Current-carrying capacity of superconducting $YBa_2Cu_3O_{7-\delta}$ films in strong magnetic fields

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Properties of polycrystalline $YBa_2Cu_3O_{7-\delta}$ films were investigated in strong magnetic fields $H \leqslant 40$ kOe. In the range $H \leqslant 0.3H_{c2}(T)$ the current-carrying capacity of these films was governed by a bulk force pinning vortices at boundaries of misoriented crystallites. In the range $H > 0.3H_{c2}(T)$ the pinning force set the limit to shear deformation of the vortex lattice.

The first investigations of the electric-current characteristics of bulk $YBa_2Cu_3O_{7-\delta}$ (YBCO) ceramic samples have revealed low (not exceeding $j_c \sim 10^2$–10^3 A/cm^2) values of the critical current density at liquid nitrogen temperature and a strong dependence of this density on the applied magnetic field.[1] The majority of the authors tend to assume that such samples are three-dimensional Josephson media in which the superconducting order parameter varies with position and the weak links are either grain boundaries or twinning planes.[2,3] These microstructure defects are found to play the dominant role also in the formation of the superconducting glassy state.[2,4] The possibility of achieving high values of j_c in the absence of weak links in a sample is suggested by the experimental values of the magnetization,[5,6] because an analysis of these results in accordance with the Bean model, allowing for the real size of grains in the investigated ceramic samples, yields a maximum value of the current-carrying capacity of YBCO amounting to $j_c \sim 10^6$ A/cm^2, which is much higher than the values found by direct measurements of the current.

Such high critical current densities can be achieved in direct measurements (as deduced from the current-voltage characteristics) only in the case of YBCO films.[6–9] Therefore, films are at present probably the only material for which the magnetic and electrical properties of YBCO can be studied in the mixed state without a significant influence of the effects associated with the presence of weak links (percolation, multiple Josephson effect, etc.). In an earlier paper[10] we demonstrated that the critical current density in YBCO films prepared by laser evaporation and characterized by the superconducting transition temperature $T_c = 85$–91.5 K can exceed 10^6 A/cm^2 at 77 K.

In the present study we used films prepared by the same method to study the behavior of j_c in strong magnetic fields, which provided information on the main type of pinning centers and how they interact with the Abrikosov vortices.

1. PROPERTIES OF SAMPLES AND EXPERIMENTAL TECHNIQUES

We investigated polycrystalline YBCO films on unoriented $SrTiO_3$ substrates. The results of an electron-microscope examination[12] indicated that the films were textured with the **c** axis of a YBCO crystal oriented mainly along the normal to the substrate surface. The degree of orientation was clearly related to the characteristic grain size, which depended on the film deposition regime.

The critical temperature of the superconducting transition in our films was $T_c \approx 86$–89 K, the width of this transition was $\Delta T = 1$–1.5 K, the electrical resistivity before the transition was $\rho_0 = 200$–400 $\mu\Omega\cdot$cm, and the resistivity ratio was $\gamma = \rho_{300}/\rho_0 = 2$–$3$. The required film geometry was produced by photolithography: The width of a strip was $W = 100$ μm, the distance between the potential contacts was $s = 10$ mm (in some cases the measurements were carried out on samples with $s = 2$ mm), and the silver contact areas were formed by vacuum evaporation.

In determining the critical current density by the direct method (current-voltage characteristic) we deduced j_c from the value of the transport current which created a field amounting to 1 μV/cm. All the measurements were carried out in magnetic fields perpendicular to the plane of the film and to the transport current.

Figure 1 shows the resistive superconducting transition curves for a YBCO film of thickness $d = 150$ nm recorded in different magnetic fields. An increase in H not only shifted the $R(T)$ curve toward lower temperatures, but broadened the transition considerably. The rate of change of the second critical magnetic field with temperature dH_{c2}/dT, deduced from the values of the resistance near the transition amounting to $R/R_0 = 0.9$, 0.5, and 0.1, was -33.5 -11.3, and -6.4 kOe/K, respectively. The highest and lowest values were close to those reported for single crystals with different

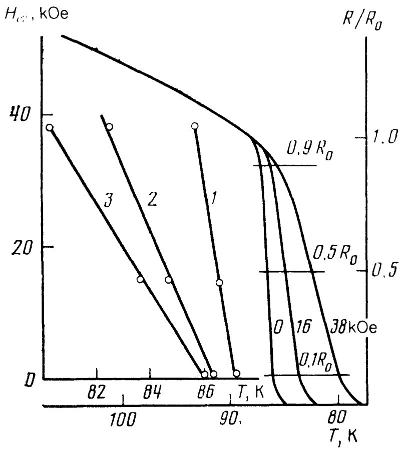

FIG. 1. Superconducting transition curves obtained for a YBCO film in different magnetic fields (0, 16, and 38 kOe). The inset shows the temperature dependences $H_{c2}(T)$ obtained for different values of the junction resistance: 1) $0.9R_0$; 2) $0.5R_0$; 3) $0.1R_0$ ($d = 150$ nm).

