Materials Science-Poland, Vol. 25, No. 4, 2007

Analysis of the pinning interaction in high-temperature superconductors

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Analysis of the pinning interaction in high-temperature (HTc) superconductors is presented. The model based on analysis of the enhancement of the energy of a superconductor under the vortex motion against its equilibrium position is described. The influence of the dimensions of pinning centres and of the elasticity forces of the vortex lattice on the critical current is considered. The magnetic induction profiles in HTc superconductors are obtained, taking into account the granular structure of ceramic materials, while the flux trapped is determined. The magnetic hysteresis losses, modified by the existence of the magnetic nickel substrates in HTc tapes of second generation are considered too.

Key words: *HTc superconductors; nanotechnology; pinning; critical current*

1. Introduction

The effect of the capturing vortices in high-temperature superconductors (HTS) has essential meaning from the point of view of electric current transport. It is also a very intriguing statistical problem of the occupation on a fixed concentration of the pinning centres, varying number of vortices, interacting with each other through the elasticity forces (cf. [1–4]). The present paper is a continuation of the author's works [5–7]. From the point of view of applications, the pinning subject deals especially with the case of the HTc superconducting tapes, an example of the second generation one being shown in Fig. 1.

Ni-W substrate enables epitaxial growth of the HTS layer but on the other hand is the reason of additional magnetic losses, due to magnetic properties of nickel. The magnetization characteristic of nickel leads to enhancement of the magnetic field in the superconducting filaments and therefore to an increase in the magnetic hysteresis losses, connected with alternating current flow.

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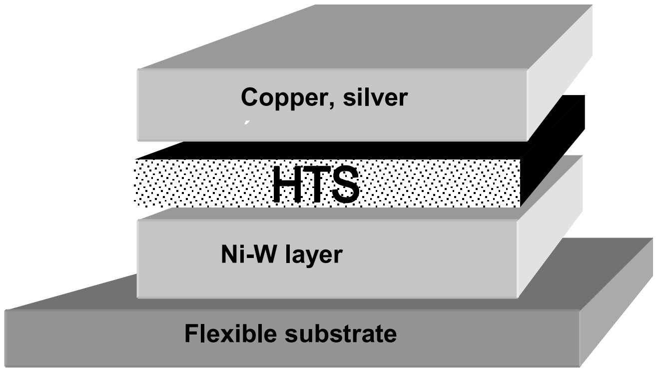

Fig. 1. The structure of the second generation HTc tape

The temperature and quality of nickel substrate may lead to modifications of magnetic characteristic, roughly described by the hyperbolic tangent function $B \propto \tanh(\mu_0 H)$, which will strongly influence the generated losses, as follows from the calculated results shown in Fig. 2 for three slightly modified characteristics of substrates.

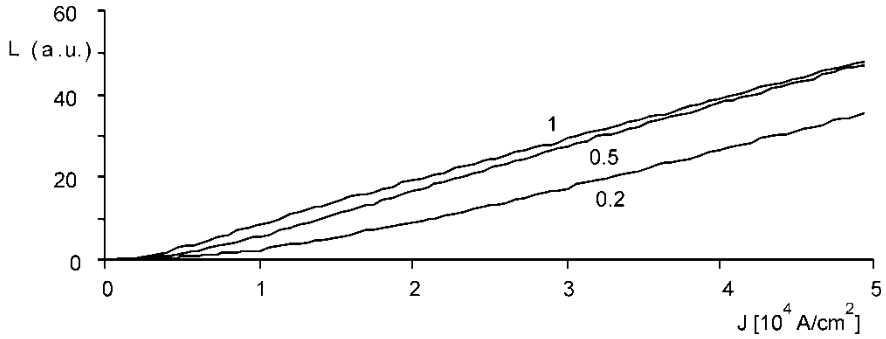

Fig. 2. Dependence of the value of losses on the transport current density for three nickel substrate magnetic characteristics described by Eq. (1); $B \propto 0.65\tanh(\beta\mu_0 H)$ for $\beta = 0{,}2$, 0.5, 1

The calculations were performed for the rectangular wire of the dimensions 5×1.5 mm^2 with 30 filaments distributed in three layers. The losses were calculated for the filament near to the middle of the wire.

