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AUTOMATED EQUIPMENT FOR MEASUREMENT OF PROPERTIES OF THERMOELECTRIC MATERIAL RODS

The paper presents the results of development of equipment for measurement of electric conductivity and thermopower distributions along thermoelectric material rods. The deviations of a real physical model of measuring equipment from the ideal model of measuring method, as well as the results of calculation of measurement errors caused by these deviations are analyzed. The method for measurement of thermal conductivity of rods is developed. A description of measuring equipment design with automation of measurement process to increase the rapidity of action and eliminate human errors is given. The use of such equipment in the manufacture of thermoelectric modules allows reducing thermoelectric material consumption to ~ 10% with a simultaneous quality enhancement of thermoelectric products by ~ 8 - 15%.

Key words: electrical conductivity, thermal conductivity, thermalEMF error thermoelectric material, automation.

Introduction

General characterization of the problem. In the production of thermoelectric modules it is important to assure step-by-step quality control of thermoelectric materials. No less important is selection of material with specified properties, optimized for each particular task. The first step of such control is measurement of properties of thermoelectric material rods.

Analysis of the literature. The electric conductivity of rods is successfully measured by a two-probe method [1]. In [2 – 5], a detailed analysis of the sources of errors of this method is given and the ways for their minimization are proposed.

To determine the Seebeck coefficient of rods, a hot probe method is generally used [6] allowing to find the local value of thermopower at probe contact point.

In [7], a description of experimental setup for determination of electric conductivity and thermopower of probes developed by the Institute of Thermoelectricity (Ukraine) is given. The measurement errors of this setup are ~ 1% for electric conductivity and ~ 2% for the Seebeck coefficient. The disadvantageous feature of this equipment is manual mode of measurement and processing of the results.

The purpose of this work is to develop equipment for measurement of properties of thermoelectric material rods through use of automation of measuring probes travel, measured results processing and plotting the distribution of material properties in the rod.

Physical, mathematical and computer models of the method

A physical model for the development of methods for determination of electric conductivity and the Seebeck coefficient of rods is given in Fig. 1. The electric conductivity was measured with the use of a two-probe method, and the Seebeck coefficient – with the use of a hot probe method. The physical model takes into account cooling and heating of the opposite ingot edges due to the influence of the Peltier heat Q_1, the release of the Joule heat Q_2 in the ingots and current conductors, as well as heat exchange between the ingot, current conductors and measuring probes and the environment (Q_3 – Q_{11}).

For calculation of the errors and optimization of measurement method it is necessary to find the distributions of electrical potential φ and temperature T in the ingot that can be obtained from the laws of conservation of electrical charge and energy written as:

$$\begin{cases} -\nabla\left(\left(\kappa_j+\alpha_j^2\sigma_jT+\alpha_j\varphi\sigma_j\right)\nabla T\right)-\nabla\left(\left(\alpha_j\sigma_jT+\varphi\sigma_j\right)\nabla\varphi\right)=0, \\ -\nabla\left(\sigma_j\nabla\varphi\right)-\nabla\left(\sigma_j\alpha_j\nabla T\right)=0, \end{cases} \quad (j=1..10), \qquad (1)$$

where α_i, is the Seebeck coefficient, σ_i is an electric conductivity and κ_i is a thermal conductivity of the elements of physical model.

The boundary conditions for such a physical model:

– the lateral surfaces of the ingot and current conductors are electrically insulated

$$\mathbf{n}\cdot\mathbf{j}=0;$$

– current of I flows through current conductors

$$\mathbf{n}\cdot\mathbf{j}=I/S_{cm.};$$

– the ends of current conductors are thermostated at ambient temperature T_0

$$T=T_0;$$

– the lateral surfaces of the ingot, measuring probes and current conductors are in a state of heat exchange with the environment

$$\mathbf{n}\cdot\mathbf{q}=h_n(T_0-T),$$

where h_n are heat transfer coefficients.

This problem was solved with the use of computer object-oriented simulation with application of finite element method implemented in Comsol Multiphysics package of applied programs.

