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A Technique and Installation for Studying Electrophysical Properties of High-Temperature Superconductors

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Abstract—This paper presents an experimental exploration of the electrophysical properties of high-temperature superconductors that is based on the determination of the constitutive equation parameters for the combined model with two sources of electromagnetic field: current density and magnetization. It involves a series of experiments in different external magnetic fields and various transition modes to the superconducting state that allows the individual field sources to be distinguished. Since conditions that would enable us to maintain a homogenous current density distributions and magnetization under varying external magnetic induction in the HTSs are not available, the magnetic field parameters and its sources in the samples are determined via computational and experimental methods, in which the magnetic field parameters in the sample are calculated using their values out of the sample. A special laboratory installation equipped with the required measuring tools and magnetic system to create a controlled external magnetic field with the magnetic flux density of 1.5 T is constructed for the practical implementation of the experimental research technique.

Keywords: electrophysical properties, high-temperature superconductor materials, technique, experimental research, laboratory setup, magnetic system, permanent magnets

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INTRODUCTION

High-temperature superconductors (HTSs) are increasingly used in industry. The main difficulties in the application of HTS-based devices are a lack of mathematical modeling and design of magnetic systems with HTS elements that take into consideration anisotropic, nonlinear, and hysteresis electrophysical properties, as well as temporary stabilization, of these materials. There are almost no experimental data on modeling electromagnetic processes in the presence of HTS elements and techniques that allow testing HTS materials that would yield the required information for the identification of their constitutive equations. The existing mathematical models used by foreign companies have a series of drawbacks, such as rough approximation, a lack of anisotropic and hysteresis properties of HTSs, and a lack of the dynamic HTS models and temporal stabilization of their properties. The technique considered in this paper for experimental studies of electrophysical properties of HTS materials is focused on the determination of the parameters of the combined model for such materials proposed in [1].

This model is based on two sources: current density **J** and magnetization **M**. The current density is a nonlinear function of electric field strength $\mathbf{J} = \mathbf{E}/\rho(B, J)$, where the specific electric resistance is approximated by the hyperbolic function

$$\rho(B, J) = \frac{\rho_0}{2}\left(1 + \tanh\left(-\frac{K_J(B, J)}{2\delta_J(T)}\right)\right),$$
$$K_J(B, J) = K\left(\frac{B}{B_c(T)}\right)K\left(\frac{J}{J_c(B, T)}\right), \quad (1)$$

where ρ_0 is the normal specific electric resistance of HTS (in the lack of the superconductivity), B is the magnetic induction, B_c is the critical magnetic induction at which the superconductivity vanishes, $K(x) = \begin{cases} 1 - |x| \text{ at } |x| \le 1, \\ 0 \text{ at } |x| > 1, \end{cases}$ is the state function, δ_1 is the model parameter that is the dispersion for the specific electric resistance, and T and T_c are the absolute temperature and its critical value at which the superconductivity vanishes.

The dependence of the critical current density on the magnetic induction is presented in the form of the power function

$$J_c(B, T) = J_{c\max}(T)\begin{cases} \left(1 - \left|\frac{B}{B_c}\right|^{\alpha}\right)^{\beta} \text{ at } |B| \le B_c, \\ 0 \text{ at } |B| > B_c, \end{cases}$$

