Observation of the influence of a magnetic field on the size of correlation regions and nature of distortions in a vortex lattice in a type-II superconductor

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Decoration by disperse ferromagnetic particles was used to observe splitting of a vortex lattice in an Nb–Mo single crystal into misoriented domains under the low-density ($\lesssim 10^8$ cm^{-2}) influence of pinning forces exerted by randomly distributed dislocations. The domain size governed the value of the critical current in accordance with the predictions of the collective pinning theory. A reduction in the magnetic induction in a sample from 120 to 14 G reduced strongly the average domain size. Moreover, this reduction altered the nature of distortions of a regular triangular lattice: in high fields the deformation of a vortex lattice was predominantly elastic (representing bending of vortex rows), whereas islands of a "vortex liquid," edge dislocations, and vacancy clusters appeared in the vortex lattices in low fields (plastic deformation of vortex lattices). The experimentally observed increase in the average domain size $\overline{R}_c$ with a magnetic field B was in qualitative agreement with the $R_c(B)$ dependence calculated from the collective pinning theory, but was slower than predicted theoretically. The discrepancy was apparently due to the complex structure of domain walls, which was ignored by the collective pinning theory.

INTRODUCTION

The nondissipative current-carrying ability of type-II superconductors is governed by the interaction between a vortex lattice and inhomogeneities and defects in a crystal (pinning). Determination of the pinning force F_p and of the critical current j_c for a given density and distribution of defects of a specific type is a complex task requiring the knowledge not only of the mechanism of the interaction between a vortex lattice and defects of a given type and, consequently, of elementary pinning forces, but also the knowledge of the laws governing summation of these forces. Considerable progress has recently been made in solving the problem of summation of elementary pinning forces because of the appearance of a theory of collective pinning proposed by Larkin and Ovchinnikov.[1] These authors[1] proposed that weak and randomly distributed pinning centers (such as dislocations, pores, small inclusions of the second phase, etc.) split a vortex lattice into elastically independent correlation regions with dimensions R_c (perpendicular to an external magnetic field $\mathbf{H}_c$) and L_c (parallel to $\mathbf{H}_c$). The total pinning force experienced by each domain in a vortex lattice is governed by the collective effect of pinning centers located within a domain, i.e., it is governed by the sum of statistical fluctuations $(N\langle \mathbf{f}_i^2\rangle)^{1/2}$, where N is the number of pinning centers in one domain and $\mathbf{f}_i$ is the pinning force exerted on a vortex lattice by the ith center. The density of the pinning force is

$$F_p = j_c B = (W/V_c)^{1/2}, \tag{1}$$

where

$$W = n\langle \mathbf{f}_i^2\rangle, \tag{2}$$

$$V_c = R_c^2 L_c = R_c^3 (C_{44}/C_{66})^{1/2}, \tag{3}$$

n is the density of pinning centers; B is the magnetic induction; C_{66} and C_{44} are, respectively, the shear and bending elastic moduli of the vortex lattice; the values of W and V_c are uniquely interrelated.[1] The average in Eq. (2) is taken over one domain in the vortex lattice. Therefore, the critical current and its field dependence are governed by the dimensions of correlation regions and by their dependence on the magnetic field.

The transverse size R_c of a correlation region is governed by the elasticity of the vortex lattice, on the one hand, and by the strength and density of the pinning centers, on the other[1]:

$$R_c = 8\pi C_{66}^{3/2} C_{44}^{1/2} r_p^2/W, \tag{4}$$

where r_p is the characteristic distance in which the pinning potential changes. The value of r_p is governed by the nature and dimensions of a pinning center and by the radius of a vortex; in the range of weak magnetic fields defined by $b = B/H_{c2} \ll 1$ (H_{c2} is the upper critical field) the distance r_p is independent of b (Ref. 2).

