THERMOPHYSICAL PROPERTIES OF DIELECTRIC CERMETS OF THE Al_2O_3–Mo, –W, –Nb SYSTEM

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The thermophysical properties of dielectric cermets of the Al_2O_3–Mo, –W, –Nb system in the temperature range 50-1900°C were investigated. A semiempirical relation is used to correlate the experimental data.

In the last 10 years alumina-based cermets have found ever-increasing application in technology [1]. The thermophysical properties of cermets, particularly of the Al_2O_3–Mo, –W, –Nb system, have received very little study. The temperature range investigated in most cases does not exceed 100-1000°C and the existing data are largely contradictory. It is difficult to analyze the results owing to the absence of information on the method of preparation of the specimens. According to the data of several papers [2-7], the thermal conductivity of cermets composed of alumina and powdered metal at temperatures up to 500-600°C is lower than that of pure corundum. At higher temperatures the thermal conductivity of the cermet begins to exceed that of the pure oxide. The thermophysical properties of Al_2O_3–Mo cermets in the temperature range 200-1400°C were investigated in [8, 9]. The thermal conductivity of the cermets in the whole range was higher than that of pure corundum, which is inconsistent with the data given in the above-cited investigations [2-7].

The aim of the present work was to investigate the thermophysical properties of alumina-based dielectric cermets ($\rho \geq 10^8$ Ω·cm at 20°C) in relation to the amount of the introduced component — molybdenum, tungsten, niobium (from 0 to 20 vol.%) — in a wide temperature range (50-1900°C).

Below we describe the preparation of the specimens. The particle sizes of the initial materials were as follows (μ): alumina [G-00 GOST (All-Union State Standard) 6912-64 technical alumina)] — 30-60; molybdenum — 5-20; tungsten — 3-20; niobium — 7-20. The chemical composition of the alumina was: 0.19% SiO_2; 0.13% ($K_2O + Na_2O$); 0.10% CaO; 0.10% MgO; 0.06% Fe_2O_3; 99.42% Al_2O_3 (from difference). The alumina was fired at 1750°C and powdered by vibration. The initial components were mixed in the prescribed amounts and the specimens were formed by semidry pressing and sintering in a vacuum furnace. The specimens were fired in vacuum (10^{-4} mm Hg) in two stages: prefiring at 1300°C (1 h) and a final firing at 1800°C (1 h). After prefiring the specimens were mechanically worked — holes were drilled and grooves cut for the thermocouple leads and the probes for measuring the voltage drop on the heater. The composition and properties of the investigated specimens are given in Table 1.

The thermal conductivity was measured by the steady-state internally heated cylinder method in the middle temperature range (500-1900°C) in an argon atmosphere (1 atm) on the apparatus of the All-Union Institute of Refractories [10]. A relatively small amount of data for specimens in air at 50-400°C were obtained by the steady heating method on the apparatus of the Leningrad Institute of Precision Mechanics and Optics [11]. The error of measurement on these apparatuses does not exceed 7-10%. The thermal conductivity of the materials was determined on at least three or four specimens. The temperature dependences of the thermal conductivity of the investigated cermets are shown in Fig. 1 (a, b, c). For comparison Fig. 1a shows the dependence for the conducting cermet GM-60.

The root-mean-square deviation of the experimental data from the approximating curve lay between 5-10% for all the cermets, which is close (in view of the difference in the specimens) to the calculated error of measurement.

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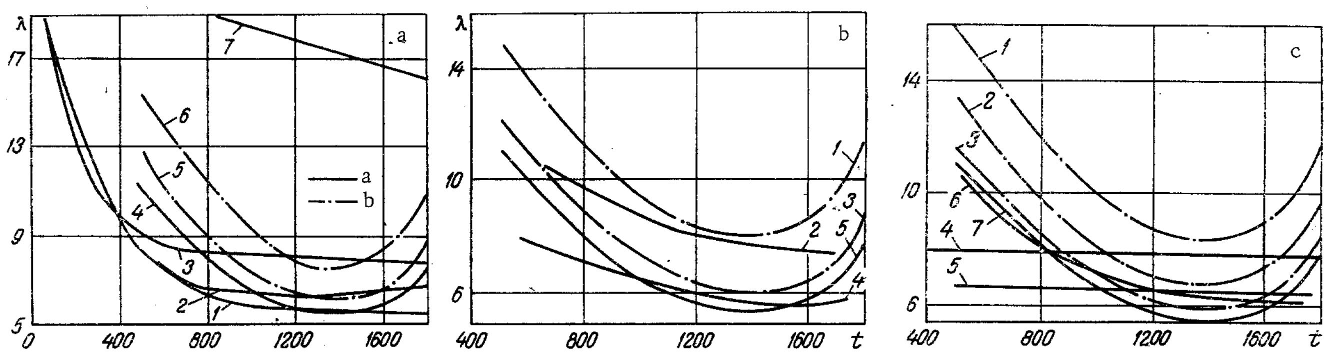

