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Dynamic vortex motion in anisotropic HTc superconductors

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Dynamic transport properties of layered high-temperature anisotropic oxide superconductors have been investigated. An analysis is performed describing the way resistivity-less transport current flows in these superconductors and how it is limited by the velocity of the vortex motion, creating resistivity determining the critical current. The specific, anisotropic shape of the vortices is considered in connection with the layered crystal structure of the high-temperature oxide superconductors taken into account. The results of numerical calculations of the current–voltage characteristics in such a case are presented, which indicate the influence of anisotropy and inter-plane interaction on the critical current in the nearest neighbours approximation. The elastic energy of the vortex lattice is also included.

Key words: *superconductivity; critical current; ceramic materials*

1. Introduction

Most of high-temperature superconductors discovered so far are planar materials containing CuO_2 planes. Exceptions from this rule are fullerides and magnesium boride, MgB_2, which, in fact, is also a layered material with hexagonal magnesium and boride layers. An example of a tetragonal layered crystal structure of Cu-based high-temperature oxide superconductors of the $YBa_2Cu_3O_{7-x}$ type with a marked antiferromagnetic order of Cu atoms is shown in Fig. 1. The planar structure of these materials influences the magnetic and electric properties of HTc superconductors. The present paper is devoted to an analysis of dynamic transport properties related to the magnetic vortex movement in such anisotropic HTc superconductors. Some basic ideas describing the dynamic vortex motion will be introduced, taking into account vortex pinning on the material inhomogeneities – pinning centres. Individual or collective pinning may then appear. Collective pinning takes place for low pinning centre concentrations, at which many vortices occupy the same pinning centres. Collective pinning is

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therefore a weak one. In the opposite case of the high pinning centre concentrations, individual pinning dominates, which is especially important for high-temperature superconductors.

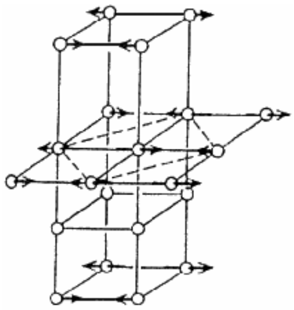

Fig. 1. Antiferromagnetic ordering of Cu atoms in a YBaCuO unit cell with indicated spins

High-temperature superconducting materials are a very promising tool for investigating this interaction of pancake-shaped vortices created in a perpendicular magnetic field and localized in individual layers. Such thin vortices interact individually with single pinning centres, while for three-dimensional low-temperature superconducting materials the flux lines are captured by many pinning centres. During current flow, the vortices tear themselves off from the pinning centres and start to move. This movement of an array of vortices, realized initially in the flux creep, and for higher currents in the flux flow process, leads to the appearance of resistivity. For low vortex velocities, the Bardeen–Stephen model [1] can be used, in which the resistivity of the flux flow motion is connected with various transition times between the normal and superconducting electrons forming Cooper's pairs, and with the inverse of this process, thus leading to the damping of the movement of vortices and to the appearance of viscosity.

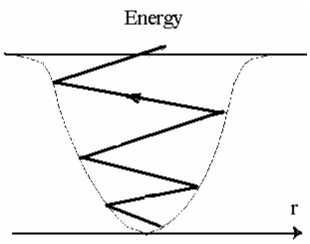

Fig. 2. The Andreev reflections of a quasi-electron in a vortex core during a rapid flux flow process

For larger currents, the quasi-stationary vortex motion changes into a dynamic one, in which electrons from the vortex core are subjected to frequent Andreev's reflections at the boundary of the core, as presented in Fig. 2. Electrons are then converted into holes, while their energy continuously increases in each reflection process.

Finally, part of the quasiparticles leave the vortex core, which collapses, while its viscosity decreases. This effect, described in the Larkin–Ovchinnikov model [2], leads to the instability of current–voltage characteristics, recently observed experimentally in the Ce-doped $Nd_{2-x}Ce_xCuO_y$ high-temperature superconductor [3].

