CONTACT THERMAL RESISTANCE OF SOME GRAPHITES

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Experimental data on the contact thermal resistance of VPP, ARV, and MPG-6 graphites in relation to the compression and finish of the contact surfaces are given.

Contact heat transfer has been the subject of considerable research in the Soviet Union and abroad [1-11]. A knowledge of the numerical values of the contact thermal resistance is essential also for graphitic materials, which are now widely used for the construction of chemical equipment, atomic reactors, and for the manufacture of components of gas turbines, heat exchangers, etc. However, the Russian and foreign literature known to us contains no experimental data on the contact thermal resistance of graphitic materials.

In this paper we give the results of an experimental investigation of contact thermal resistance in relation to the finish and compression of the contacting surfaces of VPP, ARV, and MPG-6 graphites.

These investigations were conducted in the steady heat regime on a rod-type apparatus with a lever loading system. The choice of experimental apparatus was determined by the characteristic requirements — very accurate determination of the compressive force on the contacting surfaces in time and high accuracy and reliability of the experimental data in the whole range of investigations.

These requirements were satisfied, first, by the lever loading system; second, by the use of highly heat-conducting aluminum alloys for the lower specimen heater and the upper specimen cooler; and, third, the position of the heater below and the cooler above the investigated graphite specimens.

Three blind holes of diameter 0.5 mm were drilled to the center of the specimens and copper–Constantan thermocouples of diameter 0.1 mm were inserted in them. The contact surfaces of some specimens after grinding did not have the required flatness. The faces of these specimens were finished on a grinding plate with emery paper with the aid of the special frame that is widely used for this purpose in the preparation of sections in metal research laboratories. The distances between the thermocouples in the specimens were measured with an IZA-2 horizontal comparator, which is designed for engineering measurements to an accuracy of ±0.001 mm. The finish of the contacting surfaces was determined on the "Kalibr" factory profilograph with vertical magnification of the microroughnesses ×1000.

Before starting to determine the contact thermal resistance we found the thermal conductivities on the same apparatus. Their numerical values at 440-460°K were as follows: 180 ± 5 W/(m•°K) for VPP graphite, 150 ± 5 W/(m•°K) for MPG-6, and 55 ± 3 W/(m•°K) for ARV.

The numerical values of the heat fluxes were determined by comparison with the results of a prior calibration of the investigated specimen paired with a standard M1 copper specimen. From the known thermal conductivity of M1 copper and the measured temperature gradient over the height of the standard specimen we determined the heat flux density. We then constructed a calibration plot of heat flux through the graphite specimen against temperature gradient along its axial direction. After calibration we replaced the standard specimen by the second investigated graphite specimen. The contact thermal resistance was determined by two known methods: graphically and by calculation. The root-mean-square error of the experimental determination of the contact thermal resistance did not exceed 11.6%.

The results of the experimental investigation of the contact heat transfer between these graphites in air at atmospheric pressure are shown in Figs. 1-4. The experimental values of the contact thermal resistances varied from 0.004 to 0.27 $(m^2 \cdot {}^\circ K)/kW$, the temperature differ-

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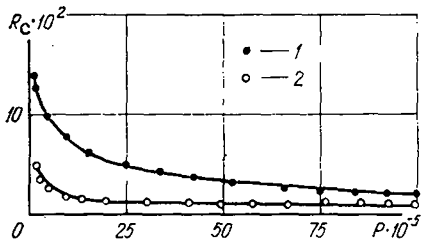

Fig. 1. Plot of contact thermal resistance against load on VPP graphite contact pair: preloading $25 \cdot 10^5$ Pa, contact zone temperature 440-460°K, mean heat flux density 525 kW/m²; finish of contact surfaces: 1) class 3, H_{av} = 90-100 μ; 2) class 5, H_{av} = 25 μ. R_c in (m²•°K)/kW; pressure P in Pa.

