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THERMOPHYSICAL PROPERTIES OF COBALT AT HIGH TEMPERATURES

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Measured values of the thermal conductivity, total hemispherical and spectral ($\lambda = 0.65\ \mu$) emittances, resistivity, and coefficient of linear expansion of cobalt are presented.

Cobalt is widely used as a basis of a large group of alloys capable of successful operation over a wide temperature range [1, 2], but its thermophysical properties have been inadequately investigated, particularly at temperatures above 1200°K.

The known investigations of the thermal conductivity of cobalt at high temperatures [3] are based on calculations using experimental values of the thermal diffusivity.

Data on radiative properties of cobalt are meager and highly contradictory [4].

The present work was undertaken to determine the thermophysical properties of cobalt at high temperatures.

The properties of cobalt were measured in the 300-1700°K range using samples made of a single bar having the following composition (wt. %): Co, 99.4; Fe, 0.4; Si, 0.15; C, 0.035; Mn, 0.01; remainder $\leqslant 0.005$.

The technique for measuring the thermal conductivity and the total hemispherical emittance is based on a solution of the steady-state energy-balance equation for an element of length of the central part of the sample heated by an electric current in a vacuum [5]:

$$\frac{d^2t}{dx^2} - Lt - K = 0, \tag{1}$$

where

$$L = \frac{P\varepsilon_0\sigma}{\lambda S}\,4T_e^3 + \frac{P\varepsilon_0\sigma}{\lambda S}\,\gamma T_e^3 - \frac{I^2\rho_0}{\lambda S^2}\,\beta, \tag{2}$$

$$K = \frac{I^2\rho_0}{\lambda S^2} - \frac{P\varepsilon_0\sigma}{\lambda S}\,T_e^4. \tag{3}$$

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TABLE 1. Thermophysical Properties of Cobalt

T, °K	293	400	500	600	700	800	900	1000
ρ^*, μΩ	0,082	0,125	0,171	0,225	0,295	0,343	0,416	0,505
$\alpha^* \cdot 10^6$, deg^{-1}	12,3	13,2	13,9	14,7	15,5	14,6	15,3	16,0
T, °K	1100	1200	1300	1400	1500	1600	1700	—
ρ, μΩ	0,590	0,690	0,775	0,843	0,882	0,921	0,959	—
$\alpha^* \cdot 10^6$, deg^{-1}	16,7	17,4	18,1	—	—	—	—	—
λ, W/m·deg	—	—	—	42,5	43,0	44,0	45,0	—
ε	—	—	0,220	0,220	0,225	0,230	0,230	—
ε_λ ($\lambda = 0{,}65$ μ)	—	—	0,44	0,415	0,40	0,395	0,39	—

*Values of ρ and α obtained during heating of samples.

Here λ, ε_0, and ρ_0 are, respectively, the thermal conductivity, the total hemispherical emittance, and the resistivity at the temperature of the central point of the sample, where $T = T_{max} = T_e$; I is the heating current; and S, P, and σ are, respectively, the cross-sectional area and perimeter of the sample and the Stefan–Boltzmann constant:

$$\gamma = \frac{1}{\varepsilon} \cdot \frac{d\varepsilon}{dT}, \tag{4}$$

$$\beta = \frac{1}{\rho} \cdot \frac{d\rho}{dT}. \tag{5}$$

The working formulas for determining λ and ε are based on the use of the solution of Eq. (1) and the derivative of the implicit function K (3) with respect to the maximum temperature at the center of the sample [6].

The investigations were performed on an arrangement for the complex study of thermophysical properties at high temperatures [6] in which the sample is heated in a vacuum of the order of 10^{-5} torr by the direct passage of a stabilized alternating electric current. In the central part of a 120 × 6 × 3-mm sample in the region of the maximum temperature T_e a parabolic temperature distribution was established along the sample. In this case λ and ε are calculated from the expressions

$$\lambda_0 = \frac{I^2\rho_0}{KS^2} \cdot \frac{\frac{d}{dT} \ln\left(\frac{\varepsilon T_e^4}{I^2\rho}\right)}{\frac{d}{dT} \ln\left(\frac{\varepsilon T_e^4}{\lambda K}\right)}, \tag{6}$$

$$\varepsilon_0 = \frac{I^2\rho_0}{SP\sigma T_e^4} \cdot \frac{\frac{d}{dT} \ln\left(\frac{I^2\rho}{\lambda K}\right)}{\frac{d}{dT} \ln\left(\frac{\varepsilon T_e^4}{\lambda K}\right)}. \tag{7}$$

An F 563 electronic voltmilliammeter with an optical pointer was used to measure ρ. The voltmilliammeter was read with a type MBS-2 two-channel microscope having its own scale with divisions from 7-20 times smaller than those of the F 563 instrument depending on whether the reading was at the beginning or the end of the scale. Under normal conditions this decreased the reading error appreciably, and thus decreased the error of the measurements of the alternating voltage made with the F 563 voltmilliammeter. The maximum random error of one measurement with a confidence coefficient of 95% varied from 0.035 at the end of the scale to 0.14% at the beginning of the scale for most of the ranges of the measurements.