Fig. 1. Plots of thermal conductivity λ, W/m•deg, of materials of systems Al_2O_3—Mo (a), Al_2O_3—Nb (b), and Al_2O_3—W (c) against temperature t, °C (a) experimental data b) data calculated from Odelevskii's equation [12]). For a): 1) GM-5; 2,4) GM-10; 3,6) GM-30; 5) Al_2O_3; 7) GM-60. b): 1,2) GN-30; 3,4) GN-10; 5) Al_2O_3. c): 1,4) GV-50; 2,5) GV-30; 3,6) GV-10; 7) Al_2O_3.

TABLE 1. Composition and Properties of Specimens

Material	Metal content, wt.%			Open porosity, %	Total porosity, %	Apparent density, g/cm³	Theoretical density, g/cm³
	Nb	W	Mo				
GN-10	10	—	—	0,48	5,6	3,95	4,18
GN-30	30	—	—	0,83	5,5	4,48	4,74
GM-5	—	—	5	14,3	16,1	3,39	4,09
GM-10	—	—	10	0,9	7,3	3,92	4,23
GM-30	—	—	30	4,7	8,9	4,43	4,86
GM-60	—	—	60	15,6	17,2	5,26	6,27
GV-10	—	10	—	1,05	11,1	3,83	4,31
GV-30	—	30	—	6,25	11,8	4,58	5,21
GV-50	—	50	—	11,2	13,8	5,66	6,57
Al_2O_3	—	—	—	1,82	5,62	3,74	3,97

The experimental results were compared with calculated values of the thermal conductivity. The investigated specimens in their microstructure consisted of a continuous phase of polycrystalline alumina in which the metal particles and a small number of pores were uniformly distributed; this allowed us to use Odelevskii's formula for the calculations [12]. As the conductivity of the continuous phase we used the experimental data obtained for pure alumina in the present investigation. These data agree with the results of the investigation of Kingery et al. [13] within the limits of experimental error. For the thermal conductivity of the metal phase we used the data recommended in [14]. In the temperature range 1000-1500°C we found good agreement between the calculated and experimental curves. In this temperature region the thermal conductivity of cermets with a molybdenum or niobium content of 30 wt. %, or a tungsten content of 50 wt. %, was 1.5 times greater than that of pure alumina. The thermal conductivity of cermets at low (400-800°C) and high (1500-1900°C) temperatures was less than that of corundum. We can agree with the opinion of the authors of [2, 4] that the lower values of the experimentally measured thermal conductivity at low temperatures in comparison with the thermal conductivity of pure corundum can be attributed to the contribution of the thermal resistance of the metal—ceramic contact to the effective thermal conductivity. This contribution decreases with increase in temperature. This obviously also accounts for the systematic differences between the curves calculated from Odelevskii's formula for mechanical matrix mixtures (Fig. 1c, curves 1, 2, c) and the experimental data. This fact agrees with the data given in the monographs [2-4]. At higher temperatures the phonon mean free path is reduced, the effect of contact resistances (grain boundaries) levels out, and there is good agreement between the calculated and experimental curves.

The differences that we found between the thermal conductivity of corundum and the cermets in this investigation can be attributed to the reduction of the radiative component of the thermal conductivity due to the screening effect of the metal particles. The reduction of the effective thermal conductivity of the continuous phase of the matrix system (corundum) due to scattering and absorption of heat radiation on the boundaries accounts for the difference between the theoretical values of the thermal conductivity and the experimental data.