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orientations of the basal plane relative to the magnetic field[13]: for the perpendicular orientation of H relative to the ab plane it was found that $|dH_{c2}/dT| + 4.6–7.1$ kOe/K and for the parallel orientation it was -23 kOe/K.

The broadening of the superconducting transition in polycrystalline films observed in a magnetic field could be attributed, as in the case of ceramic samples, to misorientation of the component crystallites characterized by an anisotropy of dH_{c2}/dT. Therefore, the specimen film had a fine-grained structure with a considerable misorientation of the directions of the c axis in neighboring grains. In the case of well-oriented YBCO films evaporated on a (100) surface of the $SrTiO_3$ substrate it was found that broadening of the transition in a magnetic field perpendicular to the surface was much weaker. The ratio of the extreme values of $|dH_{c2}/dT|$ was 2–3 and the "lower" value ≈ 5 kOe/K was retained indicating that the **c** axis of the film was oriented preferentially along the normal to the surface.

Knowing the value of dH_{c2}/dT, we could use the approximations of Ref. 14 to estimate the upper critical magnetic field at zero temperatures:

$$H_{c2}(0) \approx 0{,}69\,|dH_{c2}/dT|\,T_c.$$

In the case of perpendicular and parallel directions of the field relative to the basal plane it was found that $H_{c2}^{\perp}(0) = 382$ kOe and $H_{c2}^{\parallel}(0) = 2000$ kOe. From relationship $\xi = (\Phi_0/2\pi H_{c2})^{1/2}$, where Φ_0 is a flux quantum, we can find the coherence lengths $\xi^{\parallel}(0) = 3.0$ nm and $\xi^{\perp}(0) = 1.3$ nm. Using the expression for the depairing current[15] and allowing for the influence of the geometry of a sample,[16] we can estimate the maximum critical current density for such films:

$$j_c = 0{,}5S^{-1}(15\pi W\lambda_{\text{eff}})^{1/2}\,i_{c0}, \qquad (1)$$

where the linear density of the critical depairing current is[17]

$$i_{c0} = \Phi_0/4\cdot 3^{1/2}\pi^2\lambda_{\text{eff}}\,\xi(T),$$

S is the cross-sectional area of the film; $\lambda_{\text{eff}} = \lambda^2/d$; λ is the depth of penetration of the magnetic field; and d is the film thickness.

The penetration depth λ can be determined most accurately by visualization of Bitter patterns in YBCO single crsytals[17,18] and its value was found to be 200–300 nm. It should be pointed out that in this case the film thickness obeys $d < \lambda$ so that we could use Eq. (1). Assuming $\lambda \approx 250$ nm (representing the average value from Refs. 17 and 18), we found that Eq. (1) yields the critical current densities as follows: $j_c^{\parallel}(0) = 4.47\cdot 10^6$ A/cm^2 and $j_c^{\perp}(0) = 1.95\cdot 10^6$ A/cm^2. Extrapolation of the experimental values of the critical current density to zero temperature (Fig. 2) gave $j_c(0) \approx 5\times 10^6$ A/cm^2 (for a film of thickness $d = 150$ nm and width $W = 100\,\mu$m).

It follows that at low temperatures the specimen YBCO films had the current-carrying capacity close to the physical limit.

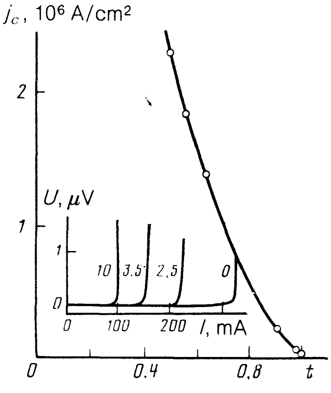

FIG. 2. Temperature dependence of the density of the critical current flowing in a YBCO film. The inset shows typical current-voltage characteristics at $t = T/T_c = 0.65$. The numbers alongside these characteristics are the values of H in kilo-oersted.

