*Int. J. Heat Mass Transfer.* Vol. 7, pp. 921–929. Pergamon Press 1964. Printed in Great Britain

# THERMAL RESISTANCE OF METALLIC CONTACTS

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(*Received* 8 *July* 1963)

**Аннотация**—Излагается метод расчета термического сопротивления контакта двух шероховатых металлических посерхностей при различных усилиях сжатия и чистоте обработки поверхности. Результаты аналитического расчета сопоставляются с опытными данными.

## NOMENCLATURE

- $R$, thermal contact resistance;
- $R_m$, thermal resistance of medium;
- $R_M$, thermal resistance of metallic contact;
- $V$, space volume between surfaces in contact;
- $S$, nominal contact area;
- $\lambda_m$, thermal conductivity of medium;
- $a$, absolute surface approach with normal loading applied;
- $h_a$, average height of microroughness (is determined by quality of surface finish);
- $r$, radius of contact spot;
- $\lambda_M$, thermal conductance of metal;
- $N$, normal loading on surface;
- $c$, coefficient taken equal to 3;
- $\sigma_y$, yield point of material in state of critical cold work taken equal to ultimate strength;
- $\sigma_B$, ultimate strength;
- $S_a$, actual contact area;
- $n$, number of contact spots on nominal contact surface.

PRESENT day power problems and other branches of engineering have to deal with high intensity heat flows through the places of contact between metal parts. Thus, for example, in nuclear power reactors the flux concentration of cooled surfaces of unbonded fuel elements is of the order of $10^6$ W/m$^2$. Under such conditions the thermal contact resistance of metal surfaces, because of the discrete nature of the contact, greatly affects the temperature distribution of parts.

It is generally known that the actual contact area of solids is only a small proportion of the nominal contact surface, even with high compressing forces and high quality of surface finish. There remain some hollows filled with alien medium (usually gas) between the surfaces in contact. The absence of close contact impoverishes the heat-transfer conditions between solids. The actual contact area and the volume filled with medium between the rough projections alter with load and surface finish, and this in turn results in change of thermal resistance. The discrete character of contact therefore gives rise to additional thermal resistance in the component bodies, i.e. contact resistance, and this may prove to be a considerable proportion of the total heat-transfer-system resistance. In spite of the theoretical and experimental works available on contact heat transfer [1–8, etc.], the calculation of thermal contact resistance is still a matter of great difficulty and not always reliable.

In the present paper a calculation method of thermal contact resistance for various contacting conditions is discussed and the results of the proposed method experimental checking are given.

Heat from one of the surfaces in contact to the other may, in general, be transported as follows:

1. by heat conduction through the places of direct contact.
2. by heat conduction through the medium filling the space between rough projections of the surfaces in contact;
3. by convective heat transfer in the medium filling this space;

4. by radiative heat transfer between the surfaces.

The limited gap dimensions in the contact zone impede the appearance of convection currents. Radiative heat transfer under the usual conditions of contact with a relatively small temperature drop between the surfaces is rather low. The heat from one of the contacting bodies to the other is, therefore, mainly transferred only by heat conduction through the places of direct contact and the medium interlayer. Accordingly the thermal contact resistance is defined by two values; the thermal resistance of direct (metal) contact $R_M$ and thermal resistance of the medium $R_m$. If the resistance of the medium and that of direct contact are presumed to have negligible effect on each other, the total thermal contact resistance can be expressed by the equation for parallel resistors

$$\frac{1}{R} = \frac{1}{R_M} + \frac{1}{R_m} \tag{1}$$

Thus the problem of the determination of thermal contact resistance reduces to a separate estimation of its components.

The possibility of theoretical determination of thermal resistance components is based on the results of the study of a contact between rough surfaces. These, on the one hand, enable the actual contact area and the degree of surface approach to be related with the surface microgeometry and strength characteristics of the contact body materials. Results, on the other hand, showed that the increase in actual area of contact with loading mainly occurs owing to an increase in number of the contact spots whose areas may be practically considered constant.

Thermal resistance of a medium interlayer of variable thickness may be represented as that of a constant-thickness layer, the volume of which equals that of the space between the projections of the contacting surfaces, i.e.

$$\delta_m = \frac{V}{S} \tag{2}$$

Since heat is transferred through the interlayer only by pure heat conduction the thermal resistance of the medium may be expressed by the formula

$$R_m = \frac{\delta_m}{\lambda_m} \tag{3}$$

(here flat contact is considered).

