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Vortex–antivortex annihilation in mesoscopic superconductors with a central pinning center

R. Zadorosny [a,*], E.C.S. Duarte [a], E. Sardella [b,c], W.A. Ortiz [d]

[a] Grupo de Desenvolvimento e Aplicações de Materiais, Faculdade de Engenharia, Univ Estadual Paulista – Unesp, Departamento de Física e Química, Caixa Postal 31, 15385-000 Ilha Solteira, SP, Brazil

[b] Faculdade de Ciências, Univ Estadual Paulista – Unesp, Departamento de Física, Caixa Postal 473, 17033-360 Bauru, SP, Brazil

[c] Univ Estadual Paulista – Unesp, Instituto de Pesquisas Metereológicas – IPMet, CEP 17048-699 Bauru, SP, Brazil

[d] Departamento de Física, Universidade Federal de São Carlos – UFSCar, Caixa Postal 676, 13565-905 São Carlos, SP, Brazil

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ABSTRACT

In this work we solved the time-dependent Ginzburg–Landau equations, TDGL, to simulate two superconducting systems with different lateral sizes and with an antidot inserted in the center. Then, by cycling the external magnetic field, the creation and annihilation dynamics of a vortex–antivortex pair was studied as well as the range of temperatures for which such processes could occur. We verified that in the annihilation process both vortex and antivortex acquire an elongated format while an accelerated motion takes place.

1. Introduction

A variety of exotic behaviors which arise from confinement effects in superconducting materials have been extensively studied both for type I [1–3] and type II [4–24] superconductors. Particularly, the penetration and propagation of vortices in superconducting materials are issues of great interest both from the theoretical point of view and in applications of these materials. In general, a vortex interacts with the surface of the sample and, after surpassing it; with other vortices, which can already have penetrated the sample; as well as with defects that might be present. Thus, trapping or controlling the motion of the vortices [25] avoid dissipation on the material, as a consequence, the critical current density, J_c, and the upper critical field, H_{c2}, can be increased.

Recently Kapra and coworkers [26] studied the vortex–antivortex motion in materials with an array of magnetic bars. It was demonstrated that, depending on the arrangements and the intensity of the magnetization of such bars, vortices and antivortices annihilates each other which causes an increase of the critical current. These kind of studies could be applicable in devices for flux manipulation. In this point of view, the knowledge of the dynamics vortex–antivortex, V–AV, annihilation is a good issue to analyze. In this interim, Misko and coworkers [3] studied the stabilization of vortex–antivortex molecules in infinity cylinders with a triangular mesoscopic cross section of a type I superconductor. In another work, Sardella et al. [27] studied the annihilation process of a V–AV pair in a square mesoscopic system with a centered square antidot, AD. As described there, the average velocity of the vortex presents distinct values for different processes, i.e., while entering, its velocity is of the order of 10^3 m/s whereas in the annihilation motion the average velocity is of the order of 10^5 m/s.

Thus, in the present work we used the TDGL equations to study, in two systems, the temperature range for which a V–AV pair should occur in the superconductor region. Such systems are infinitely long cylinders of square cross section. A square AD with lateral size of $2\xi(0)$ was inserted in the center of the system. To be far from a possible stabilization of a V–AV pair, as described in Ref. [3], we choose $\kappa = 5$. This value is equivalent of that presented by Pb-In samples [28]. The creation of a V–AV pair was done by cycling the magnetic field which was applied parallel to the axis of the cylinder. The field was increased until at least one vortex was trapped in the AD, and then decreased and reversed. In such process, a vortex is trapped in the AD and, upon decrease of the field, one of the following three events could occur, depending on the value of the temperature and the lateral size of the sample: (i) an antivortex

* Corresponding author. Tel.: +55 18 37431903.
E-mail addresses: rafazad@yahoo.com.br, rafazad@dfq.feis.unesp.br (R. Zadorosny).

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penetrates the sample and the annihilation occurs in the AD; (ii) the vortex leaves the AD and the annihilation occurs in the superconducting region, and (iii) the vortex is untied and then leaves the sample. In this work we have studied the conditions under which event (ii) can occur, and analyze the dynamics of the annihilation process. It is interesting to note that, even when the effective superconducting region has the same size of the vortex core, i.e, $d = 2\xi(0)$, a V–AV pair is formed and an annihilation process takes place.

The outline of this work is as follows. First, in Section 2, we provide an overview of the theoretical formalism used to run the simulations. Next, in Section 3 we discuss some results obtained for two systems with lateral sizes of $L = 6\xi(0)$ and $L = 12\xi(0)$ and in Section 4 we present our conclusions.

2. Theoretical formalism

The superconducting state is described by the Ginzburg–Landau theory through a complex order parameter ψ for which $|\psi|^2$ represents the density of Cooper pairs. In regions where $|\psi|^2$ is small, the superconductivity is suppressed. At the core of a vortex, $|\psi|^2 = 0$, whereas the local magnetic field h is maximum. To determine h and ψ, the time dependent Ginzburg–Landau equations, TDGL, were used:

$$\left(\frac{\partial}{\partial t} + i\Phi\right)\psi = -(-i\nabla - \mathbf{A})^2\psi + (1-T)\psi(1-|\psi|^2),$$

$$\beta\left(\frac{\partial \mathbf{A}}{\partial t} + \nabla\Phi\right) = \mathbf{J}_s - \kappa^2\nabla\times\mathbf{h}, \quad (1)$$