2. CRITICAL CURRENT IN A FILM SUBJECTED TO A MAGNETIC FIELD AND PINNING OF VORTICES BY STRUCTURE DEFECTS

Initial parts of the current-voltage characteristics of the specimen films (inset in Fig. 2), used to find the critical current density, can be described by the universal law

$$j(E) = j_c + j_1 \ln(E/E_0),$$

where $j_1 = (0.01–0.03)j_c$ and $E_0 \approx 10^{-6}$ V/m, which is typical of nonideal type II superconductors and is associated with incoherent motion of the Abrikosov vortices.[19] The parts of the current-voltage characteristics corresponding to the viscous flow of the vortices are not observed and this may be associated with the anomalously large values of the Stoeckley parameter $\alpha \approx 10^2–10^3$ (Ref. 19) at $T = 4.2$ K. The nonlinear parts of the current-voltage characteristics, described in high magnetic fields by the dependence $U(j) \propto (j - j_c)^m$ with $m \approx 2$, are followed by an abrupt transition of a film to the normal state as a result of heating, which is typical of hard superconductors.[20]

The temperature dependence of j_c (Fig. 2) near T_c is quadratic $j_c \propto (1 - t)^2$, $t \equiv T/T_c$, and cooling results in gradual weakening of this dependence. The temperature dependence of $j_c(T)$ observed for YBCO films has been explained by many authors using the model of a superconductor with weak links of the SNS, SINS, and similar types.[9,21] The main justification of this conclusion is the fact that values of j_c obtained for these films are low and that the dependence $j_c(t)$ is quadratic near $t = 1$.

It is shown in Ref. 10 and it also follows from the above estimate of j_c that for our films the influence of weak links is weak and the value of j_c is close to its physical limit. Moreover, the quadratic dependence $j_c(t)$ is predicted also by other models, such as that of a nonideal type II superconductor with a spatially inhomogeneous distribution of the mean free path of electrons[15] or pinning of vortices because of electron scattering by grain boundaries.[22] Therefore, the dependence $j_c(t)$ obtained for films with a high current-carrying ability is not related to the effects typical of structures with weak links. We shall show later that in the case of polycrystalline YBCO films it is most likely that vortices are pinned at the boundaries of misoriented crystallites,[22] and this can give rise to a dependence of the $j_c \propto (1 - t)^{3/2}$ type.

It follows from Fig. 3 and the results of Ref. 10 that the critical current density in films is much less sensitive to a magnetic field than in the case of bulk samples (see, for example, Ref. 1). Since the critical current is not related to the

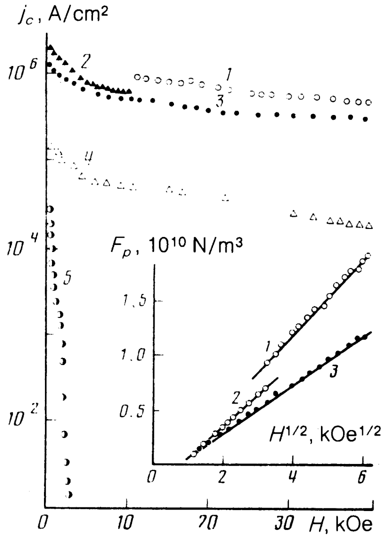

FIG. 3. Dependence of the critical current density on the magnetic field applied to a YBCO film ($d = 150$ nm) at different temperatures: 1) $t = 0.49$; 2) 0.57; 3) 0.65; 4) 0.9; 5) 0.95. The inset shows the dependence of the bulk pinning force on $H^{1/2}$ 1) $t = 0.49$; 2) 0.57; 3) 0.65.

breaking of weak links, but is a characteristic of a given material, an analysis of the $j_c(H)$ curves can give information on the bulk F_p and elementary forces pinning vortex lines to defects of the crystal structure of YBCO.

For $t \ll 1$, the critical magnetic field makes it impossible to determine the complete dependence of the bulk pinning force on the magnetic induction: $F_p(b) \equiv j_c B$, where $b = B/B_{c2}$. A large demagnetization factor for thin films perpendicular to the magnetic fields implies $B = H$, so that we shall replace the magnetic induction with the external magnetic field.

Figure 4 shows the dependence of $F_p/F_p^{\max}$ on b obtained at various temperatures for two films. These traces are bell-shaped, as expected for nonideal type II superconductors. In the range of magnetic fields corresponding to $b < 0.3$ the behavior of $F_p(b)$ can be described by $F_p \propto b^{0.5}$, as demonstrated by the inset in Fig. 3. For a batch of films the power exponent lies within the range 0.5–0.6 and the critical current density in the films thus decreases in a magnetic field in accordance with $j_c \propto B^{-(0.5-0.4)}$.

