Ferromagnetic nanoparticles as efficient bulk pinning centers in HTSC

V A Kashurnikov¹, A N Maksimova¹ and I A Rudnev¹,²
¹National Research Nuclear University, Moscow Russia
²International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw Poland

Abstract. The self-consistent interaction of Abrikosov vortex with both point and extended ferromagnetic defects was taken into account in the 2D model of layered HTSC. Magnetization curves for HTSC with magnetic nanoparticles as bulk pinning centers were obtained by Monte-Carlo method. The nonlinearity of the interaction of the superconductor with ferromagnetic defects and irreversibility of initially reversible magnetization processes due to nonlinearity were demonstrated.

1. Introduction

The effect of ferromagnetism on the superconducting state attracted considerable attention in recent years. Ferromagnetic impurities in high-temperature and low-temperature superconductors were investigated to improve current-carrying ability, and the interaction of ferromagnetic phases with superconductivity has been used for solve the problem of the coexistence of superconductivity and ferromagnetism in a mixed vortex state. An enhancement of vortex pinning by a magnetic nanoparticle is expected due to an energy of particle’s magnetic moment in the field of vortex in addition to conventional, nonmagnetic part of interaction.

For example, Fe particles in Hg-13%In were investigated and the magnetization curves were obtained for the parallel and antiparallel direct ions of the residual magnetization of the impurities and the external field [1]. The enhancement of vortex pinning with an increase of the impurity concentration was demonstrated. The interaction of a vortex with a ferromagnetic particle was described theoretically as an energy of point dipole in the field at the particle produced by vortex. The force of interaction of a single vortex line with a spherical magnetic nanoparticle of arbitrary radius was calculated [2]. Analysis of the behavior of ferromagnetic Gd in Nb [3] showed that the pinning force is due to the hysteretic loss for magnetization reversal.

A considerable part of investigations were associated with the vortex structures appearing in thin superconductor films in the vicinity of ferromagnetic nanoparticles. The enhancement of pinning of vortices in a thin film with ferromagnetic nanodots was detected experimentally, various configurations of one, two or three vortices around a magnetic dot were observed [4], the structures formed by vortices around magnetic dipole were investigated numerically [5].

Thus, analysis of the interaction of the vortex state with the ferromagnetic phase and correct estimation of the influence of its magnetic moment on the vortex dynamics in the superconductor is one of the important problems of superconductivity, it is especially important for an HTSC material due to its high critical parameters.

The aim of this paper is a correct description of magnetic particles and a superconductor as a self-consistent system and an exact calculation of magnetization reversal processes in a layered HTSC material with ferromagnetic nanoparticles as bulk pinning centers. Here, we represent the results of calculation of the magnetization reversal loops by using the Monte-Carlo method. Orientation of ferromagnetic nanoparticles’ easy axes and values of magnetic anisotropy parameter were taken into account, the case of periodic lattice of elongated ferromagnetic defects was also analyzed.
2. Model

To calculate an equilibrium distribution of vortices, we numerically minimized the Gibbs thermodynamic potential of the 2D vortex system with a varying number of pancake vortices; this potential has the form (see [6,7], where the model and the algorithm are described in details):

\[
G = sN \varepsilon + \sum_{i,j} U_{\text{in-plane}}(r_{ij}) + s \sum_{i,j} U_{p}(r_{ij}) + \sum_{i,j} U_{\text{surf}}(r_{ij}^{\text{lim}}),
\]

where \( \varepsilon \) is a self-energy of vortex, \( s \) is a thickness of a superconducting layer and \( N \) is the number of vortices in the system, the second term describes pair interaction of vortices, the third term takes into account the interaction of vortices with pinning centers and the fourth term describes the interaction of vortices with the surface and the external field. Pancakes in a plane interact with the long-range potential in the following form:

\[
U_{\text{in-plane}}(r_{ij}) = s \frac{\Phi_0^2}{8\pi^2 \lambda^2} K_0 \left( \frac{r_{ij}}{\lambda} \right),
\]

where \( r_{ij} \) is a distance between vortices and \( \lambda = \lambda(T) = \lambda(T=0)/\sqrt{1-(T/T_c)^{1.3}} \) is the magnetic field penetration depth, \( K_0(x) \) is a Bessel function and \( T_c \) is a superconducting critical temperature.

Then we take into account an ensemble of ferromagnetic nanoparticles in the bulk of superconductor. Gibbs potential of the ferromagnetic particle has a form:

\[
U_p = U + U_{\text{pn}} + U_{\text{pm}}, \quad U_{\text{pm}} = -\mu H_v,
\]

where \( \mu \) is the projection of the magnetic moment onto the direction of the external field, \( H_v \) is the field produced by the vortex at the point of location of the particle. In our calculations, we choose \( \mu \approx 10^3 \mu_0 \cdot U_{\text{pm}} \) is the nonmagnetic part of the interaction, \( U \) is a part of particle’s energy, not associated with vortices. Ferromagnetic defects may be represented as an assembly of magnetic moments with fixed absolute value. For each magnetic moment,

\[
U = KV \sin^2(\varphi - \theta) - \mu H_{\text{M}} \cos \varphi,
\]

where \( \theta \) is the angle between the easy axis and the external magnetic field, \( \varphi \) is the angle between the particle magnetic moment and the external field, \( KV \) term represents the energy of magnetic anisotropy [8], \( H_{\text{M}} \) is the magnetic field by Meissner current. In an assembly of ferromagnetic nanoparticles, the elementary process of a change in the magnetization is the rotation of the magnetic moment of a particle. Figure 1 represents the calculated magnetization loops of such an assembly at different values of \( \theta \): \( \theta = 0 \) (easy axes parallel to an external field), \( \theta = \pi / 2 \) (perpendicular), and the last curve is for the case of ferromagnetic nanoparticles with randomly oriented easy axes.