The main sources of errors in the measurement of electric conductivity:

– current density inhomogeneity in the ingot due to current supply to ingot end only at points of contact to current conductors, rather than uniformly along its entire surface;

– non-isothermal conditions caused by the influence of the Peltier and Joule effects, as well as by heat exchange with the environment.

It was established that the errors due to current density inhomogeneity near the ends can be considerable – more than 45% – in the case when current supply to the ingot is done by one point current conductor on each end (Fig. 2).

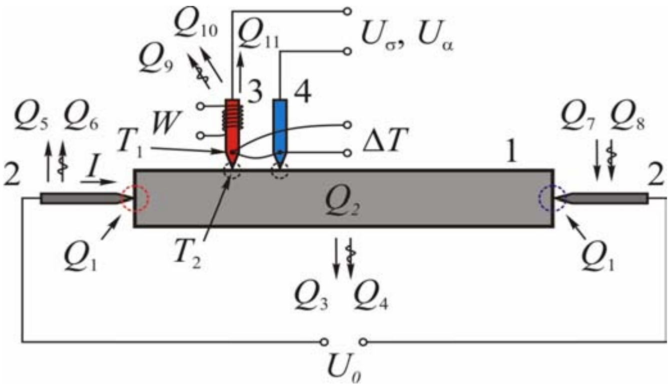

Fig. 1. Physical model of measuring the electric conductivity and Seebeck coefficient of ingots. 1 - ingot, 2 – current conductors 3, 4 – measuring probes.

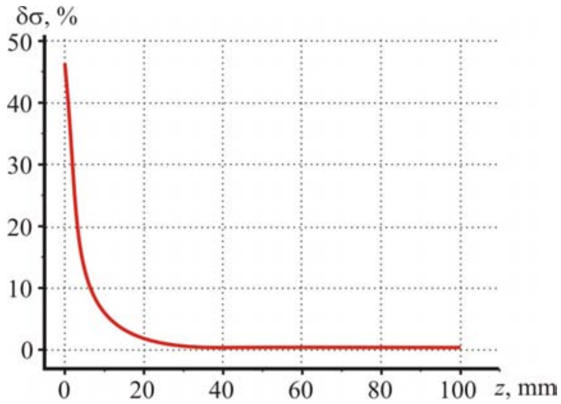

Fig. 2. Dependence of electric conductivity measurement error due to current density inhomogeneity on the distance z from the probes to ingot edge.

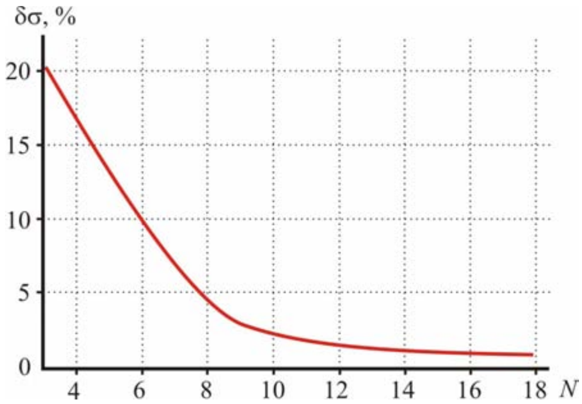

Fig. 3. Dependence of electric conductivity measurement error due to current density inhomogeneity on the number of current contacts N.

The situation is improved with increasing the number of current conductors (Fig. 3). For the case of three points the error is about 20%. Computer simulation made it possible to determine the optimal number of contact points – 16 on each end. Measurement error due to current density inhomogeneity is reduced here to 0.9%.

A method eliminating the influence of the Peltier effect by using optimal current through the ingot was also developed, whereby cooling action of the Peltier effect is compensated by the Joule heat. The error in this case is reduced from 6 to 0.3% (Fig. 4).

