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Peculiarities of magnetization anisotropy of high-temperature superconducting $YBa_2Cu_3O_x$ tapes

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The dependence of the magnetization of high-temperature superconducting (HTSC) tapes of composition $YBa_2Cu_3O_x$ (SuperOx, Moscow) on the magnetic field, temperature and orientation of the magnetic field relative to the plane of the tape has been studied. The tape magnetization values decrease by approximately two orders of magnitude when the angle of magnetic field direction relative to the plane of the tape changes from 90° (normal field orientation) to 0° (parallel orientation). It was found that in a large range of angles from 90° to 60°, the values of the magnetization component along the direction of the applied field change insignificantly. Near the parallel orientation (from 0° to 15°), the magnetization values increase approximately twofold, which is significantly less than the rate of change of magnetization in the angle range 15–60°.

Keywords: High-temperature superconductor, SuperOx tape, magnetization, anisotropy, magnetic field.

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Irreversible magnetization of hard type II superconductors is characterized adequately by the critical state model [1,2]. Planar superconductors (plates, tapes, thin films) feature a significant dependence of magnetization on the magnetic field orientation relative to the sample plane. This anisotropy was analyzed within the critical state model in, e.g., [3,4]. In the general case, one needs to factor in the surface barrier for penetration of vortices (the Bean–Livingston barrier) [5], the anisotropic crystal structure of the superconducting compound [6], and the possible anisotropy of defects (pinning centers) [7] to perform an analysis of magnetization anisotropy. It was demonstrated that the anisotropy of magnetization of superconductors with a large lateral size to thickness ratio is attributable more to shape anisotropy than to lattice anisotropy of the compound. It was also found that the magnetic moment of a planar superconductor remains directed normally to its plane within a fairly wide range of angles of deviation of the magnetic field from the normal. When the magnetic field direction deviates from the sample plane, the magnetic moment also remains oriented in-plane, albeit within a narrower range of angles [8,9].

Studies of the anisotropy of critical currents and magnetization of planar superconducting samples have assumed special significance with the advent of second-generation high-temperature superconducting (HTSC) tapes. When magnetic systems are constructed based on such tapes, one needs to take the anisotropy of magnetization and critical currents into account, since different winding regions are subjected to the influence of a magnetic field oriented differently relative to the tape plane.

In the present study, we report the results of measuring the anisotropy of magnetization of a $YBa_2Cu_3O_x$ HTSC tape produced by SuperOx (Moscow). The magnetization was measured as a function of temperature and magnitude and orientation of the magnetic field with a VSM vibration magnetometer of the PPMS-14 setup within the 0–1 T field range. Angle α of the magnetic field orientation relative to the sample plane was fixed with the use of sample holder inserts; angles $\alpha = 0°$ and $\alpha = 90°$ corresponded to the magnetic field oriented along the sample plane and normally to it, respectively. It should be noted that the vibrating sample magnetometer measures the component of the magnetic moment parallel to the applied magnetic field.

The lateral dimensions of the $YBa_2Cu_3O_x$ HTSC tape (SuperOx) sample were 3×2.5 mm (the greater dimension being along the tape length). Since the approximate thickness of the HTSC layer in the tape is 1 μm, the sample had a distinct shape anisotropy with a transverse size to thickness ratio close to 3000. The HTSC tape is a multilayer structure with buffer and protective layers complementing the superconducting $YBa_2Cu_3O_x$ layer applied to a substrate made of Hastelloy C276 alloy.

The temperature dependence of magnetization of the HTSC tape measured in a 1 kOe field is shown in Fig. 1 for a number of angles between the magnetic field direction and the tape plane. The critical temperature of the HTSC tape determined from the $M(T)$ dependence is 90 K. The magnetization values at angles of 90 and 0° differ substantially, while the $M(T)$ values at angles of 90 and 60°, as well as at 0 and 15°, differ only slightly.

