Relaxation of the remanent state in thin superconducting samples

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Abstract

We report the importance of the induction planar component \( B_y \) in the relaxation of the remanent state in thin superconducting samples. Analysis based on the one-dimensional rate equation for thermally activated flux motion, which considers only the normal component \( B_x \), yields unphysical divergence of the average flux line velocity as the neutral line is approached. Two-dimensional analysis resolves this problem and yields a modified scenario for the flux creep process in which vortex bending and the neutral line play a major role. These results are demonstrated in analysis of the local relaxation data obtained from a thin \( \text{Nd}_{1-\delta}\text{Ce}_{0.15}\text{CuO}_4 \) crystal in the remanent state.

Keywords: \( \text{Nd}_{2-\delta}\text{Sr}_x\text{CuO}_4 \); Magnetic relaxation; Neutral line

The description of flux creep in superconductors is commonly based on the assumption that the sample is infinite in the field direction (the \( z \)-axis) and that straight flux lines parallel to the field enter or exit the sample through its edges. Accordingly, analyses of magnetic relaxation data are based on the one-dimensional (1D) rate equation [1-4]:

\[
\frac{\partial B_x}{\partial t} = -\frac{\partial}{\partial x}(B_x v_x),
\]

where \( v_x \) is the average flux line velocity. For thin samples, especially in the remanent state, the assumption of straight flux lines is no longer valid and the above scenario must be modified. In this paper we analyze magnetic relaxation data for a thin \( \text{Nd}_{1-\delta}\text{Ce}_{0.15}\text{CuO}_4 \) crystal in the remanent state using a two-dimensional (2D) rate equation [5,6] which takes into account both the normal and planar components of the induction \( B \). Based on this 2D analysis, a modified scenario for the relaxation process of the remanent state is described.

The 10 \times 340 \times 1200 \, \mu\text{m}^3 \text{Nd}_{1-\delta}\text{Ce}_{0.15}\text{CuO}_4 \) crystal was in direct contact with an array of 11 miniature Hall-probes (active area of 10 \times 10 \, \mu\text{m}^2). After zero-field cooling the sample to 8 K, the magnetic field was ramped up to \( H = 1300 \, \text{Oe} \) and then turned off. The \( B_x \) profile of the remanent state was consequently measured by the Hall array every 50 s. Using the raw \( B_x(t) \) data we calculate the local electric field \( E_x = (1/c)B_x v_x \) by integrating \( \partial B_x/\partial t \) [4]. Results are shown in Fig. 1 (open circles). As expected, \( E_x \) increases with the distance \( x \) from the sample center up to the “neutral line” \(^1\) where it reaches a maximum. This calculation of \( E_x \) is valid in both the 1D and 2D analyses. The problem in the 1D approach becomes apparent when one considers the behavior of \( v_x = cE_x/B_y \), as shown in Fig. 2 (solid circles); Since \( B_y = 0 \) at the neutral line, and has different signs on both its sides, the 1D analysis yields \( v_x \rightarrow \pm \infty \) as this line is approached. This unphysical result is avoided by using a 2D version of the rate equation [5,6] as shown below.

For an infinite strip in the \( y \) direction, \( B = (B_x,0,B_y) \) and \( E_y = (1/c)(B_z v_x - B_x v_z) \), where \( v_x \) and \( v_z \) are the

\(^1\) The neutral line is defined as the contour of points in the sample for which \( B_y \) equals the external field \( H \). Thus, for the remanent state, at the neutral line \( B_y = \partial B_y/\partial t \equiv 0. \)
The spatial distributions of $v_x$ and $v_z$ are plotted in Fig. 2. Note that $v_z$ always points towards the neutral line, and $v_x$ is always directed towards the plane $z = 0$ going through half thickness of the sample ($v_z(z)$ changes sign at $z = 0$ because $B_x$ changes sign at this plane).

The above analysis clearly indicates that the relaxation of the remanent state is not associated with flux exit through the sample edges. Instead, the remanent state relaxes by collapse of closed vortex loops [8] centered at the crossing line of the neutral line and the $z = 0$ plane.

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References