THERMAL CONTACT RESISTANCE IN A GASEOUS MEDIUM

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The thermal contact resistance of junctions with rough flat surfaces in a gaseous medium is studied theoretically and experimentally. A working equation taking account of the Smolukhovskii effect is derived.

It was shown in [1, 2] that by making a number of assumptions the thermal contact resistance R_c of flat rough surfaces in contact in a gaseous medium is described by the equation

$$\frac{1}{R_c} = \frac{1}{R_m} + \frac{1}{R_g}. \tag{1}$$

The thermal resistance of the actual contact R_m arising from the redistribution of the heat flow lines within each of the contacting bodies, with circular areas of contact of radius a uniformly distributed over the nominal contact surface, can be written in the form

$$R_m = \frac{\pi a}{2\lambda_m} \cdot \frac{\varphi}{\eta}, \tag{2}$$

where an analytic solution for the coefficient of constriction for constant temperature of the area of contact has the form

$$\varphi = 1 - 1.7\eta^{1/2} + 0.7\eta. \tag{3}$$

The main difficulty in using Eq. (2) is in finding η and a. The value of η can be calculated from a universal relation recommended in [3]:

TABLE 1. Values of ν, b, r_{trans}, r_{long}, γ_{trans}, and γ_{long}

Type of preparation	Class of surface finish	ν	b	r_{trans}, μ	r_{long}, μ	γ_{trans}	γ_{long}
Steel 45, steel 80, 1 Kh18N9T, 30KhGSA, brass							
Surface grinding	∇5	2,05	0,616	6,2	1250	10°	1°
	∇6	1,95	0,93	7,5	3110	8°	40′
	∇7, ∇8	1,76	1,37	12,4	4700	4°	20′
	∇9	1,46	1,97	20,6	15290	2°30′	10′
Shaping	∇4	2,1	1,64	17	157	12°	2°
	∇5	1,97	1,97	30	246	9°30′	1°30′
	∇6	1,95	2,04	92	610	6°	40′
			2,1	164	940	5°	30′
D16, D16T, D1T, titanium							
Surface grinding	∇5, ∇6	1,87	1,0	15	235	18°	2°30′
	∇7	1,62	1,25	21	441	15°	1°30′
	∇8	1,3	1,38	30	663	12°	45′
	∇9	1,22	1,6	33	870	6°	30′
Shaping	∇4	2,00	2,1	23	175	12°30′	2°
	∇5	1,85	2,28	45	297	8°30′	1°
	∇6	1,63	2,35	121	707	7°	50′
	∇7	1,53	2,46	180	1044	5°	40′

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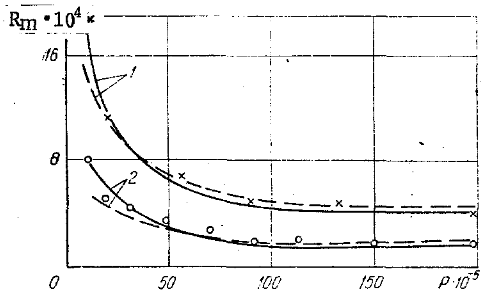

Fig. 1. Thermal resistance of actual contact R_m in $m^2 \cdot deg/W$ as a function of the load P in Pa for a 1Kh13 pair at initial loading ($T_c = 438°$ K): 1) ∇9b (grinding, ∇6a (shaping): $h_{max_1} = 2.4 \cdot 10^{-6}$ m; $h_{max_2} = 14.1 \cdot 10^{-6}$ m; $\gamma_{trans} = 4°$; $\gamma_{long} = 20°$; $\nu = 1.97$; b = 2; $r_{trans} = 92 \cdot 10^{-6}$ m; $r_{long} = 611 \cdot 10^{-6}$ m; 2) ∇9b (grinding), ∇ba (grinding): $h_{max_1} = 2.55 \cdot 10^{-6}$ m; $h_{max_2} = 5.2 \cdot 10^{-6}$ m; $\gamma_{trans} = 3°$; $\gamma_{long} = 20°$; $\nu = 1.76$; b = 1.37; $r_{trans} = 50 \cdot 10^{-6}$ m; $r_{long} = 310 \cdot 10^{-6}$ m. Open curve calculated from Eq. (7).

