Critical currents in niobium bicrystals

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A systematic study of critical currents in niobium bicrystals was carried out to determine the mechanism of the interaction of vortices with grain boundaries in type-II superconductors. By using bicrystal specimens, the elementary pinning force—the interaction force between a vortex of unit length and a grain boundary—could be determined directly from the experimental results, and was $\sim 10^{-6}$ to 10^{-5} N·m^{-1}. The experimental results can be explained on the basis of a mechanism connected with the anisotropy of superconducting properties. In bicrystals with the tilt boundary close to the twin boundary, pinning can be produced by the formation of a localized superconducting state along such a boundary.

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1. INTRODUCTION

Two types of problem usually arise when studying the pinning of Abrikosov vortices at defects in the crystal structure of type-II superconductors. There is first the determination of the physical cause of the elementary pinning force exerted by the defect on a single vortex (and, connected with this, the determination of the magnitude of the force). There is second the problem, related to the summation of these elementary forces, of the determination of the parameters of the critical state of a three-dimensional superconductor, in particular its critical current. However, it is usually very complicated to separate these two problems in an experimental situation, since it is simplest (and most usual) to study the critical stage in superconducting specimens containing a very large number of uniformly or nonuniformly distributed defects of one and the same type.[1,2]

Investigation of the interaction between the vortex system in a superconductor and one or several defects has been carried out either with the help of a fairly complicated method for decorating the magnetic flux,[3,4] which in the majority of cases only gives qualitative information, or by studying pinning by the surface of the superconductor, using usual critical-current or magnetic-moment measurements.[5,6] The interaction between vortices and a single grain boundary in niobium bicrystals has also been studied,[7] and conclusions were drawn about the action of the pinning mechanism associated with segregated impurities near a grain boundary. Because this conclusion does not agree with our results for polycrystalline Pb-In alloys[1] and polycrystalline niobium,[8,9] in which the dominant role of the pinning mechanism connected with anisotropy of the superconducting properties was shown, we have carried out a systematic study of critical currents in niobium bicrystals. The first results of the investigations were reported in a short note.[10] The present work is devoted to a study of critical currents in niobium bicrystals with different crystal misorientations θ.

2. SPECIMENS AND METHOD OF MEASUREMENTS

Niobium bicrystals with a given crystal disorientation were grown by electron beam zone melting.[11] The bicrystals were 20-mm diameter cylinders, 60 to 80 mm long, with $\langle 110 \rangle$ growth axis and inclination 2 to 3°. The boundary passes through the diameter plane of the crystal. A cylindrical dumbbell-shaped specimen 13 mm long with maximum diameter 3 mm was used to measure the critical currents. Specimens were cut along and perpendicular to the growth axis by electro-sparking.[10] A cylinder was first cut out by a copper tubular electrode and then the central part of the specimen was selected by a plane electrode with continuous rotation of the specimen. The cutting was finished by polishing with the "weakest" electro-erosion treatment. The work-hardened layer was removed by chemical polishing in an acid mixture consisting of 5 parts HNO_3 + 5 parts HF + 2 parts H_3PO_4 at a temperature of not more than 20 °C. The specimens were than annealed at a temperature of 300 °C for 10 min at atmospheric pressure to reduce the surface pinning.[6] Indium current and potential contacts were soldered-on with an ultrasonic soldering iron. The distance between the potential contacts was 5 mm and the specimen diameter in the region between the contacts was $D = 2$ mm. The resistance ratio $\gamma = R_{300K}/R_{4.2K}$ was 200 to 300 for all the specimens measured. Critical currents were measured in a perpendicular magnetic field. The criterion for the critical current was the appearance of a voltage of 5×10^{-9} V between the potential contacts. Smooth rotation of the specimen around the axix coinciding with the direction of current flow and perpendicular to the magnetic field was achieved with a mirror goniometer head and a laser pointer, and the relative angles of rotation were measured with accuracy better than 0.05°. Measurements were made with the specimen rotated in 0.1° steps.

Cooling to nitrogen temperature was carried out slowly—in 2 to 3 hours—to prevent fine niobium hydride particles from separating,[12] as these firmly pin the vortex system. After cooling, all the measurements were made on each specimen without warming it to room temperature.

A single-crystal specimen cut from a large bicrystal was chosen for measuring the anisotropy of H_{c2}. The cylindrical specimen (with generator parallel to the $\langle 110 \rangle$ axis) was rotated in the magnetic field in 5° steps. The $I_c(H)$ dependence

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was measured near H_{c2}, the latter determined by extrapolating the rapidly falling section of $I_c(H)$ to $I_c = 0$. The determination of H_{c2} was facilitated by the existence of the "peak effect" near H_{c2}, due to which a sufficiently sharp fall in I_c was observed.

