RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 42, NUMBER 13 1 NOVEMBER 1990

Twin-boundary effects on flux entry and lower critical fields in single-crystal $YBa_2Cu_3O_{7-\delta}$

A. Umezawa*, G. W. Crabtree, U. Welp, W. K. Kwok, and K. G. Vandervoort†
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

J. Z. Liu
Department of Physics University of California, Davis, California 95616

(Received 3 August 1990)

We report measurements of the field of first magnetic flux entry and the derived values of the lower critical field H_{c1} for different orientations of the applied field with respect to the twin boundaries. For a field orientation perpendicular to the twin boundaries, increased values of H_{c1} are found. The results are interpreted in terms of an increased vortex creation energy when the vortex intersects a twin boundary. In an untwinned crystal, H_{c1} saturates at low temperatures, in agreement with measurements of penetration depths from other experiments. We find no significant *a-b* anisotropy in H_{c1} in the untwinned crystal.

In $YBa_2Cu_3O_{7-\delta}$, the existence of twin boundaries has been discussed as having a significant effect on superconducting properties. Magnetization measurements have found a difference for the magnetic field parallel and perpendicular to the twin planes.[1] Transport measurements[2] and magnetic torque measurements[3] have found significant flux pinning by the twin boundaries for **H** parallel to the twin planes. Theoretical and experimental papers have discussed the effect of twin planes on the upper critical field.[4-7] In this paper, we present the temperature dependence of the flux entry field in twinned and untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$. We find that H_{c1}, defined from the initial deviation of the magnetization curve from linearity, is dependent on the twin-boundary orientation *at all temperatures.* We interpret these results as an increased vortex creation energy in the presence of twin boundaries rather than as a pinning behavior.

Three single crystals of $YBa_2Cu_3O_{7-\delta}$ with different twin characteristics were chosen for magnetization measurements. All the samples were platelike with the *c* direction normal to the plate and with dimensions approximately 1.0–3.0 mm in the plane of the plate and approximately 0.2 mm thick. One crystal had twin boundaries running along both the $\langle 110\rangle$ and $\langle \bar{1}10\rangle$ directions (designated hereafter as the dual-boundary sample) while another crystal had twins running along only one of the $\langle 110\rangle$ directions (designated as the single-boundary sample). The third crystal had the twins mechanically removed through an annealing process described earlier.[8] All the crystals were of high quality with $T_c \geq 92$ K and had sharp resistive and inductive transitions, similar to those reported earlier.[9] The dual-boundary crystal was the same sample used for dc magnetic measurements of H_{c2}.[9]

Detailed magnetization measurements were taken on a commercial superconducting quantum interference device magnetometer for fields in the *ab* plane of the crystal, at temperatures from 5 to 85 K in 5-K steps. At each temperature, after zero-field cooling, the magnetization was sampled to 1–5-G intervals at low fields and 10–100-G intervals once the curvature in the magnetization became evident. To maximize the resolution in determining the field of first flux entry, the data points were subtracted from a linear least-squares fit of the low-field Meissner region of the magnetization curve. Similar methods were used in our previous measurements of the entry field at 11 K for a single crystal of $YBa_2Cu_3O_{7-\delta}$.[10]

Figure 1(a) shows the magnetization curves for the dual-boundary sample at 10, 45, and 80 K. The initial linear portions of the three curves superimpose upon one another confirming the expected temperature independence of the Meissner slope and the demagnetization factor. The demagnetization factor, *n*, calculated from the slope of the Meissner region of the magnetization curve ranged from 0.06 to 0.15 for the three crystals depending on crystal shape and field orientation. Corresponding values of *n* obtained from ellipsoidal approximations[11]

