EXPERIMENTAL INVESTIGATION OF THE ELECTRICAL RESISTIVITY OF SOME MOLTEN BISMUTH–TIN BINARY ALLOYS AND OF THE THERMAL CONDUCTIVITY OF BISMUTH, TIN, AND A EUTECTIC BISMUTH–TIN ALLOY

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The paper gives the results of an experimental determination of the electrical resistivity of some binary alloys of bismuth and tin, as well as the thermal conductivity and electrical resistivity of bismuth, tin, and a eutectic bismuth–tin alloy. It describes the design of the apparatus used for measuring the electrical resistivity by the contact method. The error of the measurements was ±1.5% for the electrical resistivity and ±10% for the thermal conductivity.

Liquid-metal coolants are coming into more and more widespread use in various branches of industry, and therefore there has been a considerable growth of interest in the study of the properties of metals and alloys in the molten state.

We measured the electrical resistivity of five binary alloys of the bismuth–tin system, as well as the electrical resistivity and thermal conductivity of bismuth, tin, and a eutectic bismuth–tin alloy.

The specimens were prepared by simple melting of bismuth with tin in an argon atmosphere with

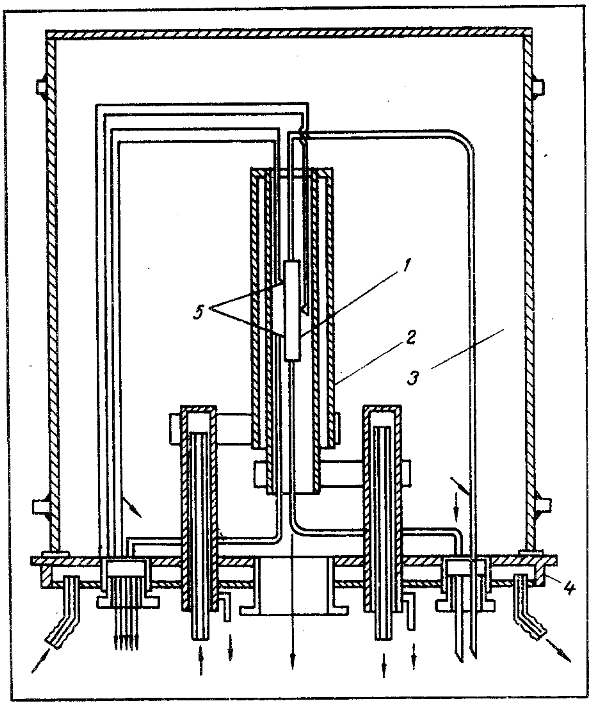

Fig. 1. Diagram of the apparatus used for measuring electrical resistivity by the contact method: 1) specimen; 2) furnace; 3) vacuum chamber; 4) base plate; 5) thermocouple leads.

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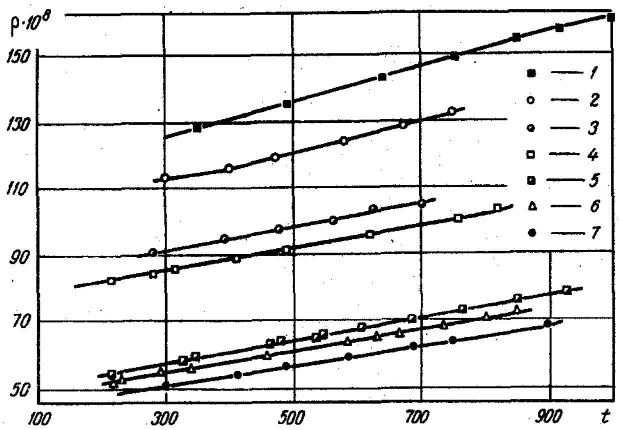

Fig. 2. Electrical resistivity as a function of temperature: 1) 99.35 Bi; 2) 89.08 Bi-10.92 Sn; 3) 80.5 Bi-19.4 Sn; 4) 59.20 Bi-40.80 Sn; 5) 20.54 Bi-79.46 Sn; 6) 10.47 Bi-89.5 Sn; 7) 99.999 Sn. ρ is measured in Ω-m; t is measured in °C.

continuous mixing. While the containers were being filled, a number of specimens were taken for chemical analysis. After the containers were filled, they were sealed with an argon-arc weld.

