lapping; 4) turning, ∇8, copper coating, lapping]; 5, 6) VM-1 – Kh18N10T, 45-μ silver coating, helium, $P_c = 2.5 \cdot 10^5$ N/m² [5) first variant of coating; 6) second variant of coating].

contacts was lower by a factor of 2-10 than the value for the contacts with no coating. The contact thermal resistance was also lowered when a copper foil approximately 0.02 mm thick was inserted into the contact. As the contact pressure was increased, both the coatings and linings became more effective.

Increasing the contact pressure from $4.8 \cdot 10^5$ N/m² to $56 \cdot 10^5$ N/m² resulted, for most uncoated pairs, in a reduction of R_c by a factor of 2.7-3. For pairs with well-lapped coatings the contact thermal resistance was reduced practically to zero as the loading was increased (curve 6, Fig. 2a).

Increasing the height of the microscopic irregularities and the nonplanarity of the contact surfaces resulted in an increase in R_c, both for coated and for uncoated surfaces; when the nonplanarity of the surface was increased, the thermal resistance was found to be less affected by the contact pressure.

It can be easily seen from Fig. 2a that for lapped surfaces either with or without a coating the contact thermal resistance is only a fraction of its value for unlapped surfaces. The reason for this is that in the lapped surfaces the height of the microscopic irregularities and the nonplanarity were less (Table 2) than in the turned surfaces.

As the nonplanarity increased, the coatings became much less effective.

Figure 2b shows the results of experiments performed on a number of pairs whose surfaces had macroscopic irregularities of various kinds (nonplanarity, local thickening of the sheet metal, etc.). Even at fairly low contact pressures we observed a considerable reduction of the thermal resistance of contacts with copper linings.

Thus, for a KhN78T – KhN78T pair the insertion of a copper lining into the contact reduced the value of R_c by a factor of 3-5 for contact pressures of $P_c = (2.5\text{-}29) \cdot 10^5$ N/m² and temperatures of $t_c = 300\text{-}600$°C. When the nonplanarity of the specimen surface was 10-15 μ (Table 2), the contact thermal resistance was found to be relatively high, varying little with loading (by a factor of less than 2).

For comparison, Fig. 2b also shows the results of experiments on the same pair in helium. In this case the insertion of a copper lining into the contact did not reduce R_c but actually increased it somewhat. In the other experiments we observed either some increase (10-20%) or a very slight reduction of R_c when a copper lining was inserted into the contact. In the investigated range of contact pressures, linings in a gas medium with high thermal conductivity were found to have little effect. For a contact without a copper lining the value of R_c was less by a factor of 15-20 in helium than in a vacuum. This indicates that in this case the heat transfer at the contact takes place mainly through the gaseous interlayer.

For a VM-1–VM-1 pair in which the nonplanarity of the specimens was about 2 μ, inserting a copper lining into the contact led to a reduction of the contact thermal resistance by a factor of 5-6 for $P_c = (4.8\text{-}56) \cdot 10^5$ N/m^2 and $t_c = 500°C$. Even when the materials of the bodies in contact have high thermal conductivity, the insertion of a soft-metal lining considerably reduces the contact thermal resistance.

Thus, in [2] it was found that when lead or aluminum foil was inserted into the contact formed by an aluminum–aluminum pair, the contact thermal resistance in a vacuum was reduced by a factor of 2-4. The contact pressure did not exceed $2.5 \cdot 10^5$ N/m^2, and the total nonplanarity of the specimens in the contact pair was in the 43-114 μ range.

In order to verify the effect of a thickening of the electrochemical coating on the boundaries of the surface, we prepared two variants of specimens with silver coatings 45 μ thick. In the first variant, we first prepared specimens from Kh18N10T steel and then applied the coating. In the second variant, the specimen was cut from the central portion of a large sheet of metal coated with silver over its entire surface.

Both in the first and in the second variant, the coating was applied to a polished surface (smoothness grade 9).

Both the coated and the uncoated steel specimens had macroscopic deviations from a plane surface of the order of 10 μ, chiefly at the edges, as a result of the deformation of the material when the specimens were cut from the sheet.

The experiments showed that in all cases the thermal resistance of the contact was lower and changed more rapidly with loading for the second-variant specimens than for the first-variant specimens (Fig. 2b).

In the range of contact pressures investigated ($P_c = (2.5\text{-}29) \cdot 10^5$ N/m^2) the value of R_c was less by a factor of 4-5 for a VM-1–Kh18N10T pair with a silver coating (second variant) than for a VM-1–Kh18N10T pair with no coating.

The physical properties of the materials of the bodies in contact, as well as the coefficient of thermal conductivity of the gaseous medium filling the space between the microscopic projections, depend on the temperature. We therefore obtained experimental curves of R_c as a function of temperature for constant contact pressure. Some of the curves are shown in Fig. 3. In all cases we observed a reduction in the contact thermal resistance as the temperature increased, a fact explained by the reduction in the strength, and the associated hardness, of the materials. Another important factor is the variation in the thermal conductivity of the materials with temperature.

In curves 5 and 6 the most important factor causing a reduction of R_c with temperature is the increase in the thermal conductivity of helium.

The results obtained indicate that contact thermal resistances in a vacuum (even at relatively low compressive loadings) can be effectively reduced by applying thin linings or coatings of soft metal with high thermal conductivity to the matched surfaces.

NOTATION

α_c	is the thermal conductivity of contact;
R_c	is the thermal resistance of contact;
P_c	is the contact pressure (specific compressive loading);
t_c	is the temperature of contact;
Δt_c	is the temperature drop at the contact;
q	is the heat flux through the contact under investigation;
λ_m	is the thermal conductivity of the material;
$\bar{\lambda}_m = (2\lambda_{m_1}\lambda_{m_2})/(\lambda_{m_1} + \lambda_{m_2})$	is the converted thermal conductivity (where the subscripts 1 and 2 refer to the materials of the bodies in contact).

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