The first direct confirmation of the splitting of a vortex lattice in a three-dimensional superconductor into correlation regions was obtained in our earlier paper.[3] The method of decoration of the surface of a superconductor by disperse ferromagnetic particles[4] was used in our investigation[3] of samples containing randomly distributed dislocations and we found that in the transverse section the vortex lattice consisted of misoriented domains. The domain size was equal to the transverse correlation distance R_c calculated from the collective-pinning theory using the known values of the pinning force in the investigated samples. An additional confirmation of the conclusion that the domains observed in a vortex lattice were correlation regions formed as a result of the collective effect of dislocations on a vortex lattice and governing the critical current, was provided by the observation that the changes in their size with variation of the magnetic field in a sample agreed with the predictions of the collective pinning theory.

There still remains the question of the nature of deformation of a vortex lattice when correlation regions are formed and of the structure of boundaries of these regions.

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The theory of Ref. 1 deals only with the elastic deformation of a vortex lattice. However, the observed[5] abrupt (tenfold) jump of the critical current of superconducting amorphous films near H_{c2} can be explained only by the formation of screw dislocations in a vortex lattice (in the case of elastic distortions we would expect a smooth rise of the critical current).[6] Moreover, individual edge dislocations in a vortex lattice had been observed even in the case of defect-free samples.[7] An investigation reported in Ref. 8 is based on a simple model of correlation regions of quadratic cross section formed as a result of the appearance of four dislocation loops at the corners of the square and it was shown there that in magnetic fields $b \ll 1$ and $b > 0.7$ the optimal adjustment of a vortex lattice to the configuration of pinning centers could be due to plastic deformation of the lattice. The pinning force F_p and the critical current j_c may then be higher than the values predicted by the original theory[1] and, consequently, the dependences of j_c and of the correlation size on the magnetic field will be different. A direct determination of the nature of distortions in a vortex lattice and of changes with the magnetic field could shed light on this problem.

The results of a direct observation of a vortex lattice in a superconductor containing randomly distributed dislocations in weak magnetic fields $b \ll 1$ are reported below.

SAMPLES AND EXPERIMENTAL METHOD

We investigated samples of a weakly deformed single crystal of an alloy of the Nb–5.5 at.% Mo composition with the resistance ratio $\gamma = R_{300\,K}/R_{4.2\,K/8\mathrm{kOe}} = 10$; $T_c = 7.6$ K. A detailed description of the methods used in the preparation of the samples and the results of electron-microscopic investigations were given in our earlier papers.[9,3] We decorated samples in the form of platelets of $3\times3\times0.15$ mm dimensions with the (111) orientation of the wide face and found that these samples contained randomly distributed (mainly screw) dislocations present in a relatively low density of $\lesssim 10^8$ cm^{-2} (with a typical distance between dislocations amounting to 0.5 μm). A vortex lattice was investigated within the same sample.

Decoration with disperse iron particles took place in an evacuated chamber containing gaseous helium at a pressure of 5×10^{-2} Torr and a temperature of 4.2 K. A sample was subjected to an external magnetic field perpendicular to the surface of the plate and it was then cooled from $T > T_c$ to 4.2 K; this was followed by evaporation of iron. A detailed description of the decoration method can be found in Ref. 10. The distribution of the Fe particles on the surface of a sample, corresponding to the distribution of the vortices,[10] was investigated with a scanning electron microscope in the secondary-electron regime. A sample was then washed and the experiments were repeated using the next value of the external magnetic field.

The vortex lattice patterns were recorded in fields H_c = 12, 40, 75, 100, and 120 Oe. The magnetic induction inside a sample was taken to be $B = n_0\Phi_0/S$, where $\Phi_0 = 2.07\times10^{-7}$ G·cm^2 is a magnetic flux quantum and n_0 is the number of vortices in an area S. In all cases we had $B = H_c$, as expected for a thin plate in a transverse magnetic field for which the demagnetization factor D was close to 1: in fields exceeding the penetration field $H = H_{c1}(1-D)$ ($H_{c1} = 260$ Oe is the lower critical field for Nb–5% Mo) the magnetic flux was not expelled from the sample.