Measurements at 4.2 K and below were carried out in liquid helium. Measurements above 4.2 K were carried out in helium vapor. In both cases the accuracy in maintaining a given temperature was no worse than 0.01 K.

Foils for the electron microscope were prepared by the method of electrochemical polishing of a window in an acid mixture of 48 parts $C_3H_6O_3$ + 34 parts H_2SO_4 + 18 parts HF at 7 V and a temperature 0 °C. Electron-microscope studies[11] showed that the boundaries between the two crystals in the bicrystals studied are microscopically straight and that neither within the body of the grains nor along the boundaries are there segregations of a second phase with dimensions > 30 Å. The initial bicrystals contain a fairly large number of dislocations, their density being 7×10^7 cm^{-2}, but no preferred positions for them were observed. The orientation of the crystalline components of the bicrystals was determined by x-ray diffraction and was confirmed by electron diffraction. The accuracy in determining the orientation was not worse than $\pm 1°$.

3. EXPERIMENT

3.1 Orientational dependence of the critical current in a bicrystal

We studied the dependence of critical current I_c on the angle of rotation φ of the plane of the grain boundary in a bicrystal relative to the direction of the external magnetic field H. In most cases a maximum of the critical current was observed in the region of angles $\varphi = 0$. (The special conditions under which such maxima were not observed were described earlier.[11]) The shape of the peak in the critical current corresponded to the curvature of the grain boundary. A narrow peak with half-width up to 0.2° was observed in specimens with a macroscopically flat boundary (see Fig. 1a). Several peaks were found for specimens with a ragged grain boundary, and the angles between them corresponded to the angles between sections of the boundary. A smoothly bent boundary gave a low smeared-out maximum on the $I_c(\varphi)$ plot (see Fig. 1b). In this way the geometrical form of the grain boundary in the bicrystal studied could be judged from the shape of the $I_c(\varphi)$ peak. This shape depends on the external magnetic field (Fig. 2) and on the temperature (Fig. 3). It can be seen that as the magnetic field is decreased the half-width of the peak, δ, increases. It should be noticed that as the field is decreased the maximum of the peak shifts to one side noticeably. For the specimen studied (Fig. 2) the shift amounted to 0.25° with changing field from $h = H/H_{c2} = 0.9$ to $h = 0.4$, at which field a peak in $I_c(\varphi)$ is still observed. On increasing the temperature from $t = T/T_c = 0.2$ to $t = 0.95$ a broadening of the peak of comparable magnitude occurs (see the insets in Figs. 2 and 3), while its shift does not exceed 0.1°.

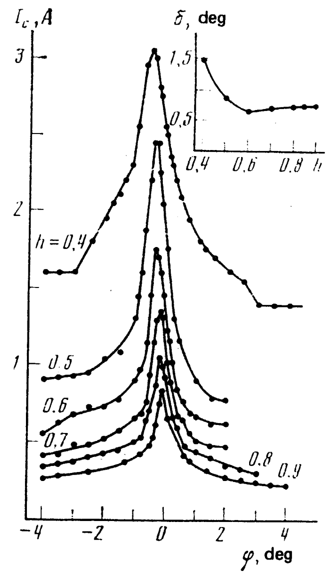

FIG. 2. Form of the peak in $I_c(\varphi)$ as a function of reduced magnetic field h. The inset shows the dependence of half-width on h. Bicrystal with $\theta = 15°$.

To eliminate as much as possible the grain boundary shape factor, comparison of critical currents was carried out only for specimens with $I_c(\varphi)$ peak half width $\delta \leqslant 1°$ at $T = 4.2$ K and $H = 2.4$ kOe.