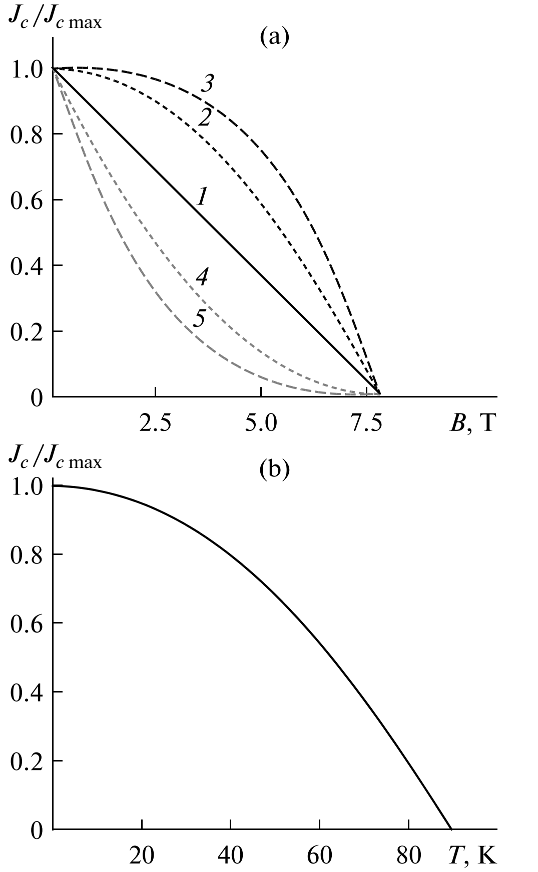

Fig. 1. The simulated normalized dependencies of the critical currents on the magnetic induction: (a) at various parameters α and β; (b) on the temperature: (*1*) $\alpha = 1$, $\beta = 1$; (*2*) $\alpha = 2$, $\beta = 1$; (*3*) $\alpha = 3$, $\beta = 1$; (*4*) $\alpha = 1$, $\beta = 2$; and (*5*) $\alpha = 1$, $\beta = 3$.

where $J_{c\,\max}(T)$ is the maximum critical current density at the given temperature and α and β are real positive numbers—the model parameters.

Figure 1a displays the normalized critical current densities as function of the magnetic induction at various α and β parameter values. The accepted form of the approximating functions enables us to change them over wide limits, which reflects the possibility of varying the properties of existing HTSs.

For approximation of the dependencies of critical parameters on the temperature, power functions [2] are most widely used:

$$B_c(T) = B_{c0}\left(1 - \left(\frac{T}{T_c}\right)^2\right),$$

$$J_{c\,\max}(T) = J_{c0}\left(1 - \left(\frac{T}{T_c}\right)^2\right),$$

where B_{c0} and J_{c0} are the critical magnetic induction and critical current density at the absolute zero, respectively.

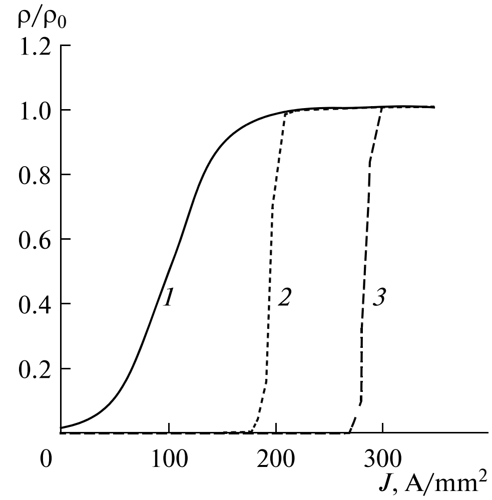

Fig. 2. The normalized specific electric resistance as a function of the current density at various temperatures: (*1*) $T = 85$ K, (*2*) $T = 80$ K, and (*3*) $T = 75$ K.

The $B_c(T)$ and $J_{c\,\max}(T)$ functions are assumed to vanish at $T > T_c$. This normalized dependence is shown in Fig. 1b. At a constant magnetic induction—for example, $B = 2.0$ T, $\delta_1 = 0.001$, $\alpha = 2$, and $\beta = 1$—the dependence of the normalized specific electric resistance for HTS on the current density at various temperatures will be as shown in Fig. 2. When the temperature tends to a critical value and the superconductivity vanishes, this dependence becomes flatter and superconductivity is lost at a smaller current density.