EXPERIMENTAL RESULTS

Figures 1–3 show the images of a vortex lattice obtained for three values of the magnetic induction in a sample: $\overline{B} = 120$, 40, and 14 G, respectively. These photographs show qualitative changes in the degree and nature of the distortion of a vortex lattice on reduction of the magnetic field. When the magnetic induction was $\overline{B} = 120$ G (Fig. 1a), a regular triangular lattice was distorted relatively weakly: the main effect was smooth bending of the vortex rows, so that the vortex lattice split into misoriented irregular domains. Inside these domains, which are typically of 15–20 μm in size, the vortices are distributed almost periodically. When the magnetic induction was $\overline{B} = 40$ G (Fig. 2a), the vortex lattice was on the whole less ordered, but it still consisted of regions rotated relative to one another and characterized by a periodic distribution of vortices inside such regions. The characteristic size of these regions was 6–8 μm. In this field we observed a new feature of the vortex structure which did not appear in higher fields, namely vortex-lattice "Meissner" regions free of vortices which could be regarded as vacancy clusters in the vortex lattice. One of such regions is identified by arrows in Fig. 2a and it is shown on a larger scale in Fig. 2b. When the magnetic induction was $\overline{B} = 14$ G (Fig. 3), it was found that the vortices were practically completely disordered and the hexagonal correlation was observed only at certain points and solely for the nearest neighbors. Vortex-free regions became more pronounced.

We thus found that for all the values of the magnetic field (induction) used in our investigation a vortex lattice consisted of misoriented domains (correlation regions) with a characteristic size which decreased on reduction in the magnetic field. There was also a change in the structure of boundaries of correlation regions. When the field was 120 G, it was found that bending of vortex rows was the main effect at domain walls (Fig. 1a). Some parts of the walls were formed because of the appearance of edge dislocations in the vortex lattice, but the relative length of such regions was small. One of them, representing a part of a domain wall identified in Fig. 1a, is shown also in Fig. 1b. An analogous pattern was observed when the field was $\overline{B} = 100$ G, but bending of vortex rows and the appearance of dislocations at domain walls became equiprobable. For $\overline{B} = 40$ G the boundaries of the correlation regions became wider: islands of a "vortex liquid" of size up to several intervortex spacings appeared between regions with a periodic distribution of vortices, and vacancy clusters appeared in a vortex lattice. In some parts of a sample it was possible to identify isolated edge dislocations; bending of vortex rows at the walls occurred relatively rarely. All these features are demonstrated quite clearly in Fig. 2c.

The dimensions of the observed domains could be determined when their walls were found accurately. This was done assuming that, within one correlation region, all three directions of vortex rows and the periodicity of their distribution should be preserved. If there were a deviation of vortex rows from the initial direction or "breakdown" of vortex rows, i.e., in the case of a displacement of one part of a row relative to another in the perpendicular direction, a region was regarded as a part of a wall. Islands of the vortex liquid