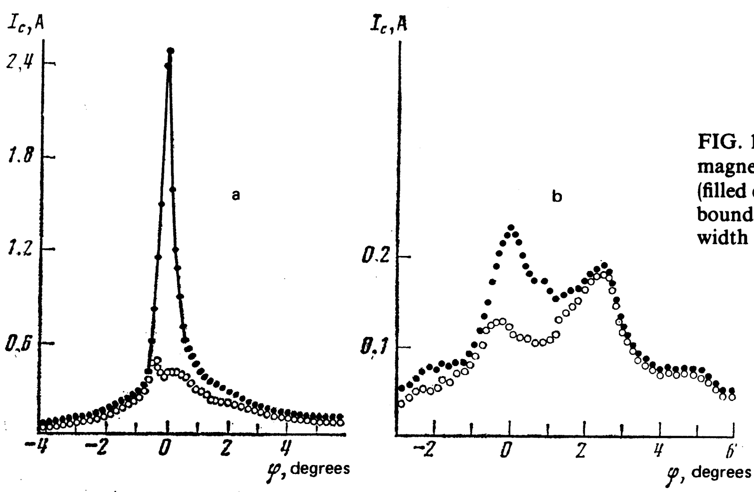

FIG. 1. Dependence of critical current I_c^+ on the angle φ between the magnetic field vector and the bicrystal boundary at $H = 2.4$ kOe; $I \parallel \langle 110 \rangle$ (filled circles); ○—opposite direction for current flow I_c^-: a—for a plane boundary with disorientation of the component crystallites $\theta = 20°$ (half-width of the peak $\delta = 0.5°$; b—for curved boundary with $\theta = 15°$.

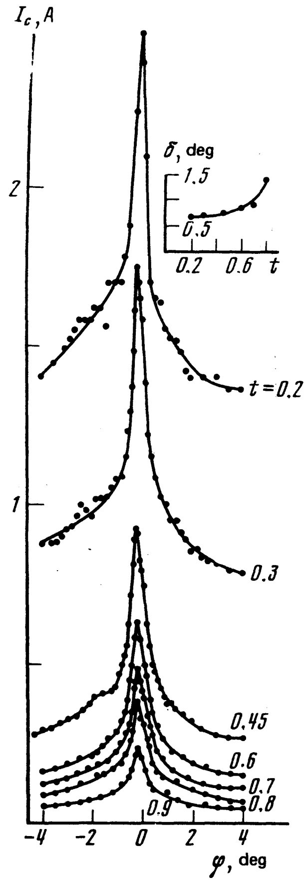

FIG. 3. Form of the peak in $I_c(\varphi)$ as a function of reduced temperature t. The inset shows the dependence of half-width on t. Bicrystal with $\theta = 15°$ (the same crystal as in Fig. 2).

An important feature of the $I_c(\varphi)$ peaks is their asymmetry (Fig. 1) relative to the direction of the applied magnetic field or of the current. A dependence of the maximum critical current on its direction is always observed to a greater or lesser extent. The difference in $I_{c\max}$ for various current directions is larger the greater the absolute value of the more I_c^+ peak and amounted to 50 to 60% of the smaller of the peaks for plane boundaries.

3.2 Possible reasons for anisotropy of the critical current

Since the main result of this work is based on the singularities observed on the $I_c(\varphi)$ curves for bicrystals, we shall consider possible reasons for the anisotropy of I_c. Such an anisotropy is actually found even in measurements on single crystals and can be due to a number of causes. These are pinning by anisotropically positioned growth dislocations, anisotropic of surface pinning due to different depths of oxidation on different faces, and finally pinning at Nb hydride particles which, althouhg few in number, must be present in chemically polished and then cooled Nb specimens. Since the Nb hydride particles are strictly oriented in the crystal, namely in the form of plates[12] in the (100) plane, pinning in such a system should be anisotropic. We shall consider, for example, the $I_c(\varphi)$ plot in Fig. 4 of the single crystal on which the anistropy of H_{c2} was measured. The crystallogra-

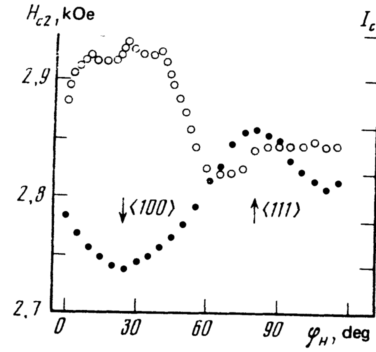

FIG. 4. Anisotropy of critical current in a niobium single-crystal (pinning by niobium hydrides): ○—I_c ($h = 0.8$), ●—H_{c2}. Orientation of the specimen was determined from measurement of the anisotropy in H_{c2}; $I \parallel \langle 110 \rangle$ (symbols as in Fig. 1).

phic orientation of the specimen relative to the magnetic field can be determined with great accuracy by comparing the anisotropy of H_{c2} (Ref. 13) the anisotropy of critical current. A sharp maximum in I_c is seen in Fig. 4 for $H \parallel \langle 100 \rangle$, i.e., when the magnetic field is parallel to the plane of the niobium-hydride particles. However, the magnitude and shape of this maximum differ sharply from those observed in bicrystals.[1)]

Chemical polishing of a bicrystal produces etching grooves with depth and width $\sim 10\,\mu$m on its surface at the place where the grain boundary emerges. To check on the possibility of pinning of vortices on the resultant surface irregularities we attempted to model this situation on a single-crystal specimen by drawing with a needle two parallel scratches with corresponding dimensions. However, the situation in this case was complicated by the evident deformation of the crystal near the scratches. The measured critical currents are shown in Fig. 5. The "parallel" position of the "decorated face" corresponds to $\varphi = 65°$. The broad and low maximum of the critical current is, from geometrical considerations, evidently connected with just the deformation of the crystal near the scratches and does not resemble the peaks observed in bicrystals at all. This experiment shows the relatively weak influence of etching grooves on the pinning of flux lines in bicrystals.

