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CRITICAL CURRENT DENSITY IN SUPERCONDUCTING NIOBIUM FILMS*

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ABSTRACT

We have measured the critical current at 4.2 K in Nb-strips of 1 μ m thickness and different width, w , prepared by electron-beam vacuum-deposition. The substrate temperature during the deposition was varied between room temperature and 800°C. The width of the Nb strips ranged between 20 and 300 μ m. Whereas up to 600°C the different substrate temperatures yielded about the same average critical current density, J_c , (critical current divided by sample cross section) the specimens prepared with 800°C substrate temperature showed a reduction of J_c by a factor of 4-6. In zero applied magnetic field the samples prepared with 400°C substrate temperature or lower showed a decrease of J_c roughly proportional to $w^{-1/2}$. Our critical current data obtained in an applied perpendicular field, for the high-field regime, were compared with Kramer's theory of flux pinning which assumes plastic shearing of the flux-line lattice around individual pinning sites during flux flow.

INTRODUCTION

The breakdown of superconductivity in a type-II material at the critical current density generally results from flux motion and its energy dissipation. The moving flux lines can be generated by the transport current and by an applied magnetic field. At the critical current density the Lorentz-force density starts to exceed the pinning force density and continuous flux motion sets in. We report measurements of the critical current density in superconducting niobium film strips with constant thickness of 1 μ m and different width w as a function of an applied perpendicular magnetic field. Our results for zero applied field may provide information on the distribution of the current density and the magnetic field across the strips in the critical state. Our data for high applied fields are compared with Kramer's recent theory¹ of flux pinning which assumes the plastic shearing of the flux-line lattice around the pinning site during flux flow.

EXPERIMENTAL

The Nb films were prepared by electron-beam vacuum deposition on quartz substrates. They were 1 μ m thick and ranged in width between 20 and 300 μ m. The Nb was deposited at a rate of 100 $\text{\AA}/\text{sec}$ the rate being held constant between $\pm 2\%$. The background pressure during the deposition was $0.5-1.5 \times 10^{-6}$ Torr. A preliminary Ti evaporation served to getter residual gases such as H_2 , O_2 , and H_2O . Samples were prepared at substrate temperatures of room temperature, 200°C, 400°C, 600°C, and 800°C. Specimens with wide end sections for a four-probe configuration were manufactured by photo-etching. The length between the voltage probes ranged between 2.5 and 5 mm. In this way up to four specimens of different width could be obtained from a single Nb film deposited on a 22-mm-diameter substrate.

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The critical currents were measured at 4.2 K with the samples being in direct contact with liquid helium. Data were taken in zero applied magnetic field and also as a function of a perpendicular field. The external field was supplied by a superconducting coil surrounding the sample. The Nb strips were protected against destruction by thermal runaway through a shunt of about 50 m Ω within the liquid He. Except for the case of applied fields close to H_{c2} at the critical current a large fraction of the sample always switched abruptly into the normal state. For a reproducible measurement of the critical current, I_c , it was important to increase the current slowly and to avoid abrupt current variations. Electrical noise from various sources in the laboratory and fluctuations in the sample current were found to be able to trigger the transition into the resistive state. However, with mild precautions I_c was reproducible within a few percent. Data were always taken by increasing the current from zero, and each measurement was repeated several times. Upon setting a new value of the applied field, sometimes the value of I_c was initially relatively low and increased during subsequent current sweeps, reaching a reproducible value after 4-5 runs. Such "training effects" were most pronounced at low fields.

RESULTS

Figure 1 shows the average critical current density J_c (critical current I_c divided by the cross-sectional area of the strip) in zero applied field as function of the width w of the sample for the substrate temperatures of room temperature, 200°C, and 400°C. Although the data scatter considerably, they indicate a trend toward lower values of J_c with increasing w . Figure 2 shows the average critical current density J_c in zero applied field versus the sample width for all substrate temperatures studied. Apparently, up to 600°C the different substrate temperatures yield about the same value of J_c , whereas the samples prepared with 800°C substrate temperature show a reduction of J_c by a factor of 4-6.