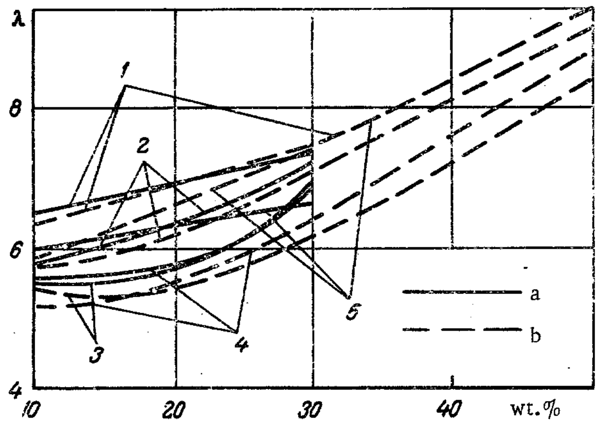

Fig. 2. Plots of thermal conductivity λ (W/m·deg) of materials of Al_2O_3 system against molybdenum content (wt. %) at different temperatures: 1) t = 500°C; 2) 900; 3) 1300; 4) 1500; 5) 1800 [a) experimental data; b) values calculated from Eq. (1)].

Thus, the obtained experimental data are a good illustration of the violation of the mixing laws in the temperature range where interaction of the phases alters the mechanism of thermal conductivity. It should be noted that this fact (for the low-temperature interval) has been discussed in [2].

A comparative analysis of the experimental and theoretical curves reveals that the indicated systematic differences are not only qualitative, but also quantitative. We were thus able to correlate the experimental thermal conductivity data for the cermets Al_2O_3–Mo, –W, –Nb on the basis of the following semiempirical relation:

$$\frac{\lambda_{\text{eff}}}{\lambda_{Al_2O_3}} = (0.49 - 0.29\cdot10^{-3}t + 0.116\cdot10^{-5}t^2 - 0.507\cdot10^{-9}t^3)\,(1 - 1.5P_0)\,\frac{(2+\nu)+2K(\nu-1)}{(2+\nu)-K(\nu-1)}\,. \qquad (1)$$

Plots of the thermal conductivity of Al_2O_3–Mo at temperatures of 400-1800°C against Mo content, obtained from Eq. (1) and from the experimental data, are compared in Fig. 2. The curves for the other cermets have a similar shape. The proposed relation correlates the obtained experimental data with an error of not more than 10-20%, which justifies its recommendation for approximate estimates of the thermal conductivity of other dielectric cermets of the Al_2O_3–metal system.

To obtain the set of thermophysical characteristics – thermal conductivity, specific heat, and thermal diffusivity – we need to know two of these parameters. The specific heat can be calculated sufficiently accurately from the additivity law. However, evidence of restricted applicability of the additivity law for dispersed materials, particularly cermets, has recently been published [15]. The discrepancy is attributed to additional specific heat components due to the intercomponent interface (contribution of free surface energy and anharmonicity of the vibrations of surface atoms to the specific heat). In view of this, we considered it advisable to test experimentally the validity of the additivity law for our materials. For this purpose we investigated experimentally the specific heat of two compositions with molybdenum content 10 and 30% by the method indicated in [16]. The experimental results were compared with the values of the enthalpy and specific heat calculated from the initial data recommended in [17, 18]. The disagreement between calculation and experiment did not exceed 1-2%, which is within the limits of measurement error and confirms the validity of the adopted method of calculating the specific heat of the investigated group of materials. The interphase boundaries probably have no appreciable effect on the specific heat of refractory cermets.

NOTATION

ρ, resistivity; t, temperature, °C; λ, thermal conductivity; λ_{eff}, thermal conductivity calculated from general relation; $\lambda_{Al_2O_3}$, thermal conductivity of corundum; P_0, porosity; $\nu = \lambda_M/\lambda_{Al_2O_3}$; λ_M, thermal conductivity of metal phase; K, volumetric content of metal phase.

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RADIATION CHARACTERISTICS OF GAS INFRARED HEATERS IN RADIANT HEATING SYSTEMS

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Results of an experimental study of the radiation characteristics of commercial models of gas infrared heaters are presented. An analytic expression is obtained for the distribution of irradiance over a flat object at various distances from the heater.

Engineering methods for the design of radiant heating systems which are used in construction, petrochemistry, communal economy, and other fields are based on such radiation characteristics as radiation surface density, emissivity of heat-releasing surfaces, and radiant component of heat emission (radiant efficiency).

The characteristics listed are properties of the IR heater materials and depend on its mode of operation. As far as absorptive and reflective capabilities are concerned, they are

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