3.3 Dependence of critical current on the magnetic field and temperature

The field dependence of critical current $I_c(H)$ for a single-crystal specimen cut out of one crystallite is described by a monotonic decreasing function in the mixed state, and the peak effect is only observed in a narrow region near H_{c2}. There is no asymmetry of I_c at various directions of current flow or magnetic field. A similar $I_c(H)$ dependence is observed for bicrystals when the magnetic field is inclined to the direction parallel to the boundary ($\varphi \neq 0$). The $I_c(H)$ curves for bicrystals with asymmetrical tilt boundaries[2)] have a more complicated field dependence for magnetic field directions parallel to the boundary of the bicrystal and a strong asymmetry of I_c (Fig. 6b). Two peaks are in general observed near H_{c2} and their position is related to the angle of

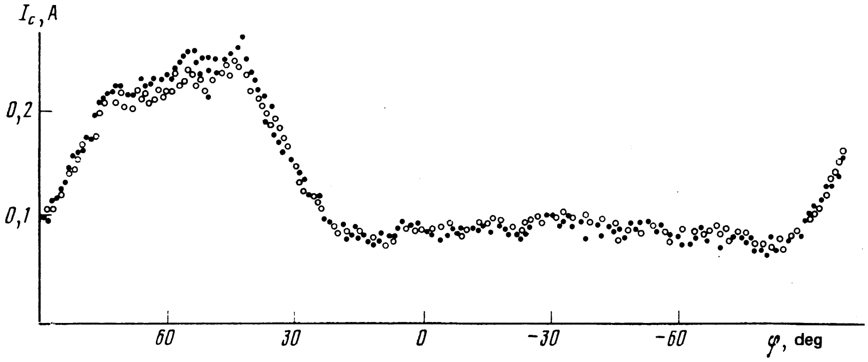

FIG. 5. Orientational dependence of critical current in a Nb single-crystal with "decorated boundary" (symbols as in Fig. 1).

disorientation of the bicrystal and with the orientation of the separate crystals. We have already reported[15] on the singularities of the $I_c(H)$ curve near H_{c2}.

The field dependence for specimens with symmetrical boundary inclination ($\theta = 100°$) differs both from $I_c(H)$ for a single-crystal specimen and from $I_c(H)$ for specimens with asymmetrical boundary in that sections exist with small growth of I_c or with a plateau in weak fields (Fig. 6c). An especially noticeable and important difference is the high critical current in fields above $H_{c2\,\max}$. An increase in critical current beyond H_{c2} could be observed in these specimens only for a magnetic field parallel to the boundary and for a current direction corresponding to the maximum[3)] I_c. The critical currents in these bicrystals decrease to the usually observed values of the surface critical current only in a field $H \approx 3450$ Oe at 4.2 K, while for Nb of this purity $H_{c2\,\max} = 2860$ Oe.