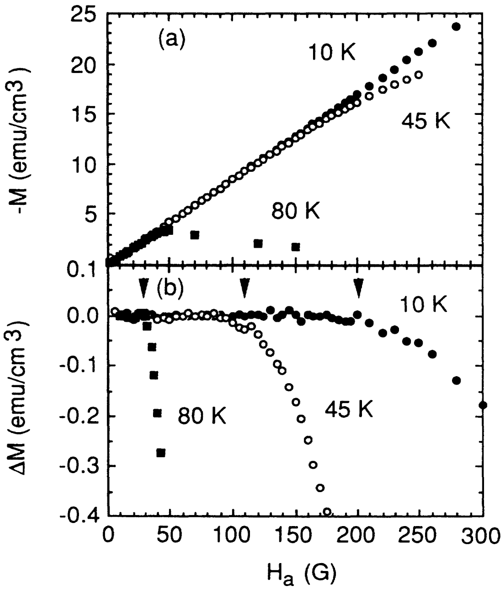

FIG. 1. (a) Magnetization of the dual-boundary sample for **H**‖**ab** for 10, 45, and 80 K. (b) Deviation curve for the above data. The horizontal axis shows the applied field H_a. The arrows indicate the points of deviation from the Meissner state.

ranged from 0.05 to 0.2, in good agreement with those measured from the slope. The low values of n indicate that the effect of sample shape on the measurements of the magnetization and flux entry is minimal.

Figure 1(b) shows the curves corresponding to those in Fig. 1(a), after the linear fit extrapolation of the low-field data was subtracted. The field of first flux entry is chosen as the field where the magnetization first deviates from linearity resulting in a nonzero value of the difference ($\Delta M \neq 0$). Figure 1(b) shows sharper deviations from linearity with increasing temperature, reflecting decreased pinning strength. If H_{c1} is defined as the internal field where the flux first enters the sample and H_e is defined as the applied entry field, then H_{c1} is given by

$$H_{c1} = H_e/(1-n) , \tag{1}$$

where n is the demagnetization factor.

The temperature dependence of H_{c1} for the dual-boundary and untwinned samples is shown in Fig. 2. For the dual-boundary sample, the temperature dependence of H_{c1} does not show a BSC-like behavior, as was discussed in a previous paper.[12] Instead, H_{c1} increases steadily with decreasing temperature with no indication of saturation at low temperatures. Similar behavior in the temperature dependence of H_{c1} has been observed by others who have measured magnetization on single crystals and oriented polycrystals of $R\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ ($R=$ rare earth).[13–16] H_{c1} can be related to the penetration depth λ by the equation

$$H_{c1} = (\phi_0/4\pi\lambda^2)\ln\kappa , \tag{2}$$

where κ is the Ginzburg-Landau parameter. Thus an anomalous temperature dependence in H_{c1} should also appear as an anomalous behavior of λ. However, measurements of λ by muon spin rotation (μSR),[17,18] rf penetration,[19] and the temperature dependence of M at low fields,[20] on single crystals and oriented polycrystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ find that λ follows a more conventional saturating behavior at low temperatures. No explanation of this discrepancy in the temperature dependence of H_{c1} and λ has yet been given.

Figure 2 shows measurements of the H_{c1} for **H**$\|$**a**, **H**$\|$**b**, and one angle approximately 45° between a and b (**H** 45°ab) for the untwinned crystal. H_{c1} is lower for the untwinned crystal than for the dual-boundary crystal at all temperature for all three field orientations. The independence of H_{c1} on the field orientation implies no significant a-b anisotropy in the lower critical field, consistent with the absence of a-b anisotropy in the slope of H_{c2} near T_c for an untwinned sample.[8] It should be noted that if the effective-mass anisotropy between the a and b axis is 1.3, as inferred from decoration experiments,[21] the anisotropy of H_{c1} will be 1.14:1. This small difference falls within the resolution of our data and may not be observed.

To observe the dependence of H_{c1} on twin-boundary orientation, magnetization measurements were done on the single-boundary sample with fields parallel, perpendicular, and 45° from the twin planes. As shown in Fig. 3, when the field is parallel to the twin planes, H_{c1} agrees with the untwinned sample. However, when the field is perpendicular or 45° from the twin planes, H_{c1} increases to near that of the dual-boundary sample. If the twin boundaries are regions of easy flux entry, the magnetic flux would enter the sample through the twins before it enters the bulk, thus decreasing the entry field. Such an effect would occur most readily for **H** along the twin planes. The similarity of H_{c1} for **H** parallel to the twin planes and for the untwinned crystal indicates that twin planes are not planes of easy flux entry. This conclusion agrees with earlier measurements of pinning in twinned and untwinned samples.[22]