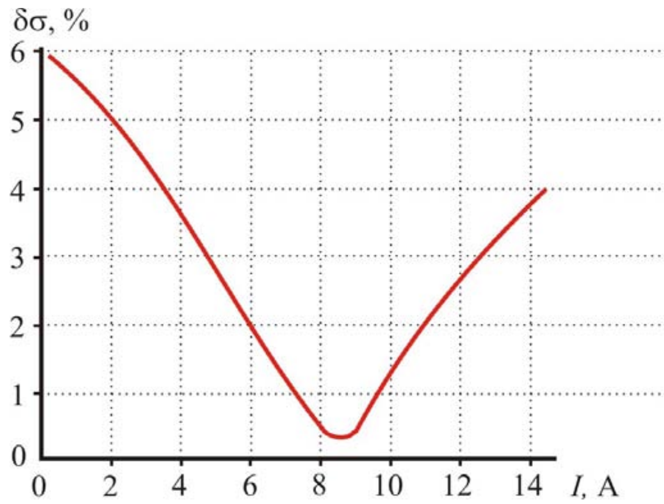

Fig. 4. Dependence of electric conductivity measurement error due to the Peltier effect on the distance from current through the ingot.

Total error of electric conductivity measurement with regard to instrumental errors is 1.5%. Thus, using the elaborated methods the accuracy of electric conductivity measurement near the ends has been increased more than a factor of 15.

The errors in the determination of the Seebeck coefficient are caused by the difference between temperature T_1 at point of thermocouple location on the probe and temperature T_2 at point of probe contact with the rod surface. Computer simulation was used to obtain the dependences of correction factor K on measuring probe geometry in order to take this temperature difference into account in the calculation of the Seebeck coefficient

$$\alpha = \frac{U_\alpha}{K(T_1 - T_0)}.$$

The probe with a cone-shaped tip was used. The probe base diameter was d_1, the probe tip diameter - d_2. Figs. 5, 6 show the dependences of correction factor K on probe dimensions for the cases of copper (1) and tungsten (2) tip.

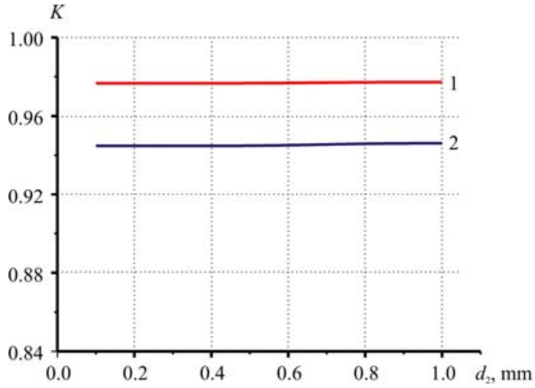

Fig. 5. Dependences of correction factor for calculation of the Seebeck coefficient of ingot on probe tip diameter.

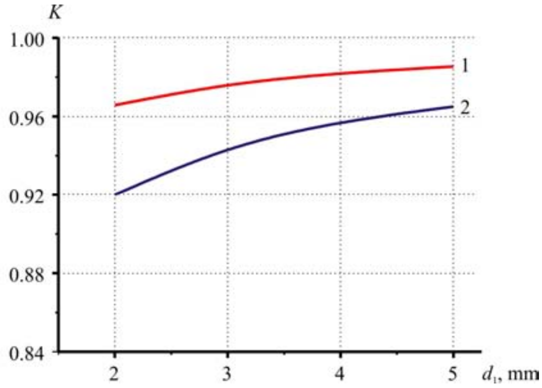

Fig. 6. Dependences of correction factor for calculation of the Seebeck coefficient of ingot on probe base diameter.

A method for measuring thermal conductivity of ingots was developed, too. For this purpose a computer model was studied that allows finding temperature distribution in the ingot at an arbitrary time moment. An ingot of thermoelectric material was considered having on one of its end faces an electric heater. The temperature distribution equation is of the form:

$$\rho C \frac{\partial T}{\partial t} + \nabla(-\kappa \nabla T) = 0, \tag{2}$$

where ρ is a density, C is heat capacity, κ is a thermal conductivity of ingot material.

Solving of Eq. (3) with the boundary conditions that take into account heat exchange between the ingot and the environment yielded calibration curves for determination of thermal conductivity of material from the time of reaching given temperature difference between two points on the surface of the ingot (Fig. 7).