$$\eta = \left(\frac{\alpha^{\omega/\nu} b^{\omega/\nu} \bar{r}^{\omega} P}{h_{max}^{\nu} KB} \right)^{\frac{\nu}{\nu+\omega}}. \tag{4}$$

By analogy with [2, 4-6] crude approximations for average loadings can be made by taking the radius of microcontact areas as constant and equal to 30 μ. For accurate calculations it is necessary to take account of the change in size of the contact areas with roughness, the kind of material, and the loading. We use a conical model of rough surfaces and introduce the following restrictions: 1) the height of the microprojections is the same in the transverse and longitudinal directions; 2) the radius of the base of a cone is equal to $h_{max} (\tan \gamma_{trans} \tan \gamma_{long})^{-1/2}$. Then for a rough surface in contact with a smooth surface the radius of the area of contact for a deformation of a projection by an amount d is equal to

$$a = d / |\operatorname{tg} \gamma|. \tag{5}$$

By substituting for d from the equations in [3] $\varepsilon = d/h_{max}$, $\eta = b\varepsilon^{\nu}$, the last expression becomes

$$a = \frac{h_{max} (\eta/b)^{1/\nu}}{|\operatorname{tg} \gamma|}. \tag{6}$$

Combining (2), (3), and (6) we obtain

$$R_m = \frac{h_{max} (\eta/b)^{1/\nu}}{0.637 \lambda_m |\operatorname{tg} \gamma|} \left(\frac{1 - 1.7\eta^{1/2} + 0.7\eta}{\eta} \right). \tag{7}$$

Here h_{max} for repeated loadings is replaced by $h_{max} (1 - \varepsilon_{cr})$.

Ordinary engineering calculations can be performed by using the values of b, ν, r_{trans}, r_{long}, γ_{trans}, and γ_{long} from Table 1 obtained by processing a large number of curves of reference surfaces constructed from profiles of metal surfaces treated by the most typical mechanical processes.

The correctness of Eq. (7) was tested by using samples of 1Kh13 on an arrangement of the rod type [6] in a high vacuum. Figure 1 shows that the experimental and theoretical results are in satisfactory agreement.

The thermal resistance of the medium due to the resistance of the gaseous interlayer is given in general form by the expression

$$R_g = \frac{\bar{\delta}}{\lambda_g}. \tag{8}$$

By the equivalent thickness $\bar{\delta}$ we understand the thickness of a hypothetical gaseous interlayer which has the same conductivity as the variable thickness interlayer for the same thermal head. As a consequence of the variable thickness of the interlayer of the medium the heat-transfer process will change as the width of the gas gap approaches the mean free path of the gas molecules. Taking account of the Smolukhovskii effect [7] the equivalent interlayer thickness is given by [8]

$$\bar{\delta} = S_n \Big/ \int_0^{S_n} \frac{dS_n}{\delta_i + l_1 + l_2}. \tag{9}$$

Here the lengths of the temperature jumps l_1 and l_2 depend on the kind of gas and the surface of the solid and are determined from molecular-kinetic concepts [9].

To estimate the influence of the Smolukhovskii effect on $\bar{\delta}$ we introduce by analogy with [8] the dimensionless quantities

$$X = \frac{\delta_{max}(1 - \varepsilon)}{l_1 + l_2}, \quad Y = \frac{\delta_{max}(1 - \varepsilon)}{\bar{\delta}}. \tag{10}$$

TABLE 2. Results of Processing Reference Curves of Surfaces in Relative Coordinates

