DETERMINATION OF THE THERMAL RESISTANCE IN VACUUM OF CONTACTS BETWEEN METALLIC SURFACES WITH VARIOUS DEGREES OF ROUGHNESS

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Inzhenerno-Fizicheskii Zhurnal, Vol. 11, No. 3, pp. 329–337, 1966

UDC 536.212

A measurement has been made of the thermal resistance in a vacuum of contacts between metal surfaces of various degrees of quality (from Class 5 to Class 10). Formulas have been obtained for calculating the thermal resistance of contacts, taking account of the degree of roughness. The experimental and theoretical data are in satisfactory agreement.

The problem of determining the thermal resistance between two surfaces reduces to finding the area of the actual contact. There are a number of formulas for determining S_a, based on various models of the surface [2]—rod-shaped, spherical, conusoidal, and ellipsoidal. In these models (apart from the ellipsoidal), the roughness is assumed to be the same in all directions. In fact, as may be seen from the catalog of surface quality [3], the heights of microprotuberances in the transverse and longitudinal directions are commensurate with regard to motion of the processing tool, while the pitch of the roughness in the longitudinal direction is greater than in the transverse, sometimes by a factor of several tens.

The existing formula for the thermal resistance of a metal contact [1],

$$R = \frac{3\sigma_{rot} S_n}{2.1\, P\lambda} \cdot 10^4 \qquad (1)$$

does not take account of the degree of roughness, and does not express quite correctly the dependence on the compressive force.

In this article an attempt has been made to obtain a formula which takes account of the quality of the actual surface. The conusoidal model of surface roughness is assumed. The different waviness in the transverse and longitudinal directions is accounted for by the fact that the diameter of the base of the cone is assumed equal to $\sqrt{lL}$. The values of the pitch of micro-roughnesses l and L may be determined from profilograms of the surface. or taken from the catalog [3]. The following assumptions have been made: 1) the heights of the micro-protuberances in the transverse and longitudinal directions are the same; 2) the diameters of the areas of contact are the same.

Taking into account that the distance between a rough and an absolutely smooth (and hard) surface is equal to the deformation of the highest protuberances ([1], p. 82), it is easy to obtain

$$d_1 = \sqrt{lL\,\delta\, H_{max}}. \qquad (2)$$

The amount of crumpling of a micro-protuberance, δ, is proportional to its height:

$$\delta = \varepsilon H_{max}. \qquad (3)$$

The relation between the relative separation, ε, and the relative area of contact, η, may be expressed by the formula [4]

$$\eta = b\,\varepsilon^{\nu}, \qquad (4)$$

which agrees well with experimental data.

Following substitution of the value of ε from (4) into (3), and further substitution of δ into (2), we obtain an expression in final form for the diameter of the region of contact

$$d_1 = \sqrt{lL}\,(\eta/b)^{1/\nu}. \qquad (5)$$

Since the actual area of contact is

$$S_a = m\,\frac{\pi}{4}\,d_1^2 = \eta S_n,$$

the number of contact regions per unit nominal area is determined to be

$$m_{spec} = 4\eta/\pi d_1^2. \qquad (6)$$

From (5) and (6) we find

$$m_{spec}\, d_1 = 4\eta^{(\nu-1)/\nu}\, b^{1/\nu}/\pi\sqrt{lL}. \qquad (7)$$

Taking into account the assumption regarding the circular shape of the region of contact, we may write for m_{spec} of the regions of contact [1]

$$R = 1/\lambda\, m_{spec}\, d_1. \qquad (8)$$

After substituting Eq. (7) into this expression, we obtain the final form of the formula for the specific thermal resistance of the pair of materials in contact as a function of the surfaces in contact and their compressive force:

$$R = \pi\sqrt{lL}/4\lambda\eta^{(\nu-1)/\nu}\, b^{1/\nu}. \qquad (9)$$

The thermal resistance of a stack of identical plates is equal to the sum of the thermal resistances of the pairs of contacts comprising the stack.