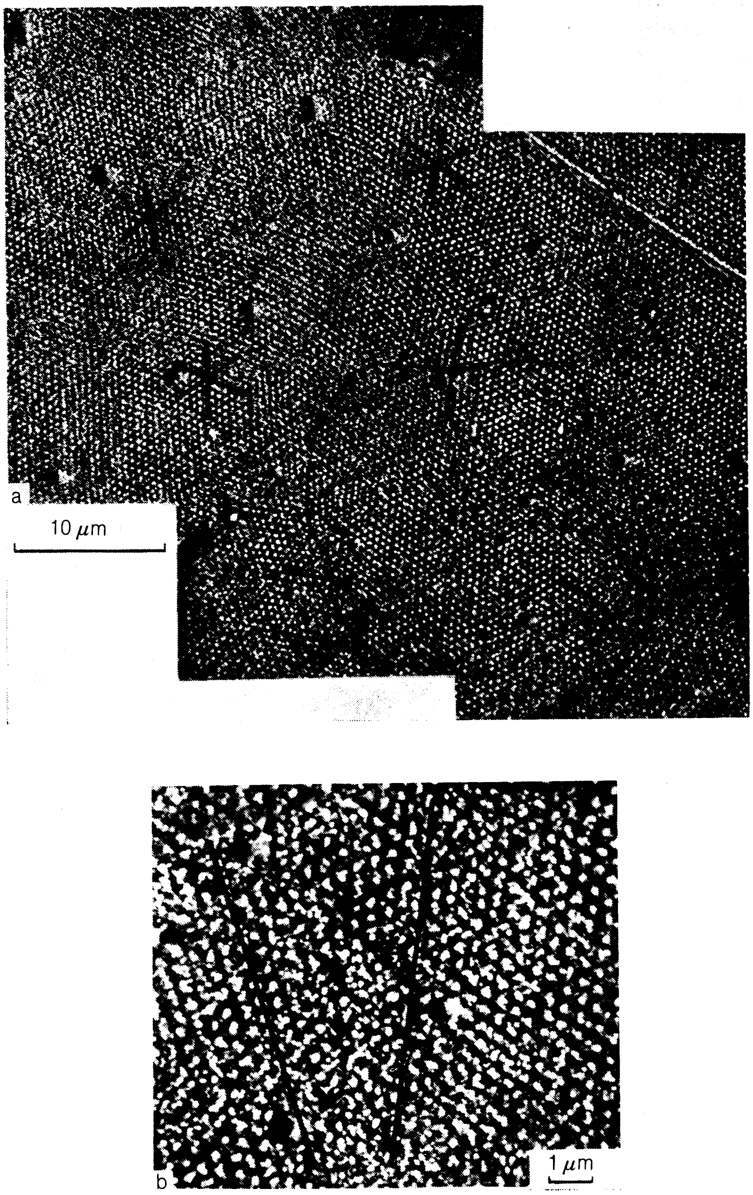

FIG. 1. a) Image of a vortex lattice in a magnetic field $\overline{B} = 120$ G. The dashed curve is the wall of one of the domains and the continuous curves are the directions of close-packed vortex rows which change at domain walls. b) Part of a domain wall (on the left in the lower part of the figure) identified in Fig. 1a and formed due to the appearance of edge dislocations in a vortex lattice. The edge dislocations ($\perp$) and the directions of close-packed vortex rows in neighboring domains are shown.

and the Meissner regions were not regarded as parts of domain walls. The correlation regions identified by this method in one part of the panorama in Fig. 2a are shown in Fig. 2c. The size of the nth domain was defined as $R_c^{(n)} = (S^{(n)})^{1/2}$, where $S^{(n)}$ is its area.

By way of example, we plotted in Fig. 4 the distribution of the domain sizes for $\overline{B} = 40$ G. This was close to the Gaussian distribution, as expected in accordance with the statistical nature of the total force experienced by each domain.[1] Similar distributions had been reported for other values of the magnetic field. This was used to find the statistical average values of the domain size $\overline{R}_c(B)$ in a vortex lattice. The scatter of the values of R_c given below was a measure of the precision of determination of the statistical average value.

DISCUSSION OF RESULTS

According to the collective pinning theory,[1] the dependence of the transverse correlation size R_c on the magnetic field is governed by the corresponding dependences of the elastic moduli of the vortex lattice $C_{66}(b)$ and $C_{44}(b)$ and of the individual pinning force $f_i(b)$ [see Eq. (4)].

The elastic moduli of a vortex lattice were calculated by Brandt for different ranges of the magnetic field.[11,12] In magnetic fields $H < H_{c1}$ the bending modulus C_{44} was governed by the intrinsic energy of a vortex and by the vortex density[12]:

$$C_{44} = BH_{c1}/4\pi. \tag{5}$$

The shear modulus decreased exponentially in this range of fields; a simple interpolation formula valid throughout the range $0 < b < 1$ was given in Ref. 11:

$$C_{66} = \frac{H_{c2}^2}{4\pi}\frac{b(1-b)^2}{8\varkappa^2}\left(1-\frac{1}{2\varkappa^2}\right)\left(1+\frac{0{,}17}{\varkappa^2}\right) \times (1-0.29b)\exp\left(\frac{b-1}{3\varkappa^2 b}\right), \tag{6}$$

where $\varkappa$ is the Ginzburg–Landau (GL) parameter.