2. The influence of the pinning interaction on vortex dynamics

Two-dimensional vortices generated in the layered cuprate superconductors in a perpendicular magnetic field are localised in the individual CuO_2 planes, shown in Fig. 1 and are therefore called pancake vortices. The magnetic quantised flux is localized in the base layer, generating circulating currents at distances in the range of the penetration depth. In the surrounding planes, this magnetic flux is screened by induced currents, having therefore opposite direction. This indicates that if the direction of the screening currents is taken into account, pancake vortices in the same plane repel each other, while those in opposite planes attract each other. Therefore, the total electric current flowing in a layered high-temperature superconductor in a perpendicular magnetic field is superposition of the currents generated by individual pancake vortices localized in the surrounding CuO_2 planes.

In the present chapter, the vortex dynamics of high-temperature oxide superconductors is investigated in the framework of the flux creep model, which precedes the flux flow process presented previously. The flux creep effect appears in real HTc superconductors with the inclusion of normal phase precipitations for instance, which act as pinning centres. According to scanning microscopy results and the applied bending strain process, the existence of flat pinning centres has been considered which can arise during the winding procedure of HTc windings from superconducting tapes, in the process of constructing superconducting electromagnets, among others. Micro-cracks, edge dislocations, and other mechanical defects of the flat geometrical shape then appear. They diminish the tape cross-section, which is a dominant effect decreasing the critical current, as well as insert additional pinning centres.

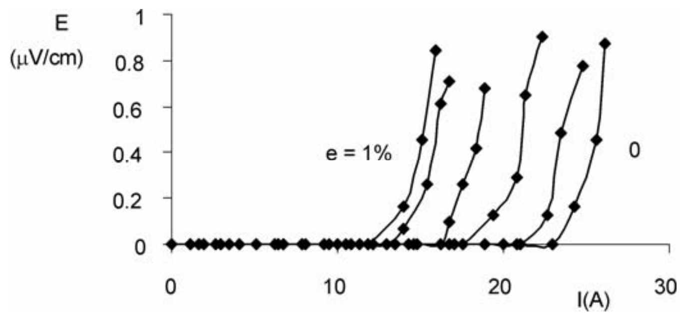

Fig. 3. Experimental results of measurements at 77 K of the current–voltage characteristics for HTc BiSCCO tape versus bending strain e in per cents (from the right side e = 0, 0.2, 0.4, 0.6, 0.8, 1)

The experimentally observed influence of defects on current–voltage characteristics for HTc superconducting tape is shown in Fig. 3. The figure presents the influence of the bending strain creating mechanical defects on the current–voltage characteristics of BiSrCaCuO tape. Measurements were performed at liquid nitrogen temperature, while the tape was directly immersed into a cryostat filled with liquid nitrogen. The tape-mounting part of an experimental sample holder, which introduces the desired bending strain, is shown in Fig. 4.

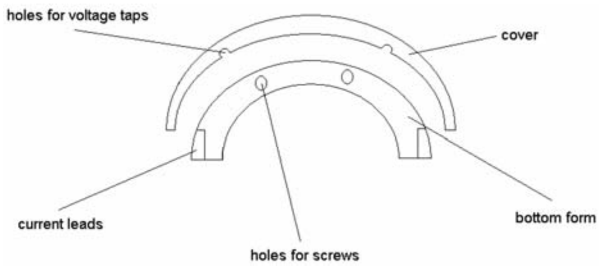

Fig. 4. View of the experimental setup for mounting the sample
for measuring the influence of the bending strain on the critical current