We shall simplify (9) by substituting for the numerical values of the coefficients b and ν. On the basis of Tables 6 and 9 in [4], we shall take b = 2 for surfaces of quality class 5–8, and b = 5 for surfaces of quality class beyond 8. We shall take coefficient ν equal to 3 for surfaces of quality class 5 and above.

The ratio of the actual area of contact to the nominal η, may be calculated from (4) according to the formula

$$\eta = \frac{P_{spec}}{C\sigma_T} + 2.7\,\frac{b^{1/\nu}\nu\rho}{H_{max}}\left(\frac{1-\mu^2}{E}\right)^2 \cdot (C\sigma_T)^{(1+\nu)/\nu}\,(P_{spec})^{(\nu-1)/\nu}. \qquad (10)$$

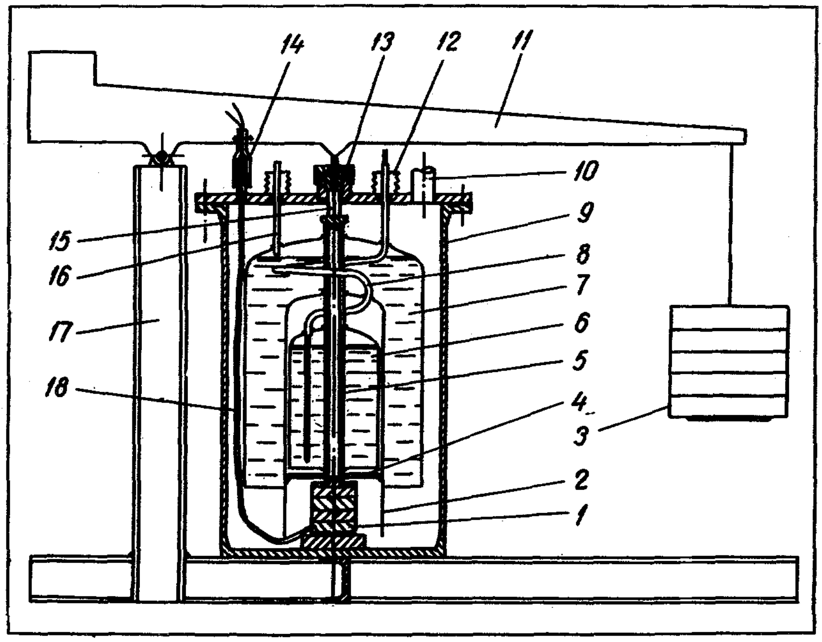

Fig. 1. Schematic of the instrument for measuring the thermal resistance in plane contacts.