The resistivity ρ was measured from room temperature to 1500°K on a special installation using a compensation method while heating the samples in a resistance oven with a molybdenum heater in a vacuum of 10^{-5} torr. Temperatures were measured with type Pr 30/6 thermocouples.

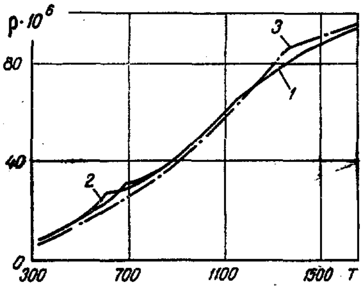

Fig. 1. Resistivity (Ω · cm) as a function of temperature (°K). 1) Heating; 2) cooling; 3) 99.95% pure cobalt [3].

In the experiments on the measurement of ρ the geometrical factor of the working portion $\Gamma = S/l$, where S is the cross-sectional area of the sample and l is the distance between the potential electrodes, was calculated from the measured value of the resistivity of the sample at 20°C.

The values of ρ measured on various installations are in good agreement in the region of comparable temperatures, and this is a further criterion for the reliability of the results obtained.

The coefficient of linear expansion of cobalt was measured with a Leitz differential optical dilatometer for an average rate of heating of the samples of 5 deg/min. The optical magnification along the axis of ordinates was 250, and the sensitivity was $4 = 6 \times 10^3$ [7]. The random error of a measurement of α in the 300-1300°K range for an interval of 100°K was 3.5%.

Smoothed values of the experimental data are shown in Table 1.

The maximum error of the measurements (random + systematic) corresponding to a confidence interval of 95% was 10% for λ, 10 and 11%, respectively for ε and ε_λ, 8% for ρ in the 300-1300°K temperature range and 1% in the 1300-1700°K range.

The Lorentz number of cobalt calculated from the measurements remains constant at 2.55×10^{-8} WΩ/deg² in the 1400-1700°K range.

Our measured values of the thermal conductivity (Table 1) agree within 5% with those calculated in [3] for the 1400-1700°K temperature range. The values of the total hemispherical emittance agree within 4.5% with the results in [8].

Our values of the spectral (λ = 0.65 μ) emittance are 10% higher than the data of [9] at 1300°K.

It should be noted that the values of ε_λ given in [8, 10] are the lowest known values for metals, including those of group VIII. The Lorentz function for Co obtained by Jain et al. [11] is appreciably smaller than the theoretical value of 2.45×10^{-8} WΩ/deg².

Figure 1 shows the temperature dependence of the resistivity of cobalt for heating (curve 1) and cooling (curve 2) of a sample and the values of ρ of cobalt from [3] (curve 3). The temperature dependences of the coefficient of linear expansion and the resistivity show hysteresis in the region of the allotropic transformation of cobalt. The measurements of α and ρ show that the temperature of the allotropic transformation during heating of the sample is higher than the transformation temperature during cooling by approximately 100°K. In this case the high temperature β phase with an fcc crystal lattice has smaller values of α and ρ.

The resistivity of cobalt is approximated by the following equations:

$$\rho = -0.032 + 3.67\cdot10^{-4}\,T + 1.57\cdot10^{-10}\,T^3\ \mu\Omega\cdot\mathrm{m},$$
$$T = 300 - 1200\,^\circ\mathrm{K},$$
$$\rho = 0.325 + 3.8\cdot10^{-4}\,T\ \mu\Omega\cdot\mathrm{m},$$
$$T = 1400 - 1700\,^\circ\mathrm{K}.$$

The maximum deviation of the measured values from these relations does not exceed 1.5% except in the allotropic transformation region where it reaches 5%.

A comparison of our data on ρ with values in the literature [3] shows that the $\rho = f(T)$ curve for our sample intersects the $\rho = f(T)$ curve for 99.95% pure cobalt at 1200°K, and above this temperature its resistance is smaller than that of the purer metal. This behavior of ρ of the cobalt sample investigated apparently results from a decrease in the magnetic component of the resistance due to impurities [12].

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COMPARATIVE METHOD FOR MEASURING THERMAL CONDUCTIVITY

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A comparative method is developed for measuring the thermal conductivity of solid and dispersed materials with $\lambda = 0.1$-80 W/(m · °K). The method is accurate, rapid, and simple to use.

As the number of standard materials increases, comparative methods of measuring thermophysical characteristics are more and more widely used. As a rule, these methods involve the measurement of a smaller number of parameters, eliminate certain systematic errors, and are as accurate as absolute methods.

The method proposed is simple to use, is highly accurate, and can be used to determine the thermal conductivity of various materials with $\lambda = 0.1 - 80$ W/(m · °K). Since the experiment is of short duration, the method can be used to measure the thermal conductivity of moist materials.

A schematic diagram of the method is shown in Fig. 1a. The sample 1 in the form of a plate and contiguous heat meter 2 are placed between two massive metal blocks 3 with the same heat capacity. The lateral surface of the blocks, the sample, and the heat meter are surrounded by ideal thermal insulation 4. The temperature of one of the blocks, for example, the upper one, is raised 5-10°K above that of the lower. After a certain time a nearly steady heat flux is established between the blocks; this flux depends on the initial temperature difference between the upper and lower blocks and the thermal resistance of the sample under study. If the heat capacities of the blocks are large enough, their temperatures remain practically

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