Before the measurements the filled containers were kept at a temperature of 800°C for 1 h for the electrical-resistivity measurements and at 500°C for 4 h for the thermal conductivity measurements.

According to the results of the chemical analysis, the composition of the investigated alloys and the original materials was the following: 99.35 Bi; 89.08 Bi-10.92 Sn; 80.51 Bi-19.4 Sn; 59.20 Bi-40.80 Sn; 20.54 Bi-79.46 Sn; 10.47 Bi—89.5 Sn; 99.999 Sn.

To measure the coefficient of thermal conductivity, we used the stationary method of longitudinal heat flux. The method used for measuring the coefficient of thermal conductivity has been described in detail in [1]; this is one of the variants of the classical plane-layer method, which is most suitable for the measurement of the thermal conductivity of liquids.

The heat flux in the specimen was directed downward, and therefore no convective flows were created in the liquid. We used a system of heaters (side and end heaters) which made it possible to reduce the heat losses to 1-5% of the total heater power, and the use of monitoring thermocouples made it possible to take these losses into account.

The electrical resistivity was measured by the contact method, on the basis of which we designed and constructed an apparatus which was convenient to work with and simple to service. A diagram of the apparatus used for measuring the electrical resistivity is shown in Fig. 1.

Through the base plate 4, using vacuum packing, we passed a set of water-cooled conductors, wires for passing a direct current through the specimen, and leads for the thermocouples. The furnace 2 was made of two coaxially placed pipes 350 mm in length, with diameters of 30 and 20 mm and a wall thickness of 1 mm. The material of the pipes was 1Kh18N10T stainless steel. The furnace was connected to an OSU-20/0.5 transformer whose primary voltage was regulated by an AOSK-25/0.5 transformer. Specially conducted measurements showed that in the central part of the furnace the temperature field did not vary with distance, and it was in this part of the furnace that we placed the container holding the specimen. The container was a pipe made of 1Kh18N10T steel, sealed on both sides; its diameter was 6 mm, with a wall thickness of 0.2 mm and a length of 100 mm, and it was approximately three-quarters full of the material under investigation.

All the measurements were conducted in a vacuum at about 10^{-3} mm Hg. The design of the apparatus made it possible to make measurements in an inert-gas atmosphere. The calculation of the electrical resistivity was carried out according to Ohm's law by means of the formula

$$\rho = \frac{uS}{Il} - \frac{S}{S_c}\rho_c,$$

where the term $(S/S_c)\rho_c$ is used to take account of the measurement error introduced by the container.

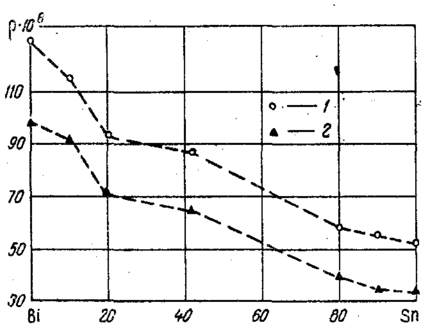

Fig. 3

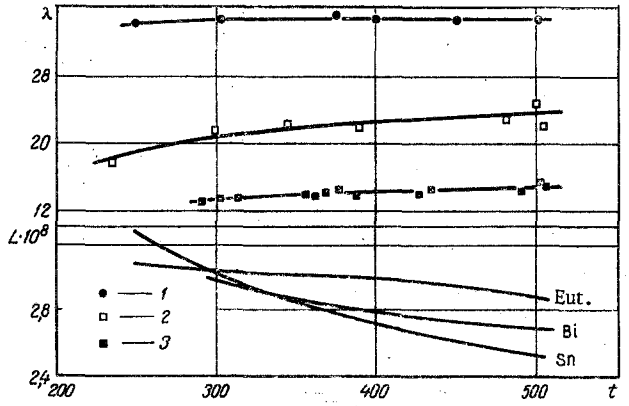

Fig. 4

Fig. 3. Isotherm showing electrical resistivity versus composition: 1) resistivity as a function of composition for t = 350°C; 2) residual resistivity as a function of composition. ρ is measured in Ω-m; the Sn is shown as % by weight.

