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DETERMINATION OF THE THERMAL CONDUCTIVITY OF FOAM ALUMINUM

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We present calculations and experimental data on determination of the thermal conductivity of porous foam aluminum materials. We analyze the possibility of their use for thermal insulation.

Metal foams are a comparatively new class of structural materials that combine high rigidity, low density, and low thermal conductivity. They are capable of suppressing shock waves, and this makes them promising for damping devices. The application of foam materials is high by highly diverse, but in the main this comes down to:

1) heat-insulating and soundproofing slabs;
2) foam-filled thin-walled beams for prefabricated industrial constructions;
3) foam-filled shock-absorbing chassis frames.

The technological process of preparation of foam includes mixing of powders of a foaming agent (TiH_2) and aluminum-silicon alloy. Then the mixture is subjected to cold compaction and hot extrusion to give it the needed geometric shape. The ingots obtained are placed in an electric furnace, where heating frees them from the foaming agent, and a cellular structure is formed (Fig. 1). The metal foam obtained is ready for subsequent mechanical operations (cutting, cladding with aluminum sheets, and so on). The density of the foam is equal to about 500 kg/m^3, which means that the averaged porosity of the foamy layer is 80%.

When metal foams are used as heat insulators on one or two sides of a plate, aluminum substrates are attached to them that protect them against damage; they are secured with glue or by laser welding.

The main characteristic of the degree of thermal insulation of a material is its thermal conductivity. For nonmetallic constructions $\lambda_{max} \approx 3$ W/(m·K) [1]. Solid aluminum has $\lambda \approx 150$ W/(m·K). The task of the present work is experimental and computational determination of the thermal conductivity of foam aluminum and analysis of the efficiency of its use as a thermal insulator. Samples were made in the Department of Metal Materials of Bayreuth University (Germany). A schematic of a heat-insulating foam plate is shown in Fig. 2. The porous layer is characterized by a high dispersion of the pores: there are capillaries (of size up to 1 mm) and cavitiies (of size 3–5 mm or more). In this case the problem of calculation of the thermal conductivity of a plate is aggravated by the effect of convection in the pores.

At the present time several models of calculation are developed. We will consider two of them in more detail.

For an isotropic capillary-porous body the following formulas for determining two limiting values of effective thermal conductivity are suggested [2]; the lower limit is ensured if it is assumed that two phases (in our case aluminum and air) conduct heat in succession:

$$\lambda_{\text{effmin}} = \frac{\lambda_a}{1 + \Pi \left(\frac{\lambda_{sb}}{\lambda_a} - 1\right)} . \tag{1}$$

and the upper one when it is assumed that both phases conduct heat simultaneously:

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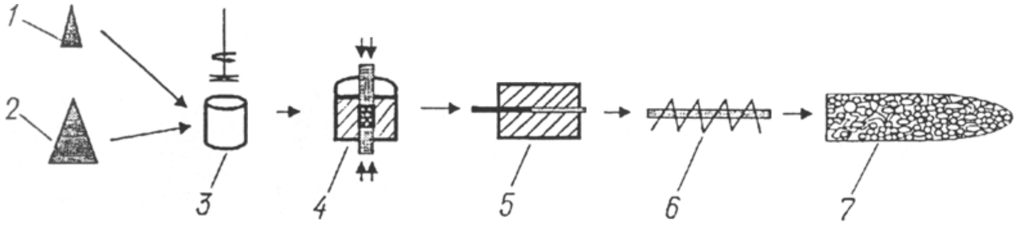

Fig. 1. Schematic diagram of the technological process: 1) foaming reagent (TiH_2 powder), 2) aluminum powder, 3) mixer, 4) press, 5) extruder, 6) heating oven, 7) foam.

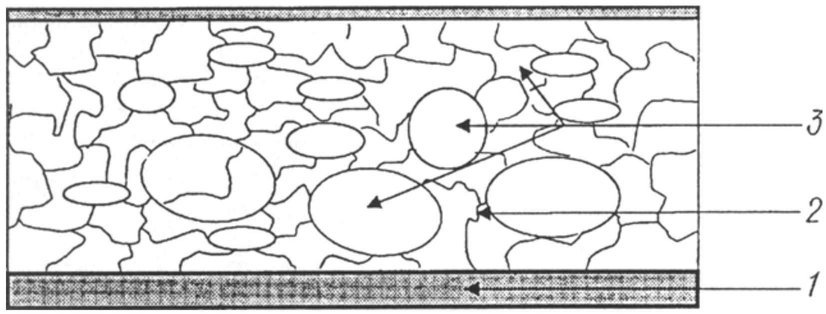

Fig. 2. Schematic diagram of foam aluminum (in section): 1) substrate, 2) foam layer, 3) pores.