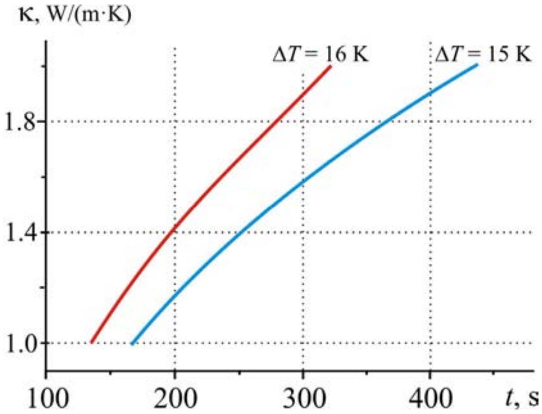

Fig. 7. Calibration dependences for determination of thermal conductivity of the ingot.

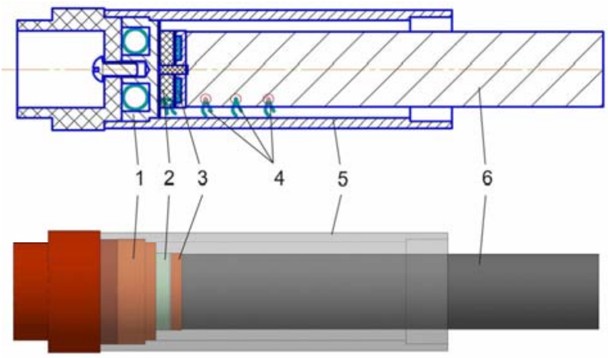

Fig. 8. Design of device for measuring thermal conductivity of ingots.

Device for determination of thermal conductivity and its external appearance is shown in Fig. 8. It comprises a reference heater 3, thermocouples-probes 4, a screen heater 1, a differential “zero thermocouple” 2 and a screen tube 5. Thermal conductivity is determined by the rate of reaching given temperature difference between thermocouples.

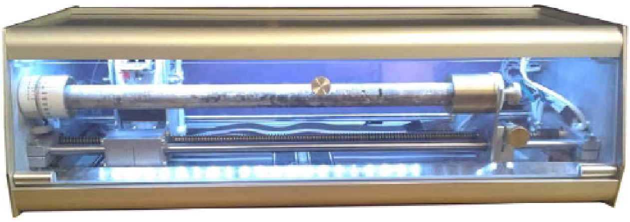

Fig. 9. External appearance of ingot holder.

The above described methods were used to develop equipment for investigation of properties of ingots whose external appearance is given in Fig. 9. The equipment is fully automated, including travel of probes and rotation of ingot about its axis, as well as the process of measurement and processing of results.

Jointly with the state enterprise “Chernivtsi Regional Scientific-Production Centre for Standardization, Metrology and Certification” (State Enterprise “Bukovinastandartmetrologiya”) the methods for metrological certification of this equipment have been developed and tests have been performed that confirmed its high precision and reproducibility of results: the error of electric conductivity measurement not more than 0.5% and the error of thermopower measurement not more than 1%; the error of thermal conductivity determination not more than 10%.

The elaborated equipment for determination of properties of rods can be helpful in the production of thermoelectric modules. It yields material saving of about 10% and improves the quality of modules by 8 – 15%.

Conclusions

1. Computer simulation methods have been used to determine the influence of various errors on the accuracy of measuring electric conductivity and thermopower of thermoelectric material rods. Conditions for minimization of the influence of these errors have been found.
2. Based on the results of computer simulation, an automated setup has been developed for measuring electric conductivity and thermopower of rods, as well as automatic processing of measurement results. The error of electric conductivity measurement is ~ 0.5%, of thermopower **-** ~1%.
3. Measuring setup is equipped with a device for determination of thermal conductivity of the rod in dynamic mode. The error of thermal conductivity determination is ~10%.
4. The use of the above described measuring equipment in production practice for the manufacture of cooling modules allows reducing thermoelectric material consumption up to 10% and improving quality of modules up to 8 – 15%.

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