Observation of regions of short-range order in the vortex structure in a type II superconductor

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Decoration with disperse Fe particles in a nonuniformly deformed single crystal of Nb with 5% Mo reveals a block structure in a vortex lattice at a low density of pinning centers in the sample. The lattice is completely disrupted when the density of these centers is high. The observed behavior corresponds to the predictions of the theory of collective pinning.

According to the theory of collective pinning in a type II superconductor,[1] weak pinning centers (dislocations, point defects, and so forth) disrupt the long-range order in the vortex lattice and give rise to so-called correlation regions, within which the periodicity is preserved. The critical current j_c and the pinning body force $F_p = j_c B$ (B is the magnetic induction in the sample) are determined by the volume of the correlation regions:

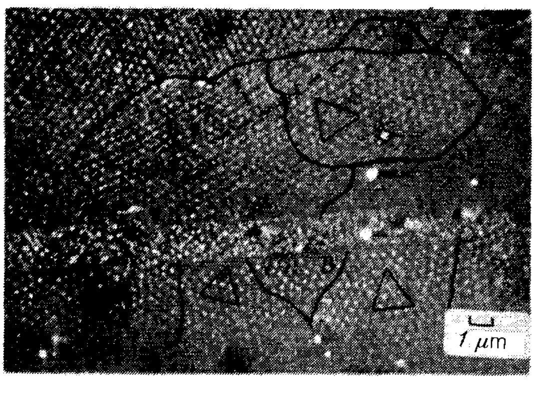
$$F_p = (W(0)/V_c)^{1/2}, \qquad (1)$$

where the quantity $W(0) = n\langle f_p^2 \rangle$ is a measure of the force f_p and the density n of the pinning centers in this volume. This quantity can also be expressed unambiguously in terms of the quantity V_c (Ref. 1).

Recent measurements of the dependence of the critical current on the magnetic field in amorphous films (Ref. 2, for example) have shown that the behavior of the critical current is determined by the field dependence predicted by the collective theory.[1] This agreement is interpreted as confirmation that regions of short-range order form in the vortex lattice. In the present study we have succeeded in observing regions of this sort in bulk samples by a direct method—involving decoration with disperse Fe particles.[3]

We studied single crystals of an alloy of Nb with 5 at. % Mo deformed by compression to $\epsilon \approx 1\%$ at 77 K. The dislocation structure of the samples was highly nonuniform: The deformation was concentrated in slip bands 1.5–10 μm wide, separated from each other by a distance of 100–300 μm. The density of dislocations in a slip-band region was $\gtrsim 10^{10}$ cm^{-2}. The dislocation density between slip bands was low: $\gtrsim 10^{8}$ cm^{-2}. A detailed description of the preparation of the samples, the results of structural studies with a transmission electron microscope, and the results of measurements of the critical current are all given in Ref. 4. The Fe particles are deposited on a surface of the sample oriented perpendicular to the slip bands under frozen-flux conditions; specifically, the sample was cooled to 4.2 K, the external magnetic field was increased from 0 to H_{c_2} (H_{c_2} is the upper critical field), and then the magnetic field was slowly reduced to 0. The magnetic flux was frozen in the sample, at a magnitude and with a distribution determined by the pinning by the defects.[5]

Figures 1 and 2 show decoration patterns recorded in a scanning electron microscope. The bright points are iron particles; their distribution corresponds to the distribution of the magnetic field at the surface of the sample.[3] It can be seen in Fig. 1, a and b, that a triangular vortex lattice with a period $a = 4.2. \times 10^{-5}$ cm forms between slip bands. This lattice consists of blocks, i.e., of regions of a regular lattice, which are irregular in shape and which are rotated with respect to each other. The average size of these blocks is $10 \pm 4\,\mu$m. The boundary region between some of the blocks consists of dislocations and islands of a "poor correspondence" in the vortex lattice (Fig. 1a). At the boundaries of other blocks, rows of the lattice are bent (Fig. 1b). The lattice is thus deformed both plastically and elastically. In the region of a slip band, the vortex lattice breaks down completely (Fig. 2); the distance between vortices is $a = (2\text{–}2.2) \times 10^{-5} \gtrsim 2\lambda$ (λ is the depth to which the magnetic field penetrates into Nb with



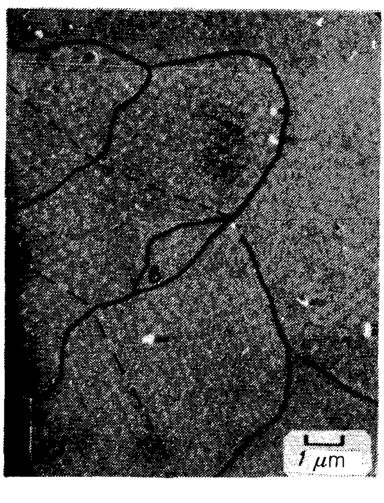


FIG. 1. a,b—Breakup of a vortex lattice into blocks. Solid lines) Boundaries of blocks; triangles) orientation of close-packed rows of vortices; dashed lines) bending of vortex rows at the boundaries of blocks; B) regions of "poor correspondence" in the vortex lattice.

