INVESTIGATING THE THERMAL CONDUCTIVITY AND ELECTRICAL RESISTANCE OF ALUMINUM AND OF A GROUP OF ALUMINUM ALLOYS

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Results are presented from the measurement and calculation of thermal conductivities for three aluminum alloys in the temperature range 293-673°K.

The purpose of these experiments was to verify the possibility of using existing theoretical relationships to calculate the thermal conductivity of slightly alloyed materials, provided that the thermal and electrical conductivities of the basic component are known, in addition to the electrical conductivity of the alloys. The tests were performed on aluminum and its alloys from the Al–Mg system (AMG-3, AMG-5, AMG-6).

The electrical resistance ρ of the specimens was measured in accordance with a well-known potentiometric procedure.

The error in the measurement of ρ did not exceed 0.5% in the test. The rather high accuracy of these measurements was achieved through the unique design of the furnace in which the specimen was kept. The temperature difference across the working area of the furnace did not exceed 1°K. For the potential leads we used a Chromel wire which oxidizes slightly when heated to 800°K in air and which develops a low thermal emf in the vapor with the aluminum specimen when a temperature difference develops across the specimen. The Chromel wire was clamped in brass mounts by means of which the voltage drop across the specimen was recorded. Special tests were performed to determine the possibility of an additional thermal emf because the Chromel wire is not in direct contact with the specimen. No temperature difference was noted between the wire and the specimen (at the point of specimen contact with the clamps). The temperature of the specimen was measured with Chromel–Alumel thermocouples mounted next to the potential clamps. The measurements involved opposed current in the specimen, on the order of 1 A. The specimens were 100 mm in length and exhibited a diameter of 4 mm.

The thermal conductivity λ of the specimens (52 mm in length and 8 mm in diameter) was measured on a Rozhdestvenskii installation [1] which employed a relative method of measuring thermal conductivity. The test specimen is tightly clamped in this installation between two specimen standards (made of 1Kh18N9T steel). This assembled specimen is positioned between heaters of differing temperature. The side specimen surface is surrounded with several screens between which is poured a thermal insulation. The temperature distribution on the screen, similar to the temperature distribution on the specimen, is achieved with above-mentioned heaters. The installation can simultaneously test 4 identical assembled specimens, which significantly raises the measurement accuracy. The experiments are conducted with heat flows moving in opposite directions, i.e., initially one of the heaters exhibits a higher temperature than the other, and then, vice versa. The error in the measurement of the thermal conductivity did not exceed 6%.

The literature contains numerous data on the thermal conductivity of pure aluminum. However, the values range from 14 (at room temperature) to 40% (at 800°K), with the data of certain authors indicating that the thermal conductivity increases with a rise in temperature, while according to the data of other authors it diminishes. The resort to any literature data for the calculations proved therefore to be impossible. We investigated the thermal conductivity of 4 specimens of 99.946% pure aluminum. Our data on the thermal conductivity of pure aluminum, in comparison with the data of other authors, and the results obtained in measuring the thermal conductivities of aluminum alloys are presented in Fig. 1.

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TABLE 1. Chemical Composition of the Alloys (%)

Brand	Cu	Mg	Mn	Zn	Si	Ti	Fe	Other elements	other impurities	Specific weight, (kg/m³) · 10^{-3}
				no more than						
AMG-3	⩽0,05	3,2—3,8	0,3—0,6	0,2	0,5—0,8	—	0,5	—	0,1	2.67
AMG-5	⩽0,05	4,8—5,8	0,5—0,8	0,2	0,4	0,02—0,1	0,4	0,0001—0,005Be	0,1	2,64
AMG-6	⩽0,1	5,8—6,8	0,5—0,8	0,2	0,4	0,02—0,1	0,4	0,0001—0,005Be	0,1	2,63

Note: The alloys were annealed for 1 h at a temperature of 583-623° K.

