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Analysis of Electromagnetic Phenomena in HTc Superconductors

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Unique electromagnetic properties, especially concerning recent observations of the giant remanent magnetic moment in HTc superconductors, require new approach to modeling these phenomena in the oxide ceramics. The present paper is devoted to the analysis of the influence of flux pinning on critical current and flux trapping in HTc superconductors. Modeling of the interaction between nanosized pinning centers and pancake vortices is presented, allowing to determine critical current density, taking into account elasticity forces of the vortices lattice. Ceramic structure of oxide superconductors was considered in trapped flux analysis. The mechanism of trapped flux generation was regarded as strongly related to vortex pinning and critical current phenomena.

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1. Introduction

High temperature oxide superconductors (HTc) were discovered more than twenty years ago. Therefore now it is time, beside conducting pure basic research, for application of these materials in various kinds of electric devices, for instance in magnetic bearing shown in Sect. 3. Exceptional electromagnetic phenomena appearing in these materials should be taken into account for this aim. One of them is connected with fabrication of large single grains Y-123 superconducting monoliths, trapping magnetic induction significantly exceeding the values achievable using other permanent magnets [1, 2]. This effect allows to treat HTc superconductors not only as resistivity-less perfectly conducting materials but also as very promising permanent magnets.

2. Interaction of nanosized pinning centers with pancake vortices

According to the Ginzburg–Landau theory [3], the superconducting state is characterized by the order parameter, which means that this state is energetically more favorable than the normal one. Increase in the volume of the normal phase enhances therefore the energy of the system, whose amount should be minimized. This effect is considered just in the proposed electromagnetic pinning interaction model, in application to the pancake type vortices appearing in HTc layered superconductors. Capturing the pancake vortex, whose normal core has the radius ξ — coherence length, on the nanosized pinning center, decreases the normal state energy of the superconductor in comparison with the geometry of the not bounded, freely moving vortex. On the other hand, the Lorentz force acting on the pinned vortex, tears off the vortices from the pinning centers during the flow of current. The elasticity forces have the analogous meaning, according to which anchorage of vortex leads to the deflection of the vortex from its equilibrium position in lattice and in this way enhancement of the elasticity energy. The potential barrier rises, being a function of the mentioned parameters: transport current density, elasticity forces of vortex lattice, pinning centers dimensions and as usually magnetic field and temperature. According to the above briefly presented model, the final mathematical expression for the potential barrier level $\Delta U(i)$ has been obtained

$$\Delta U(i) = \frac{\mu_0 H_c^2 l \xi^2}{2} f(d,i) - \alpha \xi^2 \sqrt{1-i^2}\left(2-\sqrt{1-i^2}\right), \tag{1}$$

where the function $f(d,i)$ appearing above is determined according to the relation

$$f(d,i) = \arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2} - \arcsin i. \tag{2}$$

H_c is the magnetic critical thermodynamic field, l — nanosized pinning center thickness, ξ — coherence length describing the radius of the vortex core, while d is the width of the nanosized pinning center and $i = j/j_c(0)$ is reduced current density. Appearance in Eq. (1) of coherence length leads also to anisotropy of the pinning interaction. The variable j denotes transport current density, while $j_c(0)$ corresponds here to the critical current density for the flux creep process, without taking into account the elasticity forces of the vortex lattice. Elasticity interaction of captured vortex with lattice reduces the pinning energy and is expressed in the model by an additional term to the energy balance of superconductor

$$U_{el} = \frac{2c_s \pi \xi^2 (\xi - x)^2}{l_a} = \alpha(\xi - x)^2. \tag{3}$$

Parameter α in Eq. (3) describes the increase in the elasticity energy of the vortex lattice U_{el}, while c_s is the corresponding elasticity shear modulus. $l_a \approx l$ denotes the length on which the magnetic field of vortex is distorted, approximated here by the pinning center thickness l. x is the deflection of the vortex core from its equilibrium position inside the pinning center. For $x = \xi$ the vortex leaves the capturing center and returns to its appropriate position in the lattice, not increasing anymore elasticity energy. Examples of the numerical calculations, according to the above model, of the influence of the vortex lattice elasticity forces expressed by the parameter α defined in Eq. (3) on critical current density are shown in Fig. 1.