The current density model includes thus six parameters: B_{c0}, J_{c0}, T_c, δ_1, α, and β, which should be defined experimentally. The magnetization model is similar to the current one with the use of the hyperbolic tangent. To approximate the relative permeability of the material, an equation analogous to (1) is used:

$$\mu_r(H, T) = 0.5\left(1 + \tanh\left(-\frac{K_m(H)}{2\delta_m}\right)\right),$$

where the following parameters are assumed for the state function:

$$K_m(H) = K\left(\frac{\mu_0 H}{B_{cm}(T)}\right), \quad \delta_m(T) = \delta_2 \Big/ \left(1 - \frac{T}{T_{cm}}\right).$$

Electric field strength is used as the permeability function argument instead of magnetic induction by analogy with the constitutive equations for ferromagnetics. The critical magnetic induction for the magnetization $B_{cm}(T)$ and critical point T_{cm} can differ from their values for current density $B_C(T)$ and T_C:

$$B_{cm}(T) = B_{c0m}\left(\left(1 - \frac{T}{T_{cm}}\right)^2\right).$$

For the parameter $\delta_2 = 0.001$ and the function $B_{cm}(T)$ from the formula for the current density, the

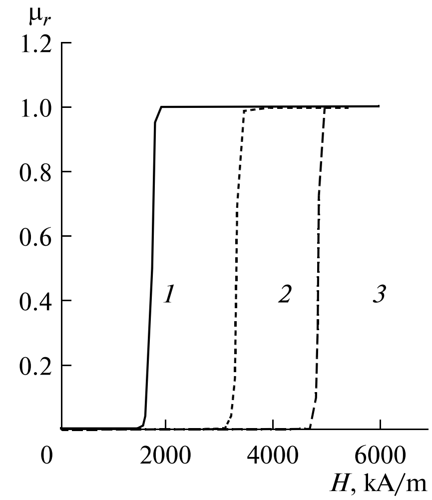

Fig. 3. The relative magnetic susceptibility as a function of the magnetic field strength at various temperatures.

dependencies of the relative permeability on the electric field strength at various temperatures are depicted in Fig. 3.

The magnetization of the material is determined by the magnetic susceptibility and electric field strength:

$$M(H, T) = (\mu_r(H, T) - 1)H.$$

To describe the hysteresis properties of the diamagnetic arising with the change in the sign of the electric field strength derivative respective to time $\partial H/\partial t$, the expression for a partial remagnetization cycle with the relevant vertex (H_p, M_p) is used.

In the general case the current density model includes three parameters—B_{c0m}, T_{c0m}, and δ_2—which are expected to be determined experimentally. The technique for experimental definition of the electrophysical parameters of HTS must provide tests of the samples over a wide range of magnetic induction of the external magnetic field. During tests of conventional magnetic materials, it is possible to provide the homogeneity conditions for magnetic induction, magnetic field strength, and magnetization in the tested samples due to their shape (toroids and long rods) or in a closed magnetic circuit. This allows comparing the measured magnetic field parameters of the samples with their values in the materials.

Neither the shape nor the external magnetic circuit maintains conditions at which the homogeneous current density and magnetization distributions would be retained when the external magnetic induction changes in HTSs. In this connection, the determination of the magnetic field and its sources in the material should be based on the computation and experimental methods when the magnetic field parameters in the sample are calculated from their values from the sample. Such a technique requires experimental studies of both integral parameters (forces, magnetic flows, and strengths) and the magnetic field distributions near the sample with varying of the external magnetic field and in various modes of translation in superconductivity. The measurements that are carried out are expected to allow the magnetic field parameters of the induced currents and magnetization parameters to be distinguished. The following experiments are provided with this technique.

Experiment 1. No currents are induced in the inhomogeneous external magnetic field (the cooling mode in FC field) when the sample undergoes the transition to the superconductive state. With the emergence of magnetization, the magnetic field is partially displaced from the sample bulk; i.e, manifestation of the Meissner effect occurs. The force of the sample ejection from the magnetic field will be the integral characteristic of the magnetizaton effect.

Experiment 2. After transferring the sample to the superconductive state under the FC mode, the total magnetic moment of the HTS sample is measured with the external magnetic field source in Helmholtz coils. The magnetic moment of the magnetic field source, the parameters of which are expected to exhibit no dependence on the HTS sample state, is measured separately. The desired magnetic moment induced by the HTS sample magnetization is measured using differential schemes with two identical Helmholtz coils and the magnetic field source.

Experiment 3. The total induced current in the ring that can arise due to the unstable external magnetic field is additionally controlled on the ring HTS specimens in Experiment 2. The total current is determined via integration by moving the magnetometer readings—for example, in measurements on the continuous line passing through the hole in the HTS sample.