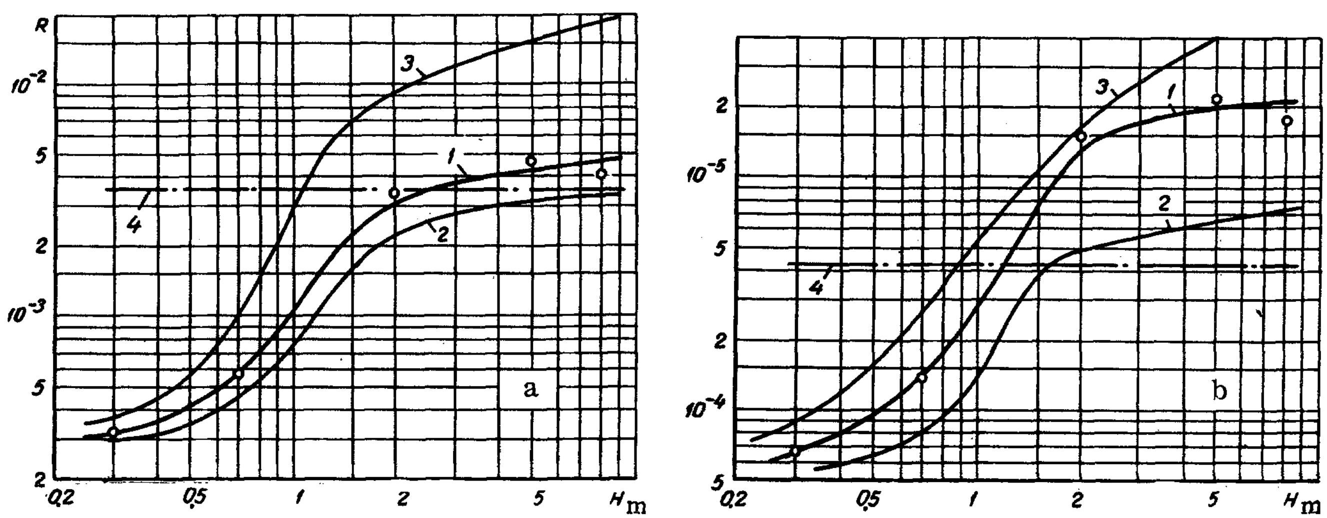

Fig. 2. Dependence of the thermal resistance R (degree · m^2/W) of a contact between metal surfaces on the level of roughness, H_m (μ), with P_{spec} = 3 Mn/m^2 (a), and 30 Mn/m^2(b); 1) test data for Kh18N9T and Kh21G7AN5 steels; 2) according to Eqs. (11) and (12); 3) according to (19); 4) according to (1).

The coefficient C in (10) is roughly equal to 2.6. The limit of fluidity is $\sigma_T \cong \sigma_{rot}$, since the micro-proturbances which are in contact are at the cold work limit.

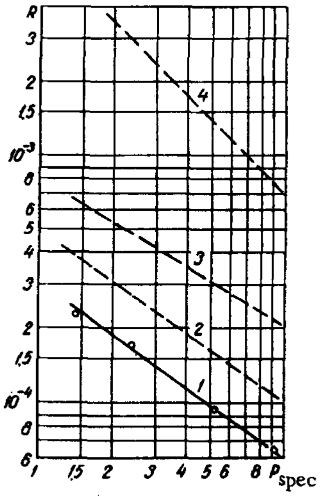

Fig. 3. Dependence of the thermal resistance R (degree · m²/W) of a contact between two plates of thickness 0.02 mm made of stainless steel on the specific pressure P_{spec} (Mn/m²), for a stack of 209 plates: 1) experimental data of [5]; 2, 3, and 4) according to Eqs. (12), (19) and (1).

For surfaces which are not very smooth, we can say, taking into account that there is elastic deformation of the micro-protuberances, that the second term is small in comparison with the first, which takes account of plastic deformation, and we may therefore neglect the second term.

As a result we obtain two formulas for calculating the specific thermal resistance of a metallic contact:

for surfaces of quality class 5–8

$$R = 1.18\,\frac{\sqrt{lL}}{\lambda}\left(\frac{\sigma_{rot}}{P_{spec}}\right)^{2/3}, \tag{11}$$

for surfaces of quality class 8

$$R = 0.46\,\frac{\sqrt{lL}}{\lambda}\,\frac{1}{\eta^{2/3}}. \tag{12}$$

Formulas (11) and (12) have been derived for the case of contact between two surfaces which have the same roughness and are fabricated from the same material.

We may also obtain a formula for calculating the specific thermal resistance of a metallic contact by using theory [2]. Assuming that the deformation of a micro-protuberance is plastic in nature, it is not difficult to obtain from the geometrical dimensions of a micro-protuberance

$$\delta^2 = \frac{P_1}{\pi C \sigma_T}\,\frac{4H^2_{max}}{lL}. \tag{13}$$

The total number of micro-protuberances on a rough surface is

$$M = S_n lL. \tag{14}$$

The number of micro-protuberances in direct contact, per unit nominal area, from the theory of [2], taking account of the equality $H_{cr} = H_{max} - \delta$ and of formula (14), is

$$m_{spec} = \frac{P_{spec}}{P_1} = \frac{1.1}{2lL}\left[\exp\left(0.7\cdot 2\,\frac{H^2_{max}\delta}{\alpha^2} - 0.7\,\frac{\delta^2}{\alpha^2}\right)\right]\Big/\left[\exp\left(0.7\,\frac{H^2_{max}}{\alpha^2}\right)\right], \tag{15}$$

where, according to [2], $\alpha = 1.99 \cdot n \cdot H_m$; n = 0.33 for milled, 0.5 for ground, and 0.66 for polished surfaces.