![Figure 1. The magnetization loops for ferromagnetic nanoparticles magnetized with an external field with different easy axes orientation.](image-url)
3. Calculation results
Consider now the magnetization process for the case of ferromagnetic particles randomly distributed in the bulk of the superconductor. The magnetization data for HTSC sample and ferromagnetic nanoparticles are replotted in figures 2 and 3. As shown in figure 2, the magnetization loop for the particles with easy axes parallel to an external field in HTSC is wider than the same curve for isolated particles, and in figure 3 (easy axes perpendicular to an external field) an initially reversible magnetization process becomes irreversible for particles in HTSC. This effect is due to the nonlinearity of the interaction of the superconductor with ferromagnetic defects (see figure 4): the value of magnetic field at the location of each particle is $n\Phi_0$ ($n$ is vortex concentration), which does not coincide with the value of an external field.

Figure 2. Magnetization curves for the case of particles’ easy axes are parallel to the external field. Inset: magnetization curves for nanoparticles only. $T=10K$, particles’ concentration everywhere $c = 1.1 \cdot 10^6 cm^{-2}$.

Figure 3. Magnetization curves for the case of particles’ easy axis are perpendicular to the external field. Inset: magnetization curves for nanoparticles in SC. $K$ value is given in units of $\Phi_0^2/(4\pi\lambda)^2$. $T=10K$.

Figure 4. Nonlinear interaction of a ferromagnet with a superconductor: the magnetization curves for nanoparticles only and a pure superconductor (inset) and comparison of the result of exact calculation for superconductor with ferromagnetic defects with the magnetization loop obtained by direct summation of the curves in the inset.

Consider now a periodic lattice of extended ferromagnetic defects. In our calculations, an extended defect is represented as a cluster of isolated magnetic moments, the distance between moments in the cluster is $\sim \lambda$. The results of calculations for the case of elongated defects are parallel and perpendicular to the direction of vortex entrance, are represented in figure 5. As shown, the linear size of defect does not influence on the magnitude of remanent magnetization in the parallel case and strongly influence on the remanent magnetization in the perpendicular case (see inset in figure 5). There is also a peak near $H_{c1}$ on the curve for perpendicular case. Both effects are due to so-called...
screening of regions near surface [9, 10]. Magnetic flux, pinned on elongated defects, does not let next vortices enter the sample.

Interaction between magnetic moments is strong enough only for particles in the same cluster, when distance between particles is less than $\lambda$ and we may disregard screening effects. The interaction energy is assumed to be an interaction energy between two point dipoles and reads:

$$U_{\text{int}} = -\frac{\mu_1 \mu_2}{R_0^3} \left[ 2 \sin \varphi_1 \sin \varphi_2 - \cos \varphi_1 \cos \varphi_2 \right]$$

(5)

where $\varphi_1$ and $\varphi_2$ are the angles between magnetic moment dipoles $\mu_1$ and $\mu_2$ and an external field. The magnetization data for clusters of ferromagnetic nanoparticles are shown in figure 6.

Figure 5. Magnetization curves for HTSC with elongated magnetic defects with fixed distance $d_x$ between magnetic moments in cluster. Inset: dependence of residual magnetization on the $d_x$ value.

Figure 6. Magnetization curves for ferromagnetic nanoparticles with interaction.

4. Conclusion

In summary, the magnetization reversal loops of 2D layered HTSC were calculated by Monte-Carlo method for both point and extended ferromagnetic defects. Orientation of ferromagnetic nanoparticles’ easy axes and interaction between magnetic moments in extended defect were taken into account. It was shown, that interaction between magnetic moments within extended defect decreases the area of magnetization loop, coercive force and, therefore, hysteresis energy losses.

Acknowledgements

The work was supported by RFBR, Grant 12-02-00561.

[1] Alden T H, Livingston J D 1996 J. Appl. Phys. 37 3551
[2] Snezhko A, Prozorov T, Prozorov R 2005 Phys. Rev. B: Condens. Matter 71 024527
[3] Palau A, Parvaneh H, Stelmashenko N A et al 2007 Phys. Rev. Lett. 98 117003
[4] Shapoval T, Metlushko V, Wolf M, Holzapfel B et al 2010 Phys. Rev. B: Condens. Matter 81 092505
[5] Milosevic M V, Yampolskii S V, Peeters F M 2002 Phys. Rev. B: Condens. Matter 66 174519
[6] Lawrence W E, Doniach S 1970 in Proceedings of LT 12 ed E Kanda, p 361
[7] Kashurnikov V A, Rudnev I A, Gracheva M E, Nikitenko O A 2000 JETP 90 (1) 173
[8] Prozorov R, Yeshurun Y, Prozorov T, Gedanken A 1999 Phys. Rev. B 59 6956
[9] Zyubin M V, Rudnev I A, Kashurnikov V A 2003 JETP 96 (6) 1065
[10] Kashurnikov V A, Rudnev I A, Zyubin M V Supercond. Sci. and Techn. 2001 14(9) 695