Experiment 4. The magnetic moment and total current are measured under the transition regime of the ring HTS sample into the superconductive state given an absence of an external magnetic field (ZFC mode) with subsequent application of an external magnetic field. The magnetic moment of the sample will be induced by induction currents and magnetization. The total current value is assigned only to the induction current. Distinguishing the magnetic moments of two magnetic field sources is difficult because of their unknown distribution in the sample bulk. Reduction of this factor is possible with the use of a specific shape of the samples—for example, small hollow cylinders with a small wall thickness relative to their diameters.

Experience 5. The magnetic field topography is measured near the HTS sample in different transition modes into the superconductive state at various external magnetic fields.

The volume distribution of the magnetic field sources—current density and magnetization vectors—can be approximately determined by solving the inverse magnetostatic problem. In the FTS sample state under consideration, let us measure the distributions of the magnetic induction vector components near the sample surface $\mathbf{B}(x, y, z)$, magnetic moment $\mathbf{m}$ and, if possible, total current I. In the sample bulk, let us distinguish N small element volumes where we will consider desired current densities $\mathbf{J}_j$ and magnetization values $\mathbf{M}_j$, $j = 1, 2, ..., N$. We construct the set of equations for the measured magnetic induction values as the sum of the contributions from the magnetic field sources in the elementary volumes:

$$\mathbf{B}(x, y, z) = \sum_{j=1}^{N} (a_{i,j}\mathbf{J}_j + d_{i,j}\mathbf{M}_j),$$

where i is the number of the point where the magnetic induction is measured.

For all measurement points, the magnetic induction equations will be written in the matrix form $\mathbf{B} = \mathbf{AJ} + D\mathbf{M}$.

These equations are completed by the measured magnetic moment and total current values. The magnetic moment of the current density is calculated as the product of the current in the isolated tubes by the surface area covered by the tube. For the considered discrete model, this operation is simply implemented only in axisymmetric current structures. For the discrete model, the magnetic moment induced by the magnetization is calculated as the sum of the products of the projections onto the chosen magnetization vector direction in the individual small elements on their volume. The total current is calculated as the current density vector flux through the cross section of the ring sample.

Generally, all linear algebraic equations can jointly be presented in the matrix form: $\mathbf{Cx} = \mathbf{f}$, where $\mathbf{C}$ is the rectangular matrix of the coefficients; $\mathbf{x}$ is the column vector of the desired vector source components; and $\mathbf{f}$ is the column vector formed of the measured magnetic induction vector, magnetic moment, and total current components. Such a set of equations is solved using the Tikhonov regularization

$$(C^{\mathrm{T}}C + \alpha E)\mathbf{x} = C^{\mathrm{T}}\mathbf{f},$$

where E is the unit diagonal matrix and $\alpha > 0$ is a small number selection of which is based on the measuring errors.

In the development of the laboratory setup for the experimental studies of HTS materials, a series of engineering problems were solved. The setup includes (Fig. 4) base *1* at which three mutually orthogonal Helmholtz ring pairs are fixed for compensation of external magnetic fields *2*. Nonmagnetic plate *3* at which rails *4* are mounted is also fixed at base *1*. Platforms with fixed permanent magnets *5* are moved on rails *4* by linear bearings and induce a homogeneous magnetic field with tuned magnetic induction up to 1.5 T in the tested sample. The magnetic induction is tuned via movement of the platforms by means of gear

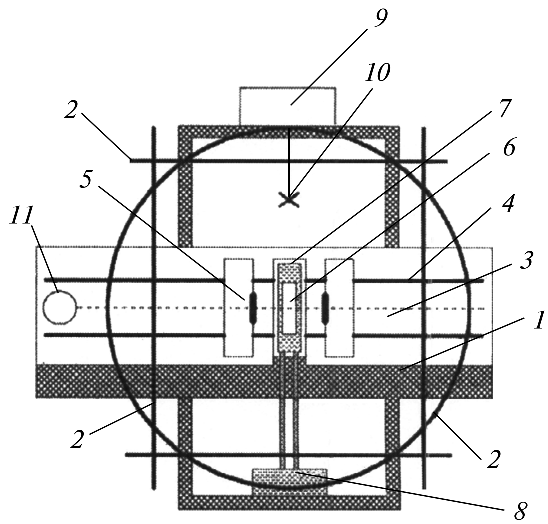

Fig. 4. The scheme of the experimental setup for the studies of HTS materials.