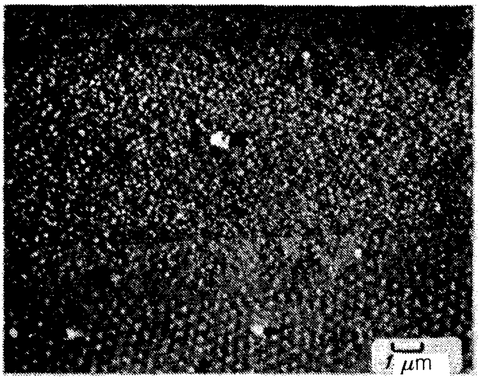


FIG. 2. Magnetic structure of a sample in and near a slip band.

5% Mo at 4.2 K). Assuming that the observed blocks in the vortex lattice constitute a cross section of correlation regions[1] and that their size corresponds to the correlation radius R_c, we can estimate the pinning force F_p caused by the low dislocation density between slip bands. We can also estimate the pinning force exerted by the slip bands, noting that the short-range order is disrupted in the latter case, i.e., that the relation $R_c \approx a$ holds.

Larkin and Ovchinnikov[1] derived the following relations between $W(0)$ and R_c and between V_c and R_c in a study of the elastic deformation of vortex lattices:

$$W(0) = 4\pi^{1/2} \frac{c_{44}^{1/2} c_{66}^{3/2} a^2}{R_c} ; \tag{2}$$

$$V_c = R_c^2 L_c = R_c^3 \left(\frac{c_{44}}{c_{66}}\right)^{1/2} \tag{3}$$

where L_c is the longitudinal dimension of the correlation region, and c_{66} and c_{44} are the shear and bending moduli of the vortex lattice. These moduli were calculated in detail by Brandt,[6] who took account of the nonlocal effects which arise during large deformations of a vortex lattice, such that the wavelength of the displacement field becomes comparable to the distance between vortices. In weak magnetic fields $(0.3/\kappa^2) < b < 0.25$ $(b = B/H_{c_2})$ Brandt found[6]

$$c_{66}(k) = c_{66}(0) = \frac{H_{c_2} B}{4\pi} \frac{1}{8\kappa^2} , \tag{4}$$

$$c_{44}(k) = \frac{B^2}{4\pi}\left(1 + \frac{k_h^2}{k_h^2 + k^2}\right) , \tag{5}$$

where κ is the Ginzburg-Landau parameter, k is the modulus of the wave vector of the elastic displacement field in the vortex lattice, and $k_h^2 \approx (1-b)/\lambda^2$. When there is a disruption of the short-range order, expressions (1)–(5) remain valid within a coefficient ≈ 1 (Ref. 1); in this case we have $R_c \approx a$ and $k \approx 2\pi/\lambda$.

Substituting in Eqs. (1)–(5) $R_c = 10\ \mu$m, the measured magnetic induction in the vortex lattice ($B = 100$ G), and the properties of the alloy of Nb with 5 at. % Mo ($\kappa \approx 3$, $H_{c_2} = 4250$ Oe), we find the pinning force between slip bands: $F_p^{\rm calc} = 2.4 \times 10^4$ dyn/cm^3. This value agrees well with the average force which we estimate for these samples on the basis of the magnetic-field dependence of the critical current: $F_p^{\rm expt} = 1.5 \times 10^4$ dyn/cm^3. In the case in which vortices are pinned at slip bands, there is a sharp decrease in V_c as given by (3), with the result that the pinning force increases significantly: $F_p^{\rm calc} = 3 \times 10^8$ dyn/cm^3. This is a local force, associated with regions of a high dislocation density (slip bands) which occupy a small fraction of the volume of the sample. It is thus difficult to determine this force in terms of an integral characteristic: the critical current. In this situation, we find the experimental value of F_p from the gradient of the local induction,[5] which can be measured on the decoration patterns (Fig. 2). Specifically, in the region of the slip bands we find $B = 420$ G, $B_{\rm av} = 110$ G, $\Delta B = 320$ G, $\Delta x \approx 1.2 \times 10^{-4}$ cm, and $F_p^{\rm expt} = B_{\rm av}(dB/dx) \approx B_{\rm av}(\Delta B/\Delta x) = 3.5 \times 10^8$ dyn/cm^3.

Up to this point we have ignored the plastic deformation of the vortex lattice which is observed experimentally (Fig. 1a). As was shown in Ref. 7, however, when the distance (D_c) between the dislocations in the vortex lattice which bound the correlation region is large ($D_c \gg a$), the two models predict pinning forces of the same order of magnitude. Incorporating the formation of dislocations in the vortex lattice leads to[7] a logarithmic change in $W(0)$ and V_c, in comparison with (2) and (3):

$$W^D(0) = W^e(0)\,\frac{[\ln(d)]^2\,[2\ln(d) - 1]}{\pi^{5/2}\,[\ln(d) + 1]}\,, \qquad (6)$$

$$V_c^D = V_c^e\,\frac{[\ln(d) + 1]}{[2\ln(d) - 1]}\,, \qquad (7)$$

where $d = D_c/a$, and the superscripts D and e refer to the dislocation and elastic models, respectively. In our case ($D_c \approx R_c \gg a$) a calculation of the pinning force from (6) and (7) yields $F_p^{\rm calc} = 5 \times 10^4$ dyn/cm^3—a figure which is close to the estimate for an elastically deformed lattice. This circumstance is responsible for the experimentally observed coexistence of elastic and plastic deformations of the vortex lattice.

It can be concluded from these estimates that the blocks observed in the decoration patterns in the vortex lattices constitute a cross section of correlation regions. The size of these regions determines the experimental values of the critical current. This study has thus yielded the first direct experimental confirmation of the suggestion that regions of short-range order form in a vortex lattice.

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