Journal of Engineering Physics and Thermophysics, Vol. 68, No. 5, 1995

INFLUENCE OF STRUCTURE ON THE THERMOPHYSICAL CHARACTERISTICS OF POROUS METALS

V. V. Polyakov, M. A. Utemesov, and A. V. Egorov

UDC 539.32:531.002

An experimental investigation of the thermal conductivity and thermal diffusivity of porous copper and iron with different porous structures is made. A dependence of the thermophysical characteristics on the degree of porosity and the mean pore size is established. A correlation with the structural model made it possible to take into account the dependence of the pore size distribution on the parameters.

The wide use of composite materials under the conditions of alternating temperature fields calls for an investigation of the dependences of their thermophysical characteristics on structural parameters. Particular interest attaches to investigations of porous metals whose specific properties are attributable to their extremely inhomogeneous structure [1]. The use of traditional experimental methods for such investigations entails great difficulties due to the high magnitudes of their thermal conductivities [2]. For this reason, the effect of the specific features of a porous structure on the thermophysical characteristics of metals has not been fully clarified. In the present work we investigated the thermal conductivity and thermal diffusivity of porous copper and iron as functions of the degree of porosity and the pore size distribution parameters.

Specimens for measurements were prepared from P3hRV2 iron and PM1 copper powders by pressing them to the required degree of porosity P and subsequent sintering under vacuum at a temperature of 1125°C (Fe) and in an inert atmosphere at 850°C (Cu) for 2 h. The specimens had the form of cylinders with a diameter of 10 mm and height of 3–4 mm. The values of P were assigned to be from 5 to 40%. We attained a substantial variation in pore size by using a pore-forming agent (ammonium bicarbonate) with fractions of three dimensions: less than 100 μm, from 100 to 300 μm, and from 300 to 500 μm. The pore distribution parameters were determined by metallographic microsections under a NEOPHOT-32 optical microscope. Cast copper and Armco iron were used as compact materials ($P = 0$).

We determined the thermophysical characteristics by a laser-pulse method [3, 4] that permitted us to conduct reliable measurements for substances with a high thermal conductivity and that did not require a standard. In accordance with this method, a laser initiates in a specimen a heat pulse whose propagation is determined by the thermal diffusivity of the material a. In an approximation of a plane temperature wave, neglecting heat losses, it is possible to find the thermal diffusivity by the formula [3]:

$$a \cong 0.139\, L^2 t_{1/2}^{-1}, \tag{1}$$

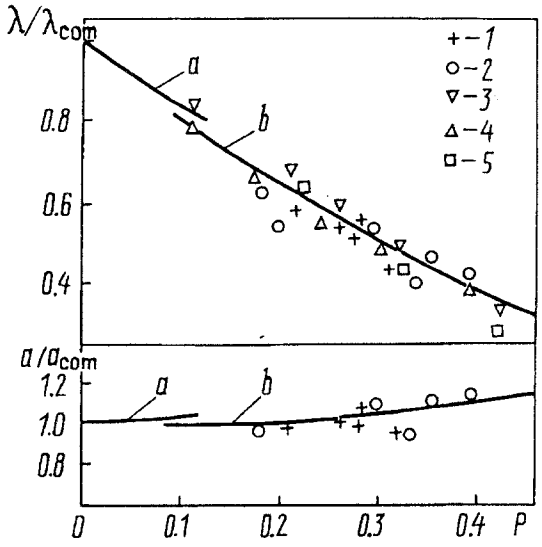
where L is the specimen thickness, and $t_{1/2}$ is the time for the rear surface to reach a temperature equal to half its maximum value. Then the thermal conductivity λ is defined as [5]:

$$\lambda = a/C_p\rho\,. \tag{2}$$

The values of λ were also determined by a modified probe method [6]. The experimental data obtained are given in the upper part of Fig. 1 as plots of the relative thermal conductivity λ/λ_{com} against the porosity P. Also given in the figure are the experimental data of [7-9]. The relative thermal conductivity decreases monotonically with an

Altai State University, Barnaul. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 5, pp. 720-723, September-October, 1995. Original article submitted September 2, 1993.