In Fig. 3 we show 3 examples of the variation of I_c with an applied perpendicular field. At small fields, I_c decreases about linearly with increasing H . The normalized slope $(\partial I_c / \partial H)_{H=0} / I_c(0)$ for the different samples is listed in Table I. This table also includes the magnetic field H_N at which the Nb films reached the normal state as indicated by their electric resistance. With exception of the 200°C-substrate-temperature sample the magnitude of the slope $(\partial I_c / \partial H)_{H=0} / I_c(0)$ increases with increasing substrate temperature. Apparently, this increase is stronger than the variation of H_N between the different samples. The observed H_N values are much larger than the upper critical field H_{c2} in pure bulk niobium,² indicating a strong enhancement of the Ginzburg-Landau parameter due to imperfections in our Nb films.

DISCUSSION

Critical Current in Zero Applied Field

The decrease of J_c for increasing width of the Nb films, seen in Fig. 1, suggests a non-uniform distribution of current density across the width of the strips. For a strong-pinning type-II superconductor in the critical state the current and field distribution is given by¹

Fig. 1. Average critical current density J_c at zero applied field versus the width w of the Nb strip for three substrate temperatures during the film deposition (room temperature, 200°C, and 400°C). The dotted curve indicates a function proportional to $w^{-1/2}$.

Fig. 2. Average critical current density J_c at zero applied field versus width of the Nb strips for five substrate temperatures during the film deposition.

Fig. 3. Normalized critical current versus the applied perpendicular field for samples Nb 12, Nb 19, and Nb 22.

TABLE I

Specimen width w , substrate temperature, critical current at zero field, magnetic field H_N at which Nb film is completely normal, and the low-field value of the slope $(\partial I_c / \partial H)_{H=0} / I_c(0)$ for different samples.

Sample	Substrate w μm	Temp. °C	$I_c(0)$ A	H_N kG	$(\partial I_c / \partial H)_{H=0} / I_c(0)$ kG ⁻¹
107	49	Room Temp.	2.9	19	-0.17
108	83	Room Temp.	4.2	20	-0.12
4	82	Room Temp.	4.2	12	-0.13
12	76	200	3.5	15	-0.0915
16	325	200	---	16	---
19	93	400	4.1	11	-0.23
22	62	600	2.4	10	-0.25
25	37	800	0.39	9	-4.2
26	64	800	0.59	---	-3.1
27	110	800	1.0	10	-3.5

$$\frac{1}{c}(\mathbf{j}_c \times \mathbf{B}) = \mathbf{F}_p \quad (1)$$

where $\mathbf{j}_c$ is the local critical current density, $\mathbf{B}$ the local flux density, and $\mathbf{F}_p$ the pinning-force density. The Lorentz-force density can be written as

$$\frac{1}{c}(\mathbf{j}_c \times \mathbf{B}) = -\frac{1}{2c} \text{grad}(H^2) + \frac{1}{4\pi} (\mathbf{H} \cdot \text{grad}) \mathbf{H} \quad (2)$$

Even with the simplifying assumption that $\mathbf{F}_p$ is field independent and homogeneous through the volume of the superconductor, a rigorous theoretical treatment of the current and field distribution from Eqs. (1) and (2) is difficult and requires the numerical solution of the coupled differential equations for the different vector components of $\mathbf{H}$. (Note that we are dealing with zero applied field.) We refer to the geometry of a long flat strip of width w and thickness d , oriented in y -direction, the wide and narrow dimension of its rectangular cross-section pointing in x - and z -direction, respectively. The origin is placed in the center, and both sample edges coincide with $x = \pm w/2$. All dimensions are much larger than the penetration depth. A qualitative understanding of the situation may be obtained, if we neglect any curvature of the flux lines in the thin film superconductor and assume that $\mathbf{H}$ has only a component in z - and minus z -direction within the film. We now have a one-dimensional problem with the solutions