By analogy with superconducting films made of transition metals, we shall assume that the main pinning centers in YBCO are grain boundaries. At least three mechanisms for the interaction of vortex lines with grain boundaries may result in pinning: elastic interaction between strain fields in the core of a vortex line and defects at a grain boundary, electron scattering at a boundary in combination with changes in the local value of the mean free path of electrons in the boundary, and finally the anisotropy of the superconducting parameters along different crystallographic directions, which is responsible for an abrupt jump at the boundary between neighboring grains.[23]

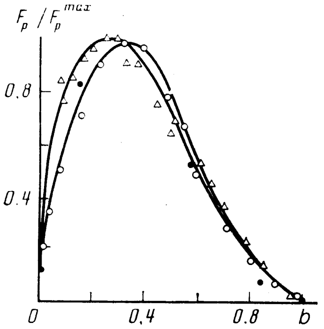

FIG. 4. Dependence of the relative bulk pinning force on the reduced magnetic field: ●) $t = 0.98$; ○) $t = 0.95$ ($d = 150$ nm); △) $t = 0.89$ ($d = 250$ nm).

A purely empirical estimate of the elementary pinning forces due to the last two mechanisms for pinning of vortex lines to grain boundaries is obtained in Ref. 22 (usually the first mechanism is assumed to be weak). It is shown there that both mechanisms give reasonable values of the critical current density subject to magnetic fields. However, it is not very likely that the pinning of vortex lines is due to the electron scattering in the specimen polycrystalline YBCO films.

First, the mean free path of electrons in metal oxides is anomalously short (this follows from the residual resistivity), so that the gain in the condensation energy near a boundary is small, i.e., the gradient of the coherence length ξ at a grain boundary (which governs the strength of the elementary interaction of a vortex line with a defect, i.e., the pinning force) is weak, since $\xi \propto (l\xi_0)^{1/2}$, and the mean free path l inside a grain differs little from its value near the boundary. Second, it follows from our electron-microscopic examination that grain boundaries formed by misfit dislocations are chemically clean and are therefore characterized by a high electrical transparency. It is clear from the results of Ref. 23 that a reduction in the electron scattering coefficient by a grain boundary weakens greatly the elementary pinning force. Third, in the case of pinning at grain boundaries because of the electron scattering the bulk pinning force predicted for low values of b should be proportional to $b^{3/4}$ (Ref. 25). However, as shown in the inset in Fig. 3, we found that $F_p \propto b^{1/2}$.

We can thus assume that pinning of vortex lines at grain boundaries observed in polycrstyalline YBCO films is primarily due to the anisotropy of the superconducting parameters and misorientation of the **c** axes of neighboring grains. Moreover, this mechanism predicts a dependence $j_c(t)$ which is weaker than $(1-t)^2$ far from $t = 1$.

It follows from the theory of pinning that the elementary pinning force j_p may be governed by the difference between the condensation energies in neighboring grains.[26] Moreover, if there is an abrupt change in the coherence length at a grain boundary (in the present case this may be due to the anisotropy of superconducting properties), the elementary pinning force can be described by [22,26]

$$f_p = \frac{B_c^2}{2\mu_0}\frac{\langle \pi\xi_1^2 - \pi\xi_2^2\rangle}{\langle\xi\rangle} = \frac{\pi}{2}\frac{\langle \delta H_{c2}\rangle}{\langle H_{c2}\rangle}\frac{B_c^2}{\mu_0}\langle\xi\rangle, \quad (2)$$

where ξ_1 and ξ_2 are the values of the coherence length in the neighboring grains; δH_{c2} is the change in the upper critical magnetic field passing across a grain boundary; $\langle ... \rangle$ denotes the average value.