 1062-0125/95/6805-0580$12.50



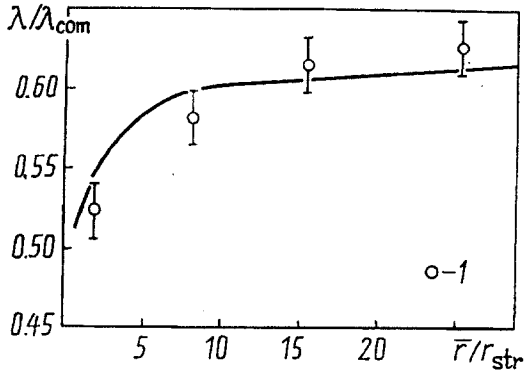


Fig. 1. Dependence of relative thermal conductivity and thermal diffusivity on porosity; experiment: 1) Cu, laser-pulse method; 2-5) Fe, 2) data of [6], 3) [7], 4) [8], 5) [9]; calculation: a) by formulas (3), and (6); 6) by formula (4).

Fig. 2. Effect of mean pore size on relative thermal conductionity of copper; calculation by formulas (4), and (6); 1) laser-pulse method.

increase in P. In the lower part of Fig. 1, similar relations are presented for the relative thermal diffusivity a/a_{com}. The value of a/a_{com} changes little in the range of porosities investigated. Figure 2 shows the dependences of the value of λ/λ_{com} on the mean pore size $\bar{r}$ for the specimens of copper with a pore former. At a fixed porosity $P = 0.3$ an increase in the relative thermal conductivity with an increasing mean pore size is observed.

In order to describe the thermophysical characteristics of porous metals theoretically by the elementary-cell method [1], we considered the dependence of the heat-transfer process on the dimensions of the compact region between pores (Fig. 3). Assuming that a region (adjacent to a pore) of compact material of size x does not participate in the process of heat transfer, in the case of isolated pores we obtain the following expression for the relative thermal conductivity of an elementary cell:

$$\frac{\lambda_1^*}{\lambda_{com}}(P, r) = (1 - f_1^2) \Big/ \left(1 - f_1^2 + f_1^3 + f_1^3 \frac{x}{r}\right), \tag{3}$$

where $f_1 = P^{1/3}$. Similarly, in the case of intercommunicating pores we find

$$\frac{\lambda_2^*}{\lambda_{com}}(P, r) = (1 - f_2)(1 - f_2)^2 \Big/ \left(1 - f_2 + 2f_2^2 + 2f_2^2 \frac{x}{r}\right), \tag{4}$$

where f_2 is assigned by the relation $3f_2^2 - 2f_2^3 = P$. We should take into consideration that when the size of the compact region $a-r$ is smaller than a certain critical value of r_{str}, determined by the parameters of the thermal wave, heat flux does not penetrate between pores, whereas in the case of $a-r > r_{str}$ the thermal wave propagates partially along a transverse "beam". These conditions are satisfied by the following expression for the quantity x:

$$x = \begin{cases} r_{str}, & r > r_{str}(f_1^{-1} - 1)^{-1}, \\ r(f_i^{-1} - 1), & r \le r_{str}(f_i^{-1} - 1)^{-1}. \end{cases} \tag{5}$$

We note that adiabatic and isothermal subdivisions [1] of the elementary cell follow from formulas (3) and (4) as particular cases when $x/r \to f_i^{-1} - 1$ and $x/r \to 0$, respectively. From expressions (3) and (4) it follows that the

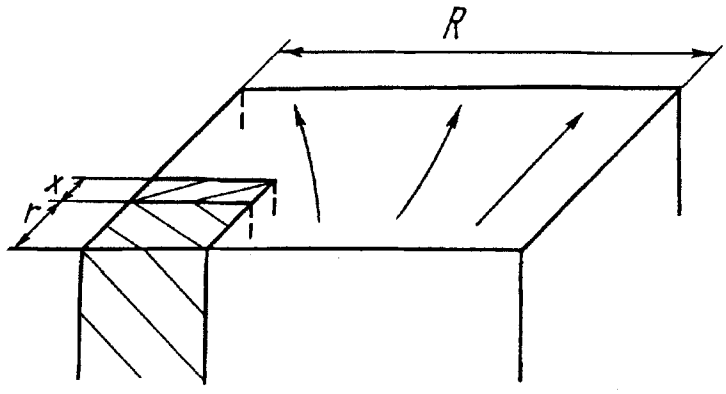


Fig. 3. Fragment of an elementary cell of porous material.

dependence of thermal conductivity on pore size is accounted for by the ratio r_{str}/r. A similar dependence was described when measurements of the electrical conductivity of powder compositions were made [10].