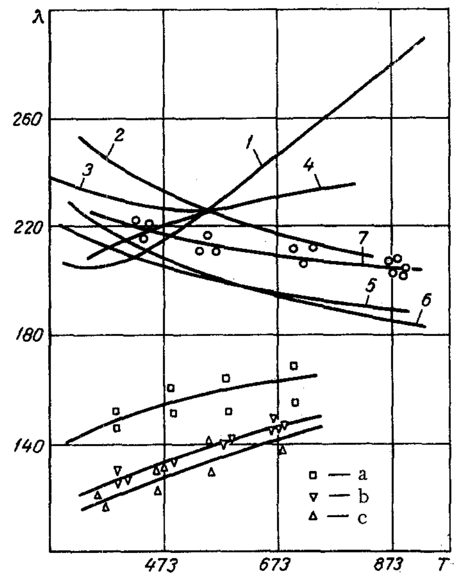

Fig. 1

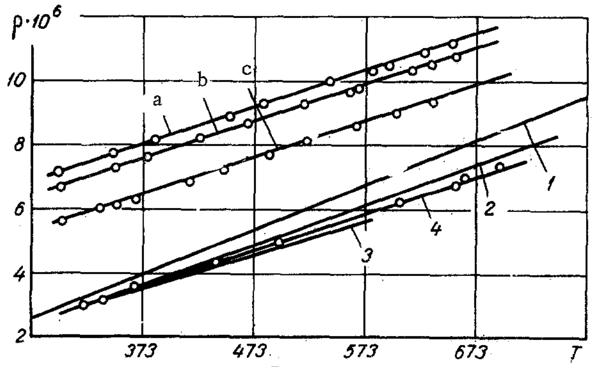

Fig. 2

Fig. 1. Results from the measurement of the thermal conductivity of pure aluminum: 1) according to [2]; 2) [7]; 3) [3]; 4) [4]; 5) [6]; 6) [5]; 7) our data; in addition, the results from the thermal-conductivity measurements with AMG-3 (a); AMG-5 (b); AMG-6 (c); (λ in W/m · deg; T in °K).

Fig. 2. Results from the measurement of the electrical resistance of pure aluminum: 1) after [4]; 2) [2]; 3) [3]; 4) our data; and the results obtained with AMG-6 (a); AMG-5 (b); AMG-3 (c); (ρ in Ω · cm; T in °K).

The measurements of the electrical resistance for the pure-aluminum specimens made from precisely that portion of the aluminum ingot from which we prepared the specimens for the determination of the thermal conductivity are shown in Fig. 2. Here we have presented the results from the measurements of the electrical resistances of the AMG-3, AMG-5, and AMG-6 aluminum alloys whose chemical composition is given in Table 1.

The data derived in the tests can be characterized in the following manner.

1. The thermal conductivity of pure aluminum diminishes with a rise in temperature, in fairly strict accord with the following law:

$$\lambda(T) = A + \frac{B}{T}. \tag{1}$$

2. At the same time, the thermal conductivity of aluminum alloys increases with a rise in temperature.

3. The electrical resistance of the aluminum increases linearly with a rise in temperature, which is in good agreement with the data of other researchers.

4. The electrical resistance of the alloys is higher than that of pure aluminum, and it increases with an increase in the impurity content.

TABLE 2. Results from the Calculation of the Thermal Conductivity of Aluminum Alloys (%)