The field dependence of the pinning forces due to the elastic interaction of vortices and dislocations in a crystal is governed by the change in the mean-square value of the gap $\langle|\psi|^2\rangle \propto (1-b)$ and the average distance between vortices

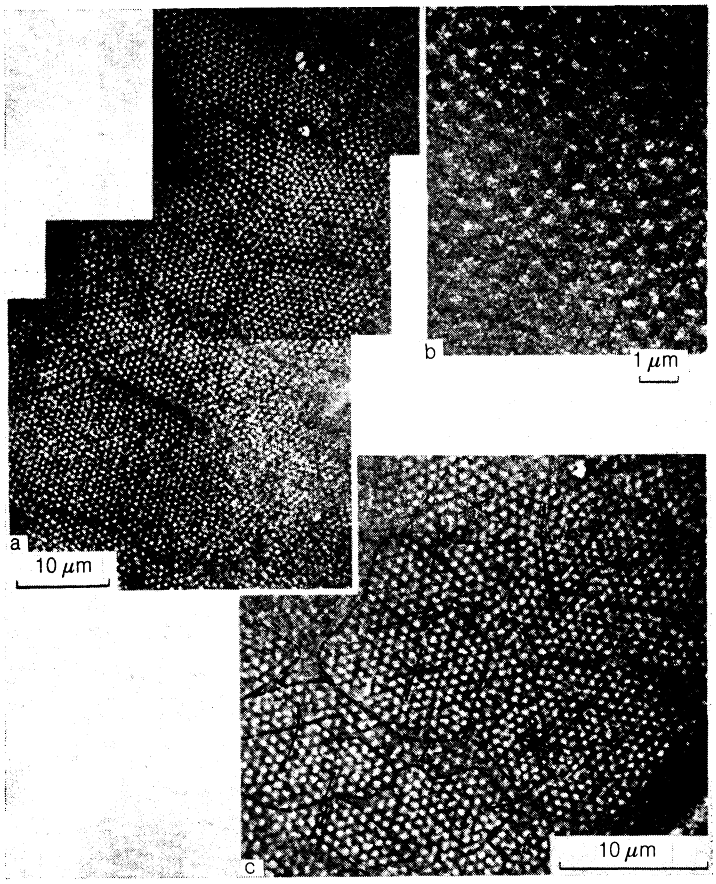

FIG. 2. a) Image of a vortex lattice in a magnetic field $\overline{B}=40$ G. b) Fragment of a panorama in Fig. 2a. The arrows identify a Meissner region (vacancy cluster) in a vortex lattice. c) Central part of the panorama in Fig. 2a. The method for the determination of the boundaries of correlation regions is demonstrated: the dashed curves are the boundaries of these regions and the continuous curves are the changes in the direction and breaks of close-packed rows of vortices at the boundaries; L are regions of a vortex liquid and $\perp$ are the edge dislocations in the vortex lattice.

$\sim b^{-1/2}$ observed when the magnetic field is varied.[13] In the specific case of the second-order elastic interaction, responsible for the pinning in our samples[9] containing mainly screw dislocations, the exact form of the dependence $f_i(b)$ was obtained in Ref. 14:

$$f_i(b)=f_0 b^{1/2}(1-b)\ln\left(\frac{\xi}{2{,}7 b_B b^{1/2}}\right) \tag{7}$$

where ξ is the coherence length and b_B is the Burgers vector of a crystalline dislocation.