A bending strain, defined as:

$$e = \frac{t}{D} \tag{1}$$

was applied up to 1% by mounting the tape between various dies – upper and bottom ones with changing radii ($D/2$), while t = 0.27 mm is the tape thickness. The tape width was equal to 3.7 mm. Not too high values of the critical current may be connected with the fact that the measurements (Fig. 3) were performed applying a rectified, non-smoothed current. Complementary investigations performed using a stabilized DC power supply really indicated larger values of the critical current. A decrease in the critical current during the bending procedure is, however, apparent. A certain concentration of defects was introduced into the tape during the technological process, because otherwise the vortex structure could not be anchored and the critical current would disappear. The bending strain inserts additional defects of the micro-crack kind. These defects reduce the superconductor cross-section and, on the other hand, create pinning centres interacting with vortices and thus stimulating current enhancement. In the investigated case, the vortices can be generated both by a weak external magnetic field and as the result of the current magnetic self-induced field. It is assumed in the present paper that in the middle of the regular vortex array a flat pinning centre is placed, whose interaction with the vortices is considered. The anisotropy of this interaction is connected with anisotropic values of the coherence length, determining the vortex core shape in the layered superconductors. The approximation of nearest neighbour interaction between vortices in the layer was assumed. Similar nearest neighbour vortices have been taken into account in the subsequent planes. This is a novel approach, since usually current–voltage characteristics are analysed in terms of the power law approximation [4], which is, in fact, a purely technical approach neglecting most of the physical phenomena that occur.

Analysing the nonequilibrium distribution of the vortices, whose gradient is determined by Maxwell's equations, the magnitude of the transport current and the shape of the current–voltage characteristics generated in the flux creep process for a flat geometry of the pinning centres has been elaborated. The initial arrangement of pancake-type vortices was considered in a square lattice in each layer, while with an increase in the transport current the vortices in the lower part of the array are shifted towards each other, decreasing the distance between them, shown by the black points in Fig. 10. The superposition of currents surrounding them, including the induced screening currents from vortices in neighbouring planes, determines the total transport current amplitude. In the calculation, real BiSCCO tape parameters, such as geometrical dimensions, critical temperature, critical magnetic field, coherence length, penetration depth, and others, were used.

3. Theoretical analysis

The influence of magnetic vortex anisotropy and interplane interaction on the current–voltage characteristics and the critical current of HTc oxide superconductors was analytically investigated according to the model presented above. The case of an elliptic vortex core was considered, assuming anisotropic values of the coherence length in a dependence on the direction:

$$y = \pm \xi_b \sqrt{1 - \left(\frac{x}{\xi_a}\right)^2} \tag{2}$$

The enhancement of the free energy of the superconductor in this geometrical approach during the movement captured by the flat pinning centre vortex, at a distance x from the equilibrium position, as shown in Fig. 5, is equal to:

$$U = \frac{\mu_0 H_c^2 \xi_b l}{2\xi_a}\left(x\sqrt{\xi_a^2 - x^2} + \xi_a^2 \arcsin\frac{x}{\xi_a}\right) - \frac{\pi\mu_0 H_c^2 \xi_b \xi_a l}{4} \tag{3}$$

where l is the thickness of the pinning centre, corresponding to the thickness of the CuO_2 layer. The force of the pinning interaction, determined by the gradient of energy as described by Eq. (3), is then given as:

$$F = -\mu_0 H_c^2 \xi_b l \sqrt{1 - \left(\frac{x}{\xi_a}\right)^2} \tag{4}$$

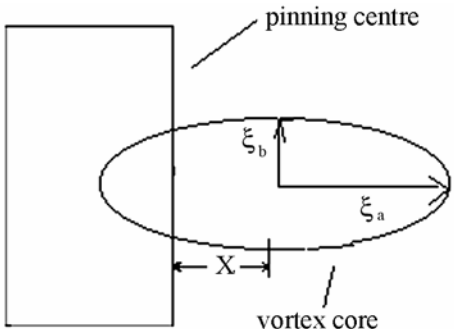

Fig. 5. A view of the investigated geometry of the anisotropic vortex interaction with a pinning centre

