High critical current densities $J_c$ are of considerable significance for multiple prospective applications of high-temperature superconductors such as wires for electric energy transmission and magnets [1]. As a rule, the limitation of $J_c$ is connected with two main factors [2]. First, $J_c$ is limited by the thermally activated magnetic flux creep; i.e., it decreases considerably under the action of a magnetic field much less than the critical field $H_c(T)$. This phenomenon is caused by the well-known properties of high-temperature superconductors, e.g., the high anisotropy and small coherence length, which lead to weak magnetic flux pinning. Second, $J_c$ in polycrystalline high-temperature superconductors is limited by the insufficient ordering of crystallites and their chemical inhomogeneity, which leads to weak coupling with low critical current densities. This problem is overcome by different methods of growing the texture such as oxide-powder-in-tube, OPIT [3]. Owing to this technology, the value $J_c > 80$ kA/cm$^2$ was reached in short multiwire Bi-2223/Ag strips at a temperature of 77 K [4].

In the last years, there appeared many new methods of creating pinning centers and, accordingly, increasing the critical current $J_c$ of high-temperature superconductors. Of the highest interest among them are the following. Amorphous cylindrical tracks with a diameter of about 10 nm and length from 1 to 10 μm were prepared by heavy-ion bombardment of $\text{YBa}_2\text{Cu}_3\text{O}_7-y$ single crystals [5]. Tracks in amorphous $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ were prepared by proton irradiation with the subsequent decay of Bi nuclei [6]. The magnetization hysteresis and critical temperature of $\text{HgBa}_2\text{CaCu}_2\text{O}_6$ were increased by its neutron irradiation [7].

However, the application of these technologies is accompanied by considerable difficulties: serious hindrances in the application of accelerators, radioactive elements, and neutron irradiation.

Obviously, it is necessary to study further the methods of the incorporation of defects or impurities into the superconducting matrix. Apparently, the most realistic approach is the preliminary mixing of nanoparticles and high-temperature superconducting powder and then the performance of the standard technological procedures, i.e., annealing, sintering, and oxygenation (if necessary). The following advantages will be achieved: the possibility of industrial application, the considerable decrease in the anisotropy of magnetic properties, and the considerable increase in the critical current when the contact between the grains is enhanced.

The nanoparticles should meet the following main requirements: first, their size should be comparable with the coherence length of the high-temperature superconductors and, second, they should be stable in a chemically aggressive medium at elevated temperatures. This is necessary for the optimization of superconductivity in the matrix material. In this work, we chose $\text{ZrO}_2$ nanoparticles for studies in the form of inclusions in a polycrystalline superconducting matrix.

In this work, the effect of $\text{ZrO}_2$ nanoparticles prepared in a low-pressure arc discharge plasma on magnetic flux pinning of granular $\text{YBa}_2\text{Cu}_3\text{O}_7-y/\text{nanoZrO}_2$ composites has been studied. It has been shown that the $\text{ZrO}_2$ nanoparticles do not change the superconducting transition and the microstructure of superconductors. At a temperature of 5 K, the addition of 0.5 and 1 wt % of $\text{ZrO}_2$ nanoparticles may lead to the additional effect of magnetic flux pinning and the increase in the critical current density $J_c$. The $J_c$ value for composites with 1 wt % is two times larger than that for the reference sample. The fishtail effect is observed for $\text{YBa}_2\text{Cu}_3\text{O}_7-y/\text{nanoZrO}_2$ composites at the temperatures of 20 and 50 K. The problems associated with the additional effect of magnetic flux pinning of granular $\text{YBa}_2\text{Cu}_3\text{O}_7-y/\text{nanoZrO}_2$ composites and the appearance of the fishtail effect have been discussed.

**DOI:** 10.1134/S002136401402009X
YBa$_2$Cu$_3$O$_{7-y}$ matrix. The melting temperature of ZrO$_2$ reaches 2400°C. They are chemically stable. The aim of this work is to study the effect of ZrO$_2$ nanoparticles on the high-temperature superconducting microgranules was prepared in a low-pressure arc discharge plasma on the magnetic flux pinning of the granular YBa$_2$Cu$_3$O$_{7-y}$/nanoZrO$_2$ composites.