Material prepared	Preparation method and surface finish class	Functions $1-\varepsilon=f(\eta)$, $Y=f(X)$	As $X\to\infty$: Y	As $X\to\infty$: $\bar{\delta}$
Steel	Surface grinding ∇9	$1-\varepsilon = 5{,}208\eta^5 - 9{,}636\eta^4 + 3{,}231\eta^3 + 1{,}634\eta^2 + 1{,}437\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}579}{(1+1/X)^2} + \frac{0{,}403}{(1+1/X)^3} + \frac{0{,}302}{(1+1/X)^4} + \frac{0{,}235}{(1+1/X)^5}$	2,519	$0{,}397\delta_{max}(1-\varepsilon)$
Steel	Surface grinding ∇5	$1-\varepsilon = -9{,}113\eta^5 + 24{,}737\eta^4 - 25{,}779\eta^3 + 1{,}25\eta^2 - 3{,}35\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}481}{(1+1/X)^2} + \frac{0{,}281}{(1+1/X)^3} + \frac{0{,}184}{(1+1/X)^4} + \frac{0{,}13}{(1+1/X)^5}$	2,076	$0{,}482\delta_{max}(1-\varepsilon)$
Steel	Shaping ∇7	$1-\varepsilon = -5{,}207\eta^5 + 13{,}279\eta^4 - 13{,}018\eta^3 + 5{,}967\eta^2 - 2{,}02\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}517}{(1+1/X)^2} + \frac{0{,}329}{(1+1/X)^3} + \frac{0{,}234}{(1+1/X)^4} + \frac{0{,}177}{(1+1/X)^5}$	2,257	$0{,}443\delta_{max}(1-\varepsilon)$
Steel	Shaping ∇4	$1-\varepsilon = -5{,}207\eta^5 + 14{,}84\eta^4 - 16{,}768\eta^3 + 9{,}28\eta^2 - 3{,}145\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}433}{(1+1/X)^2} + \frac{0{,}243}{(1+1/X)^3} + \frac{0{,}158}{(1+1/X)^4} + \frac{0{,}113}{(1+1/X)^5}$	1,947	$0{,}513\delta_{max}(1-\varepsilon)$
Duralumin alloy	Surface grinding ∇9	$1-\varepsilon = 3{,}906\eta^5 - 9{,}376\eta^4 + 4{,}429\eta^3 + 1{,}998\eta^2 - 1{,}958\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}574}{(1+1/X)^2} + \frac{0{,}373}{(1+1/X)^3} + \frac{0{,}259}{(1+1/X)^4} + \frac{0{,}189}{(1+1/X)^5}$	2,395	$0{,}417\delta_{max}(1-\varepsilon)$
Duralumin alloy	Surface grinding ∇5	$1-\varepsilon = 5{,}213\eta^5 - 11{,}98\eta^4 + 7{,}08\eta^3 + 0{,}728\eta^2 - 2{,}04\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}421}{(1+1/X)^2} + \frac{0{,}222}{(1+1/X)^3} + \frac{0{,}133}{(1+1/X)^4} + \frac{0{,}092}{(1+1/X)^5}$	1,868	$0{,}533\delta_{max}(1-\varepsilon)$
Duralumin alloy	Shaping ∇7	$1-\varepsilon = -2{,}603\eta^5 + 11{,}456\eta^4 - 17{,}185\eta^3 + 10{,}165\eta^2 - 2{,}83\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}537}{(1+1/X)^2} + \frac{0{,}349}{(1+1/X)^3} + \frac{0{,}244}{(1+1/X)^4} + \frac{0{,}18}{(1+1/X)^5}$	2,31	$0{,}432\delta_{max}(1-\varepsilon)$
Duralumin alloy	Shaping ∇4	$1-\varepsilon = -5{,}201\eta^5 + 14{,}84\eta^4 - 16{,}775\eta^3 + 9{,}28\eta^2 - 3{,}145\eta + 1$, $Y = \frac{1}{1+1/X} + \frac{0{,}415}{(1+1/X)^2} + \frac{0{,}213}{(1+1/X)^3} + \frac{0{,}13}{(1+1/X)^4} + \frac{0{,}09}{(1+1/X)^5}$	1,848	$0{,}542\delta_{max}(1-\varepsilon)$