The energy barrier is obtained by taking into account the potential related to the Lorentz force:

$$\Delta U(x) = \xi_a \xi_b l \left(\frac{\mu_0 H_c^2}{2\xi_a^2} \left(x\sqrt{\xi_a^2 - x^2} + \xi_a^2 \arcsin \frac{x}{\xi_a} \right) - \pi j B x \right) \tag{5}$$

Vanishing of the derivative from this potential indicates the position x_1, for which the potential barrier is maximal. The potential barrier height is therefore:

$$\Delta U(i) = \xi_a \xi_b l \frac{\mu_0 H_c^2}{2} \left(-\arcsin i - i\sqrt{1-i^2} + \frac{\pi}{2} \right) \tag{6}$$

where the notation $i = j/j_c$ has been introduced. The parameter j_c is defined for individual pinning centres as:

$$j_c = \frac{\mu_0 H_c^2}{B\pi \xi_a} \tag{7}$$

and has the physical meaning of the critical current density, since for $j = j_c$ the energy barrier in Eq. (6) vanishes. Inserting the potential barrier height into the constitutive equation describing the electric field generated in the flux creep process [5], we determine the shape of the current–voltage characteristics for various values of the coherence length anisotropy ξ_a/ξ_b in a fixed magnetic field and temperature. For better visualizing the influence of anisotropy, calculations were performed for a fixed perpendicular cross-section of the vortex core, namely when $\xi_a \times \xi_b$ = const. The results shown in Fig. 6 indicate that anisotropy can lead to a decrease of the critical current. Figure 7, presenting the influence of the anisotropy effects on the dependence of transport current on the potential barrier height, confirms this finding.

Equation (6) describes the case of a fully homogeneous sample, for which the critical current density j_c is constant at each point of the HTc superconductor. As we should expect, however, a real superconductor with pinning centres is characterized by inhomogeneity, causing the scattering of its cross-section and a local critical current density. This has been taken into account by considering a statistical deviation of the local reduced current density $i = j/j_c$ by a value Δi with respect to the average one. The average value of the potential barrier height ΔU has then been approximated by the relation:

$$\Delta \overset{\frown}{U}(i,\Delta i) = \frac{1}{\Delta i}\int_{i}^{i+\Delta i} \Delta U(i)\,di = \frac{\mu_0 H_c^2 l \xi_a \xi_b}{2\Delta i}\int_{i}^{i+\Delta i}\left(-\arcsin i + \frac{\pi}{2} - i\sqrt{1-i^2}\right)di \quad (8)$$

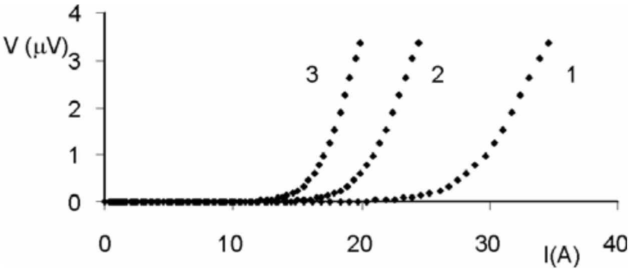

Fig. 6. Influence of the anisotropy of the vortex core shape on the current–voltage characteristics of the HTc superconductors:
1 – $\xi_a/\xi_b = 1$; 2 – $\xi_a/\xi_b = 2$; 3 – $\xi_a/\xi_b = 3$ at $T = 3$ K, $B = 2$ T