We now consider if pinning by twin boundaries can explain the enhanced entry fields in the dual-boundary sample. Increased flux pinning due to the twin boundaries would not only increase the apparent entry field but would also broaden the deviation curve for **H** beyond the entry field, as shown in Fig. 1(b) at lower temperature. Figure 4 compares the behavior of the deviation ΔM, for fields parallel, perpendicular, and 45° to the twin boundaries for 30 and 70 K in the single-boundary sample. While the entry field for **H** parallel to the twins is lower than for **H** perpendicular and 45° to the twins, the relative shape of the curves is similar for all three field orientations. In fact, if the deviation curves for **H** parallel to the twins for

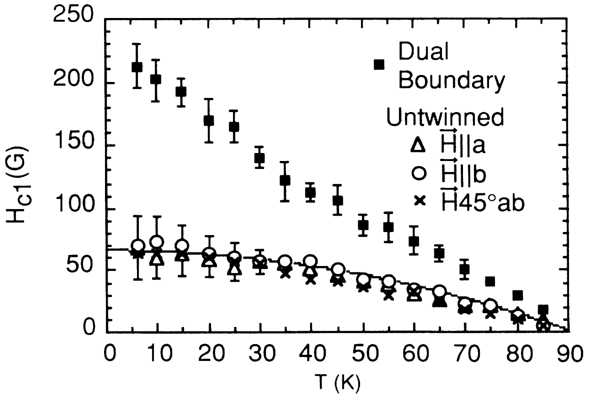

FIG. 2. Temperature dependence of the entry field H_{c1} for the dual-boundary and the untwinned samples. The line is a fit of the data for the untwinned crystal to a $1-(T/T_c)^2$ dependence.

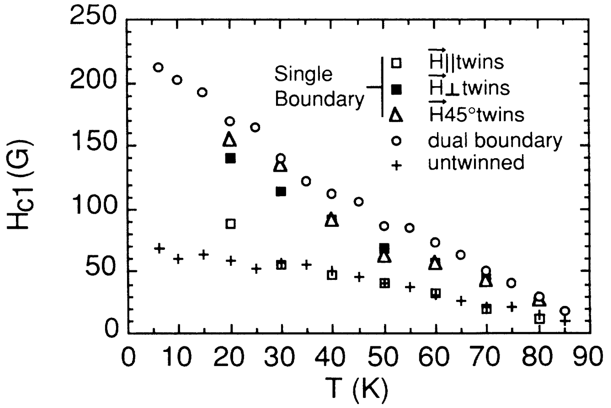

FIG. 3. Temperature dependence of the entry field H_{c1} for the single-boundary sample as compared with that of the dual-boundary sample and the untwinned sample for **H**$\|$**a**. Pinning was too strong at 10 K to make reliable measurements in the single-boundary sample.

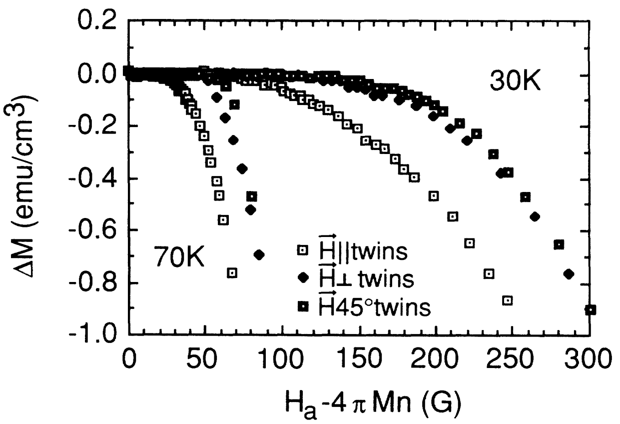

FIG. 4. The deviation curves of the single-boundary sample as a function of the internal field oriented parallel, perpendicular, and 45° to the twins for 30 and 70 K.

30 and 70 K were shifted up in field by 60 and 20 G, respectively, they would fit the deviation curves for the other field orientations quite well. This indicates that the difference observed in the entry fields is not caused from a significant difference in flux pinning at low fields. At high fields, Kwok *et al.*[2] and Gyorgy *et al.*[3] found pinning to be strongest for **H** parallel rather than perpendicular to the twins. If this trend holds at low fields as well, pinning would increase the value of the entry field for **H** parallel to the twin boundaries, exactly opposite to the effect we observe. Thus the enhanced values of the entry field for **H** perpendicular to or 45° from the twin boundaries are not consistent with expected pinning behavior.