The magnetic properties of Hastelloy and buffer layers may contribute to the anisotropy of magnetization of the HTSC tape. It was demonstrated in [10] that the Hastelloy magnetization increases below 100 K (has a paramagnetic nature), while buffer layers have little effect on the total magnetization. The magnetic properties of Hastelloy are manifested clearly at temperatures above critical temperature $T_c = 90$ K of the HTSC layer, which is evident when

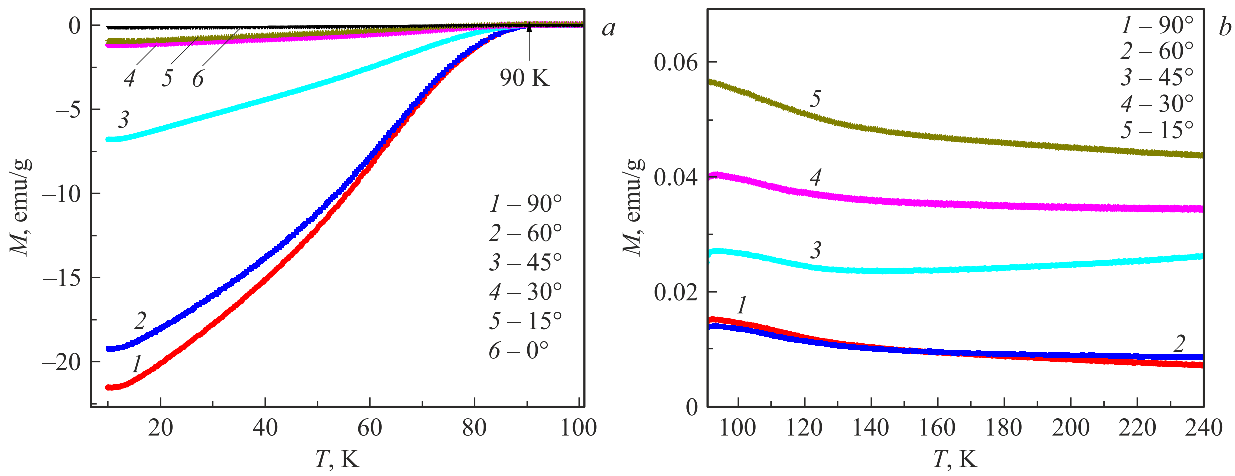

Figure 1. *a* — Temperature dependences of magnetization of an HTSC tape $M(T)$ at $H = 1$ kOe and different orientations of the magnetic field relative to the tape plane, $T < 100$ K. *b* — $M(T)$ plotted at $T > 90$ K on an enlarged scale.

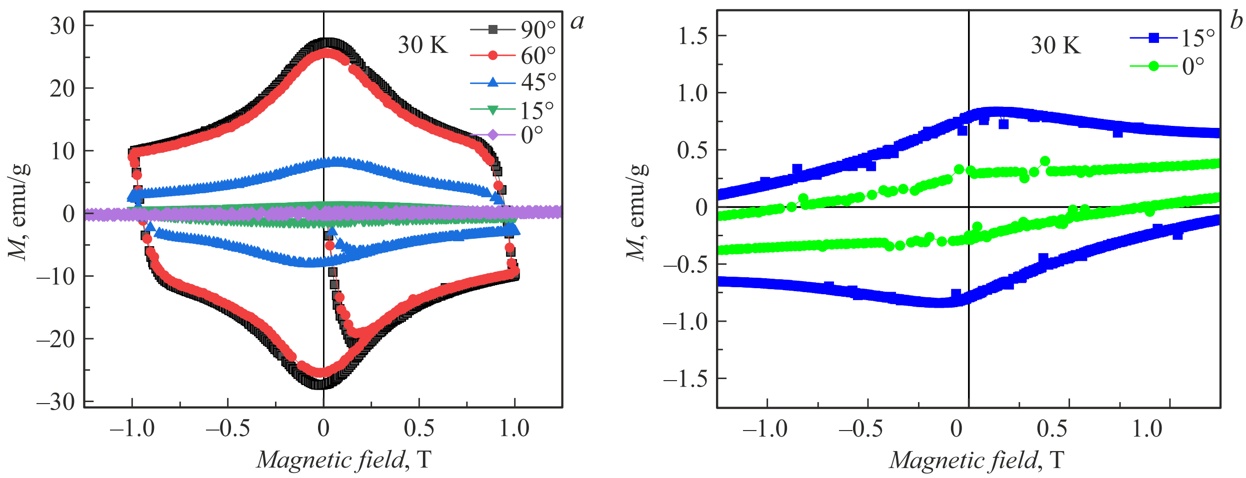

Figure 2. *a* — Dependence of tape magnetization on magnetic field $M(H)$ at $T = 30$ K and different angles between the tape plane and the magnetic field direction. *b* — Dependences $M(H)$ plotted for angles of 0 and 15° on an enlarged scale.

one examines a close-up of the $M(T)$ dependence from Fig. 1, *a* in (Fig. 1, *b*). It follows from Fig. 1, *b* that the Hastelloy magnetization at this temperature is paramagnetic in nature and has a much lower absolute value than the tape magnetization at $T < T_c$; therefore, it may be neglected in qualitative analysis of the anisotropy of magnetization of the HTSC tape.