The $R_c(b)$ dependence calculated using Eqs. (4)–(7) in the range $0<b<0.03$ is plotted in Fig. 5. [The radius of action of the pinning centers r_p, calculated in accordance with the dependence $f_i(r)$ of Ref. 14, was assumed to be 3ξ.] This figure gives the values of $R_c^{\exp}$ found from the decoration patterns by the method described above. The fitting parameter used to compare the calculations with the theory was the quantity W_0 [$W\propto W_0 b(1-b)^2$], representing the strength and density of the pinning centers. Since W_0 was not governed by the maximum but by the actual values of the forces exerted by individual centers, which depended on the relative positions of the vortices and pinning centers,[6] it could be much less than the maximum possible value $n\langle f_{\max}^2\rangle$. Therefore, we found W_0 from the known pinning force and the dimensions of the correlation regions [Eqs. (1) and (4)]. The best agreement between the theory and experimental results is obtained for $W_0=0.12$ dyn^2/cm^3. Using this value and assuming that $\overline{R}_c=12\,\mu$m for $\overline{B}=100$ G in estimating the pinning force from Eqs. (1)–(3), we found that $F_p=4\times10^3$ dyn/cm^3, which is equal to the pin-

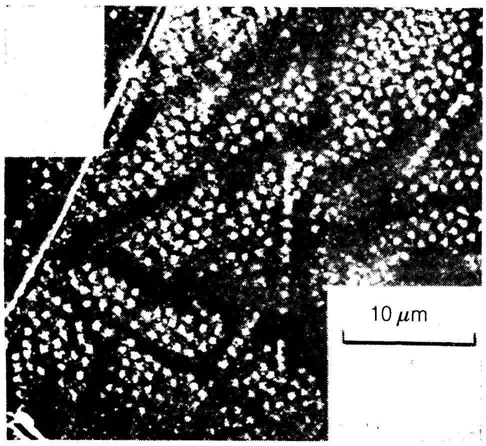

FIG. 3. Image of a vortex lattice in a magnetic field $\overline{B}=14$ G.

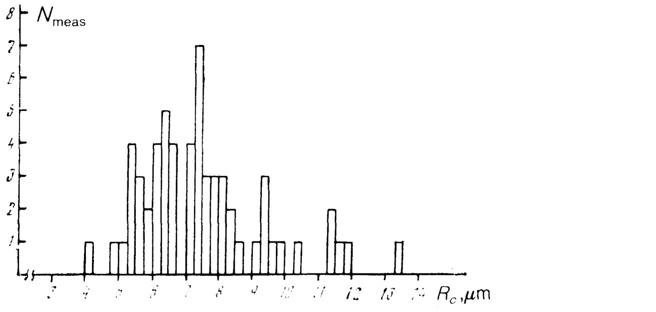

FIG. 4. Distribution of the size of correlation regions in a magnetic field $\overline{B}=40$ G.

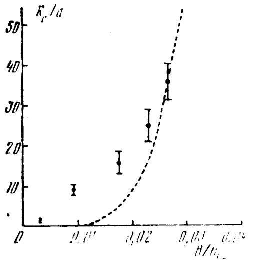

FIG. 5. Dependences of the transverse size of correlation regions R_c on the reduced magnetic field $b = B/H_{c2}$:●) experimental values of R_c; the dashed curve represents the dependence $R_c(b)$ calculated using the collective pinning theory.

ning force in our samples found in Ref. 3 from the magnetic induction gradient:

$$F_p^{\exp} = \frac{1}{4\pi}\bar{B}\frac{dB}{dx} = (3{,}2\text{–}4{,}8)\cdot 10^3 \text{ dyn/cm}^3.$$

This estimate confirms the correctness of our value of W_0.

It is clear from Fig. 5 that the experimentally observed strong reduction in the size of the correlation regions in a vortex lattice on reduction in the magnetic field is in qualitative agreement with the $R_c(b)$ dependence predicted by the collective pinning theory, but the experimental reduction occurs at a slower pace. This discrepancy is apparently due to the fact that the collective pinning theory of Ref. 1 deals only with the elastic deformation of a vortex lattice, whereas experiments demonstrate a transition from an elastically deformed vortex lattice in a field of 120 G to a strongly disordered plastically deformed vortex lattice in fields of 40 and 14 G. This transition is in good agreement with the condition for the absence of plastic shear in a vortex lattice found in Ref. 8:

$$R_c(C_{44}/C_{66})^{1/2} > 100W/C_{66}^2. \tag{8}$$

[Equation (8) is derived assuming that the maximum possible shear stress in a vortex lattice, which does not result in plastic deformation, is $C_{66}/10$.] In the specific case of our experiments this means that the purely elastic deformation is possible only in fields of 100 and 120 G.