where the supercurrent density is given by

$$\mathbf{J}_s = (1-T)\Re[\psi^*(-i\nabla - \mathbf{A})\psi], \quad (2)$$

$\mathbf{A}$ is the vector potential which is related to the local magnetic field as $\mathbf{h} = \nabla\times\mathbf{A}$, and Φ is the scalar potential. As we have worked with the normalized TDGL equations, the distances are measured in units of the coherence length at zero temperature $\xi(0)$; the magnetic field is in units of the zero temperature upper critical field $H_{c2}(0)$; the temperature T is in units of the critical temperature T_c; the time is in units of the characteristic time $t_0 = \pi\hbar/8k_BT_c$; κ is the Ginzburg–Landau parameter; β is the relaxation time of $\mathbf{A}$, related to the electrical conductivity. We have adopted, for the upper critical field, a linear dependence with respect to temperature, i.e., $H_{c2}(T) = H_{c2}(0)(1-T)$. For small size superconductors this is also valid for temperatures well below T_c, despite the microscopic derivation of the TDGL equations being valid only for T very close to T_c [29,30]. Notice that the TDGL equations [31] are gauge invariant under the transformations $\psi' = \psi e^{i\chi}$, $\mathbf{A}' = \mathbf{A} + \nabla\chi$, $\Phi' = \Phi - \partial\chi/\partial t$. Thus, in particular, we choose the zero-scalar potential gauge, that is, $\Phi = 0$ at all times and positions.

3. Results and discussion

The simulations were carried out by using $\beta = 1$ and $\kappa = 5$ for two square systems with lateral sizes $L = 6\xi(0)$ and $L = 12\xi(0)$ where a square AD of side $L = 2\xi(0)$ was inserted in the center of the system. The temperature was varied in steps $\Delta T = 0.2T_c$ and the external field in $\Delta H = 10^{-3}H_{c2}(0)$. Thus, we found the range of temperatures for which the annihilation of a V–AV pair occurs in the superconducting region. As described in Section 1 the creation of a V–AV pair was done by cycling the applied magnetic field. Thus, one of the three processes described in Section 1 could occur. Fig. 1 shows the points which delimitate the regions of the tree distinct behaviors, i.e., below the lower points, situation (i) takes place; above the higher points one has the situation (iii); and between such points, option (ii) takes place.

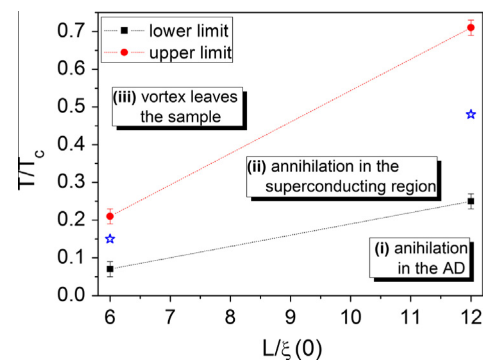

Fig. 1. Limits for the dynamics of vortex–antivortex annihilation in the superconducting region. The dashed lines are only guides for the eyes. The star symbols indicate the systems for which the annihilation dynamics was analyzed.

Fig. 2 shows a magnetization versus applied magnetic field curve, both normalized by $H_{c2}(0)$, for the simulated systems. Note that, as the superconducting region of the sample with $L = 12\xi(0)$ is greater than that for the sample with $L = 6\xi(0)$, two vortices nucleate into the sample in the first penetration, being trapped by the AD. When the field is reversed, firstly one vortex is untied from the AD and then leaves the sample. In the sequence, for negative values of the applied field, another vortex leaves the AD and a V–AV pair is created with the penetrating antivortex. Thus, the annihilation of such pair occurs in the superconducting region.

Another intriguing behavior is the formation of a V–AV pair in the smaller sample. Such sample has an effective superconducting region with width $d = 2\xi(0)$, i.e., the size of the vortex core

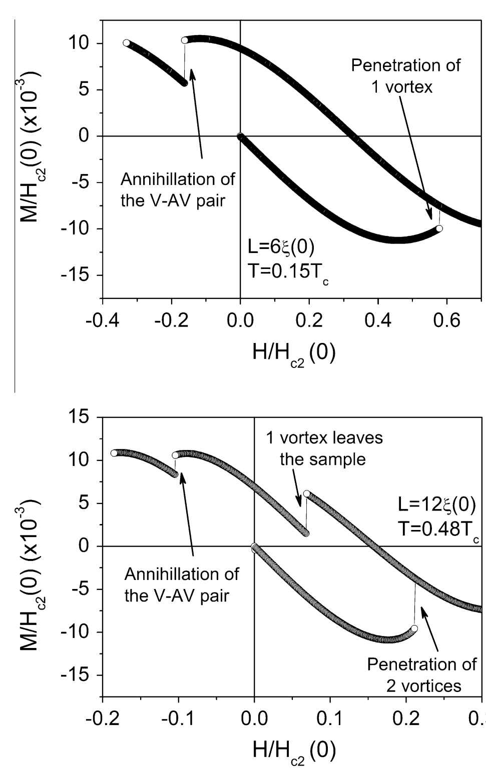

Fig. 2. Magnetization versus applied magnetic field, both normalized by H_{c2}, of the simulated systems $L = 6\xi(0)$ and $L = 12\xi(0)$. In the larger system, two vortices are nucleated in the first penetration. Then, before the annihilation of the V–AV pair, one vortex is untrapped and leaves the sample.

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