Vortex pinning in Nb bicrystals

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The critical currents of Nb bicrystals in the mixed state were investigated. Vortex pinning, which is attributable to the anisotropy of the superconducting properties of Nb, was observed at grain boundaries.

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It is customary to assume that the grain boundaries in type II superconductors are effective pinning centers; however, until now the mechanism of vortex pinning at grain boundaries has remained unclear. Most of the experiments devoted to this question have been performed on polycrystalline superconductors and the interpretation of these results has necessarily involved several factors that lend themselves poorly to analysis: the geometry of grains, the texture of the material, and the complicated summation of the individual pinning forces. Experiments with bicrystal samples, in which the interaction of the vortex system with one crystallographically defined grain boundary is investigated, are obviously the most straighforward.

In this work we chose the orientation of the boundary and the bicrystal samples in such a manner that it is possible to estimate the contribution of the anisotropy of the superconducting properties and the role of impurities in pinning at the bicrystal boundary. The dependence of the critial current I_c on the angle ϕ between the boundary plane and the direction of constant magnetic field **H** at $T = 4.2$ °K was measured. The current was transmitted along the cylindrical sample perpendicular to **H**. The samples, fabricated from large niobium bicrystals that were grown by electron-beam zone melting, had a nonsymmetrical tilt boundary, Fig. 1. Cylindrical, dumbbell-shaped samples, parallel and at right angles to the tilt axis, were cut from each bicrystal by an electric-spark method. The surface cold-worked layer was removed by chemical polishing. The samples were oxidized subsequently in the air at 300° for 10 minutes to reduce the surface pinning.[1] Cooling to nitrogen temperature was done as slowly as possible to prevent the precipitation of soft particles of Nb hydrides,[2] which pin the vortex system strongly. The described procedure made it possible to attain a critical-current level of 3–6 A/cm^2 for the criterion $E_k = 10^{-8}$ V/cm. The ratio γ of the resistances of the measured samples amounted to 200–250. The $I_c(\phi)$ dependences for bicrystals with a tilt angle $\theta = 21°$ are shown in Fig. 2. A narrow peak was observed on the angular dependence of the critical current at three sample rotation angles when the magnetic field **H** was parallel to the boundary plane (Fig. 2b), but only for samples that were cut along the tilt axis. The half-width of the peak is about 1°. In some cases we observed a splitting of the peaks on the $I_c(\phi)$ curves (see Fig. 3). This behavior of the angular dependence may be attributable, apparently, to a slight distortion of the boundary inside the sample.

In samples with those orientations, for which a peak was observed on the $I_c(\phi)$

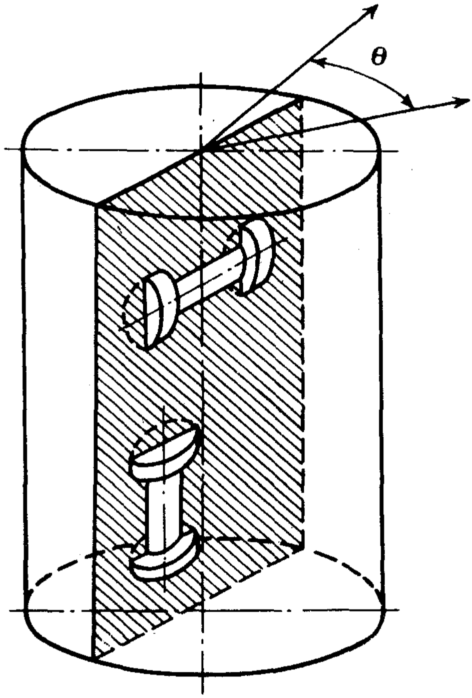

FIG. 1. Drawing illustrates fabrication of samples from large bicrystal: upper sample is cut at right angles to tilt axis and lower sample is cut along this axis. θ is the angle between the crystallographically identical directions in different parts of the crystal, i.e., the tilt angle.

curves, the magnetic-field vector parallel to the boundary plane corresponded to crystallographically different directions in different parts of the bicrystal. Such an orientation of an anisotropic superconductor indicates a presence of a discontinuity in the magnetic-field induction at the boundary of the grains. This condition is sufficient to explain the experimental results on the basis of the Dew–Hughes and Witcomb model.[3] We note that the observed dependence of I_c on the direction of the transport current is also compatible with the idea of vortex pinning by the grain boundary because of the anisotropy of the superconducting properties, such as H_{c_2}, of the material. Thus, in the Mkrtchyan and Shmidt theory, which was constructed for materials with a large κ,[4] the potential well for vortices at the grain boundary can have different wall steepness.