It was also shown in Ref. 8 that allowance for the formation of dislocations in a vortex lattice under the influence of the pinning forces results in a logarithmic increase in R_c compared with the results obtained in Ref. 1 [for the same value of the pinning force $(N\langle f_i^2\rangle)^{1/2}$]:

$$R_c^d = R_c^e\frac{\ln(d)\,[2\ln(d)-1]}{\ln(d)+1}, \tag{9}$$

where the indices d and e refer to the dislocation and elastic models, respectively; $d = R_c/a$; a is the distance between the vortices. It therefore follows that, because of transition from one model to another, the reduction in R_c on reduction in a magnetic field may be slower than predicted in Ref. 1. Moreover, we must recall that in weak fields a vortex lattice may have islands of a vortex liquid and vacancy clusters, but this is ignored in Refs. 1 and 8.

The origin of the Meissner regions observed in a vortex lattice in fields of 40 and 14 G (Figs. 2 and 3), is not yet understood. The coexistence of domains of the Meissner and Shubnikov phases (intermediate mixed state) has been encountered in superconductors with a small value of the GL parameter $\varkappa \approx 1$ (Ref. 15). It is due to attraction between vortices, which appears when $\lambda \approx \xi$ and is responsible for the existence of the minimum possible induction B_0 in such superconductors. For example, the magnetic induction in the Shubnikov phase of niobium is $B_0 = 800$ G in any external field $B < B_0$. In our case the density of the vortices in a sample varies with the external field and, moreover, we have $\lambda \gg \xi$, so that the observed state of a vortex lattice is not the classical intermediate mixed state.

It is possible that the appearance of vortex-free regions (large vacancy clusters) in a vortex lattice is a consequence of strong weakening of the interaction between vortices [for comparison, we should mention here that the shear modulus of a vortex lattice is $C_{66}(120\text{ G}) = 135$ dyn/cm^2, $C_{66}(40\text{ G}) = 2$ dyn/cm^2, and $C_{66}(14\text{ G}) = 9\times10^{-4}$ dyn/cm^2]. The tendency to form vacancies in a vortex lattice in the course of a very weak interaction between vortices was observed in Ref. 7, where the decoration method was used to study a vortex lattice in perfect Pb–In single crystals. At distances between vortices in the range > 8000 Å (in fields < 37 G) a lattice revealed "loose" regions with clusters consisting of 2–3 vacancies.

CONCLUSIONS

1. Throughout the range of magnetic fields in which it was possible to observe a vortex lattice the experiments showed that randomly distributed dislocations in a crystal split a vortex lattice into misoriented domains inside which the vortices are distributed periodically. The average size of these domains decreases strongly on reduction in the magnetic field, in agreement with the predictions of the collective pinning theory. This provides an experimental confirmation of the prediction of this theory that correlation regions can form and their size governs the critical current.

2. Variation of the magnetic field alters greatly the structure of the boundaries of correlation regions: in high fields the boundaries of these regions exhibit mainly bending of vortex rows (elastic deformation of a vortex lattice), whereas in weak fields the boundaries consist of islands of a vortex liquid, vacancy clusters, and dislocations in a vortex lattice (plastic deformation of the lattice).

3. The observed abrupt rise of the average correlation size in a vortex lattice on increase in the magnetic field is in qualitative agreement with the dependence $R_c(b)$ calculated using the collective pinning theory, but its rate is somewhat slower than predicted by the theory. The discrepancy is clearly due to the fact that the observed complex structure of the domain walls is ignored in the collective pinning theory.

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