Determination of $R_m$ reduces to finding $\delta_m$, which depends on the load and quality of surface finish.

In [9] the relation

$$R_m = \frac{h_a}{\lambda_m}\left(1 - \frac{a}{h_a}\right)^2 \tag{4}$$

was obtained for the case of contacting surfaces with the same quality of surface finish.

Numerous experiments and calculation results show that within a wide range of loads the ratio $a/h_a$ is insignificantly small. According to the data in [10], for example, this ratio value does not exceed 0·1 with a loading of 100 kg/cm$^2$ for steel turned surfaces in contact with a smooth solid surface. Even with high compression pressures of 2–3 $\times$ 10$^3$ kg/cm$^2$ the height of roughness projections diminishes slightly. With average quality of finishing (4–8th classes of surface finish according to Gost),* therefore, thermal resistance of the medium may be considered constant and, when two rough surfaces with different quality of finishing are in contact, may be defined by the relation

$$R_m \cong \frac{h_{a_1} + h_{a_2}}{2\lambda_m} \tag{5}$$

(Here and further subscripts 1 and 2 are related to the first and second surfaces in contact) or with $h_{a_1} = h_{a_2} = h_a$ by

$$R_m \cong \frac{h_a}{\lambda_m} \tag{6}$$

Such a simplification cannot introduce great error since the conductance of metallic contact increases with compression of the surfaces, and the role of the medium conductance in the total contact conductance diminishes.

The determination of the thermal resistance of the metallic contact $R_M$ is based on the following suppositions.

Owing to the narrowing of the path for the

* See Table 1.

*Table 1. The quality of surface finish of the test surfaces*

| Material | Type of finish | Average height of microroughnesses | Class of finish (according to Gost 2789–59) |
|---|---|---|---|
| D-16 | turning | 23·11 | 4 |
| M-2 | shaping | 15·0 | 5 |
| St. 3 | grinding | 2·83 | 8 |
| IXI8H9T | shaping | 11·7 | 5 |

heat flowing towards the roughness projections on the surface, and, through those projections to the actual places where the surfaces are in contact (Fig. 1) additional temperature drop appears as compared with the case of heat flow through a solid metal. This is equivalent to the introduction of additional thermal resistance in

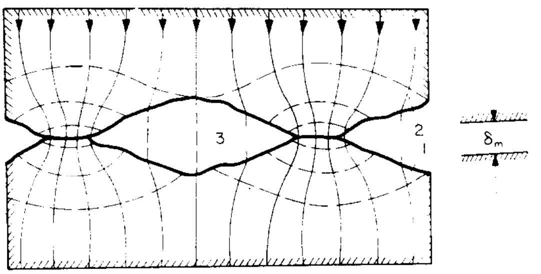


FIG. 1. Heat-flow lines in contact zone.
1 and 2, surfaces in contact; 3, cavity filled with medium; $\delta_m$, mean calculated thickness of medium interlayer.

the contact plane (since the components of thermal contact resistance are considered separately, here and further on it is assumed that $R_m = \infty$). It is this additional resistance which appears to be thermal resistance of actual (metallic) contact $R_M$.

It was mentioned above that the size of contact spots hardly depends on normal loading and under usual compression conditions it may be assumed constant. Moreover, the experiments show that the spot sizes for various materials such as steel, copper, aluminium, nickel, uranium, graphite, etc. are approximately the same, and according to [7], assuming a contact spot to be a circle, the radii are about 30 μ. In [11] the value of the spot radius is found to be about 25 μ. Thus, we may assume that, independent of loading, different surfaces are brought into contact through separate spots of about the same size. All these spots together, which form the real area, act as parallel resistors.

