Effect of sample shape on hysteresis loops of $YBa_2Cu_3O_{7-x}$ single crystals

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We have found strong experimental evidence of the dependence of the shape of the magnetic hysteresis loops on the thickness d of $YBa_2Cu_3O_{7-x}$ single crystals when the width over the thickness is much larger than 1. For crystals with similar widths, the full penetration field $\mu_0 H_p$, defined experimentally as the merging point between the virgin magnetization curve and the external envelope, increases as d increases. Similarly, the magnetic-field variation needed to reverse completely the magnetization increases with d. Our data are found to support the theoretical work performed by Clem and Sanchez using the Bean model for thin disks. Reverse legs measured at temperatures up to 70 K and for different reversal fields $\mu_0 H_m$ up to 10 T are described well by this theory.

Different shapes of magnetic hysteresis loops of $YBa_2Cu_3O_{7-x}$ (YBCO) single crystals have been reported so far.[1-5] The critical current density J_c is related to the M-H loop opening (ΔM) within the phenomenology of the Bean[6] critical state model; it is therefore essential to understand the origin of the different shapes observed experimentally to avoid erroneous interpretations. It has been shown that irradiating crystals with protons,[2] neutrons,[4] or ions[5] increases pinning and so does the magnetic hysteresis width ΔM. Accordingly, the full penetration field H_p, defined as the magnetic field at which the virgin curve and the external envelope merge, as well as the field variation ΔH, needed to completely reverse the magnetization, increase in the irradiated samples (in the Bean model, both are proportional to J_c). In this work, we compare the magnetic behavior of two thin YBCO single crystals taken from the same batch. The large differences observed in H_p and ΔH for both crystals could not be attributed to a difference in the pinning capabilities but have been successfully related to differences in the crystal's shape.

The two YBCO single crystals have been obtained by a self-flux method in which a temperature gradient (5 °C/cm) is maintained during the growth. Using yttria-stabilized zirconia crucibles with a reduced growth time leads to the growth of high-quality single crystals. Both crystals are microtwinned and have similar twinning structures. A more detailed description of the growth process as well as characterization, oxygenation, and twinning observation is given in Ref. 7. The crystals investigated here, called hereafter crystals 1 and 2, have $T_c=93.8$ K and $\Delta T_c=0.2$ K. Crystal 1 was 0.6×0.5 mm^2 and 10 μm thick and crystal 2 was 0.9×0.7 mm^2 and 110 μm thick. Thicknesses have been estimated using the mass and the theoretical density of 6.8 g/cm^3. The measurements were carried out on a 12 T vibrating sample magnetometer (Oxford Instrument, model VSM 3001). Samples were first zero-field cooled at the desired temperature, and then a sweeping magnetic field parallel to the c axis was applied, at a rate of 0.5 mT/s.

Figure 1 shows magnetic hysteresis loops up to 12 T at $T=5$ and 60 K for both crystals. We have found that ΔM scales with R, defined in rectangular samples by[8]

$$R=\frac{3}{4}a_y\left[1-\frac{a_y}{3a_x}\right], \tag{1}$$

a_x and a_y being the length and width, respectively.

This scaling with R is expected from the Bean model for a cylinder, where $\Delta M=2J_cR/3$. However, we observe clear differences in the shape of the hysteresis curve

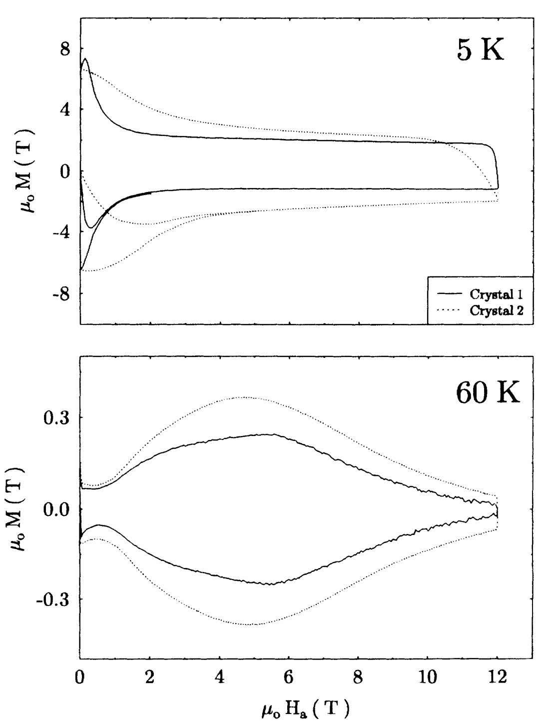

FIG. 1. Magnetic hysteresis loops at the indicated temperatures, for crystals 1 and 2.