2. Analysis of a new model of the pinning interaction

An important feature of the HTc superconducting materials is the sensitivity of their properties to the existence of structural defects, which if created in the superconducting windings working in nuclear reactors are of the nanometric size and are referred to as the columnar defects. These defects interact with the pancake vortices arising in HTc superconductors, thus stabilizing the vortex structure and permit in this way the resistiveless current flow. A new model of the pinning interaction has been developed in the paper, based on an analysis of the increase in the normal state energy during the pancake vortex deflection from nanosized pinning centre, against its equilibrium position, which is shown in Fig. 3.

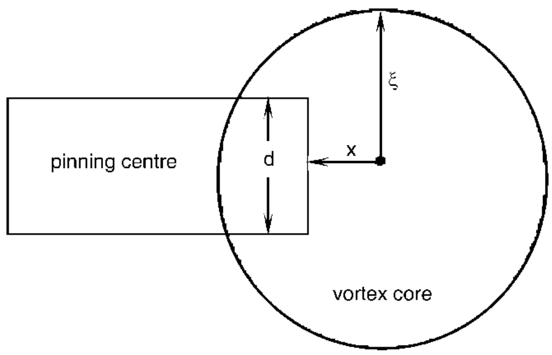

Fig. 3. View of the vortex core of the radius equal to the coherence length (ξ_0) captured on the pinning centre of the width d

The approach corresponds roughly to the consideration of the first two terms in the Ginzburg–Landau theory. As compared with previous pinning models based mainly on the force balance equation in the regime of flux flow, being the continuation of the critical state Bean's approach [8], in the present theory we consider the condition of the energy equilibrium and flux creep approximation. Two effects have been investigated of the increase in the normal state energy during the vortex movement, as well as opposite one of the increase in the elasticity energy of the vortex lattice during the capturing process, deflecting vortex from its equilibrium site in the vortex matrix.

In the initial state of the captured vortex on the flat pinning centre of nanosized dimensions d, smaller than the coherence length ξ, the normal state energy of the vortex core is:

$$U_1(0) = \frac{\mu_0 H_c^2 l}{2}\left[\pi\xi^2 - \xi^2 \arcsin\frac{d}{2\xi} - \frac{d\xi}{2}\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right] \tag{1}$$

while for a vortex deflected by the distance x against this equilibrium position it is given, as follows from Fig. 3:

$$U_2(x) = \frac{\mu_0 H_c^2 l}{2}\left[\pi\xi^2 + dx - \xi^2 \arcsin\frac{d}{2\xi} - \frac{d\xi}{2}\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right] \tag{2}$$

for $x < x_c$, where x_c is defined as:

$$x_c = \xi \sqrt{1 - \left(\frac{d}{2\xi}\right)^2} \tag{3}$$

The deflection of vortex is caused by the flow of current which leads to the Lorentz force appearance. Additionally, the elasticity forces are taken into account also related to the magnitude of the vortex deflection in the vortex lattice. Thus a barrier of potential ΔU arises, being a function of the ratio of the current density j and the critical current density for the flux creep process j_C, defined as the current density for which barrier of potential disappears, for pinning centre dimension equal to the vortex core diameter:

$$\Delta U(i) = \frac{\mu_0 H_c^2 l \xi^2}{2} z + \alpha \xi^2 \sqrt{1-i^2}\left(\sqrt{1-i^2} - 2\right) \tag{4}$$