The average value $\langle \delta H_{c2}\rangle / \langle H_{c2}\rangle$ can be deduced from the data given in Ref. 13 on the orientational dependence of dH_{c2}/dT for a YBCO single crystal relative to the basal

TABLE I.

d, nm	t	ξ, nm	H_c, kOe	$f_p^{exp}\cdot 10^{-5}$ N/m	f_p, 10^{-5} N/m	$\langle D\rangle_{theor}$, mn
150	0.98	11.8	0.16	0.02	0.11	106
150	0.95	7.5	0.4	0.1	0.44	160
150	0.9	5.3	0.8	0.4	1.3	120
150	0.65	2.8	2.8	2.75	8.2	115
150	0.57	2.5	3.4	3.7	11.2	107
150	0.49	2.3	4.0	4.6	14.4	82
250	0.89	5.0	0.9	0.8	1.4	97

plane ab. Since the temperature dependence of the upper critical magnetic field remains linear for any orientation of **H** relative to the ab plane in the range of magnetic fields and temperatures of interest to us,[13,27] it follows that the required parameter can be described by

$$\langle H_{c2}\rangle\approx(T-T_c)\langle dH_{c2}/dT\rangle,$$
$$\frac{\langle\delta H_{c2}\rangle}{\langle H_{c2}\rangle}\approx\int_0^{\pi/2}\frac{H_{c2}'(\theta)-H_{c2}'(\theta-\pi/6)}{H_{c2}(\theta)}d\theta, \quad (3)$$

where

$$H_{c2}'\equiv|dH_{c2}/dT|,\qquad T=T_c,$$

and θ is the angle of rotation of the **c** axis between two neighboring grains. We shall assume approximately that the maximum angle θ is 30°. We then obtain $\langle\delta H_{c2}\rangle/\langle H_{c2}\rangle\approx0.3$. The thermodynamic value of the magnetic field is $H_c=\Phi_0/2^{3/2}\pi\xi(T)\lambda(T)$; the values of $\lambda(0)$ and $\xi(0)$ are defined as described above.

Some calculated properties are listed in Table I. We simply mention that the average value $\langle\xi\rangle$ is the coherence length deduced using the data for dH_{c2}/dT in the middle of the superconducting phase transition. It is clear from Table I that the calculated elementary pinning forces are quite close to the experimental values determined from the relationship $f_p=j_c\Phi_0$, $j_c=j_c(B=0)$. The theoretical values of the elementary pinning force are slightly higher than the experimental values; this is probably due to errors in the selection of the central angle of misorientation of the **c** axis between neighboring grains.

It follows from Eq. (2) that in weak magnetic fields the elementary vortex-line pinning force, due to the crystallographic anisotropy of the superconducting properties, is independent of b. An increase in the external magnetic field should reduce the force proportionally to the superconducting order parameter: $f_p\propto(1-b)$ (Ref. 26).

In a sufficiently strong magnetic field, when it is necessary to sum over the elementary interactions, we can use the framework of Ref. 28 to obtain the following results:

$$F_p=\frac{n_p^{1/2}f_p(b)}{V_c^{1/2}}\approx\frac{n_p^{1/2}f_p(b)}{a_0}=\frac{n_pf_p}{a_0(H_{c2})}b^{1/2}(1-b), \quad (4)$$

where $a_0(H_{c2})$ is the period of a vortex lattice at $H=H_{c2}$; V_c is the correlation volume of the vortex lattice[28]; n_p is the distance between the pinning centers.

In the derivation of Eq. (4) it is assumed, as usual, that there is no flexural deformation of the line, so that the correlation length is $L_c=d$; it is assumed that $f_p(b)\equiv f_p/d$ (which is the elementary pinning force along a filament): The correlation radius is postulated to be equal to the period $R_c=a_0$ of a vortex lattice (i.e., strong single-particle pinning perturbations destroy the long-range order of a vortex lattice). In spite of the fact that Eq. (4) gives the bulk pinning force accurately apart from the numerical coefficients, we can use the experimental values of $F_p(H)$ and f_p^{exp} to estimate the average distance between pinning centers, which in this case is related to the average grain size D: $n_p^{1/2}\approx D^{-1}$.

Our estimates (Table I) indicate that $D\approx100$ nm, which is of the same order of magnitude as the result obtained by electron microscopy. Moreover, Eq. (4) gives the correct dependence of the bulk pinning force on b in the range of low values of the magnetic field $b<0.3$.

We can therefore conclude that the mechanism of pinning of vortex lines at grain boundaries because of the anisotropy of H_{c2} can account in a consistent manner for all the experimental data on the current-carrying capacity of polycrystalline superconducting YBCO films.

The behavior of $F_p(b)$ for $b\geqslant0.3$ requires a separate analysis for these films. It follows from the experimental data (Fig. 4) that $F_p(b)\propto b^{1/2}(1-b)^n$, where $1<n\leqslant2$, i.e., the pinning force cannot be described by a linear dependence on $(1-b)$ in the limit $b\to1$, as predicted by Eq. (4).