$$\lambda_{\text{effmax}} = \frac{\lambda_{\text{sb}}}{1 - \Pi\left(1 - \frac{\lambda_{\text{a}}}{\lambda_{\text{sb}}}\right)}. \tag{2}$$

The porosity Π is defined as the ratio of the total volume of the pores to the overall volume of the body:

$$\Pi = \frac{W - m/\rho_{\text{sb}}}{W}. \tag{3}$$

For a material consisting of a solid skeleton with arbitrary air inclusions it is possible to apply A. Misnar's model [3], in which heterogeneous bodies are considered as a mixture of a viscous phase with particles of a filler. The latter may have the most arbitrary configuration, but for theoretical consideration of thermal conductivity they are given a regular geometric shape. It is assumed that the particles are uniformly distributed throughout the entire volume and that there is close contact between the components of the mixture, so that it is possible to neglect the thermal resistance of the contacts. Then

$$\lambda_{\text{eff}} = \lambda_{\text{sb}}\left[1 + \frac{1 - \lambda_{\text{sb}}/\lambda_{\text{a}}}{1 - \Pi^{1/3}(1 - \lambda_{\text{sb}}/\lambda_{\text{a}})}\right]. \tag{4}$$

Here $\lambda_{\text{sb}} >> \lambda_{\text{a}}$.

If we assume that there are no cracks in the material investigated and the air inclusions have a more or less spherical shape and if air is considered as the filler, then the ratio $\lambda_{\text{sb}}/\lambda_{\text{a}}$ is large. In this case from Eq. (4) it follows that

$$\lambda_{\text{eff(1)}} = \lambda_{\text{sb}}(1 - \Pi^{2/3}). \tag{5}$$

However, if air virtually surrounds the solid material and there is no contact between particles ($\lambda_{\text{a}}/\lambda_{\text{sb}} \approx 0$), then

$$\lambda_{\text{eff(2)}} = \lambda_{\text{a}}[1 + \Pi(1 - \Pi^{1/3})]. \tag{6}$$

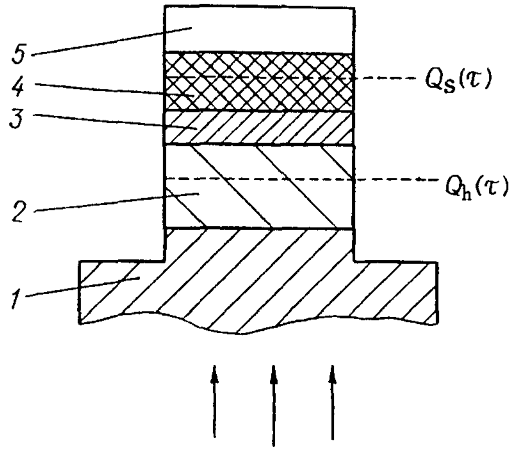

Fig. 3. Thermal scheme of the method of measurement of the thermal-conductivity coefficient.

An analysis shows that it is difficult to use the above formulas since they give extremely inconsistent results. The actual value of λ_{eff} lies somewhere between these values. Therefore the effective thermal conductivity of a dry porous material can be expressed in the following form:

$$\lambda_{eff} = a\lambda_{eff(1)} + b\lambda_{eff(2)}, \tag{7}$$

where $a + b = 1$. The values of a and b are determined by the nature of the material and depend, in particular, on the shape of the cavities and the length of the transverse cracks.

The intensity of heat exchange is influenced by the convective component. It is evaluated by the Nusselt number, which is defined as [4]

$$\mathrm{Nu} = \frac{\alpha_{con}}{\lambda_{sb}} d .$$

For a laminar flow

$$\mathrm{Nu} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} .$$

If $\mathrm{Nu} > 1$, the effect of convection on the thermophysical characteristics is appreciable. It is also evaluated by the values of the coefficients a and b.

Due to the large number of models and methods of calculation of the thermophysical characteristics of porous bodies, the basic source of information on the value of the thermal-conductivity coefficient is experimental measurements. For experimental determination of the thermal conductivity of foam samples, we selected the method of monotonic heating of them by an external one-sided through heat flux [5].

The thermal scheme of the method is shown in Fig. 3. Test sample 4, plate 3, and rod 5 are heated monotonically by the heat flux $Q(\tau)$ coming from base 1. The side surfaces of the rod, sample 4, and plates 2, 3 are insulated adiabatically. Rod 5 and contact plate 3 are made of copper, which has a high thermal conductivity, and therefore the temperature drops in them are insignificant. The heat flux $Q_h(\tau)$, passing through the middle cross section of plate 2 of the heat-measuring device, is partially absorbed by it, while the flux $Q_s(\tau)$ heats plate 3, sample 4, and rod 5. The dimensions of the system are selected so that the working layer of the heat-measuring device has a negligibly small heat capacity compared to the rod and has a low thermal resistance so that the fluxes that are accumulated by the sample and the plate are at least 5–10 times smaller than those absorbed by the rod. In this case the character of the temperature field of sample 4 and plate 2 turns out to be close to linear, and all parts of the system are heated at almost the same rate.

