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Physica C 341–348 (2000) 1217–1218

PHYSICA C

www.elsevier.nl/locate/physc

Thickness Effects on the Pinning by Columnar Defects

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We compare the angular dependence of the pinning of equivalent columnar defects in $GdBa_2Cu_3O_7$ thin films and a thicker $YBa_2Cu_3O_7$ single crystal. The tracks' related enhancement of the critical currents is much smaller for the case of the thin films. We interpret this thickness dependence as resulting from a competition between the pinning of the correlated structures, related to total sample thickness, and surface boundary conditions, which force the vortices to depin from the columnar defects near the sample surface.

The influence of the surface boundary conditions in the vortex pinning by inclined columnar defects (CD) in High T_c superconductors (HTSC) is not completely understood. Vortex currents must reach the surface parallel to it,[1] thus the vortex must leave the CD at a certain distance from the surface[2], and so the effective pinning length of a CD is shorter than its total length. Then, pinning should be smaller in thinner samples, where this surface effect involves a larger fraction of the vortex length.

To address this issue we measured the angular dependence of the irreversible magnetization (M_i) in $GdBa_2Cu_3O_7$ (GdBCO) thin films (~100nm) with CD tilted with respect to the crystallographic *c* axis; and compared the results to those of YBCO single crystals and as-grown GdBCO films. The *c*-textured films were grown by dc magnetron sputtering.[3] The CD were introduced through 300 MeV Au^{+29} ion irradiation at the TANDAR facility.[4] Measurements were done in a SQUID magnetometer equipped with a system[4] that allows to rotate the sample around an axis perpendicular to both the applied field (**H**) and the surface normal (*c*-axis). For each angle (Θ), a hysteresis loop was measured. From them, $M_i(H,\Theta)$ was determined ($\Theta = 0°$ for **H** // *c* and $\Theta = 90°$ for **H** $\perp$ *c*). The $M_i(H,\Theta)$ data can be converted into critical current density (J_c), using the critical state model.

For the as grown films at high fields we observe a broad peak (~20°) centered at the *c* axis. This is a signature of pinning by intrinsic correlated planar defects, such as twin or grain boundaries. At higher angles, $\Theta > 50°$, a monotonic increase of $J_c(\Theta)$ is observed, due to the material's anisotropy.[5]

Figure 1 shows $M_i(\Theta)$ at different fields and two temperatures, for a GdBCO thin film with CD at 60° from the *c* axis and matching field of 2T. At low temperatures, T = 35K, the broad peak at 0° related to the intrinsic planar defects is still present, as expected. An additional broad peak appears at the tracks' direction, signaling the uniaxial pinning of the CD. At higher temperatures, T = 60K, the signature of the intrinsic defects disappears while that of the CD remains. At low fields the CD-related pinning appears only as a perturbation to the angular dependence of J_c arising from anisotropy.

A comparison with the data obtained for a 4 μm thick YBCO single crystal[6] with columnar defects at a similar angle is shown in figure 2. The ion source and the matching field are the same. The difference between both samples is apparent. The peak for the crystal looks sharper and is at least a factor of 4 larger than for the film. This difference cannot be due to the different rare earth ion, since the structural and superconducting properties of YBCO and GdBCO are equivalent.[7] Also, the pinning produced by CD in *crystals* of 123 compounds with different rare earth is similar.[8] Finally, $M_i(\Theta)$ in YBCO thin films with inclined CD also exhibits a

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Work partially supported by ANPCYT PICT97_03-00061-01117, CONICET PIP 4207 and Fundación Balseiro.

0921-4534/00/$ – see front matter
PII S0921-4534(00)01118-7

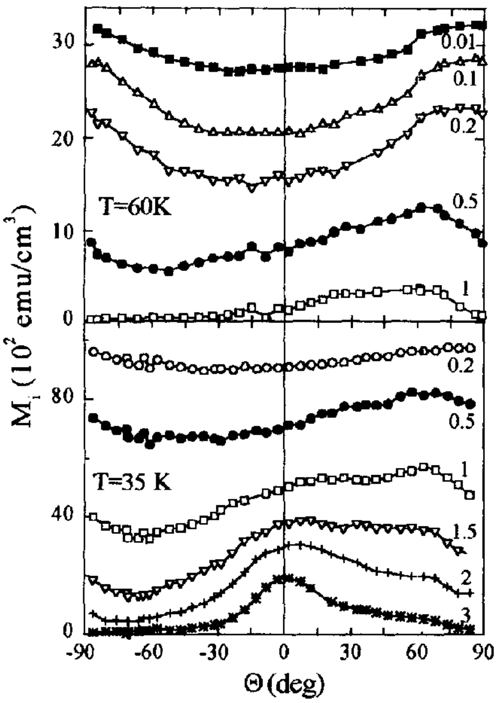

Figure 1: Angular dependence of M_i at different H and T for a 100nm thick $GdBa_2Cu_3O_7$ film with CD. The dashed line indicates the direction of the defects. The numbers indicate H in Tesla.

broad and small peak,[9] similar to our GdBCO data.

Vortex orientation in HTSC with CD is determined by the competition of several energies, as discussed in refs. 4 and 5. First, the uniaxial pinning of the CD tends to confine the vortices into the tracks. Second, the line tension decreases with Θ due to anisotropy, thus the energy decreases if vortices tilt towards the *a,b* planes. Third, shortening the vortex length reduces the elastic energy, thus vortices tend to align normal to the sample surface. Finally, the term $-\mathbf{B}.\mathbf{H}/4\pi$ is minimized if the average vortex orientation (that defines the direction of **B**) coincides with **H**. For $H \gg H_{c1}$ the last term dominates, thus **B** // **H**, and J_c maximizes for **H** // CD.

In addition to the previous *bulk* effects, we must take into account that at the sample surface the normal component of the currents must cancel, so a vortex must reach the surface perpendicularly.[1] For CD inclined with respect to the sample normal, this boundary condition pulls the vortices out of the

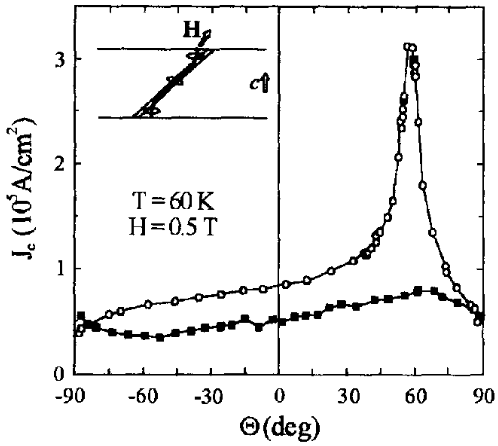

Figure 2: Effect of CD in the angular dependence of M_i for a 100 nm thick $GdBa_2Cu_3O_7$ thin film, solid squares, and a 4 μm thick $YBa_2Cu_3O_7$ single crystal, open circles. Inset: a sketch of the effect of surface boundary conditions on the vortex configuration.

tracks at both surfaces, as sketched in the inset of figure 2, reducing the effective pinning length. This reduction is more significant in thinner samples. Figure 2 provides a clear evidence of this effect, as equal distributions of CD produce widely different pinning in two samples of different thickness.

The simplest analysis suggests that the length of the depinned segment should be comparable to the penetration depth (λ), the characteristic length scale for vortex distortions. However, the fact that the uniaxial pinning by CD is still visible in the GdBCO film of thickness ~λ/2 indicates that the vortex cores remain trapped into the tracks up to a distance from the surface considerably smaller than λ. This may be due to the softening of the dispersive vortex line tension at short wavelengths in high κ materials.[5]

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