The powder of the precursor YBa$_2$Cu$_3$O$_{7-y}$ was prepared using the conventional solid-phase synthesis. The YBa$_2$Cu$_3$O$_{7-y}$/nanoZrO$_2$ composite was synthesized according to the technique described in detail in [8, 9]. The material was synthesized under the following conditions. Technically pure zirconium was used as the sputtering cathode. Prior to the evaporation, the cathode was heated to a working temperature of 800 K. The purification in the glow discharge was performed at the voltage on the substrate of 1000 V for 1 min. The ion bombardment activation was performed for 1 min at an arc discharge current of 20 A and a voltage on the substrate of 1000 V. The rotation frequency of the mixing device was 8 min$^{-1}$. The vibration amplitude was 1 mm. The vibration frequency was 50 Hz. The direct deposition of the ZrO$_2$ nanoparticles on the high-temperature superconducting microgranules was performed at a discharge current of 500 A. The longitudinal magnetic field strength created by the focusing coil of the cathode surface was 6366.2 A/m. To implement the plasma-chemical reaction, a 5% O$_2$ + 95% He gas mixture was inserted in the chamber using a two-channel regulator of the gas flow rate after the preliminary evacuation to a pressure of 1 mPa. The synthesis was performed at a pressure above 120 Pa. After the deposition of the nanoparticles, the samples were passivated in a pure oxygen atmosphere for a day. The prepared samples of the material contained from 0.1 to 1 wt % of nanoparticles.

The prepared mixture was preliminarily heated to 940°C and kept at this temperature for 30 h. The preliminarily heated powder was ground and then pressed into tablets with a diameter of 1 mm and a thickness of 5 mm at a pressure of $1.2 \times 10^5$ N/cm$^2$. Finally, the granules were sintered at 940°C for 24 h and then cooled to room temperature in an oven in air.

Magnetization was recorded by differential Hall magnetometry with the use of two semiconductor Hall sensors switched opposite to the Hall potential outputs. The first Hall sensor was far from the sample and measured the external magnetic field $H$. The second sensor was placed on the sample surface and measured the magnetic flux density. As a result of the apparatus subtraction of the Hall potential of the first Hall sensor from the potential of the second Hall sensor, the resultant signal appeared corresponding to the magnetization $M(H)$. According to the Bean formula including the demagnetization factor and the dependence of the critical current on the magnetic field, $J_c(H) = 30M(H)/d$, where $M$ is the width of the magnetic hysteresis loop and $d$ is the average size of the crystallite. We used the value $d = 6\mu$m obtained from the electron microscopy results. The hysteresis magnetic loops were measured at 5, 20, and 50 K. The pinning force was calculated using the equation $F_p(B) = J_c(B)B$ [10].

The phase composition of the high-temperature superconducting samples was studied on an XRG-6000 diffractometer using CuK$_\alpha$ radiation. The phase composition and the size of the coherent scattering regions were analyzed using the PCPDFWIN database.

The sample structure was studied by scanning electron microscopy on a JEM-100CX electron microscope with an ASID-4D scanning device at an accelerating voltage of 40 keV.

Figure 1 shows the X-ray diffraction patterns of all YBa$_2$Cu$_3$O$_{7-y}$/nanoZrO$_2$ composites. Peaks related to the admixture of the ZrO$_2$ phase or other oxides are absent. The characteristic peaks of YBa$_2$Cu$_3$O$_{7-y}$/nanoZrO$_2$ nanoparticles were detected using scanning electron microscopy. Thus, the ZrO$_2$ nanoparticles are homogeneously distributed over the superconducting matrix. The field dependences $F_p(B)$ and $J_c$ of the YBa$_2$Cu$_3$O$_{7-y}$/nanoZrO$_2$ composite are shown in Figs. 2–4.

Figure 2 shows the magnetic field dependences of the calculated critical current density $J_c$ and the pinning force $F_p$ at a temperature of 5 K for all studied composites. It is seen in Fig. 2a that, for all applied magnetic fields, $J_c$ is much higher for composites with 0.5 and 1.0 wt % of ZrO$_2$ nanoparticles than that for the sample without the addition of ZrO$_2$ nanoparticles. For the composite with 1.0 wt % of ZrO$_2$ nano-