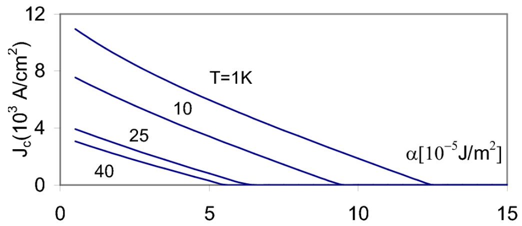

Fig. 1. Influence of the vortex lattice elasticity forces, expressed by the parameter α on the critical current density versus temperature, at $B = 1$ T.

Calculations were performed for the pinning centers concentration equal to 2×10^{12} cm^{-3}, while other parameters such as critical temperature, coherence length, critical magnetic thermodynamic field correspond to physical properties of the BiSrCaCuO layered superconductor. Temperature variation of H_c and ξ was taken into account, while thickness of the pinning centers of the size near to 2ξ, was equal to the thickness of the CuO_2 layer. Critical current density was determined then basing on the electric field E criterion deduced from the flux creep equation, valid for flux creep processes in the forward and backward vortex motion

$$E = -B\omega a \left[\exp\left(-\frac{\Delta U(0)}{k_\mathrm{B}T}(1+i)\right) - \exp\left(-\frac{\Delta U(i)}{k_\mathrm{B}T}\right)\right], \tag{4}$$

ω is average hopping frequency on the distance a between pinning centers, k_B — Boltzmann's constant, T — temperature.

3. Investigations of the trapped flux

The present paper is devoted to an analysis of the electromagnetic phenomena in HTc superconductors related to the flux pinning mechanism — critical current and flux trapping. Pinning interaction described in the previous section determines critical current density and also influences magnetic properties of HTc superconductors, especially magnetic induction distribution and therefore the trapped flux magnitude. This parameter is important, while using HTc superconductors as permanent magnets, also in magnetic levitation. From one side perfect diamagnetism of superconductors in a weak magnetic field can be utilized in this process, while the state of a trapped magnetic field can also be useful, especially for larger inductions produced by permanent magnets.

In Fig. 2 there are shown calculated profiles of the magnetic field lines in a superconducting bearing, constructed of superconducting, diamagnetic shield rotating above 10 disks of normal permanent magnets. Calculations of magnetic field lines for presented bearing geometry were performed here using the finite

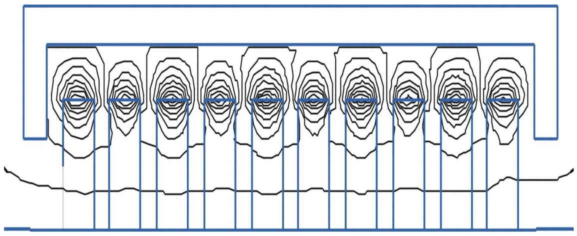

Fig. 2. Calculated magnetic field lines in the cross-section of the magnetic bearing built of a superconducting cylinder levitating above 10 disks of permanent magnets.

element method. The flux trapping state, allowing to treat HTc superconductors as permanent magnets, can be also utilized in this process.

In Fig. 3 there is shown a model of magnetic induction distribution in oxide ceramics considered in this part. Existence of the individual grains and intergrains boundary regions characterized by worse superconducting properties is assumed. Weak intergranular currents in ceramic materials, as compared with strong intragranular currents, are in this approximation treated as Josephson's currents and

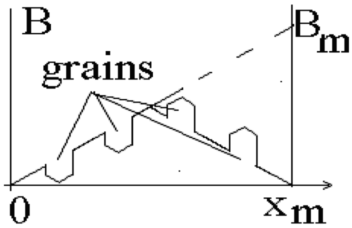

Fig. 3. Model of the magnetic induction distribution in the flux trapping state of a ceramic plate. Superconducting grains with much higher critical current are schematically marked, too.