In the only work known to us, which was performed on niobium bicrystals with a resistance ratio $\gamma = 70$–90,[5] the boundary orientation was chosen in such a manner as to rule out the possible action of the vortex-pinning mechanism, which is attributable to anisotropy of the superconducting properties of niobium. Nevertheless, the authors observed a narrow peak of the critical current for a magnetic field orientation parallel to the boundary plane, and they attributed this to impurities or segregations at the grain boundary. We cannot explain our results in terms of pinning by impurity clouds at the boundary, as was done by the authors of the above-cited paper.[5] In fact, from

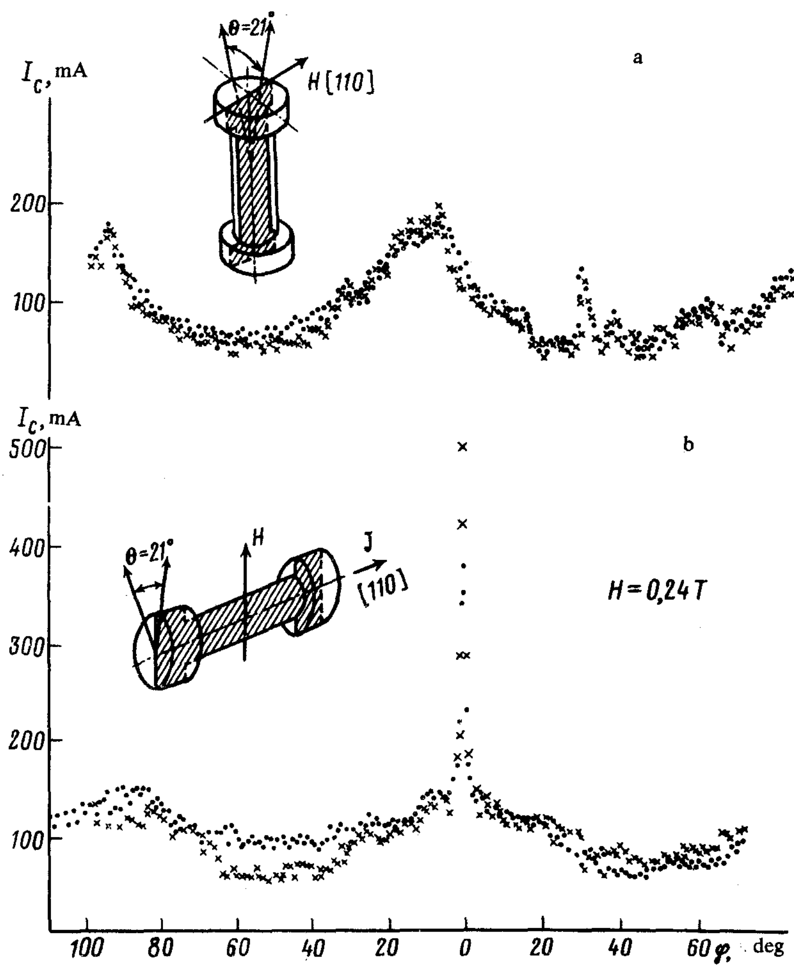

FIG. 2. Angular dependence of the critical current $I_c(\phi)$ of Nb bicrystals. Here and in Fig. 3, ○ and × denote the forward and reverse current directions: (a) the sample is cut at right angles to the tilt axis, (b) the sample is cut along the tilt axis. The directions perpendicular to the [110] tilt axis and parallel to the grain-boundary plane are close to $[\bar{1}15]$ in one part of the bicrystal and to $[\bar{3}35]$ in the other part.

the viewpoint of the mechanism proposed by them, the interaction of the vortex system with the grain boundary should not be greatly different for the orientations illustrated in Fig. 2. We can determine the interaction forces of the vortices with the boundary for our crystals. Just as in Ref. 5, the expression

$$f_p = (I_c - I_{c_0}) B a_0 / D \qquad (1)$$

for the individual interaction force of a vortex with the boundary is obviously valid for our samples. Here, I_{c_0} is the background level, B is the magneticfield induction, $a_0 \simeq (\sqrt{\Phi_0/B})$ is the lattice parameter of the vortices, Φ_0 is a magnetic flux quantum, and D is the sample diameter. Substituting our experimental data ($D = 2$ mm), we