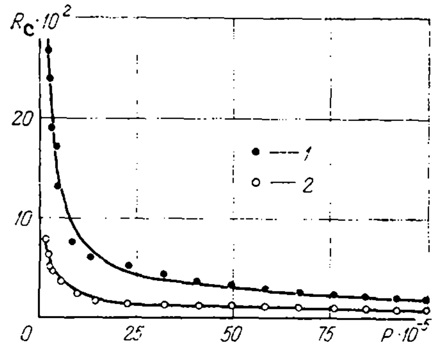

Fig. 2. Plot of contact thermal resistance against load for ARV graphite; contact zone temperature 435-455°K; heat flux density 295 kW/m²; surface finish: 1) class 3, H_{av} = 65 μ, without preloading; 2) class 5, H_{av} = 18 μ, preloading $25 \cdot 10^5$ Pa.

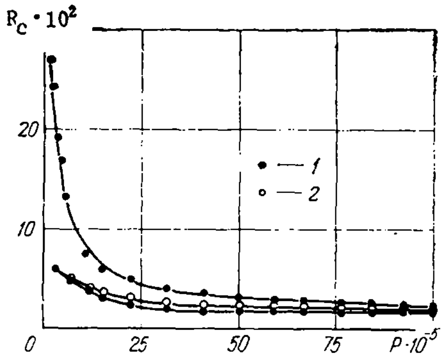

Fig. 3. Hysteresis of contact thermal resistance of ARV graphite during contact process; surface finish class 3; H_{av} = 65 μ; without preloading; contact zone temperature 440-460°K; mean heat flux density 300 kW/m²: 1) increase; 2) reduction of load.

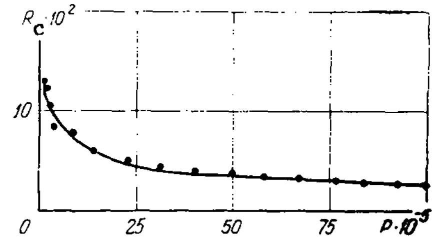

Fig. 4. Plot of contact thermal resistance against load for MPG-6 graphite; preloading $25 \cdot 10^5$ Pa; class 3 surface finish; H_{av} = 85 μ; contact zone temperature 410-430°K; heat flux density 420 kW/m².

ence in the contact zone reached 1.3-65.0 °K, and the heat flux density through the test specimens was 210-550 kW/m².

All the plots show the contact thermal resistance R_c against the load P for different finishes of the contacting surfaces. Figures 2 and 3 show plots of the thermal resistance against load in its first application to ARV graphite specimens with a class 3 finish. The curves in Figs. 1 and 4 show the resistance in relation to load after preloading with $25 \cdot 10^5$ Pa, while Fig. 3 shows the hysteresis of the contact thermal resistance of ARV graphite in relation to increase and reduction of the load during contact. Figures 1 and 2 show plots of the contact thermal resistance of VPP and ARV graphites against load and surface finish.

All the experimental data indicate that the contact resistance always decreases with increase in load. In contacting pairs with a class 3 finish a sharp reduction of resistance is observed in the load range from 0 to approximately $25 \cdot 10^5$ Pa, after which there is a gradual reduction of the resistance at loads $25 \cdot 10^5$-$50 \cdot 10^5$ Pa, and a quite insignificant reduction at loads above $50 \cdot 10^5$ Pa. The contact thermal resistance also decreases with improvement in the finish of the contact surfaces, but with improvement in surface finish the range of loads at which the most rapid reduction of resistance occurs moves toward the coordinate origin. For instance, for surfaces with a class 5 finish the most rapid reduction of resistance occurs in the load range from zero to approximately $10 \cdot 10^5$ Pa (Figs. 1 and 2).

A comparison of the numerical values of the contact thermal resistance shows that the highest values of the resistance, other conditions being equal, are always obtained in the case of initial application of the load. As Fig. 3 shows, in the load range up to $25 \cdot 10^5$ Pa the values of the resistance during the initial and second application of the load differ very distinctly from one another (the factor of difference can be two or more). With increase in load the effect of preloading tends to zero. At loads above $75 \cdot 10^5$ Pa it can be neglected.

The nonlinearity of the obtained plots of contact thermal resistance against load can be attributed to the following causes.

In the initial stage of contact the area of direct contact of the microprojections of opposing surfaces of the contact pair is an insignificant fraction of the nominal area of contact. It is obvious that opposing microprojections whose sum of heights is greatest will always come into contact first. With increase in compressive force more and more pairs of opposing microprojections, with a smaller and smaller sum of heights, will come into contact. When the bulk of the microroughnesses are in contact, the approach of the contacting surfaces toward one another slows down and the increase in area of actual contact tends to zero.