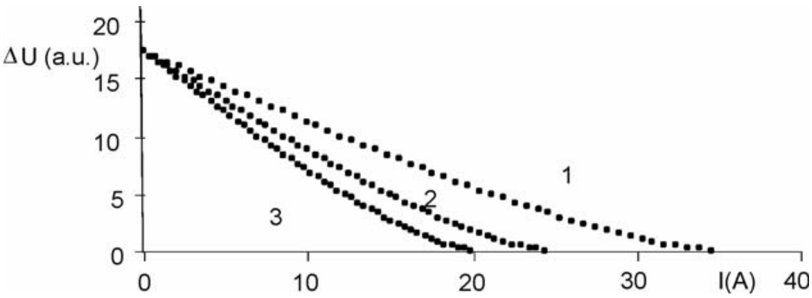

Fig. 7. Influence of the anisotropy of the vortex core shape on the pinning potential barrier of the HTc superconductor in reduced units:
1 – $\xi_a/\xi_b = 1$, 2 – $\xi_a/\xi_b = 2$, 3 – $\xi_a/\xi_b = 3$ at $T = 3$ K, $B = 2$ T

If we use the integral relation:

$$\int \arcsin\frac{x}{a}dx = x\arcsin\frac{x}{a} + \sqrt{a^2 - x^2} \quad (9)$$

then the final expression for the potential barrier height in the presence of sample inhomogeneity is obtained in the form:

$$\Delta\bar{U} = \frac{\mu_0 H_c^2 l \xi_a \xi_b}{2\Delta i}\left(i \arcsin i + \frac{\sqrt{1-i^2}}{3}(2+i^2) - i' \arcsin i' + \frac{\pi \Delta i}{2} - \frac{\sqrt{1-i'^2}}{3}(2+i'^2) \right) \quad (10)$$

where we have introduced the notation: $i' = i + \Delta i$. The parameter Δi in this model is related to the magnitude of the inhomogeneity of material, which for clean materials should be much lower than 1. The results of numerical calculations of the current –voltage characteristics versus magnetic field for $\Delta i = 0.1$ and 0.2 are shown in Fig. 8 for an anisotropy ratio $\xi_a/\xi_b = 2$, indicating the way the sample inhomogeneity influences the *I–V* curves. The values of other parameters used in calculations are given in the diagrams. The material inhomogeneity can be connected with the existence of high concentrations of mechanical defects, acting as pinning centres, and thus reducing the superconductor volume of the sample and leading to the decrease of the average total critical current density. Equation 7 describes the critical current density in the case of a single pinning centre, and is later modified by taking into account the decrease of the superconducting tape cross-section connected with the existence of microcracks.

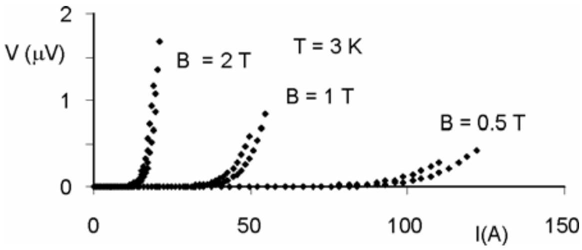

Fig. 8. Influence of the material inhomogeneity, expressed by the parameter $\Delta i = 0.1$ (right) and $\Delta i = 0.2$ (left curve) on the current–voltage characteristics as the function of the magnetic field for HTc superconductor for an anisotropic case $\xi_a/\xi_b = 2$

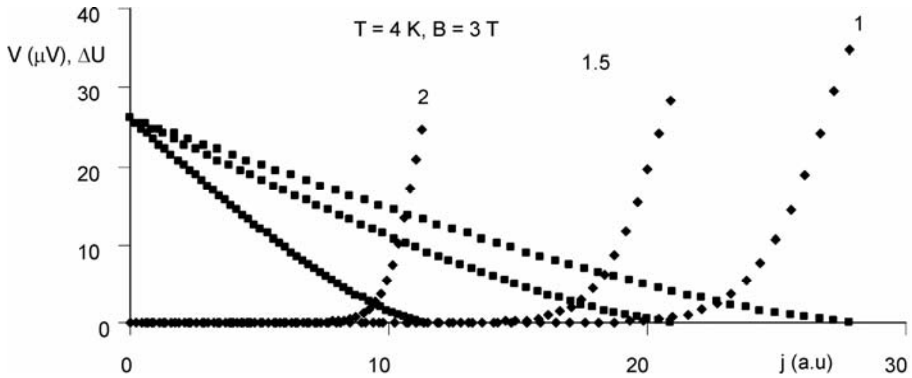

Fig. 9. Influence of the surface pinning centres concentration (in units of 10^{17} m^{-2}) on the current –voltage characteristics and potential barrier height Δ in reduced units for an anisotropic case $\xi_a/\xi_b = 2$