$$H_z(x) = \left(\frac{\partial n}{\partial x} F_p \right)^{1/2} \sqrt{x} \quad (3)$$

$$j_c(x) = c \left(\frac{F_p}{2\pi} \right)^{1/2} \frac{1}{\sqrt{x}} \quad (4)$$

and by integration

$$I_c = cd \left(\frac{1}{2} \right)^{1/2} (F_p w)^{1/2} \quad (5)$$

From Eq. (5) we conclude that the average critical current density (I_c divided by cross-sectional area) decreases proportional to $w^{-1/2}$. A function proportional to $w^{-1/2}$ is shown in Fig. 1 by the dotted line and

reasonably represents the trend of the experimental data. Inserting Eq. (5) into Eq. (3) we find for H_z at the sample edge

$$H_z \left(\frac{y}{c} \right) = \frac{2\pi}{cd} I_c \quad (6)$$

Equation (6) yields rather large fields for the critical currents found in our specimens. However, using a magneto-optical method,⁶ we were unable to detect the large fields predicted by Eq. (6). This is not surprising since we have neglected any field component H_z in x-direction in our treatment and a more complete calculation has to be done.

An infinite critical current density at $x = 0$, as indicated in Eq. (4), is of course unphysical, and $j_c(x)$ must be truncated at the intrinsic critical current value. However, this does not seriously affect the result of Eq. (5). Our assumption of a field-independent pinning-force density may be subject to criticism. Various functional forms $F_p(B)$ have been proposed,^{1,11} and different pinning systems will require different functions $F_p(B)$. However, these functions $F_p(B)$ usually show only a weak dependence upon B over a wide range of flux density such that our assumption appears to be not so unreasonable.

A calculation of the field distribution in a type-II superconducting strip with rectangular cross section has been reported by Norris.⁷ However, aside from a center region with zero current and field, Norris assumed a constant current density across the width of the strip up to the edge instead of the (we think more realistic) assumption of a constant Lorentz-force density.

Critical Current for Large Perpendicular Fields and Comparison with the Kramer Theory

Recently Kramer⁸ proposed a theory of flux pinning in hard type-II superconductors for the applied magnetic field regime between zero and H_{c2} . Here we are concerned only with the range close to H_{c2} . According to Kramer's model, at high fields pinned flux lines do not break away from their pinning sites, and flux motion occurs through plastic shearing of the flux-line lattice around the pinning sites. For the pinning-force density Kramer obtained

$$F_p = 2C_p (H_{c2})^{1/2} H_c^2 h^{1/2} (1-h)^2 \text{ dyn/cm}^2 \quad (7)$$

where $h = H/H_{c2}$ and C_p is a constant of value between 0.14 and 0.56 depending on the density of the pinning sites. We have compared the result of Eq. (7) with our experimental data on the critical Lorentz-force density [Eq. (1)] for large perpendicular fields in 7 different samples. The functional dependence of F_p on h always agreed reasonably with that predicted by Kramer. In this comparison we used a computer fitting procedure for obtaining the value of H_{c2} such that a plot of F_p versus $h^{1/2}(1-h)^2$ resulted in a straight line through the origin. The H_{c2} values thus obtained were in general close to the H_N values of Table I. For the samples 107, 108, 12, and 22 the slope of these straight lines agreed well with the theoretical value calculated for the limit of low pinning-site density. For the samples 4, 16, and 19 the slopes were appreciably smaller than expected from Kramer's theory. Here we have taken the value $H_c(4.2 \text{ K}) = 1600 \text{ Oe}$.²

Influence of Substrate Temperature on J_c

The reduction of the average critical current density for the substrate temperature of 4.2°C may be associated with the fact that above 4.2°C oxygen dif-

fuses sufficiently fast through $\text{Nb}^{3,9}$ such that the formation of NbO precipitates acting as pinning sites is largely avoided. Further, at 800°C structural lattice defects present in the Nb films at the lower substrate temperatures may anneal out. Further investigations of the metallurgical microstructure are required for clarifying this point.

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