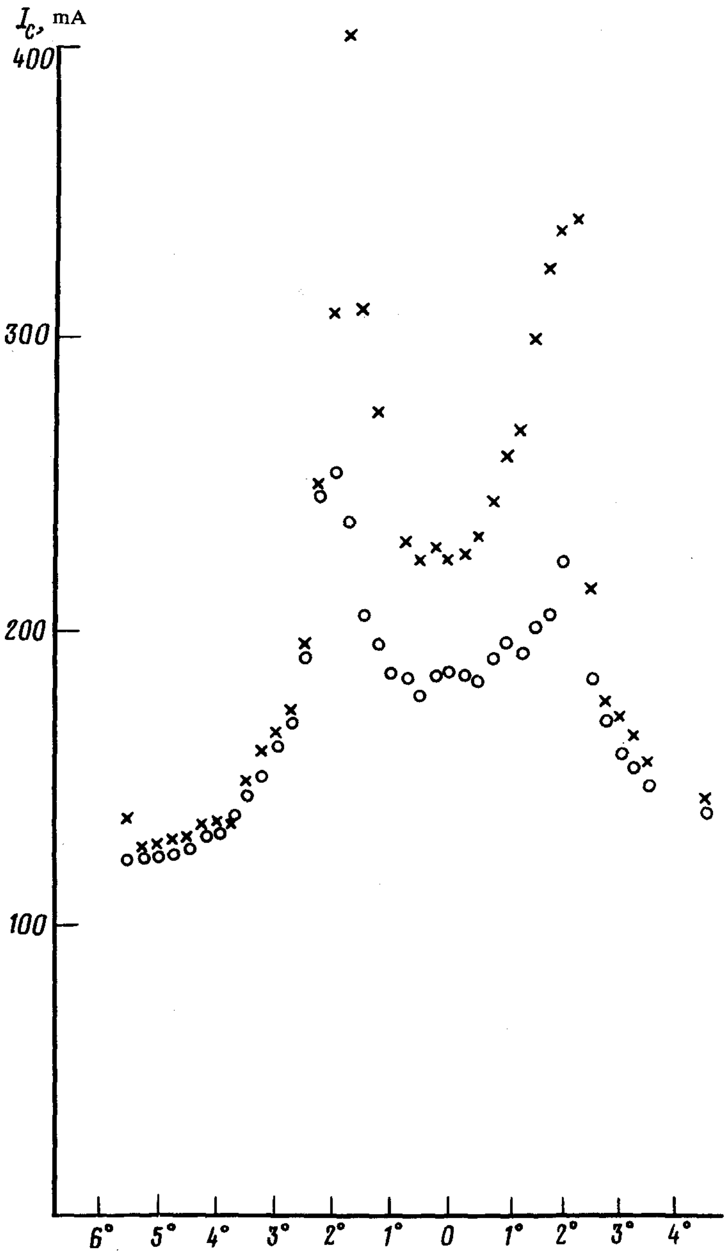

FIG. 3. $I_c(\phi)$ for Nb crystals with a disorientation $\theta = 50°$; the sample is cut along the tilt axis (similar to Fig. 2b). The directions perpendicular to the 110 tilt axis and parallel to the grain-boundary plane are close to $[00\bar{1}]$ in one part of the bicrystal and to [111] in the other part.

obtain $f_p = 4.3 \times 10^{-6}$ N/m. Since the experiment was performed on Nb, a material with small κ, pinning of the vortex filament core—essentially the difference in condensation energies—probably plays the major role. Thus, we obtain from Ref. 6

$$f_p = \pi \mu_0 \left(\frac{H_{c_2}}{\sqrt{2}\kappa} \right)^2 \xi (1 - b) \frac{\Delta H_{c_2}}{H_{c_2}} \qquad (2)$$

where b is the reduced induction, ξ is the coherence length, κ is the constant of the Ginzburg–Landau theory, and ΔH_{c_2} is the difference of the upper critical fields of the bicrystal. According to our data, $H_{c_2} \approx 700$ Oe and $\Delta H_{c_2}/H_{c_2} = 2 \times 10^{-2}$ for $\theta = 21°$. Thus we obtain $f_p = 6 \times 10^{-6}$ N/m. The good agreement of the experimental and calculated f_p values, in our opinion, also favors the interaction mechanism attributable to the anisotropy of superconducting properties.

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