When roughness is fairly uniform, the contact spots will be more or less evenly distributed over the normal contact surface. The constant mean-statistical density distribution of the contact spots, as well as the appreciable distance between them compared to the size of the spot itself allow the spot in contact with the adjacent part of contact surface to be considered in isolation. In some works [12, 13, etc.] the following expression for thermal resistance of a circular contact spot of two semi-infinite bodies of uniform material is given, the contact within the limits of the spot being taken to be ideal

$$R_{M_1} = \frac{1}{2r\,\lambda_M} \tag{7}$$

When heterogeneous metals are brought into contact, the value $\bar{\lambda}_M$ is inserted into this expression, which is defined by

$$\bar{\lambda}_M = \frac{2\lambda_{M_1}\,.\,\lambda_{M_2}}{\lambda_{M_1} + \lambda_{M_2}} \tag{8}$$

If the number of contact spots per unit of nominal contact surface is denoted by $n_1$, then, taking into account the fact that the resistors act in parallel, we obtain the following expression for thermal resistance of actual contact

$$R_M = \frac{1}{n_1} R_{M_1} = \frac{1}{2n_1\,r\bar{\lambda}_M} \tag{9}^*$$

The number of contact spots per unit of nominal contact area can be readily expressed in terms of actual contact area $S_a$. Indeed,

$$n_1 = \frac{n}{S} = \frac{S_a}{\pi\,r^2\,S} \tag{10}$$

* A similar relation may be obtained from the analysis of the expression for actual contact conductance in [4].

Introducing this expression into (9) we get

$$R_M = \frac{\pi r S}{2\,\lambda_M\,S_a} \qquad (11)$$

To define $R_M$ it is necessary to express the value $S_a$ in terms of the mechanical properties of the metal, the value of the normal loading and quality of surface finishes of the surfaces in contact. As first approximation the plastic character of the contact may be taken and the following relation

$$S_a = \frac{N}{c\sigma_y} \qquad (12)^*$$

may be used for a surface, the surface finish of which is not higher than that of the 8th class.

In this relation $c$ is taken equal to 3, but for metals with a high degree of cold work such as copper this coefficient should be 5.

When heterogeneous materials are in contact the ultimate strength of the less plastic metal is taken into account. Using expression (12) and assuming, according to [7], the radius of a contact spot equal to $3 \times 10^{-5}$ m, we can reduce formula (11) to the form

$$R_M = \frac{3\sigma_B \,.\, S}{2{\cdot}1 \times N\lambda_M} \times 10^{-4} \qquad (13)$$

Now combining formulas (5) and (13) by relation (1) we obtain the final formula for the thermal contact resistance

$$\frac{1}{R} = \frac{2\lambda_m}{h_{a_1} + h_{a_2}} + 2{\cdot}1 \times \frac{N\lambda_M}{3\,\sigma_B\,S} \,.\, 10^4 \qquad (14)$$

The calculation according to this formula yields minimum contact resistance as a function of microroughness only. The presence of waviness may cause considerable increase in contact resistance mainly by the increase of equivalent thickness of the gap between the surfaces in contact. With a known waviness character the calculation of this phenomenon is not very difficult.

The above calculation formulas are well confirmed by the available experimental data.

* When $c\sigma_B = H_B$ this formula coincides with the known formula of Bowden and Tabor.

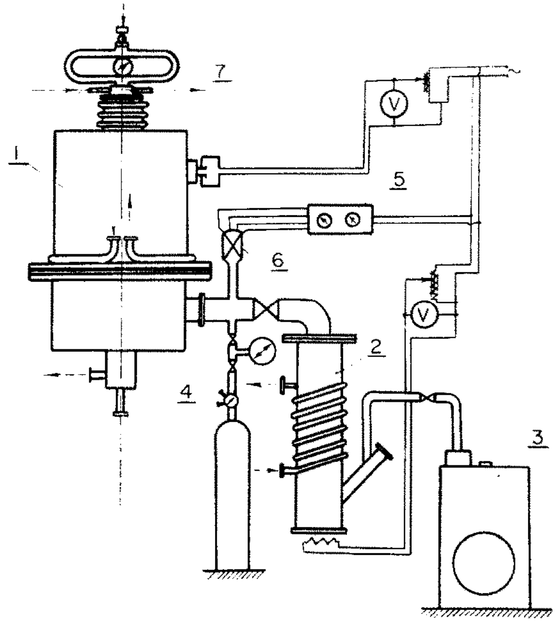


FIG. 2. Schematic drawing of experimental installation. 1, working chamber; 2, diffusion pump; 3, backing pump; 4, vacuum manometer; 5, vacuummeter; 6, manometric lamp; 7, dynamometer.

For a more detailed verification of the calculation method and the explanation of some of the properties of physical picture of the processes in the contact zone, a series of tests was carried out to determine the value of thermal resistance as a function of compressing force, the quality of surface finish, the kind of material, pressure and structure of gas medium, and the temperature of the surfaces in contact [15, 16].