We interpret the increase in H_{c1} as an increase in the creation energy of an isolated vortex when crossing a twin plane. When the field is parallel to the twin boundaries, the vortex can avoid the twins by laying between adjacent boundaries. For the intersecting geometry the energy increase would depend on the volume of the vortex–twin-boundary intersection. This feature leads to the approximate equality of H_{c1} for the perpendicular and 45° orientation of the field in the single-boundary sample by the following argument. The volume of the twin-boundary–vortex intersection depends on the density of twin boundaries encountered along the vortex line and on the intersection area of the vortex with each twin boundary. At an arbitrary angle θ, the density of twin boundaries along the vortex is $\cos\theta/L$, where L is the perpendicular distance between twin boundaries. The intersection area is $\pi l^2/\cos\theta$, where l is the characteristic length describing the size of the vortex, either ξ or λ, depending on whether the extra energy is contained in the core or in the circulating vortex currents and the associated magnetic field. The product of these two factors is independent of angle, so long as the vortex is not parallel or nearly parallel to the twin boundaries. One consequence of our interpretation is an observable dependence of H_{c1} on the density of twin boundaries. As we have not yet found a method of controlling the twin-boundary density in single crystals, we have not been able to test this prediction.

The dependence of H_{c1} on the presence of twin boundaries suggests one reason for the large discrepancies among H_{c1} measurements, ranging from approximately 100 to 600 G at $T=0$ K for **H**‖**ab**.[12–16,19,23] In addition, the saturation of H_{c1} at low temperatures in the untwinned crystal removes an obvious qualitative discrepancy in the behavior of the penetration depth measured by μSR,[17,18] rf penetration,[19] the temperature dependence of M in low fields,[20] and the entry field from isothermal magnetization.[13–16] We find that $H_{c1}(T)$ is well described by a $1-(T/T_c)^2$ dependence as shown in Fig. 2, similar to the $1-(T/T_c)^4$ temperature dependence often used to fit μSR, rf penetration depth, and low-field magnetization data. Quantitatively, assuming that $\kappa\sim 100$ and taking the low-temperature value $H_{c1}(0)=70$ G, an estimate of $\lambda^2\sim 10^{-9}$ cm^2 is derived from Eq. (2). Estimates of the penetration depths in the *ab* plane and in the *c* direction[17–20] are approximately 1300–1400 and 5000–8000 Å, respectively, giving a product of approximately $(0.7\text{-}1.0)\times 10^{-9}$ cm^2, in reasonable agreement with the estimate of λ^2 from H_{c1}. Our measurements of H_{c1} in the untwinned crystal are qualitatively similar to those recently reported for $Y_2Ba_4Cu_8O_{16}$, an orthorhombic compound without twins.[24] Martinez *et al.* found that H_{c1} measured from the entry field saturated at low temperature according to a $1-(T/T_c)^2$ dependence, showed no a-b anisotropy, and attained a value of 44 G at low temperature. The similarity of these features to those of untwinned $YBa_2Cu_3O_{7-\delta}$ crystals suggests that the superconducting properties for fields in the a-b plane are similar for these two closely related structures.

In summary, detailed magnetization measurements show that there is an increase in H_{c1} in twinned samples over untwinned samples at all temperatures. In untwinned crystals, within the resolution of our data, there is no a-b anisotropy in H_{c1}. H_{c1} is increased in twinned samples only when the vortex intersects the twin boundary. We attribute the increased values in twinned samples to a larger vortex creation energy in twin boundaries. Finally, the tendency to saturation of H_{c1} at low temperatures removes important qualitative and quantitative discrepancies of this measurement with other estimates of λ.

We thank Professor H. W. Weber for his useful comments regarding this work. This work was supported by the U.S. Department of Energy, Basic Energy Sciences–Material Science under Contract No. W-31-109-ENG-38 (A.U., J.Z.L., G.W.C., W.K.K.) and the National Science Foundation through the Science and Technology Center for Superconductivity under Contract No. STC-8809854 (U.W., K.G.V.). A.U. acknowledges support from the Killam Foundation, the University of Alberta, Canada. K.G.V. acknowledges partial support from the division of Educational Programs, Argonne National Laboratory.