T	$\rho_{Al} \cdot 10^6$	$\rho_{alloy} \cdot 10^6$			τ_{alloy}/τ_{Al}			$\lambda_{e\ alloy}$			$\lambda_{lat.\ Al}$	Thermal conductivity, λ					
		AMG-3	AMG-5	AMG-6	AMG-3	AMG-5	AMG-6	AMG-3	AMG-5	AMG-6		AMG-3		AMG-5		AMG-6	
												theor.	exptl.	theor.	exptl.	theor.	exptl.
293	2,68	5,58	6,6	7,02	0,48	0,406	0,382	94,5	80	75,3	32,5	127	138	112,5	120	107,8	115
373	3,63	6,44	7,55	7,96	0,564	0,48	0,454	111	94,6	89,5	25,6	136,6	148	120,2	126	115,1	121
473	4,8	7,57	8,71	9,14	0,634	0,552	0,526	125	108,5	103,5	20,2	145,2	152	128,7	132	123,7	128
573	5,97	8,7	9,88	10,32	0,686	0,604	0,578	135	119	113,6	16,7	151,7	156	135,7	138	130,3	134
673	7,16	9,84	11,06	11,5	0,727	0,648	0,623	143	127,5	122,6	14,2	157,2	161	141,7	144	136,8	140

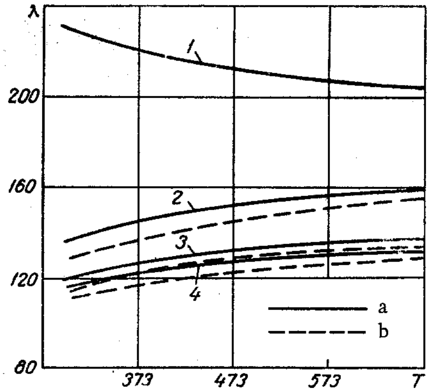

Fig. 3. Experimental values (a) of the thermal conductivity of the alloys and aluminum in comparison to the theoretical values (b): 1) Al; 2) AMG-3; 3) AMG-5; 4) AMG-6; (λ in W/m · deg; T in °K).

5. The curves showing the electrical resistance of the alloys as a function of temperature are virtually equidistant from the pure-aluminum curve, which attests to the validity of the Matthiessen rule for these alloys:

$$\rho_{alloy} = \rho_{Al} + \rho_{imp.} \tag{2}$$

Strictly speaking, the Matthiessen rule is valid for solid solutions weakly concentrated. An analysis of the state diagrams for the Al–Mg system [8] demonstrates that the solid solution of the magnesium in the aluminum (the α-solution) is the base of these alloys, with the magnesium content rather small. It is precisely in this way that we can, in our opinion, explain the experimental confirmation of the Matthiessen rule that we achieved in our tests.

We know from the theory that the resistance of the alloy in this case can be written in the form

$$\rho_{alloy} = \frac{m^*}{Nq^2\tau_{Al}} + \frac{m^*}{Nq^2\tau_{imp.}}. \tag{3}$$

The first term in the right-hand member of Eq. (3) represents the resistance of the pure aluminum, while the second term represents the resistance that is due to the additional scattering of electrons by the impurity atoms.

It follows from Eq. (3) that

$$\tau_{imp.} = \tau_{Al} \frac{\rho_{Al}}{\rho_{alloy} - \rho_{Al}}. \tag{4}$$

The total electron relaxation time in the alloy can be calculated from the formula

$$\frac{1}{\tau_{alloy}} = \frac{1}{\tau_{Al}} + \frac{1}{\tau_{imp.}}. \tag{5}$$

For the electron component of the metal thermal conductivity we have the following relationship:

$$\lambda_e = \frac{\Pi^2}{3} \frac{NK^2T\tau}{m}. \tag{6}$$

Consequently, the electron components of the thermal conductivity in the pure metal and in the alloy will differ only to the extent that there exists a difference in the carrier concentration N and in the relaxation time τ. We can expect that the predominant effect on the change in the electron component of the thermal conductivity in our alloys will be exerted by a change in the relaxation time for the free electrons. Equation (6) for these conditions can thus be modified in the following manner:

$$\lambda_{e\ \mathrm{alloy}} \simeq \lambda_{e\mathrm{Al}} \frac{\tau_{\mathrm{alloy}}}{\tau_{\mathrm{Al}}}. \tag{7}$$

The ratio $(\tau_{\mathrm{alloy}}/\tau_{\mathrm{Al}})$ can be found for all of the alloys and at each of the temperatures by means of relationships (4) and (5) from the measurement results for the electrical resistance of the alloys and the pure aluminum.