An experimental installation, of which the block-diagram is shown in Fig. 2 and a section of the working chamber in Fig. 3, was designed for this purpose. To study the contact heat transfer cylindrical models 30 mm in diameter and 34 mm long were placed into the working chamber. Heat flow was generated by a heater and a cooler. The models were compressed by means of a lever screw press. The loading value was determined with a spring dynamometer. The models were mounted inside the protective casing, of which the inner space was filled with heat insulation materials. In a number of tests a compensation heater completely eliminating lateral heat leakage was placed concentrically

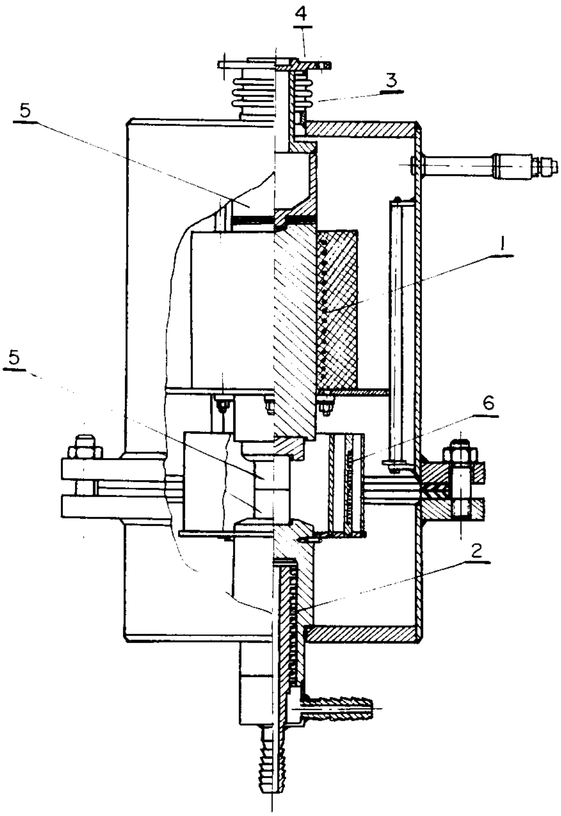


FIG. 3. Working chamber.
1, electric heater; 2, cooler; 3, bellows; 4, dynamometer; 5, experimental models; 6, protective casing.

to the models. The working chamber was carefully sealed in, which made it possible to experiment at variable pressure and vacuum up to $10^{-4}$ mm Hg.

Temperature distribution along the length of the models was measured with chromel–copel thermocouples with electrode diameter of 18 mm. Five thermocouples were caulked on lateral surfaces of each model. Special experiments showed that inserting the bead of a thermocouple into the depth of the cylindrical models up to the axis does not change the temperature distribution along the length. The extreme thermocouples were placed 2·5 mm distance from the contact surface and the rest, 5 mm distance from each other.

The distance between the thermocouples was determined correct to 0·5 mm with a microscope. The thermocouple emf was measured with the potentiometer П ПТБ-1 having a ballistical galvanometer as a zero instrument. All the thermocouples were first checked for identity of readings.

The experiments on measuring of thermal resistance were carried out at steady conditions which usually prevail after 3–4 h of apparatus working. The loading on the models varied from 0 to 200 kg/cm$^2$ in steps of 50 kg/cm$^2$. At the outset all the models were compressed to 50 kg/cm$^2$ loading to eliminate accidental microroughnesses. In some cases the power of the electric heater was changed with loading to keep the mean temperature in the contact zone constant. Temperature discontinuity in the contact plane $\Delta T$ was determined by linear extrapolation. The value of this discotinuityn ranged in experiments from 10° to 80°C.

The heat flow through the contact zone which is necessary to determine the value of thermal contact was calculated from the temperature gradients of the lower and upper models. The value of this heat flow was (10–175) $\times$ 10$^3$ W/m$^2$. The difference between heat flows for the upper and lower models was usually not in excess of 5 per cent. The mean value of heat flow $q$ was taken for calculation. Thermal contact resistance was calculated by $R_{\text{exp}} = (\Delta T/q)$.

Experimental errors averaged from 10 to 12 per cent, in some cases to 20 per cent (small heat flows).

The experiments were carried out on models; steel 3, stainless steel IX18H9T, duralumin D-16 and copper M-2. The data on the surface finish of some of the best model surfaces and physical properties of the materials chosen are given in Tables 1 and 2.