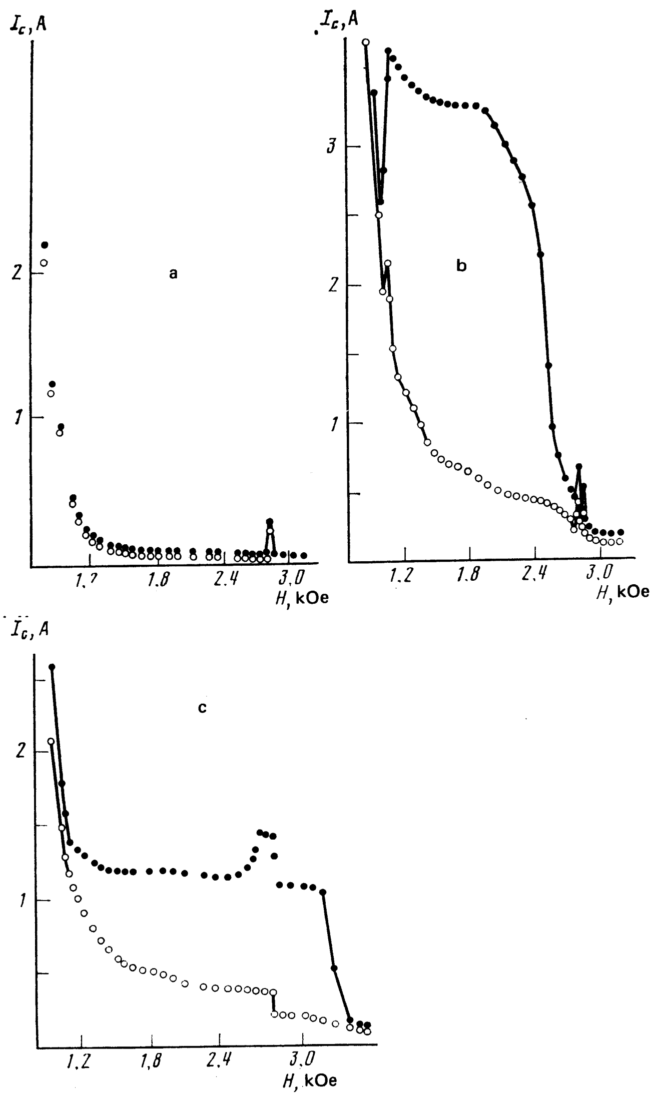

FIG. 6. $I_c(H)$ dependence for: a—Nb single-crystal, $\nu = 270$; b—bicrystal with asymmetrical tilt boundary $\theta = 20°$ at $\varphi = 0°$; c—bicrystal with symmetrical tilt boundary $\theta = 100°$ at $\varphi = 0°$.

The temperature dependences of the critical current were measured both at the maximum of the peak ($I_{c\,\max}$) and far from it ($I_{c\,\mathrm{bgrd}}$). To separate out as much as possible the temperature dependence of the pinning by the boundary from the temperature dependence of the background pinning, $(I_{c\,\max} - I_{c\,\mathrm{bgrd}})(t)$ plot for one and the same relative field is shown in Fig. 7. It should be noted that the observed nonmonotonic $I_c(t)$ dependence in the intermediate temperature region is typical only of pinning by a boundary. No such singularities were observed for $I_{c\,\mathrm{bgrd}}(t)$.

3.4. Dependence of the maximum critical current on the disorientation angle in a bicrystal

Table I shows results of measuring the maximum critical current (at $T = 4.2$ K) for bicrystals with asymmetrical boundary tilt, when the magnetic field is parallel to the boundary ($\varphi = 0$), with the specimens cut out along the tilt

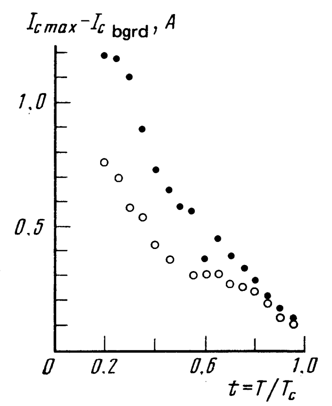

FIG. 7. Temperature dependence of critical current in a Nb bicrystal with $\theta = 15°$. $h = 0.85$ (symbols as in Fig. 1).

TABLE I.

Symbol and disorientation of the bicrystals	γ	$I^+_{c\,max}$, A	I_{c0}, A	$I^-_{c\,max}$, A	$I^+_{c\,max}-I_{c0}$, A	$\delta(H_{c2})/\delta(H_{c2})_{max}$ [16]	$\delta(\Delta)/\delta(\Delta)_{max}$ [16]	$f_p(1)$, N/m	$f'_p(3)$, N/m	$f''(4)$, N/m
B_1—5°	230	0.48	0.1	0.3	0.38	0.16	0.02	$4.0\cdot10^{-6}$	$2.8\cdot10^{-6}$	$9.7\cdot10^{-7}$
B_2—5°	230	0.64	0.29	0.59	0.35	0.21	0.04	$3.8\cdot10^{-6}$	$3.0\cdot10^{-6}$	$1.9\cdot10^{-6}$
B—15°	320	1.55	0.28	0.75	1.27	0.43	0.19	$1.4\cdot10^{-5}$	$7.4\cdot10^{-6}$	$9.7\cdot10^{-6}$
B—20°	250	2.5	0.08	0.48	2.42	0.5	0.27	$2.6\cdot10^{-5}$	$8.7\cdot10^{-6}$	$1.4\cdot10^{-5}$
B_1—25°	250	0.26	0.07	0.18	0.19	0.78	0.12	$2\cdot10^{-6}$	$1.35\cdot10^{-5}$	$5.9\cdot10^{-6}$
B_2—25°	250	0.47	0.08	0.27	0.39	0.84	0	$4\cdot10^{-6}$	$1.45\cdot10^{-5}$	0