To find the electron component of the alloy's thermal conductivity we have to isolate the electron component from among the experimental data on the thermal conductivity of the pure aluminum.

We know that

$$\lambda = \lambda_e + \lambda_{\mathrm{lat.}} \, . \tag{8}$$

Here the theoretical electron component is independent of temperature, while the lattice component is inversely proportional to the temperature, i.e.,

$$\lambda_e = A, \qquad \lambda_{\mathrm{lat.}} = \frac{B}{T}. \tag{9}$$

As was pointed out above, our relationship between the thermal conductivity of the pure aluminum and the temperature is fairly adequately described by Eq. (1). The average value of the electron portion of the pure-aluminum thermal conductivity calculated from the experimental data with the aid of formula (1) amounted to 197, while the magnitude of B was equal to 9593.

We should take note of the fact that the Lorentz number for the determined electron component of the thermal conductivity is less than the theoretical and at a temperature of 420°K (the Debye temperature for Al) amounts to $1.96 \cdot 10^{-8}$, varying only slightly (by approximately 6.5%) to 670°K. The relative constancy of the Lorentz number and the change in the pure-aluminum thermal conductivity according to formula (1) may indicate that the existing theoretical relationships are valid for aluminum, but that the coefficients in formulas (3) and (6) may be slightly different, which plays no particular role in the given calculation method.

The values of the electron component of the alloys (Table 2), calculated according to Eq. (7), show that the λ_e of the alloys is substantially lower than the $\lambda_{e\mathrm{Al}}$ and increases with a rise in temperature, i.e., if for relatively low temperatures the impurities play a significant role in the transmission of energy in the alloys, decelerating the motion of the electrons, with an increase in the temperature their influence diminishes substantially.

The magnitude of the lattice component of the thermal conductivity is determined from the formula

$$\lambda_{\mathrm{lat.}} = \frac{1}{3} c_V \bar{v} l. \tag{10}$$

The magnitude of the lattice component of the alloy may thus vary if there is a change in the volume heat capacity c_V of the alloy relative to that of the pure metal and if there is also a change in the mean free path l of the phonons.

According to the literature data [8], the specific heat capacity of the aluminum alloys does not change with small concentrations (up to 10%) of magnesium. The specific weight of the alloys diminishes slightly with an increase in the magnesium content in the alloy (see Table 1). Consequently, the volume heat capacity diminishes slightly, but at the same time the lattice constant and, consequently, the mean free path l of the phonons increases slightly with a rise in the magnesium content in the aluminum [8].

In first approximation it can thus be assumed that in aluminum–magnesium alloys with a small content of magnesium the lattice component of the thermal conductivity is equal to the $\lambda_{\mathrm{lat.}}$ of the pure aluminum at the same temperature.

The thermal-conductivity calculations carried out on the basis of the above-cited considerations for the alloys AMG-3, AMG-5, and AMG-6 in comparison with the experimentally measured values of the thermal conductivity are shown in Table 2 and in Fig. 3. The maximum divergence between the theoretical and experimental curves does not exceed 9.2% at 293°K and 5.5% at 420°K. At 670°K (i.e., when $T \gg T_D$) the deviation does not exceed 2%, which is less than the error in the thermal-conductivity measurements performed in our installation.

NOTATION

m^*	is the effective mass of the free electrons;
N and q	are their concentration and charge;
τ_{Al} and $\tau_{imp.}$	are the relaxation times of the electrons on the aluminum atoms and on the impurity atoms, respectively;
λ_e and $\lambda_{lat.}$	are the electron and lattice components of the thermal conductivity;
$\bar{v}$	is the speed of sound;
T_D	is the Debye temperature.

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