The experimental results of contact heat transfer are presented in the form of diagrams (Fig. 4–6). It can be seen from the diagrams that thermal contact resistance decreases with increasing compression of the surfaces in contact. First this decrease is sharp, then more smooth. The shapes of curves are somewhat different for different metals.

In the figures the predicted values of contact resistance are shown by broken lines. One can see a fair qualitative and quantitative agreement between the experimental data and the results

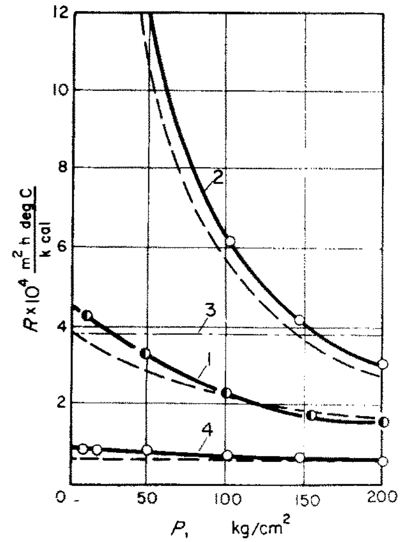


FIG. 4. Material—steel IXI8H9T, 5th class of surface finish.

1, total thermal contact resistance in air medium; 2, thermal resistance of real contact (pressure of $5 \times 10^{-3}$ mm Hg); 3, thermal resistance of air interlayer; 4, total thermal contact resistance in helium medium.

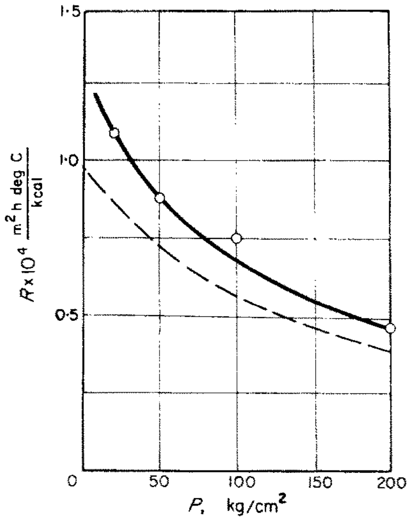


FIG. 6. Material—St. 3, the 8th class of finish. Total thermal contact resistance in air medium.

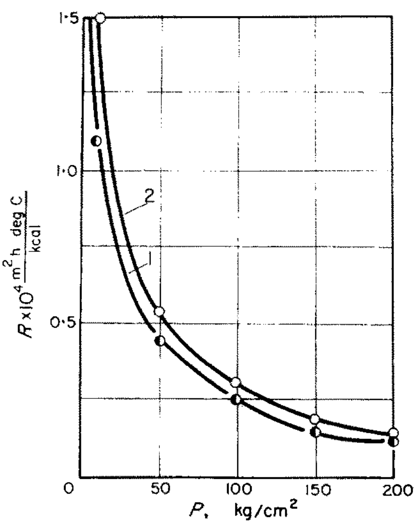


FIG. 5. Material—D-16, 4th class of surface finish.

1, total thermal contact resistance in air medium; 2, thermal resistance of actual contact (pressure of $5 \times 10^{-3}$ mm Hg). Theoretical curves fully coincide with experimental ones.

of theoretical calculations. The proposed calculation formulas are confirmed also by experimental data of other authors, which is shown in Figs. 7, 8 and 9.

The mechanical properties of the metals and heat conductance of the medium filling the spaces in the contact zone depend on temperature. A change in thermal contact resistance, therefore, should be expected when the temperature of the surfaces in contact changes. Figure 10 presents theoretical and experimental dependence of thermal resistance on temperature.

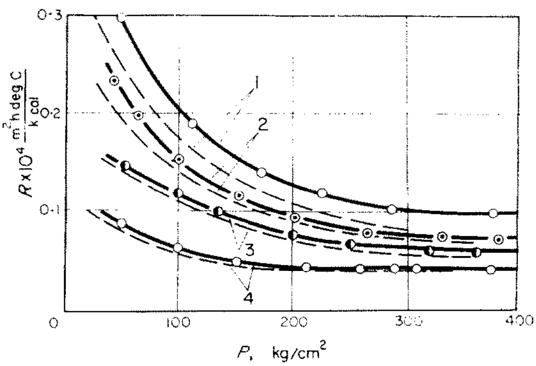


FIG. 7. Thermal contact resistance for St. 45 (according to experimental data [8]; air medium).