Fig. 4. Thermal conductivity and Lorentz number as functions of temperature for bismuth, tin, and the bismuth–tin eutectic: 1) 99.999 Sn; 2) 59.20 Bi-40.80 Sn; 3) 99.35 Bi. λ is measured in W/m · deg; L is measured in $(V/deg)^2$; t is measure in °C.

The effect of container widening was taken into account when we calculated the error introduced by the geometric dimensions of the specimen.

The maximum relative error of the resistivity measurement was ±1.5%.

The results of the resistivity measurements are shown in Fig. 2. In the case of pure bismuth, the temperature coefficient of electrical resistivity changes at about 900°C, while in pure tin the electrical resistivity is directly proportional to the temperature in the entire range of temperatures investigated, and no bends are seen in the resistivity-versus-temperature curve.

The electrical resistivity of the binary alloys of this system lies in a range between the resistivity of bismuth and that of tin.

The resistivity—composition isotherms are shown in Fig. 3. The resistivity—composition isotherm has a bend at the 20% Sn point (in the solid state this is the limit of solubility of tin in bismuth [2]).

All of the alloys investigated have a positive temperature coefficient of electrical resistivity. We carried out an analysis of the residual liquid resistivity, which is characterized by the scattering of conductivity electrons as a result of the absence of long-range order in the liquid. The isotherm showing residual resistivity versus composition has the same character as the isotherm showing resistivity versus composition at a temperature of 350°C. The results of the resistivity measurements are in good agreement with the results of [3].

The thermal conductivity of bismuth, tin, and the bismuth—tin eutectic is shown in Fig. 4. For pure tin, according to the results of our measurements, the temperature does not affect the thermal conductivity in the 300-500°C range. In bismuth there is a substantial change in the short-range order when the metal melts; the coordination number increases from 3 to 7-8 [4], and the conductivity after melting has a pure-metal character.

The thermal conductivity of bismuth increases slowly with temperature. The thermal conductivity of the eutectic alloy has a positive temperature coefficient, like that of alloys in the solid state. The value of the thermal conductivity was found to be close to the value obtained in [5].

On the basis of the measured values of electrical resistivity and thermal conductivity, we calculated the Lorentz number for pure bismuth, pure tin, and the bismuth—tin eutectic. It follows from the experimental results that the Lorentz number has a negative temperature coefficient (see Fig. 4). As the temperature increases, the value of the Lorentz number approaches the theoretical value for a degenerate electron gas, $2.4 \cdot 10^{-8}$ $(V/deg)^2$.

In [6, 7] it is proposed that certain properties of liquid metals should be described by the expressions used for the solid state. Since in the case of bismuth, melting is accompanied by a considerable destruction of the homeopolar bonds [8], which are replaced by metallic bonds, it follows that we can extend both to bismuth and to bismuth-based alloys certain conclusions derived from the electron theory of metals which are commonly used for describing processes taking place in metals and alloys in the solid state; in using these, we divided the total thermal conductivity into atomic and electronic parts. It was found that the main role in the heat-transfer process is played by the electronic part.

The atomic thermal conductivity of bismuth, tin, and the bismuth—tin eutectic in the molten state has a negative temperature coefficient; its absolute value is a fraction of 1% of the total thermal conductivity and is clearly too small to explain the behavior of the Lorentz number.

A complete theoretical solution of this problem for liquid melts has not yet been found. Qualitatively, the negative temperature coefficient of the Lorentz number can be explained on the basis of phonon-liquid scattering of the conductivity electrons, as proposed by A. I. Gubanov [7]. Since the arrangement of the ions becomes more irregular as the temperature increases, the role of phonon-liquid scattering of electrons is increased, and this leads to an increase in the inelastic scattering of conductivity electrons, with a decrease in the Lorentz number.

NOTATION

ρ, ρ_c	are the electric resistivity of specimen and container, respectively;
u	is the voltage drop across the measuring section;
S, S_c	are the cross-sectional area of specimen and container, respectively;
I	is the current passing through the specimen;
l	is the length of measuring section.

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