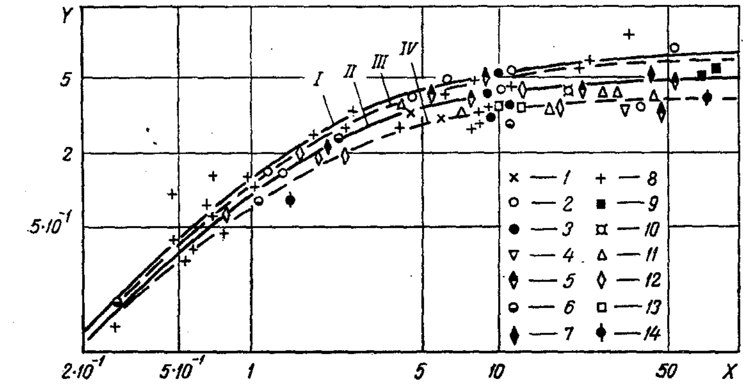

Fig. 2. Results of processing experimental data on the equivalent interlayer thickness for contacts of highly elastic metals in relative coordinates (I, II, grinding, respectively, ∇9, ∇5; III, IV, shaping and milling, ∇7, ∇5): 1) air [10]; 2) air [11]; 3) air [12]; 4) air [5]; 5) air [6]; 6) argon, helium [13]; 7) air, argon [14]; 8) helium, argon, neon [8]; 9) air [15]; 10) air [16]; 11) air, helium [17]; 12) air [18]; 13) air [19]; 14) air [20]. The curves were plotted from the equations of Table 2.

Then in relative quantities Eq. (9) for the contact of plane rough surfaces takes the form

$$Y = \int_0^1 \frac{d\eta}{\varepsilon + 1/X}. \tag{11}$$

It is of practical interest to obtain working formulas for $\bar{\delta}$ in which the surface geometry is determined by the form of the actual protuberances and their distribution in height. Such formulas can be obtained from reference surface curves.

Longitudinal and transverse surface profiles were taken from a large number of steel and Duralumin samples subjected to various forms of mechanical treatment and used to plot reference surface curves. The processing of these curves led to the family of approximating functions $1 - \varepsilon = f(\eta)$ tabulated in Table 2. The table also gives equations for the equivalent thickness of the interlayer obtained by integrating Eq. (11) using the function $1 - \varepsilon = f(\eta)$. These equations are plotted in Figs. 2 and 3.

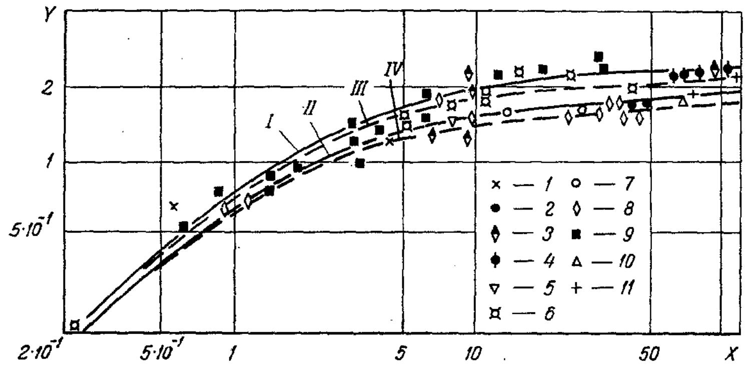

Fig. 3. Results of processing experimental data on the equivalent interlayer thickness for contacts of highly plastic metals in relative coordinates (I, II, grinding, respectively, ∇9, ∇3; III, IV, shaping and milling, ∇8, ∇4): 1) air, hydrogen [10]; 2) air [2]; 3) air [6]; 4) air [15]; 5) air [5]; 6) argon, helium [21]; 7) air [11]; 8) air [18]; 9) air, helium, hydrogen [4]; 10) air [17]; 11) air [22]. The curves were plotted from the equations of Table 2.