Structurally, the device used to measure heat conduction consists of two blocks. The block for power supply and regulation provides heating of the core of the measuring cell at a mean rate of about 0.1 K/sec and automatic

TABLE 1. Experimental Data and Calculated Values of Thermal Conductivity

No. of sample	1	2	3	4	5	6	7	9
Porosity Π	0.69	0.69	0.70	0.73	0.74	0.74	0.75	0.79
Thermal conductvity λ, W/(m·K) (experiment)	8.2	2.1	6.5	5.2	4.6	4.2	4.6	3.3
Calculation of λ according to [2] (a = 0.13)	6.0	6.0	5.7	5.2	5.0	5.0	4.9	4.1
Error Δ, %	–	–	–	0	10	19	6.5	24
Calculation of λ according to [3] (a = 0.21)	6.8	6.8	6.7	5.9	6.0	6.0	5.6	5.4
Error Δ, %	–	–	–	13	33	43	21	63

control of the temperature. The rate of heating is determined by the value of the initial voltage on the heater and the degree of its change. The measuring block incorporates the heating cell, heat-measuring device, test sample, rod, thermocouples, and a protective dome. Chromel-Alumel thermocouples were used for temperature measurements. The working layer of the heat-measuring device consists of a 12Kh18N9T stainless steel plate. To maintain adiabatic conditions on the side surfaces of the sample and the rod, an adiabatic casing and an automatic temperature regulator are envisioned. Aluminum powder was used to improve the thermal contact of the sample with the plate of the heat-measuring device and the rod. The temperature difference between the sample and the plate of the heat-measuring device was measured to determine the thermal conductivity in the process of continuous heating at fixed levels of the temperature of the rod T_r (every 25 °C) using an F136 device.

Results of the Experiments. The value of the thermal-conductivity coefficient changes slightly with increase in the temperature from 25 to 75 °C (10% maximum) (see Table 1). At the same time, the scatter in the values of λ for different samples is substantial: the smallest value is 2.1 and the greatest is 8.2 W/(m·K). This is explained by the following factors: the porosity of the samples, the shape and dimensions of the pores and cavities, and the kind of contact between the layers of pores and between the porous surface and the solid substrate. The substrate of samples 1-3 is 1.5 mm thick. The substrate of sample 1 is solded by laser to the foam layer, and the remaining substrates are glued. The substrate of sample 2 makes contact with extensive cavities, i.e., the contact heat conduction proceeds through a layer of air. Therefore, this sample has a low thermal conductivity (λ = 2.1 W/(m·K)) These values are below the thermal conductivity of the foam layer of the material. The substrate of sample 3 is glued more tightly (there are a smaller number of cavities at the place of attachment) to the porous layer, and the value of the thermal conductivity is higher than for porous samples.

Porous samples 4-8 have almost constant values of thermal conductivity but with a tendency toward a slight decrease with increase in porosity. The difference between the smallest and greatest thermal conductivities attains 36% with a change in porosity by 6%. This is explained by the dispersion of the porous structure, the presence of cavities of different sizes in the samples, the conditions of convection of air in them, and the density of the contact between the end surfaces of the sample and the measuring elements.

A comparison of the results of the experiment with calculations shows that for the foam materials investigated (without a substrate) the value of the thermal conductivity can be determined from formula (1) with the numerical value of the coefficient a = 0.13. The overall error of the calculation and the experiment is 12%. The error is much higher (34%) when expression (4) with the coefficient a = 0.21 is used.

The experiments showed that with a sufficient degree of accuracy (12%) the value of the thermal conductivity of the foam material can be calculated from the formula

$$\lambda_{\text{eff}} = 0.13 \frac{\lambda_{\text{sb}}}{1 - \Pi\left(1 - \frac{\lambda_{\text{a}}}{\lambda_{\text{sb}}}\right)} + 0.87 \frac{\lambda_{\text{a}}}{1 + \Pi\left(\frac{\lambda_{\text{sb}}}{\lambda_{\text{a}}} - 1\right)} .$$

The foam layer of aluminum has a thermal conductivity about 30 times lower than for the basic material. At the same time, it is twice that of heat-insulating building materials. However, with account for other properties of foam materials (strength, lightness, etc.) its application as a heat insulator in building constructions becomes advantageous.

NOTATION

a, b, coefficients; d, diameter; m, mass; W, volume; α, heat-transfer coefficient; λ, thermal-conductivity coefficient; ρ, density; Π, porosity; Nu, Pr, Re, Nusselt, Prandtl, and Reynolds numbers, respectively. Subscripts: a, air; con, convection; s, sample; r, rod; h, heat-measuring device; sb, solid body; eff, effective; max, maximum; min, minimum.

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