The tape magnetization anisotropy is manifested clearly in dependences $M(H)$ of magnetization on the magnetic field. Figure 2 shows the results of measuring $M(H)$ at $T = 30$ K and H values up to 1 T. The HTSC tape magnetization has the following features at this temperature.

1. The magnetization values remain significantly higher than the substrate magnetization within a wide range of angles. For example, the HTSC tape magnetization at $H = 1$ T is on the order of 10 emu/g with normal orientation and on the order of 0.3 emu/g with parallel orientation, while the substrate magnetization is on the order of 0.2 emu/g at this temperature [10]. Thus, the magnetic properties of the substrate manifest themselves only in a parallel field, which translates into a slight slope (asymmetry) of the $M(H)$ dependence of the tape (Fig. 2, *b*).

2. The shape of dependence $M(H)$ of the HTSC tape varies little with a change in the magnetic field orientation, but the magnetization decreases by approximately two orders of magnitude in transition from angle $\alpha = 90°$ to angle $\alpha = 0°$ (Fig. 2, *a*). It should be noted that the critical currents in the longitudinal orientation are an order of magnitude greater than the critical currents in the transverse orientation, since they are proportional to the $\Delta M/d$ ratio (ΔM is the hysteresis loop height and d is the sample dimension transverse to the field).

3. The preservation of shape of the $M(H)$ dependence is indicative of preservation of the pinning mechanism in transition from the normal field orientation relative to the tape plane to the parallel one. This is in contrast with the results of measurements of magnetization anisotropy for niobium tapes [11], where a significant change in the shape of the $M(H)$ dependence was observed in transition to a parallel orientation (where the surface barrier exerts a pronounced influence).

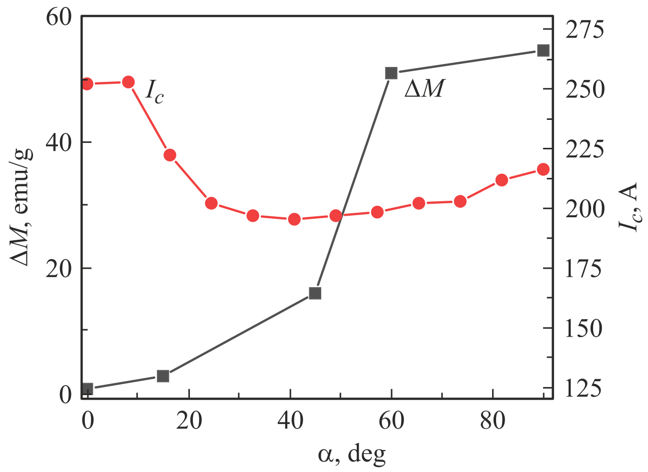

Figure 3. Dependencies of magnetization loop height ΔM $(H = 0)$ at $T = 30$ K and critical tape current I_c at $T = 77$ K and $H = 500$ Oe on the angle of application of the external magnetic field.

4. An insignificant variation of magnetization within the angular range from 90 to 60°, its weak variation at 0–15°, and a pronounced (order-of-magnitude) M enhancement in transition from 15 to 60° are important features of the angular dependence of magnetization of HTSC tapes. This is illustrated in Fig. 3, which shows the dependence of height ΔM $(H = 0)$ of the magnetization loop of the HTSC tape on angle α. The results of preliminary measurements of the dependence of critical tape current I_c on the angle of application of field $H = 500$ Oe at $T = 77$ K are also presented in Fig. 3. The critical current was measured by the non-contact method of magnetic flux capture in a superconducting ring [12]. It is evident that the critical current depends weakly on angle α within a wide range of 40–90° and within a narrow angular range around $\alpha = 0°$.

The presence of an angular interval with an insignificant magnetization (magnetization components along the magnetic field direction) variation around the normal and parallel orientations of the magnetic field has already been noted in experiments with planar superconductors (single crystals and thin films) [7]. Vector magnetometry revealed that the magnetic moment of samples within these angular ranges remains directed normally to the sample plane as the field orientation deviates from the normal [8] (or directed parallel to the sample plane as the field orientation deviates from the parallel one [9]). Two angular ranges with an insignificant variation of magnetization found in the present study may be produced by this effect of retention of the magnetic moment orientation relative to the sample plane. These two angular intervals should be taken into account when one designs magnetic systems with second-generation HTSC tapes.

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Conflict of interest

The authors declare that they have no conflict of interest.

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