We shall introduce the designation

$$x = 0.7\,\frac{\delta H_{max}}{\alpha^2}, \tag{16}$$

$$\Phi = 1.78\exp\left(0.7\,\frac{H^2_{max}}{\alpha^2}\right)\left(\frac{H_{max}}{\alpha}\right)^4\frac{P_{spec}}{\pi C\sigma_T}. \tag{17}$$

After expanding the numerator of (15) in a power series to an accuracy up to three terms, and replacing the difference $2H_{max} - \delta$ by the quantity $2H_{max}$, we shall reduce (15) to the form

$$x^4 + x^3 = \Phi, \tag{18}$$

because of the smallness of δ in the contact heat transfer region.

The solution of (18) in [6] allows us to obtain a formula for the specific thermal resistance of a contact pair, allowing for the roughness of the contact surface

$$R = \frac{1}{\lambda}\left\{\frac{4}{\pi}\eta\,\frac{1,1}{2lL\exp\left(0.7\,\frac{H^2_{max}}{\alpha^2}\right)}\times\left[\frac{5}{8} + \frac{1}{2}\left(A + B + \frac{1}{4}\right) + \frac{1}{2}\sqrt{A + B + \frac{1}{4}}\right]\right\}^{-1/2}. \tag{19}$$

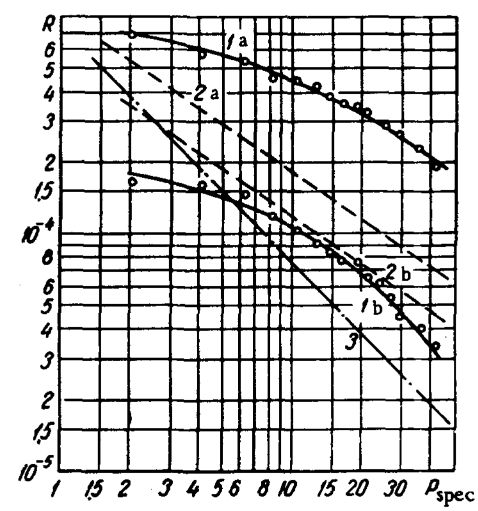

Fig. 4. Dependence of the thermal resistance R(degree · m²/W) of the contact between steel 30 surfaces on the specific force P_{spec} (Mn/m²): 1) experimental data of [7]; 2) according to Eq. (11); 3) according to (1); a) quality class 7, H_m = 5.56μ; b) quality class 8, H_m = 1.97μ.

Table 1
Characteristics of the Test Specimens

No. of specimen		1	2	3	4	5	6	7	8	9	10
Material		aluminum	Kh18N9T steel	Kh18N9T steel	VT1-1 titanium	VT1-1 titanium	VT1-1 titanium	Kh18N9T steel	Kh21G7AN5 steel	20 steel	Kh21G7AN5 steel
Class of quality		10–11	10	9	8–9	8	8	7	6	6	5
Kind of treatment		rolling		polishing		rolling		turning			metal filing
Number of contact pairs		955	51	1	2	30	16	2	2	2	2
Thickness of the plates, mm		0.014	0.1	10.0	10.3	0.4	1.2	10			
Valve surface quality parameters, μ	H_m	0.2	0.3	0.7	1.0	1.3		2.0	5.0	3.6	8.0
	l	10			50	170		200			250
	L	200	500	1200	1000	2000		2500	3000		3500

*The thermal conductivity of Kh21G7AN5 steel was measured by us at a mean temperature of ~200 °K; it is 12.6 W/m · degree.