The results of calculations of the influence defects concentration on the current –voltage characteristics and potential barrier height for an anisotropy in the range

$\xi_a/\xi_b = 2$ are shown in Fig. 9. The calculated decrease of the critical current with pinning centre concentration for high defect concentrations, leading to the modification of Eq. (7), is in a good qualitative agreement with the experimental results presented in Fig. 3. From the layered structure of HTc superconductors the surface concentration of pinning centres is determined, giving the number of pinning centres per unit surface of the layer.

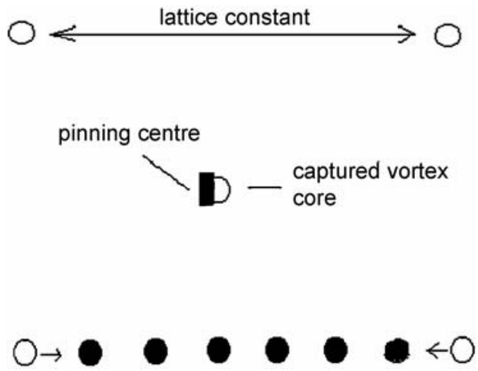

Fig. 10. A schematic view of the vortices movement caused by an increase in the transport current: • indicates the subsequent positions of the nearest vortices around the captured vortex as the function of the current amplitude, the arrows denote direction of motion

The parameter j describes the total current density at the vortex position, which is therefore a superposition of the currents generated by other vortices from the same plane as well as from the surrounding ones. For simplifying the numerical calculations, the nearest neighbour interaction approximation was applied in which it was assumed that the current density at the position of the investigated pinned vortex is a superposition of the screening currents from the nearest vortices. Figure 10 illustrates the geometry mentioned above. An increase in the transport current, according to the Maxwell's equation, leads to the appearance of a magnetic induction gradient, obtained by the shift of vortex positions, and is indicated by the arrows within the nearest neighbouring vortices approximation. The critical current in this model is determined by the condition that the distance between the nearest vortices is in the range of the coherence length, which means that cores occupying two nearest points in the applied partition of the vortex position lattice start to overlap. The same assumption was made for describing the movement of the nearest vortices in the surrounding planes. The flux in the vortices from the surrounding planes generates screening currents in the central plane. The magnitude of these screening currents is inversely proportional to the distance between a given plane and the pinned vortex, while the number of planes interacting in this way is denoted in Figs. 11 and 12 by the symbol k. The expression for the current in pancake vortices was assumed basing on the data for the magnetic induction profile in these vortices [6]:

$$B(r) = \frac{s\Phi_0}{4\pi\lambda^2 r}\exp\left(-\frac{r}{\lambda}\right) \tag{11}$$

Then the current distribution obtained from Maxwell's equation is given by the relation:

$$j_\theta(r) = \frac{s\Phi_0}{4\pi\lambda^2 r}\exp\left(-\frac{r}{\lambda}\right)\left(\frac{1}{r}+\frac{1}{\lambda}\right) \tag{12}$$

where s is the distance between the superconducting layers. The results of calculations of the current–voltage characteristics and potential barrier height versus transport current in a single layer, taking into account interlayer interaction, are shown in Figs. 11 and 12, and indicate the importance of this interaction.