*A number of specimens with small disorientation angles from 2 to 5° were measured as well as those shown. They were cut perpendicular to the tilt axis (as in Ref. 10) but with small inclination of the bicrystal growth axis from the exact ⟨110⟩ orientation. The values for them of $I^+_{c\,max} - I_{c0}$ were lower than the levels shown in the table for the first crystals.

direction.[10] The orientation of the magnetic field relative to the crystals and the disorientation angle θ are shown schematically in Fig. 8, where polar diagrams are given of the upper critical field H_{c2} and of the energy gap Δ.[16] In addition, results are given in the table for the relative residual resistance γ and for I_{c0}, the corresponding background level in the angular dependence $I_c(\varphi)$; $I^+_{c\,max}$ and $I^-_{c\,max}$ correspond to opposite directions of current flow. The values of I_{c_0} were calculated by averaging the critical currents measured over the interval $-180°$ to $+180°$ in 1° steps, except for a 30° range near the peak. The quantity $I^+_{c\,max} - I_{c0}$ is a measure of the pinning by the bicrystal boundary. Values of $\delta(\Delta)/\delta(\Delta)_{max}$ and $\delta(H_{c2})/\delta(H_{c2})_{max}$ were calculated from the diagram in Fig. 8. for certain directions parallel to the grain boundaries in the bicrystals studied.

The pinning force at a bicrystal boundary per unit flux-line length can be determined from the relation[7]

$$f_p=(I_{c\,max}-I_{c0})Ba_0/D, \tag{1}$$

where B is the induction, $a_0\approx(\Phi_0/B)^{1/2}$ is the vortex lattice parameter, $\Phi_0\approx 2\times10^{-15}$ Wb is the quantum of magnetic flux, and D is the specimen diameter. The values of f_p are shown in the table for $h=0.85$.

4. DISCUSSION

1. As has been shown,[17] the interaction of a vortex lattice with a grain boundary vanishes in an infinite specimen

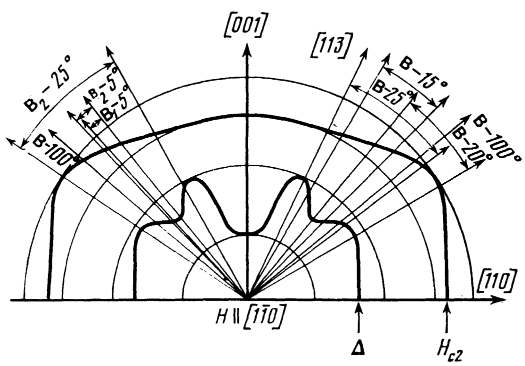

FIG. 8. Polar diagrams of H_{c2} and Δ vs direction in the (1$\bar{1}$0) plane.[16] The arrows indicate the directions in this plane parallel to the grain boundaries for the bicrystals studied (see Table I).

for however small an inclination of the plane of the boundary to the magnetic field direction. In this case, any change in position of the vortex lattice relative to the boundary leads to no change in the specimen's free energy in a magnetic field. In a specimen of finite dimensions there is always some interaction-angle interval connected with the finite vortex dimensions and with the elastic properties of the vortex lattice. It is just the existence of this interaction-angle interval which leads to the experimental possibility of observing pinning produced by a bicrystal boundary.

The half-width of the peak is determined by the curvature of the boundary and the elastic properties of the vortex lattice. For a given boundary in a specimen the half-width is related to the "adjustment" of the flux line to the boundary, i.e., it is larger the smaller the stiffness (the elastic moduli) of the vortex lattice. Qualitatively the dependence of half-width on applied field and on temperature agrees with the corresponding changes in the flexural modulus C_{44} of the vortex lattice. The experimentally observed variations of this angular interval [the peak half-width in the $I_c(\varphi)$ plot] as h and t change confirm the assertion made above. For example, as the field increases, C_{44} increases like BH (Ref. 18) and can decrease again only in fields very close to H_{c2} (Ref. 19). As can be seen from Fig. 2, we actually observed a reduction in half-width with increasing h. As the temperature is lowered in a given applied field, C_{44} increases like $H^2_{c2}(t)$. This corresponds experimentally to a reduction in the half-width of the peak of the $I_c(\varphi)$ curve in Fig. 3. The effect of adjustment of the vortices to the boundary is shown also by the small shift in the position of the maximum of the peak with change of h and t. The effects noted may be related not only to a change in the flexural modulus C_{44} but also to a change in the elementary pinning force.