Table 2
Data on Thermal Resistance of Metallic Contacts in Vacuum

No. of specimen	P_{spec}, MN/m²	Thermal resistance of a single contact, $R \cdot 10^4$, degree·m²/W	No. of specimen	P_{spec}, MN/m²	Thermal resistance of a single contact, $R \cdot 10^4$, degree·m²/W
1	1.6	0.038	6	1.9	15
	4.7	0,019		5.6	8.4
	9.4	0.017		9.4	3.3
	22.3	0.015		15.0	3.2
				19.7	2.9
2	1.2	5.1		23.4	2.6
	4.1	1.7			
	10.4	0.94	7	2.7	35
	18.2	0.73		14.7	32
				33.0	22
3	3.2	5.7	8	1.9	48
	11.0	3.2		10.3	37
	23.2	1.7		18.3	25
	41.2	0.60		29.2	21
4	0.9	10	9	1.3	3.3
	6.0	5.6		5.0	1.8
	10.8	2.5		17.2	1.6
	16.5	1.3		21.0	1.5
5	1.9	25	10	1.9	43
	5.8	14		6.1	35
	9.5	8.4		14.5	27
	13.2	7.2		23.0	19
	17.8	4.3		31.0	17

Here

$$A=\left(-\frac{\Phi}{2}-\frac{3}{128}+\right.$$

$$\left.+\frac{64}{27}\Phi^3+\frac{1}{4}\Phi^2+\frac{3}{128}\Phi+5.5\cdot 10^{-4}\right)^{1/3}, \quad (20)$$

$$B=\left(-\frac{\Phi}{2}-\frac{3}{128}-\right.$$

$$\left.-\frac{64}{27}\Phi^3+\frac{1}{4}\Phi^2+\frac{3}{128}\Phi+5.5\cdot 10^{-4}\right)^{1/3}. \quad (21)$$

It should be noted that formulas (1), (11), (12) and (19) do not take account of the influence of waviness of the following types—buckling, lack of planeness, curvature of the plates, etc., which must increase the contact thermal resistance if present on the surfaces in contact.

Using the instrument of Fig. 1, we measured the thermal resistance in vacuum of contacts between metallic surfaces in the form of a single pair and a stack of thin plates.

The thermal resistance of a stack of plates or of a single pair in contact 1 was determined under steady thermal conditions by measuring the amount of liquid oxygen evaporated from the inner vessel 6 and the temperature difference between the hot and cold ends of the specimen, with the aid of the manganin-constantan thermocouples 18 of wire diameter 0.1 mm, inserted from the jacket 9 through the seal 14.

To reduce the spurious heat flux, the inner vessel was surrounded by a guard chamber 7 with liquid oxygen and the copper guard ring 4. The heat current from the lateral surface of the specimen due to radiation was reduced by means of a cold copper screen. Tubes 8 and 16 were used for filling with the liquid.

The instrument was evacuated through tube 10. After the liquid oxygen was poured in, the pressure in the evacuated space was maintained at $1-2\cdot 10^{-2}$ N/m^2 by means of a zeolite adsorption pump.

Compression of the specimen was accomplished with the aid of the lever 11, fastened on the pillar 17, by putting on the weights 3. The maximum loading was 5000 N. The load was transmitted to the specimen through the thin-walled tube 5, the SVAM plexiglass bearing 15 and the Kh18N9T steel rod, which could move to and fro in the mushroom seal 13. The displacement of tubes 8 and 16 due to compression of the specimen was compensated for by the sylphon bellows 12.

The experimental and calculated data are shown in Tables 1 and 2. The values of l and L for the three specimens were measured with the aid of a profilograph; for the others values were taken approximately according to the catalog of quality of machined surfaces [3]. The mean height of micro-protuberances was determined for all the specimens with the aid of the profilograph, and for specimen No. 1, on an interferometer. The specimens had diameters of 14–20 mm, and the surfaces tested were non-planar to the extent 0.04–0.06 mm.

The plate curvature was least when their thickness was 0.1 mm (0.2 mm for diameter 20 mm), and decreased with both increasing and decreasing thickness. The heat flux in the tests did not exceed 24 W, and the temperature difference was 30°–180°; the mean temperature was in the range 145°–200° K, and was mainly 180° K. The contact thermal resistance R was determined by subtracting the thermal resistance of the metal from the total measured resistance of the specimen.