Thus, because of the nonlinear dependence of the approach distance on the load at the initial stage of application of the contact load the thermal resistance decreases very rapidly. With further increase in load the rate of reduction of the thermal resistance becomes smaller and smaller, and the nonlinear dependence of the contact thermal resistance on the load tends more and more to a linear relationship (Figs. 1-4).

According to Demkin's data [12], with repeated loading the nonlinearity of variation of the approach distance degenerates and is shifted into the region of smaller loads. This relation is confirmed by the presented experimental curves, which express the relation between the contact thermal resistance and the load in the case of repeat loading (Fig. 3). On repeat loading without shear of the contacting surfaces the deformation will be elastic until the load exceeds the initially applied load. The most intense plastic deformation (flattening) and the greatest stage-by-stage destruction of the microroughnesses occur during the first loading in the region of relatively small loads until the bulk of the microroughnesses come into direct contact. For this reason, under small loads the contact thermal resistances of the same graphite with different surface finishes differ much more from one another than under higher loads (Fig. 2).

The hardness of the contacting surfaces has a definite effect on the contact thermal resistance, as experimental data showed. The microhardness of the investigated graphites was as follows: $1.4 \cdot 10^8$ Pa for ARV, $2.3 \cdot 10^8$ Pa for VPP, and $4.4 \cdot 10^8$ Pa for MPG-6. A comparison of the curves in Figs. 1-4 shows that the thermal resistance is slightly greater in contacting MPG-6 graphite, whose microhardness is 2-3 times greater than that of VPP and ARV. When one takes into account, however, that the thermal conductivity of MPG-6 is almost three times greater than that of ARV, we can conclude that the above-mentioned differences in the properties of these graphites almost completely cancel one another out; i.e., the microhardness and thermal conductivity have approximately equal and opposite effects on the contact thermal resistance.

Thus, we can conclude from the above that the contact thermal resistance of graphite components must be taken into account in practice and that it can be artificially regulated in a very wide range.

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EFFECT OF TEMPERATURE, PRESSURE, AND COMPOSITION OF ATMOSPHERE ON THERMAL CONDUCTIVITY OF HEAPS OF POWDERED TITANIUM, ZIRCONIUM, AND SILICON

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The thermal conductivity of titanium, zirconium, and silicon in a vacuum and in helium was experimentally investigated. The obtained experimental thermal-conductivity data are compared with calculated values for titanium and zirconium.

For optimization of the conditions of the sintering process we measured the thermal conductivity of finely dispersed titanium and zirconium powders at 300-1000°C in a vacuum ($P = 5 \cdot 10^{-3}$ mm Hg) and in a helium atmosphere ($P = 220$ mm Hg). The main characteristics of the investigated powders are given in Table 1.

The thermal conductivity was measured by the steady radial heat-flux method with indirect heating of the specimen (tube method). The investigated powder was poured into the annular gap formed by a porcelain tube of diameter 20 mm and a graphite cylindrical container of diameter 80 mm and wall thickness 1.5 mm. The length of the tube and container was 300 mm. The porcelain tube contained a heater of diameter 12 mm, made of carbon with low thermal conductivity (8-10 W/m•deg). In view of the low thermal conductivity of the heater material, the leakage of heat in the axial direction was slight. This loss was calculated from the known thermal conductivity and temperature drop along the heater axis. The test section in the center of the specimen was 50 mm long. Measurements showed that the gradient of the temperature field in the test section was slight and, hence, the axial heat loss in the specimen could be neglected. The sample temperature was measured with four Chromel—Alumel thermocouples, two of which were mounted on the outer surface of the porcelain tube along its axis, and the other two were mounted on the inside surface of the graphite container parallel to its axis. Four thermocouples were required for averaging of the radial temperature field

TABLE 1. Main Characteristics of Dispersed Titanium, Zirconium, and Silicon

Material	Particle diameter, μ	Bulk density, g/cm³	Density, g/cm³	Porosity
Titanium	70	1,685	4,5	0,625
Zirconium	70	2,525	6,49	0,61
Silicon	50	0,805	2,33	0,655

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