When the differences in pore size are substantial, it is necessary to move from the monodisperse case, described by formulas (3) and (4), to allowance for the pore size distribution. Specifying this distribution by the probability density $F(r, \bar{r}, D)$, we obtain an expression for calculating the effective thermal conductivity of a polydisperse material:

$$\frac{\lambda_i}{\lambda_{com}}(P, \bar{r}, D) = \int_0^\infty \frac{\lambda_i^*}{\lambda_{com}}(P, r) F(r, \bar{r}, D)\, dr. \tag{6}$$

In this case the effective thermal diffusivity is calculated by formula (2). Expression (6) makes it possible to describe the thermophysical characteristics as functions of both the porosity and the pore distribution parameters $\bar{r}$ and D.

We used formula (6) to calculate the effective thermal conductivity of the porous metals investigated. For the calculations, the function $F(r, \bar{r}, D)$ was selected in the form of a normal distribution with superposition [11]; the structural parameters were determined from the data of metallographic measurements. For specimens with a pore former the pore distribution had a characteristic "double-humped" form; for its description we used the superposition of two distribution functions with different parameters. The calculation results are given in Figs. 1 and 2 in the form of curves. As is seen from Fig. 1, the calculated curves agree with the experimental values for the thermal conductivity and thermal diffusivity in the range of porosities investigated. The curve in Fig. 2 correctly reflects the behavior of the thermal conductivity as a function of pore size.

The results obtained in the present work make it possible to estimate the influence of the specific features of the structure of porous metals on their thermophysical characteristics. The theoretical approach used can be employed to analyze and interpret experimental data on the thermal conductivity and thermal diffusivity of materials with different porosities.

NOTATION

λ, λ_{com}, thermal conductivity coefficients of porous and compact materials; λ_1, λ_2, thermal conductivity coefficients for the cases of isolated and intercommunicating pores; λ_1^*, λ_2^*, thermal conductivity coefficients of monodisperse structures; a, a_{com}, thermal diffusivity coefficients of porous and compact materials; C_p, specific heat; ρ, density; P, porosity; r, $\bar{r}$, size and mean size of pores; r_{str}, structural parameter; D, variance of pore size; R, size of an elementary cell; $F(r, \bar{r}, D)$, differential function of pore size distribution.

REFERENCES

1. G. N. Dul'nev and V. V. Novikov, Transfer Processes in Inhomogeneous Media [in Russian], Leningrad (1991).
2. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids [Russian translation], Moscow (1964).

3. T. W. Wojtatowicz and K. Rozniakowski, Thermal Conductivity: Proc. 20th Int. Thermalal Conductivity Conf., Vol. 20, 367-375 (1989).
4. D.J. Jaklitsh and J. W. Walkinshaw, Ind. Eng. Chem. Res., 27, 702-706 (1988).
5. G. N. Dul'nev and A. V. Sigalov, Inzh.-Fiz. Zh., 39, No. 1, 126-133 (1980).
6. V. V. Polyakov, M. A. Utemesov, T. V. Bondarchuk, and A. P. Sheyda, Proc. 8th All-Union Conf.: Thermal Properties of Substances [in Russian], Pt. II, Novosibirsk (1989).
7. G. I. Aksenov and R. Zabbarov, Poroshkov. Metallur., No. 6, 39-47 (1967).
8. V. I. Kononenko, V. M. Baranovskii, and V. P. Dushchenko, Poroshkov. Metallur., No. 3, 19-22 (1968).
9. P. I. Mal'ko, V. F. Nemchenko, S. N. L'vov, and V. S. Pugin, Poroshkov. Metallur., No. 1, 62-66 (1969).
10. Yu. P. Zarichnyak, S. S. Ordan'yan, A. N. Sokolov, and B. K. Stepanenko, Poroshkov. Metallur., No. 6, 97-101 (1986).
11. N. L. Johnson and F. C. Leone, Statistics and Experimental Design in Engineering and the Physical Sciences [Russian translation], Moscow (1980).