lead to the characteristic saw-tooth shape of the magnetic induction distribution, shown in Fig. 3. In the proposed model expressions for the flux trapping F_{tr} were received as a function of maximal external magnetic induction B_{m}, applied to the surface of the superconducting plate of the thickness $2x_{\mathrm{m}}$, in the magnetic induction cycle $0 \to B_{\mathrm{m}} \to 0$. Here $B_{\mathrm{m}} = B_{\mathrm{e}} - B_{\mathrm{c1}} - \Delta$ is the difference between the maximum applied magnetic induction B_{e}, first penetration induction B_{c1} and superconducting surface barrier Δ. F_{tr} values are normalized here to the sample cross-section, which allows to avoid the dependence of the results on the sample dimensions and treat this value as the remanence, parameter usually used for characterization of permanent magnets. For $B_{\mathrm{m}} < 0$ trapped flux disappears: $F_{\mathrm{tr}} = 0$. For next range of magnetic induction increase, it is for $B_{\mathrm{p}} > B_{\mathrm{m}} > 0$ the trapped flux is given as follows:

$$F_{\mathrm{tr}} = \frac{B_{\mathrm{m}}^2}{4B_{\mathrm{p}}}, \tag{5}$$

where $B_p = \mu_0 j_{\mathrm{c}} x_{\mathrm{m}} - B_{\mathrm{c1}} - \Delta$ is the minimum value of the magnetic induction penetrating to the center of the flat superconducting sample. For the next range of the magnetic field amplitudes described by condition $2B_{\mathrm{p}} > B_{\mathrm{m}} > B_{\mathrm{p}}$ the trapped flux is described by the relation

$$F_{\mathrm{tr}} = B_{\mathrm{m}} - \frac{B_{\mathrm{m}}^2}{4B_{\mathrm{p}}} - \frac{B_{\mathrm{p}}}{2} + nB_{\mathrm{g}}\left(\frac{B_{\mathrm{m}}}{B_{\mathrm{p}}} - 1\right), \tag{6}$$

where parameter n describes relative concentration of the grains in ceramic superconductor, while B_{g} is averaged to the grain's cross-section trapped induction in individual grain: $B_{\mathrm{g}} = B_{\mathrm{c1g}} + \frac{\mu_0 j_{\mathrm{cg}} R_{\mathrm{g}}}{3}$. Index g corresponds to the grain's parameter. For higher values of the magnetic induction, satisfying the condition $B_{\mathrm{m}} > 2B_{\mathrm{p}}$ the trapped flux saturates

$$F_{\mathrm{tr}} = \frac{B_{\mathrm{p}}}{2} + nB_{\mathrm{g}}. \tag{7}$$

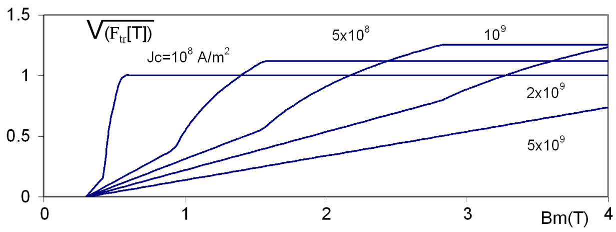

Fig. 4. Theoretical dependence of the square root of the flux trapping F_{tr} (T) normalized to the sample cross-section (averaged frozen magnetic induction) on the maximum induction in cycle B_{m}, as a function of the intergranular critical current density.

Figure 4 presents results of calculations using this model of the influence of weak intergranular, Josephson's like currents, flowing in the matrix surrounding the grains, on trapped flux. These theoretical results are in qualitative agreement with experimental data given in [4].

4. Conclusions

In the paper electromagnetic phenomena have been considered appearing in HTc ceramic superconductors, related to the pinning interaction. Critical current density was analyzed taking into account the elasticity forces of the vortex lattice and magnetic flux trapping, allowing to treat HTc superconductors as permanent magnets.

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