1 is the 5th class of finish; 2 is the 6th class of finish; 4 is the 8th class of finish.

*Table 2. Physical properties of the materials studied*

| Material | $\lambda_M$ kcal/m h degC | | | $\sigma_B$ kg/mm² | | |
|---|---|---|---|---|---|---|
| | 20°C | 100°C | 200°C | 20°C | 100°C | 200°C |
| D-16 | 147 | 160 | 175·5 | 48 | 29·5 | 19·5 |
| M-2 | 346 | 332 | 326 | 23·5 | 23 | 21·6 |
| St. 3 | 45 | 44·8 | — | 40·3 | 37·8 | 28·5 |
| IXI8H9T | 12·9 | 13·9 | 15·2 | 65·5 | 51 | 46·5 |

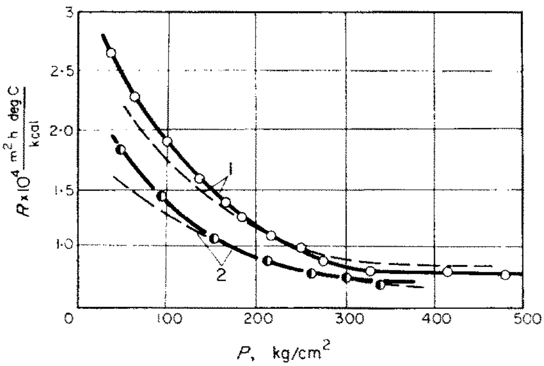


FIG. 8. Thermal contact resistance for steel ЭЖ-1 (according to experimental data [8]; air medium).

1, 6th class of finish; 2, the 7th class of finish.

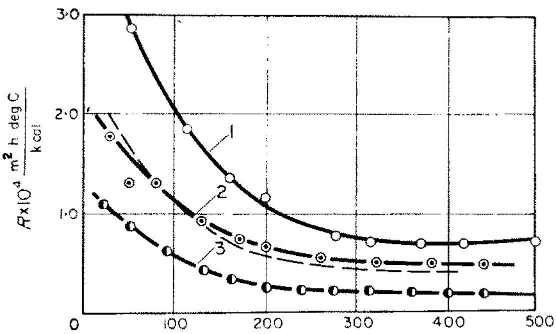


FIG. 9. Thermal contact resistance, St. 45 and D-16, 4th class of finish. (From experimental data [8]; air medium).

1, St. 45–St. 45 pair; 1, D-16–D-16 pair; 3, St. 45–D-16 pair.

A separate experimental estimate of thermal resistance components is of great interest for correct estimation of the phenomena in the contact zone and confirmation of the theoretical premises of the calculation. This kind of a study

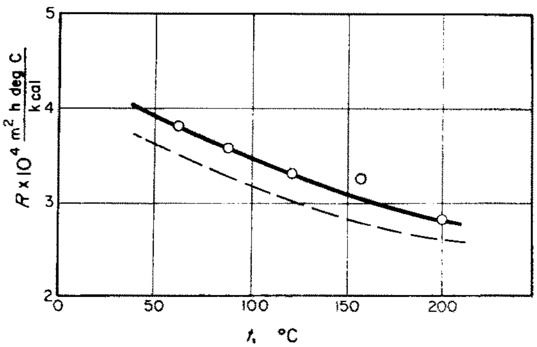


FIG. 10. Temperature dependence of thermal resistance (material—steel IXI8H9T, 5th class of finishing, loading of 50 kg/cm², air medium).

was carried out in the present work. For this purpose tests at high vacuum were used when gas heat conductance is negligible and the entire heat amount, except for a small contribution due to radiative heat transfer (1–2 per cent) flows through the place of actual contact. Calculation shows that increase of thermal resistance with falling gas pressure starts at pressures of about 100 mm Hg. To determine the vacuum in which heat conductance of a gas can be neglected some tests were carried out at different air pressures (Fig. 11). From these tests one can conclude that heat conductance of a gas becomes practically zero at a pressure of $10^{-1}$ mm Hg. Tests in the above vacuum, therefore, enable us to define thermal resistance of the actual contact. The same diagram (Fig. 11) shows that thermal contact resistance can appreciably increase when the environmental pressure decreases, which should be taken into consideration in practical calculations.