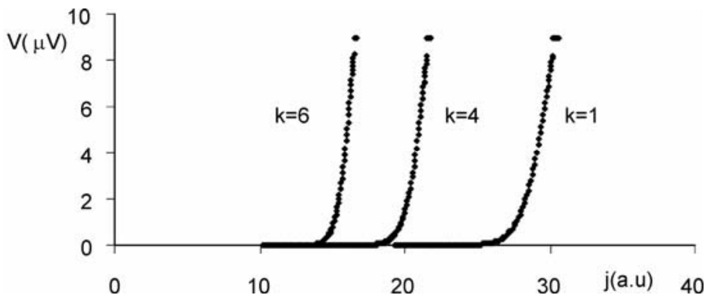

Fig. 11. Influence of the interlayer interaction on the current–voltage characteristics for the HTc superconductor at $T = 40$ K, $B = 0.5$ T. The parameter k determines the number of the interacting CuO_2 planes containing pancake vortices

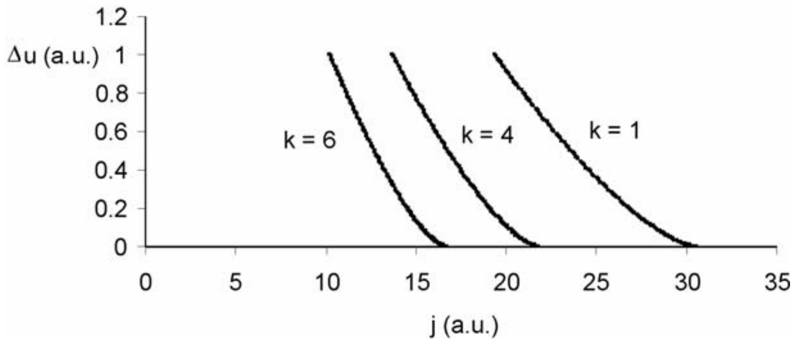

Fig. 12. Influence of the interlayer interaction on the pinning energy barrier for a HTc superconductor at $T = 40$ K, $B = 0.5$ T. The parameter k determines the number of the interacting CuO_2 planes with pancake vortices

In principle, the elastic energy of vortices should also be taken into account in these considerations. From the elastic properties of the vortex lattice the pinning centres acting on the fluxons enhance the energy of the system by moving vortices from their equilibrium position by a distance x. This leads to an increase in the vortex elastic energy, which is described now by the formula:

$$U_{\mathrm{el}} = \alpha\left(x-\xi_{\alpha}\right)^{2} \tag{13}$$

where the parameter α includes the elasticity shear modulus c_s. The results of calculations of the influence of the parameter α on the critical current density, as a function of the magnetic field, are shown in Fig. 13.

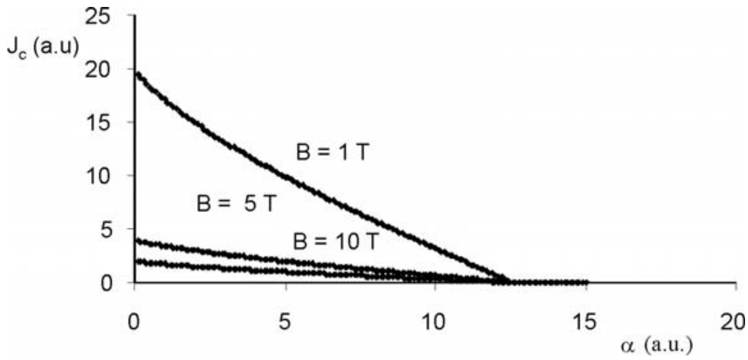

Fig. 13. Influence of the elastic vortex lattice energy described by the parameter α on the local critical current density as the function of the applied magnetic field for $T = 1$ K

4. Final remarks

This paper discusses the dynamics of vortex motion in HTc superconductors. The cases of low and high vortex velocity in the flux flow process have been considered in layered superconductors. The flux creep effect was investigated in the pinned HTc BiSrCaCuO material taking into account the anisotropy of the material parameters and their inhomogeneity, as well as the interaction between vortices in surrounding layers within a nearest-neighbour proximity.

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