The parameter z in Eq. (4) is determined here according to the relation:

$$z = \arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{1 - \left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2} - \arcsin i \tag{5}$$

where $i = j/j_c$ is the reduced current density, H_c magnetic thermodynamic critical field, l the pinning centre thickness. Parameter α describes the elasticity energy of the vortex lattice. Inserting Eqs. (4), (5) into the constitutive relation:

$$E = -B\omega a\left[\exp\left[-\frac{\Delta U_0}{k_B T}\left(1 + \frac{j}{j_C}\right)\right] - \exp\left(-\frac{\Delta U}{k_B T}\right)\right] \tag{6}$$

describing the generated electric field in the flux creep process, just as a function of the potential barrier height, we obtain the dependence of the real critical current density, i.e. that satisfying the electric field criterium, on the material parameters. ΔU_0 is the potential barrier height without current, ω – a characteristic frequency, which in the present paper has been assumed constant, T – temperature and k_B – Boltzmann's constant, the parameter a describes the defect concentration. Selected results of calculations are presented in Figs. 4, 5, pointing to the importance of the pinning centre dimensions as well as the elasticity constant α for the critical current density.

For too low pinning centre dimensions as well as too high elasticity constant of the vortex lattice, the critical current density vanishes; this result should be interesting from the technological point of view. The new model of the pinning mechanism allows us therefore to predict the critical current of the HTc materials in function of material parameters. The peculiar property of these ceramic superconductors is the existence of Josephson's junctions on the grain boundaries which modify the total critical current density. We will investigate this subject focusing on the trapped flux analysis.

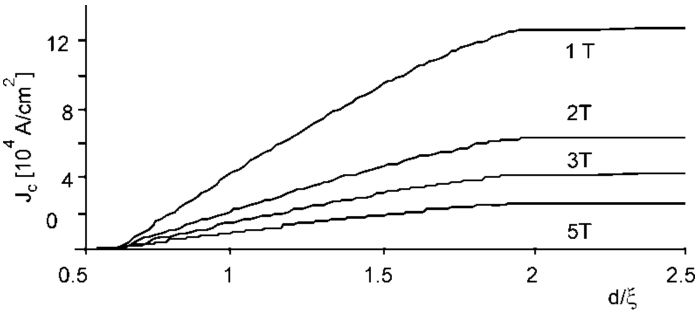

Fig. 4. Dependence of the critical current density satisfying the electric field criterion on the pinning centre dimensions for various magnetic fields; pinning centre concentration equal to 2×10^{14} cm^{-3}

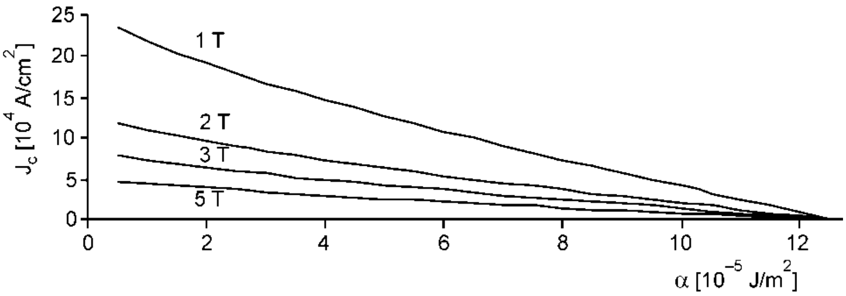

Fig. 5. Dependence of the critical current density on the elasticity force of the vortex lattice (described by the parameter *J*) versus magnetic induction for pinning centre concentration equal to 2×10^{14} cm^{-3}

3. Influence of Josephson's currents on trapped flux in HTc ceramics

The trapped flux shown in Fig. 6 is defined as the remnant moment of the magnetization curve in the magnetic field cycle 0–B_m–0.

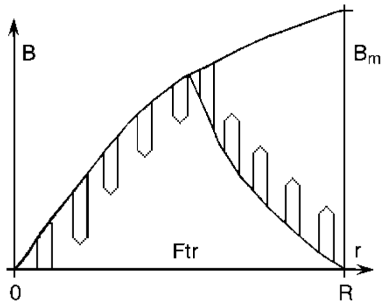

Fig. 6. Magnetic induction profile in the trapped flux state of the ceramic HTc superconductor for the magnetic field cycle 0–B_m–0