The experimental results in a high vacuum shown in Figs. 4, 5 and 12 confirm the correctness of proposed calculation formula (13).

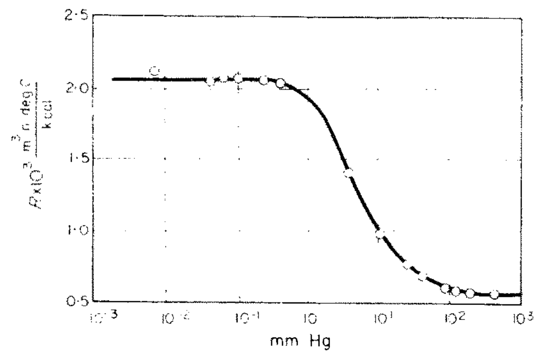

FIG. 11. Air-pressure dependence of thermal contact resistance (material—steel IXI8H9T, the 5th class of finish, loading of 20 kg/cm²).

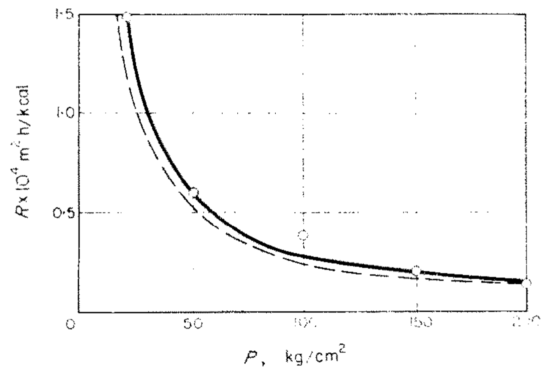

FIG. 12. Thermal resistance of real contact. Material—copper M-2, 5th class of finish, pressure $10^{-4}$ mm Hg.

It was already noted that thermal contact of the interlayer changes very little with increase of surface compression and for a given quality of surface finish can be practically assumed constant. (See formula (6).) The experiments on determination of actual contact resistance are confirmed by the fact that a change of total thermal resistance depending on compression is caused by change of heat conductance through the places of direct contact.

It is of interest to define the role of some components of thermal contact resistance and their relative influence on the total thermal resistance dependence on loading. In Fig. 5 the relations between total thermal resistance of a contact and thermal resistance of an actual contact for duralumin D-16 with high heat conductance are given. Close alignment of these curves indicates that the main role in heat transfer through the contact zone can be ascribed here to the conductance of the metallic contact. A similar diagram for steel IXI8H9T with lower heat conductance (Fig. 4) shows that conduction through gas is of essential significance in this case. The dependence of total thermal resistance on loading here is less sharp, since the relative significance of the variable component of total thermal resistance is less in this case than in the case of duralumin.

The dependence of total thermal resistance on loading is also affected by the environmental thermal conductance. Figure 4 shows the dependence of thermal contact resistance for steel IXI8H9T in helium. Because of the high heat conductance of helium the role of the variable component of total thermal resistance here becomes insignificant and the main heat flows through the gas.

As a result of theoretical and experimental investigation one can conclude:

1. Thermal contact resistance can be defined with sufficient degree of accuracy by calculations.
2. In case of soft metals with relatively high heat conductance the main heat flow through the contact zone through the places of actual contact, whilst for hard metals with relatively low heat conductance the environmental heat conductance is of importance.
3. Change of total thermal resistance depending on loading is caused by change of real contact conductance.

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**Abstract**—A calculation method for thermal resistance of a contact between two rough metal surfaces with different compressing forces and quality of finishing is considered. The results of analytical calculation are correlated with experimental data.

**Résumé**—On examine une méthode de calcul pour la résistance thermique d'un contact entre deux surfaces métalliques rugueuses avec différentes forces de compression et qualités de fini. Les résultats du calcul analytique sont corrélés avec les données expérimentales.

**Zusammenfassung**—Es wird eine Berechnungsmethode angegeben für den thermischen Kontaktwiderstand zwischen rauhen Metallflächen, die mit verschiedener Güte bearbeitet waren und wovon je zwei mit veränderlichem Druck aneinandergepresst wurden. Die Ergebnisse der analytischen Betrachtung werden mit experimentellen Daten verglichen.