3. INFLUENCE OF PLASTIC DEFORMATION OF A VORTEX LATTICE ON THE BULK PINNING FORCE

The transition to the resistive state occurring in magnetic fields characterized by $b\to1$ in nonideal type II superconductors may be due to two mechanisms: detachment of vortices from pinning centers and plastic flow of weakly pinned vortex rows.[23] In the former case the bulk pinning force is proportional to the strength of the elementary interaction of vortex lines with defects and its dependence on the reduced magnetic field is governed by the behavior of the elementary pinning force [and by the validity of Eq. (4)]. In the second case the motion of a magnetic flux appears at the moment when the Lorentz force (which is the magnetic pressure force) exceeds the shear strength of a vortex lattice and then we have $F_p\propto C_{66}$, where C_{66} is the shear modulus of such a lattice.

It is shown in Ref. 29 that the field dependence of the shear modulus of a vortex lattice for type II superconductors is of the form ($\varkappa\gg1$ is the Ginzburg–Landau parameter)

$$C_{66}=\frac{B_{c2}^2}{\mu_0}\frac{b(1-b)}{8\varkappa^2}(1-0.58b+0.29b^2). \quad (5)$$

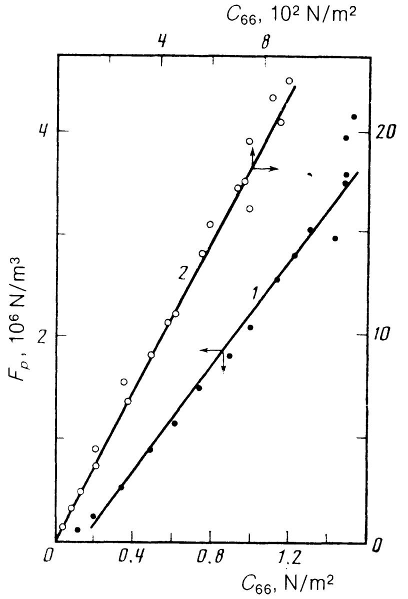

FIG. 5. Dependence of the bulk pinning force on the shear modulus C_{66}: 1) $t = 0.95$ ($d = 150$ nm); 2) $t = 0.89$ ($d = 250$ nm).

Since for all of our samples the bulk pinning force obeyed $F_p \propto (1-b)^n$, where $1 < n \leqslant 2$, we may draw the conclusion that the transition of films to the resistive state in the limit $b \to 1$ occurs in this case in accordance with the second mechanism.

We assume that the pinning centers in polycrystalline films form a channel-like structure parallel to the Lorentz force. At the edges of these channels a vortex lattice is pinned more strongly than in the middle. Therefore, as soon as the Lorentz force exceeds the shear stress for the flow of a vortex lattice, the vortex lines begin to move inside the channels relative to the rigidly pinned vortices at the edges and the superconductor goes over to the resistive state. The bulk pinning force is then governed by the maximum shear stress $F_p = 2\sigma_{\max}/L$, where L is the width of the channel of weakly pinned vortex lines. It follows from the theory of strength of metals that $\sigma_{\max} = C_{66}/2\pi$, so that $F_p = C_{66}/L\pi$ (Ref. 25).

Figure 5 shows the dependence of the bulk pinning force on the shear modulus C_{66} found from Eq. (5). The values of H_{c2} were determined experimentally and $\varkappa$ was deduced from $\varkappa = \lambda(T)/\xi(T)$. The linear dependence $F_p(C_{66})$ demonstrates that the bulk pinning force in superconducting crystalline YBCO films subjected to magnetic fields in the range $b > 0.3$ is governed by plastic shear of a vortex lattice and not by the strength of the elementary interaction with pinning centers. An estimate of the width of weakly pinned channels gives $L = 150$–200 nm, which is of the same order of magnitude as the grain size.

It therefore follows that the specimen films represent a channelled pinning system in which the local values of the pinning force vary over distances proportional to the grain size. In view of the strong inhomogeneity of the microstructure, a pinning lattice can always exhibit weakly pinned channels along which single vortex rows can flow.

We can now draw the following conclusions.

1. The temperature and field dependences of the critical current density in YBCO films prepared by laser evaporation are typical of nonideal type II superconductors and can be described using theoretical models which allow for spatial variation of the mean free path of electrons.

2. Vortices in polycrystalline YBCO films are pinned at grain boundaries and the effect is due to a strong anisotropy of the superconducting properties.

3. In strong magnetic fields the bulk pinning force in polycrystalline YBCO films is governed by shear plastic deformation of a vortex lattice.

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