It may be seen from the tables that as the degree of quality of the surfaces making contact gets worse, from Class 5 to 10, the thermal resistance decreases by roughly a factor of 10. Therefore, a sufficiently reliable determination of the thermal conductivity of metallic contacts is impossible without taking account of their quality and the kind of treatment they have had.

A comparison of the experimental and theoretical data for Kh18N9T and Kh21G7AN5 steels, which have about the same thermal conductivity and hardness, is shown in Fig. 2. The experimental values of R fall between those calculated from (11) and (12), and those found from (19). In the roughness range from Class 5 to Class 8 the actual values are on the average higher by a factor of 2 than those calculated from (11). This may be attributed to the non-planeness of the thick plates and to the curvature of the thin plates. In the smoother contact region the deviation is about 10%. The straight line 4, obtained from (1), intersects the experimental curve at the quality class of about 7–8.

Figs. 3 and 4 show a comparison with theory of the experimental data of other investigators. It may be seen from Fig. 3 that calculation according to (12) gives the best approximation to the experimental data, somewhat greater values being obtained using (19). The slope of lines 2 and 3, constructed according to (12) and (19), is close to that of the experimental Curve 1. The straight line 4, constructed according to (1), not only gives values of thermal resistance increased by a factor of 10, but also differs appreciably from the experimental curve as regards slope.

The dependence of the thermal resistance on pressure for the straight lines on Fig. 4, constructed according to (11), is also closer to the experimental value, than for the straight line constructed according to (1).

The same holds also for the majority of the other experimental data, not shown here, obtained in the references mentioned.

Analysis of the experimental and theoretical data leads to the following conclusion. Since actual surfaces always have macro-waviness, in addition to micro-roughness, in particular buckling, lack of planeness, and curvature, which increase the thermal contact resistance, formulas (11) and (12) should be used for practical calculations, with numerical coefficients increased by a factor of 1.5–2.0 over the theoretical values.

NOTATION

H_m, H_{max} denote, respectively, the mean and maximum heights of micro-protuberances; H_{cr} is the height of the crumpled micro-protuberances; l and L are the distance between adjoining micro-protuberances in the transverse and longitudinal directions of the roughness, respectively; ρ is the radius of curvature of the tops of the micro-protuberances; d_1 is the diameter of the region of contact of one micro-protuberance; S_a, S_n are the actual and nominal areas of contact of a pair of profiles, respectively; $\eta = S_a/S_n$ is the relative area of contact; M is the total number of micro-protuberances on the surface; P is the compressive force; μ is the Poisson ratio; λ is the thermal conductivity of the contact material; R is the thermal resistance between the two metal surfaces. Subscripts: 1 refers to a single region of contact; spec refers to unit nominal surface area.

REFERENCES

1. Yu. P. Shlykov and E. A. Ganin, Contact Heat Transfer [in Russian], Gosenergoizdat, 1963.

2. P. E. D'yachenko, N. N. Tolkacheva, G. A. Andreev, and G. M. Karpova, Area of Actual Contact of Conjugate Surfaces [in Russian], Izd. AN SSSR, 1963.

3. P. E. D'yachenko, V. E. Vainshtein, and B. S. Rozenbaum, Quantitative Evaluation of Uneveness of Machined Surfaces, Appendix I [in Russian], IMASh AN SSSR, Izd. AN SSSR, 1952.

4. N. B. Demkin, Actual Area of Contact of Solid Surfaces [in Russian], Izd. AN SSSR, 1962.

5. Maxwell and Scott, collection: "Topics in Deep Freezing" [in Russian], ed. M. P. Malkov, IL, 1961.

6. Mechanical Engineering Handbook, 1, 127 [in Russian], Gos. nauchno-tekhn. izd.-vo mashinostroitel'noi literatury, Moscow, 1951.

7. I. T. Shvets, E. P. Dyban, and N. M. Kondak, Tr. Instituta teploenergetiki AN SSSR, no. 12, 1955.

27 April 1966

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