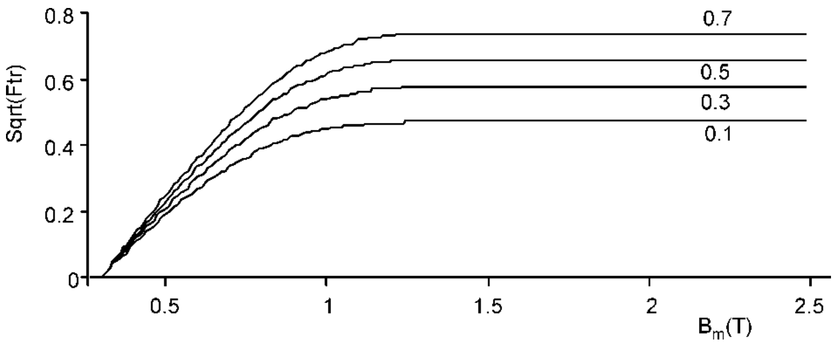

Fig. 7. Influence of filling the ceramic superconductor with grains on the square root of the flux trapped [Sqrt(Ftr)] versus maximum magnetic field in a cycle

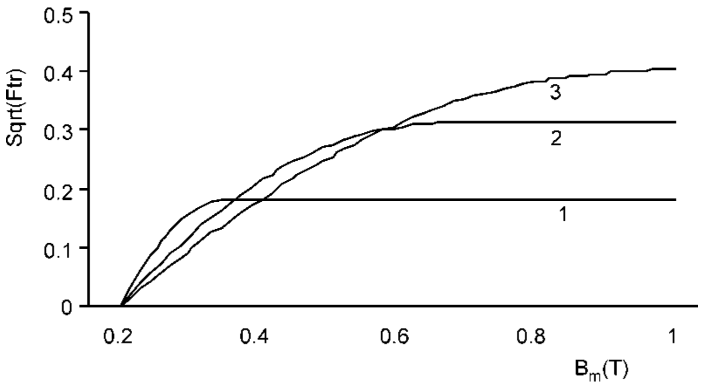

Fig. 8. The influence of the intergranular critical current density of the ceramic superconductor on a square root of the flux trapped [Sqrt(Ftr)] versus maximum magnetic field in the cycle. Indexes 1–3 indicate the case of the increasing critical current density

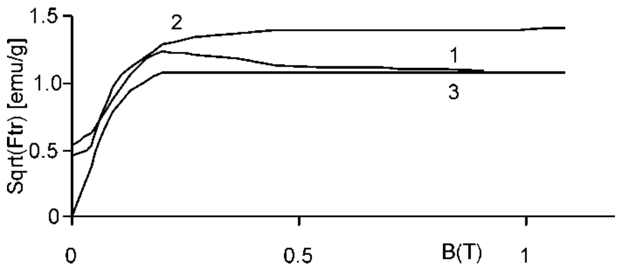

Fig. 9. Experimental shape of the measured flux trapped versus maximum magnetic field for three YBaCuO–Fe (4%) doped samples [9]. Numbers 1–3 refer to: original bulk ceramics (1) bulk ceramics measured after one week (2), and powdered sample (3)

The existence of weak intergranular Josephson's currents, mentioned previously, and the current inside grains lead to the tooth-like shape of the magnetic induction profile given schematically in this diagram. The performed analysis of this effect allowed us to determine the influence on the trapped flux (Ftr) of the superconductor filling with the grains as well as of the intergranular critical current. The results of calculations presented in Figs. 7, 8, correspond well with the experimental data shown in Fig. 9, measured on YBaCuO-Fe doped samples.

4. Conclusions

In the paper, analysis is presented of the pinning interaction in HTc superconducting materials taking into account the specific structure of these granular materials. Performed calculations indicated the importance of the dimensions of the nanosized pinning centres and the elasticity constants of the vortex lattice for determining the critical current density. Analysis of the influence of the critical current density in granular HTc superconductors on the flux trapped has also been performed. The comparison of the theoretical results with previous experimental data is enclosed.

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Received 9 May 2007
Revised 28 September 2007