If, however, C_{44} decreases with decreasing h and t, to which a broadening of the $I_c(\varphi)$ peak corresponds, the elementary pinning force in the first case increases and in the second decreases, as will be seen from the model discussed below. Over the interval of variation of h and t considered, a change takes place, comparable in magnitude, in the half-width of the peak, while the shift in the maximum of the peak is appreciably greater when h is varied. Comparison of these results shows that the broadening of the peak is mainly connected with a reduction in the modulus C_{44}, while the shift in position of the maximum is produced both by a reduction in C_{44} and by an increase in f_p.

2. The pinning of the core of a vortex line is appreciable in type-II superconductors with small values of the parameter κ of the Ginzburg-Landau (GL) theory, and is $8/\kappa$ times larger than the electromagnetic pinning of the vortex cloud.[18] Under the action of the mechanism of the pinning by the grain boundaries, connected with the anisotropy of the superconducting properties (the action of just this mechanism was demonstrated by direct experiments[10]), the pinning of the vortex core is related to a change in the condensation energy, i.e., to a change in core dimension ξ. It can be deduced from the relation $\Phi = 2\pi\xi^2 H_{c2}$ of the GL theory that the change in correlatoin length ξ follows the change in H_{c2}. It is not quite clear why the maximum critical currents (see Table I) correspond better to the change in energy gap Δ than to the change in upper critical field H_{c2}.

If we consider that pinning in our situation is due to a change in free energy of the vortex core, then by transforming Eq. (7.12) of Campbell and Evetts[18] we find that the elementary pinning force in our case

$$f_p = {}^1/_2 \pi\mu_0 H_c^2 \delta(\xi)(1-b) \tag{2}$$

should be directly connected with the change in ξ, i.e., with H_{c2} and not Δ. The discrepancy noted between the results and this simple relation does not invalidate the main conclusion reached from a comparison of the maximum critical currents (see Table I), namely, that the critical current depends on the relative disorientations of the crystals. Since an electron-microscope comparison of bicrystal specimens with different disorientation showed the absence of any pronounced difference in their structure up to a resolution of 30 Å, it must be concluded that in our situation pinning is only connected with a change in the superconducting parameters on passing through the bicrystal boundary.

The action of the pinning mechanism associated with anisotropy of the superconducting properties is also confirmed by a comparison of the temperature dependences of the maximum critical current, Fig. 7, with the temperature variation of the maximum anisotropy of H_{c2}. We found that the $(\Delta H_{c2}/\langle H_{c2}\rangle)(t)$ dependence was nonmonotonic in the same temperature interval as $(I_{c\,\max}(t))$ in Fig. 7.

It is evidently possible to reconcile the above disparity by taking direct account of the variation in ξ in an anisotropic material.[20] The order of magnitude of the critical current connected with pinning by a grain boundary can be obtained from the relation for the difference in condensation energy,[18] rewriting it in a form with an explicit dependence on the anisotropy of H_{c2}. The elementary pinning force is

$$f_p' = \pi\mu_0 \left(\frac{\langle H_{c2}\rangle}{\sqrt{2}\,\varkappa}\right)^2 \xi(1-b)\,\frac{\delta(H_{c2})}{\langle H_{c2}\rangle}. \tag{3}$$

Pinning by the boundary in a bicrystal of an anisotropic superconductor, on the other hand, can be formally considered as pinning by the boundary separating two different superconductors.[18] The pinning force should be proportional to the difference $\delta(H_c^2/8\pi)$ of condensation energy in the two crystals, which in this case can be considered to be proportional to the difference in the energy gap $\delta(\Delta)$.[21] The elementary pinning force per unit vortex length is

$$f_p'' = \pi\mu_0 H_c \delta(H_c)\,\xi(1-b). \tag{4}$$

For Nb at 4.2 K we have $H_c = 1550$ Oe and $\xi = 4.5\times10^{-8}$ m. The value of H_c was calculated from results[16] on $\delta(\Delta)/\delta(\Delta)_{\max}$, given in Table I which also shows results of calculating f_p'' according to Eq. (4).

3. The existence of a change in superconducting properties, in particular H_{c2} or Δ, on passing through the boundary is thus necessary for observing vortex pinning by the boundary. However, as indicated above, we have come upon cases when this experimental rule does not hold. The $I_c(H)$ dependence shown in Fig. 6b turned out to be typical of pinning in these situations, with one important singularity, namely high critical currents in fields above H_{c2}. An increase in critical current in these specimens was only observed for a magnetic field strictly parallel to the boundary.[4)] We thus have a basis for concluding that alongside a grain boundary there is an associated localized superconducting state. Such a localized state was recently observed on twin boundaries in tin.[22] In this case pinning for superconducting-region dimensions $\gg\xi$ must be connected with the pinning of flux lines at the boundaries of such a region. We have observed an increase of the critical field for specimens with a symmetrical tilt boundary inclined at 5° to the exact twinning position. It should be remembered that similar features in the $I_c(H)$ dependence at fields above H_{c2} were observed[7] in bicrystals with symmetrical tilt boundary and disorientations of 9 and 16°. The authors related the smearing of the transition at H_{c2} to the existence of a region of impurity segregation near the boundary.