motor *11* that is controlled by the frequency converter and screw transmission. HTS sample *6* is placed between magnetic system poles *5*, being in cryostat *7*. Liquid nitrogen is pumped through cryostat *7* by means of closed cycle refrigeration unit *8*. Magnetic induction is measured by three-axis positioning device *9*, at which magnetic induction meter probe *10* is fixed. The resulting magnetic moments of the transport currents and magnetization are measured by means of Helmholtz coils connected to the magnetic flux meter (the heat flux meter). The total current in the ring samples is measured via integration of the magnetic field strength values on the line through the internal hole of the sample and cryostat. The forces acting the sample were measured by the sensors through which the cryostat was fixed onto the stationary base. The setup also includes a PC for control, collection, and processing of the measured data.

A magnetic field was induced by a magnetic system containing two blocs of high-coercivity permanent NdFeB magnets with residual induction of 1.35 T (Fig. 5). There are no magnetic units in the construction, since the HTS sample induces its own magnetic field, which can change the magnetic state of the units made of the magnetic material and, thus, affect the external magnetic field. This effect leads to significant errors in determination of the electrophysical properties of the studied samples.

To induce homogeneous magnetic fields with high magnetic induction, permanent magnets are installed in the form of Halbach structures (Fig. 5), where the central part of the magnet is magnetized along the axis and the side magnets are magnetized along the radius. The magnetization direction of the individual segments is indicated with arrows in Fig. 5.

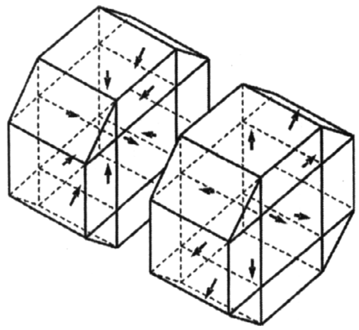

Fig. 5. The magnetic system of the permanent magnets of the setup.

The magnetic induction distribution in the middle gap part between the magnets where the tested sample is placed is shown in Fig. 6a. The dependence of the magnetic induction at the gap center on the distance between the magnets is displayed in Fig. 6b.

Magnetic induction is tuned by changing the distance between the magnets. The permanent magnets affixed onto the platforms are moved on the rails by means of the gear motor controlled by the frequency converter and screw transmission. The rails, linear bearings, and screw transmission detect the emerging interactions between the magnets, which attain 6400 N. Either the symmetric displacement of the magnets relative to the sample or the displacement of a single magnet is possible. The magnet position is determined and fixed by the software or the operator.

The magnetic induction is measured by a magnetometer possessing probes with Hall converters that are oriented so that all three magnetic induction vector components can be measured. The meter is equipped with a system for automatic compensation of the thermal instability of the Hall converter over the temperature range from 40 to 300 K. The measured magnetic induction values are saved in the memory of the PC connected to the device together with the sensor center coordinates. The three-axis probe positioning system is controlled by the PC through the controller in accordance with the predetermined movement program implemented by three stepped motors with screw mechanical transmission or manually.

The geomagnetic field is compensated by three Helmholtz coil pairs placed in three coordinate planes. The coils are powered by three independent direct current sources. The diameter of coils is 1200 mm, and the distance between them is 600 mm. The system is aligned in conditions of a lack of permanent magnets before testing the HTS materials. The sensor of the magnetic induction meter is placed at the cryostat center subsequently in three coordinate planes. The currents in the Helmholtz coils are tuned so that one can achieve zero readings on the magnetic induction meter for each coordinate axis.