[*] Also at the University of Alberta, Edmonton, Alberta, Canada T6G 2J1.

[†] Also at the University of Illinois at Chicago, Chicago, Illinois 60680.

[1] L. J. Swartzendruber, A. Roitburd, D. L. Kaiser, F. W. Gayle, and L. H. Bennett, Phys. Rev. Lett. **64**, 483 (1990).

[2] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, Phys. Rev. Lett. **64**, 966 (1990).

[3] E. M. Gyorgy, R. B. van Dover, L. F. Schneemeyer, A. E. White, H. M. O'Bryan, R. J. Felder, J. V. Wasczak, W. W. Rhodes, and F. Hellman (unpublished).

[4] A. A. Abrikisov and A. I. Buzdin, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 204 (1988) [JETP Lett. **47**, 247 (1988)].

[5] A. I. Buzdin, B. U. Vujicic, and D. A. Kupstov, Supercond. Sci. Technol. **2**, 249 (1989).

[6] L. I. Burlachov and L. I. Glazeman, Physica C **166**, 75 (1990).

[7] M. M. Fang, V. G. Kogan, D. K. Finnemore, J. R. Clem, L. S. Chumbley, and D. E. Farrell, Phys. Rev. B **37**, 2334 (1988).

[8] U. Welp, M. Grimsditch, H. You, W. K. Kwok, M. M. Fang, G. W. Crabtree, and J. Z. Liu, Physica C **161**, 1 (1989).

[9] U. Welp, W. K. Kwok, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu, Phys. Rev. Lett. **62**, 1908 (1989).

[10] A. Umezawa, G. W. Crabtree, J. Z. Liu, T. J. Moran, S. K. Malik, L. H. Nunez, W. L. Kwok, and C. H. Sowers, Phys. Rev. B **38**, 2843 (1988).

[11] J. A. Osborn, Phys. Rev. **67**, 351 (1945).

[12] A. Umezawa, G. W. Crabtree, K. G. Vandervoort, U. Welp, W. K. Kwok, and J. Z. Liu, Physica C **162-164**, 733 (1989).

[13] J. P. Strobel, A. Thomä, B. Hensel, H. Adrian, and G. Saemann Ischenko, Physica C **153-155**, 1537 (1988).

[14] M. Wacenovsky, H. W. Weber, O. B. Hyunn, and D. K. Finnemore, Physica C **162-164**, 1629 (1989).

[15] Y. Ishikawa, K. Mori, K. Kobayashi, and K. Sato, Physica C **153-155**, 1471 (1988).

[16] H. Adrian, W. Assmus, A. Höhr, J. Kowaleski, H. Spille, and F. Steglich, Physica C **162-164**, 329 (1989).

[17] D. R. Harshmann, L. F. Schneemeyer, J. V. Waszczak, G. Aeppli, R. J. Cava, B. Batlogg, L. W. Rupp, E. J. Ansaldo, and D. Ll. Williams, Phys. Rev. B **39**, 851 (1989).

[18] B. Pümpin, H. Keller, W. Kündig, W. Odermatt, I. M. Savić J. W. Schneider, H. Simmler, P. Zimmermann, J. G. Bednorz, Y. Maeno, K. A. Müller, C. Rossel, E. Kalidis, S. Rusiecki, W. Assmus, and J. Kowalewski, Physica C **162-164**, 151 (1989).

[19] S. Sridar, D. H. Wu, and W. Kennedy, Phys. Rev. Lett. **63**, 1873 (1989).

[20] L. Krusin-Elbaum, R. L. Greene, F. Holtzberg, A. P. Malozemoff, and Y. Yeshurun, Phys. Rev. Lett. **62**, 217 (1989).

[21] G. J. Dolan, F. Holtzberg, C. Feild, and T. R. Dinger, Phys. Rev. Lett. **62**, 2184 (1989).

[22] U. Welp, W. K. Kwok, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu, Appl. Phys. Lett. **57**, 84 (1990).

[23] L. Krusin-Elbaum, A. P. Malozemoff, Y. Yeshurun, D. C. Cronemeyer, and F. Holtzberg, Phys. Rev. B **39**, 2936 (1989).

[24] J. C. Martinez, J. J. Préjean, J. Karpinski, E. Kaldis, and P. Bordet, Solid State Commun. **75**, 315 (1990).