4. As had been pointed out, a strong dependence of the maximum critical current on its direction was found in all experiments. Such a situation could probably be explained by the accepted model of pinning of the vortex core with a step-function form of the pinning potential if an absolute asymmetry of the effect were observed (i.e., if pinning were observed for one direction and not for the opposite direction).

A possible explanation of the observed partial asymmetry of the effect is as follows: If the boundary is absolutely straight and the current flows along it,[17] such a current flow along the plane will produce a generally uniform change in the magnetic field (Fig. 9a), and the free energy of the vortex and its energy gradient at the boundary can consequently change, while the shape of the barrier remains as before. However, if the boundary is not macroscopically flat and the current flows only along separate sections of the λ "crust" the magnetic field produced by the current along the boundary will in this case decrease with distance and will change the pinning potential locally as shown in Fig. 9b. The fact that the influence of the current can be sufficiently large can be seen from simple estimates. Even a current of 1 A uniformly distributed over the diametral plane of a specimen ($D = 2$ mm) leads to a change in H by 6 Oe. Such a jump in field can be quite comparable with that observed due to an-

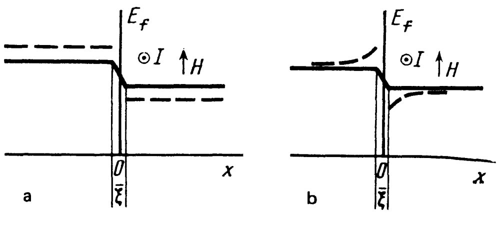

FIG. 9. Change in pinning potential (the dependence of the energy of a single vortex in a magnetic field on the distance from the grain boundary) when the intrinsic field of the transport current is taken into account. The dashed line shows the deformation of the pinning potential by the current: a—uniform current flows along the whole boundary; b—owing to the nonuniformity of the grain boundary, the current flows only in a small channel along it.

isotropy of H_{c2}. As can be seen from Fig. 9b, such a potential well deformation by the intrinsic field of the current should not possess absolute asymmetry of its restoring force. The deformation of the pinning potential and consequently the reduction of the asymmetry of the critical current will in this case be more appreciable the smaller the longitudinal region of transport current flow, i.e., the stronger the curvature of the grain boundary.

5. CONCLUSIONS

The discussion above of the observed experimental angular interval for interaction of flux lines with grain boundaries is especially relevant when considering critical currents in an anisotropic polycrystalline specimen with random orientations of the grains relative to the direction of the magnetic field. As has been shown,[9] the critical current in this case is appreciably higher than that obtained from the model of pinning by small spherical zones of boundaries parallel to the magnetic field. The correspondence established between the flexural modulus and the conditions for interaction of the vortex lattice with grain boundaries can be useful for explaining I_c in polycrystalline specimens of anisotropic superconductors.

The main arguments advanced in Ref. 7 in favor of a negligible influence of pinning grain boundaries as a result of the anisotropy of superconducting properties were the specific specimen geometry which cannot accomodate the action of this mechanism, and also the qualitative and quantitative disagreement between the theoretical and experimental pinning potentials. As can be seen from the investigation described above, special pinning conditions can be realized in the specimens of Ref. 7, which have symmetrical tilt boundaries, this owing to formation of localized superconducting states along such boundaries. The resultant critical currents are comparable with those associated with pinning by the anisotropy mechanism realized in bicrystals with arbitrary boundary orientation; this mechanism plays apparently the most significant part in the pinning of vortices in polycrystalline specimens. A specific consideration of the observed qualitative and quantitative features of vortex pinning by bicrystal boundaries indicates agreement with the model based on anisotropy of the flux vortex core energy.

[1)] The critical current for pinning by niobium hydrides depends on the degree of dispersion of these particles and can vary considerably at rapid rates of cooling.[14]

[2)] In such bicrystals the corresponding directions in the crystals are turned through various angles relative to the plane of the boundary.

[3)] Since the specimens studied were of pure niobium with roughly the same resistance ration, γ, the small variation of H_{c2} is mainly connected with the anisotropy of H_{c2} and has no bearing on the strong effect described.

[4)] If the discussion that follows is valid, the angular interval for observing this effect should correspond to the angular interval for strong pinning. In the present case it is $\sim 1°$.

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