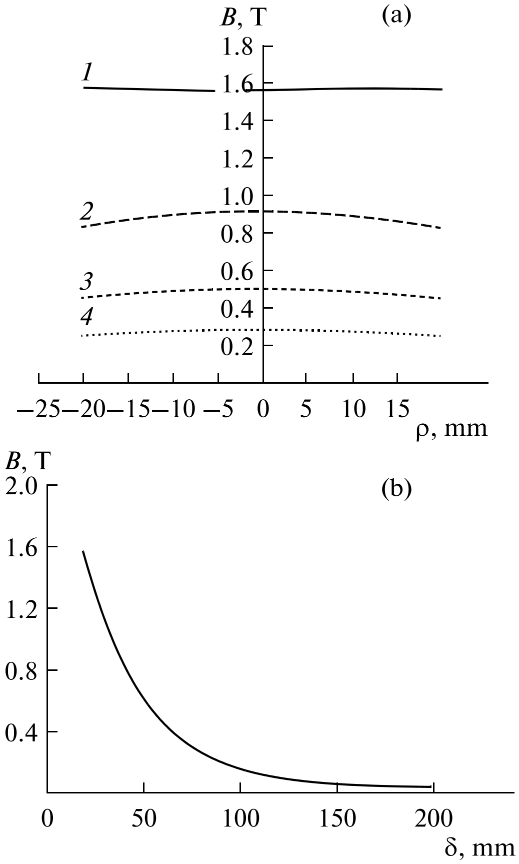

Fig. 6. (a) The magnetic induction distribution in the middle part of the gap between the magnets: (*1*) $\delta = 20$ mm, (*2*) $\delta = 40$ mm, (*3*) $\delta = 60$ mm, and (*4*) $\delta = 80$ mm and (b) and the dependence of the magnetic induction at the gap center on the distance between the magnets.

The total magnetic moment is measured by Helmholtz coils, the diameters of which are above $10l$, where l is the highest linear size of the sample, and the distance between the coils of which is equal to the coil radius. Both coils are subsequently connected and are connected to the magnetic flux meter (the heat flux meter). The studied HTS samples are put together with a cryocamera at the coil center. For this, the coils are moved toward the cryocamera. The coil flux linkage measured by the heat flux meter is proportional to the total magnetic moment of the currents and magnetization along the Helmholtz coil axis $m = \Psi/(\mu_0 k)$, where m is the total magnetic moment, Ψ is the measured flux linkage value, and k is the Helmholtz coil constant.

The total current is measured for the samples with the internal hole. The total current is equal to the curvilinear integral of the magnetic field strength over the closed contour surrounding this current. Since the Rogovskii coil is usually not applied in the experimental conditions, the total current is determined via the direct integration of the measured magnetic field strength along the continuous line passing through the internal hole of the sample $I_\Sigma = \left\{ \int_A^B H_x dx \right\}$, where H_x is the projection of the magnetic field strength onto the *AB* line. The length of the *AB* line is chosen from the condition $h \geq 15l$, which gives a measuring total current error of below 1%.

The magnetic field strength is measured by a magnetometer, data from which are saved in the PC and are integrated.

The forces acting the sample are measured by the force sensors mounted between the support plate and cryostat. The setup enables us to measure the HTS samples during both transition into superconductivity in the lack of the magnetic field (ZFC) and an applied external field (FC).

In the ZFC regime, permanent magnets are kept at a distance of at least 1 m from each other by the drive with a manual transition. The cryostat with the sample is connected to the cooling system. After a time delay for filling the system with liquid nitrogen and cooling of the sample (at least 5 min), the setup is ready for the measurements in accordance with the required regime.

In the FC regime, the permanent magnets are fixed by a manual transmission drive at a distance corresponding to the required magnetic induction in the sample relative to the calibration curve (Fig. 6). The cryostat with the sample is connected to the cooling system. After a time delay for filling the system with liquid nitrogen and cooling of the sample (at least 5 min), the setup is ready for measurements in accordance with the required regime.

CONCLUSIONS

To check new models of electrophysical properties of HTS materials that include two electromagnetic field sources—induced current density and magnetization—a new technique of experimental studies of such kind of materials has been proposed. It included a series of experiments that allowed assigning the gathered experimental information to the specific source type.

For practical implementation of this technique, we developed a setup equipped with necessary measuring tools that enabled us to measure the HTS samples over an external field magnetic induction range of up to 1.5 T both in transition into a superconductive state and without it.

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