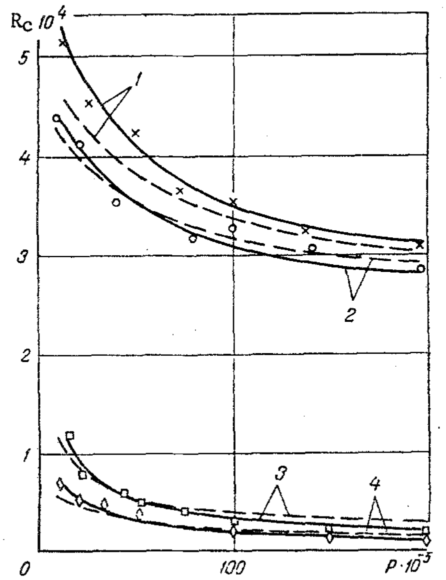

Fig. 4. Thermal contact resistance R_c in m^2 deg/W as a function of loading for 1Kh18N9T pairs (1, 2) and D16 (3, 4) for initial (1, 3) and subsequent (2, 4) loadings: 1, 2) surface finish ∇8a, ∇5, $P_{max} = 350 \cdot 10^5$ Pa, $T_c = 383$°K; 3, 4) ∇5, ∇9a, $P_{max} = 220 \cdot 10^5$ Pa, $T_c = 373$°K. Open curves calculated from Eq. (14).

An analysis of the equations of the equivalent interlayer thickness shows that for small values of X (direct contact) $Y \to X$ or $\bar{\delta} \to l_1 + l_2$; i.e., heat is transferred through the gaseous interlayer mainly by free molecular heat conduction. As $X \to \infty$, i.e., for a continuous intercontact medium, Y and $\bar{\delta}$ approach the limiting values given in Table 2. The data in this table on the choice of $\bar{\delta}$, in contrast with model schemes in the interpretation of the authors of [2, 8], were obtained by taking account of the geometry of the actual surfaces.

The correctness of the proposed equations can be judged from the calculated curves shown in Figs. 2 and 3 and data for the conductivity of the medium calculated from experimental values from various papers. For $X > 0.2$, which is of the greatest practical interest, the experimental points are in good agreement with the values calculated from the equations of Table 2. The spread of points is characteristic of experiments under small loads where it is difficult to select the actual value of δ_{max} because of the lack of data on h_{max}.

Taking account of the above, Eq. (8) is rewritten in the form

$$R_g = \frac{(h_{max_1} + h_{max_2})(1 - \varepsilon)}{\lambda_g Y}. \quad (12)$$

Here Y is found graphically from Figs. 2 and 3 or analytically from the equations of Table 2. For contacts experiencing repeated loadings up to pressures no higher than P_{max}, the numerator of Eq. (12) must be replaced by $(h_{max_1} + h_{max_2})(1 - \varepsilon_{cr})$ and assumed independent of pressure.

The relative convergence can be determined from the expression given in [3]:

$$\varepsilon = \left(\frac{\bar{r}^{\omega} P}{\alpha b K B h_{max}^{\omega}}\right)^{\frac{1}{\nu+\omega}}. \quad (13)$$

Substituting (7) and (12) into (1) gives a final expression for the total thermal contact resistance of junctions with plane rough surfaces

$$\frac{1}{R_c} = 0.637\bar{\lambda}_m \frac{|\operatorname{tg}\gamma|}{h_{max}(h/b)^{1/\nu}} \cdot \frac{\eta}{(1 - 1.7\eta^{1/2} + 0.7\eta)} + \frac{\lambda_g Y}{(h_{max_1} + h_{max_2})(1-\varepsilon)}. \quad (14)$$

Figure 4 compares the theoretical and experimental data for contact pairs of 1Kh18N9T and D16. It is clear that in the region $P/E > (1\text{-}1.2) \cdot 10^{-5}$ for highly elastic metals and $P/E > (2\text{-}3) \cdot 10^{-3}$ for highly plastic metals the experimental data are in good agreement with the theoretical curves plotted from Eq. (14).

The working formula (14) enables one to compute the contact resistance for a given surface finish, materials of the contacting pair, and loading.

NOTATION

R_c, total thermal contact resistance; $\bar{\lambda}_m = 2\lambda_{m1}\lambda_{m2}/(\lambda_{m1}+\lambda_{m2})$, reduced thermal conductivity of materials of contacting bodies 1 and 2; λ_g, thermal conductivity of intercontact medium; η, relative area of actual contact; ε, relative convergence of surfaces; ε_{cr}, critical convergence at P_{max}; P, P_{max}, respectively, contact pressure and maximum specified contact pressure; h_{max}, maximum height of microroughness; S_n, nominal surface of contact; r, radius of protuberances of microroughnesses; the subscripts trans and long refer to machining in the transverse and longitudinal directions; γ, angle of inclination of microroughnesses; ν, b, parameters of reference surface curve; ω, coefficient depending on the nature of the deformation; B, coefficient characterizing the material properties; K, coefficient depending on ν and ω; α, coefficient characterizing the ratio of areas during convergence; δ_i, δ_{max}, respectively, local and maximum thicknesses of the interlayer; T_c, average temperature in the contact zone.

LITERATURE CITED

1. T. N. Cetinkale and M. Fischenden, in: International Conference of Heat Transfer, Institute of Mechanical Engineers, London (1951).
2. Yu. P. Shlykov, Teploénergetika, No. 10 (1965).
3. N. B. Demkin, Contact of Rough Surfaces [in Russian], Nauka, Moscow (1970).
4. F. Boeschoten and F. Van der Held, Physica, 23, No. 1 (1957).
5. B. K. Sanokawa, Bulletin of ASME, 11, No. 44 (1968).
6. V. M. Popov, Heat Exchange in the Contact Zone of Separable and Permanent Junctions [in Russian], Énergiya, Moscow (1971).
7. R. S. Prasolov, Mass and Heat Transfer in Furnace Equipment [in Russian], Énergiya, Moscow (1964).
8. A. C. Rapier, T. M. Jones, and J. E. McIntosh, Int. J. Heat Mass Transfer, No. 6 (1963).
9. E. Eckert and R. Drake, Introduction to the Transfer of Heat and Mass, McGraw-Hill, New York (1950).
10. E. P. Dyban, N. M. Kondak, and I. T. Shvets, Izv. Akad. Nauk SSSR, No. 9 (1954).
11. V. S. Miller, Contact Heat Transfer in Elements of High-Temperature Machines [in Russian], Naukova Dumka, Kiev (1966).
12. V. M. Kapinos and O. T. Il'chenko, Izv. Vyssh. Uchebn. Zaved., Énergetika, No. 9 (1958).
13. V. A. Mal'kov, Inzh.-Fiz. Zh., 18, No. 2 (1970).
14. N. D. Weills and E. A. Ryder, Trans. ASME, 71, No. 4 (1949).
15. L. C. Laming, in: ASME International Heat-Transfer Symposium, Part 1, Boulder (1961).
16. H. Fenech and W. Rohsenow, Trans. ASME, J. Heat Transfer, 85, 15 (1963).
17. Yu. P. Shlykov and E. A. Ganin, Contact Heat Transfer [in Russian], Gosénergoizdat, Moscow (1963).
18. P. E. Khizhnyak, "Investigation of contact thermal resistance," in: Transactions of the State Scientific-Research Institute of the Civil Air Fleet, USSR [in Russian], No. 39, Riga (1963).
19. J. Henry and H. Fenech, Trans. ASME, J. Heat Transfer, 86, 543 (1964).
20. W. B. Kouvenhoven and I. H. Potter, J. Amer. Welding Soc. 27, No. 10 (1948).
21. P. D. Sanderson, in: ASME International Heat-Transfer Symposium, Part 1, Boulder (1961).
22. A. M. Baklastov and V. A. Gorbenko, Izv. Vyssh. Uchebn. Zaved., Mashinostr., No. 8 (1971).