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for the two crystals, in particular, the virgin curve, the reverse leg, and a large difference in the related parameter H_p. These differences are unlikely to be explained by differences in pinning characteristics.

We have found that the shape of the crystals was important. As our crystals are thin platelets, the magnetic field, in transverse geometry, wraps the sample and therefore has tangential components of opposite sign on the top and the bottom surface of the sample. Consequently, the critical state can occur through the thickness rather than through the width of the samples.[9–12] The measured magnetization, resulting from an applied magnetic field H_a parallel to the c axis, is produced by current loops of density J circulating in the (a,b) plane around the entire samples. These currents are related to the magnetic field H by the Maxwell equation. This can be written for cylindrical geometry, as follows:

$$J_\theta = \frac{dH_x}{dz} - \frac{dH_z}{dr} . \tag{2}$$

It is clear from the above equation that current loops in the (a,b) plane could lead to either a gradient of the radial component H_r through the thickness (d) or a gradient of H_z through the width of the crystals (characterized by the parameter R). In samples where the ratio $\alpha = R/d \ll 1$, the first term in the right-hand side of Eq. (2) is negligible and $J_\theta \approx -dH_z/dr$, which is usually assumed in the application of the Bean model. However, in thin samples, $\alpha \gg 1$, we find that $J_\theta \approx dH_r/dz$. In the latter case, Clem and Sanchez.[12] have worked out the equations relating the magnetization to the applied magnetic field H_a for thin disks in the Bean model where the critical current density J_c is supposed to be constant. According to these results, the field at which the virgin curve and the external envelope merge, H_p, is approximately $J_c d$ (actually, the difference between the first and the fifth leg of the M-H loop tends asymptotically to zero and the merging point tends to infinity, but, practically when the difference is within the experimental errors, we can assume that the two curves merge; for $H_a = J_c d$, the relative difference between the first and the fifth leg of the magnetization is found to be of the order of 3×10^{-3}). In the other limit, when $\alpha \ll 1$, one finds $H_p = J_c R$. Experimentally, the ratio of the full penetration field H_{p1} of crystal 1 over H_{p2} of crystal 2 is roughly 6 at all temperatures up to 70 K. This value is closer to the ratio of the thicknesses $d_2/d_1 = 11$ rather than to $R_2/R_1 = 1.4$. Hence penetration in these crystals does happen through the thickness rather than radially.

In order to further check the above statements, we concentrated on the second leg of the M-H loop, called hereafter reverse leg. After zero-field cooling to the desired temperature (between 5 and 70 K), the magnetic field is increased up to a maximum value $\mu_0 H_m$ (between 0.1 and 10 T) at which the sample has developed a magnetization M_m. Data were then taken while decreasing the magnetic field down to a field where the magnetization becomes nearly constant reaching the saturation value M_s. Figures 2(a) and 2(b) show an example of the results obtained at 60 K for crystal 2. The reversal field $\mu_0 H_m$ has been varied by steps of 0.1 T up to 1 T and by steps of 1 T up to 10 T but, for clarity, only data up to 5 T are represented.

According to the calculations by Clem and Sanchez,[12] the reverse leg for a thin disk should be given by

$$M_{z\downarrow} = \frac{4}{\pi}\frac{M_s}{H_d}\left[-H_m S\left[\frac{H_m}{H_d}\right] + (H_m - H_a) S\left[\frac{H_m - H_a}{2H_d}\right]\right] , \tag{3}$$

where $H_d = J_c d/2$ is the radial magnetic field at the surface of the sample, $M_s = J_c R/3$ is the saturation value of the magnetization, and $S(x)$ is given by

$$S(x) = \frac{1}{2x}\left[\arccos\left[\frac{1}{\cosh x}\right] + \frac{\sinh x}{\cosh^2 x}\right] .$$

In our case, $H_m \gg H_d$ and, therefore, Eq. (3) could be

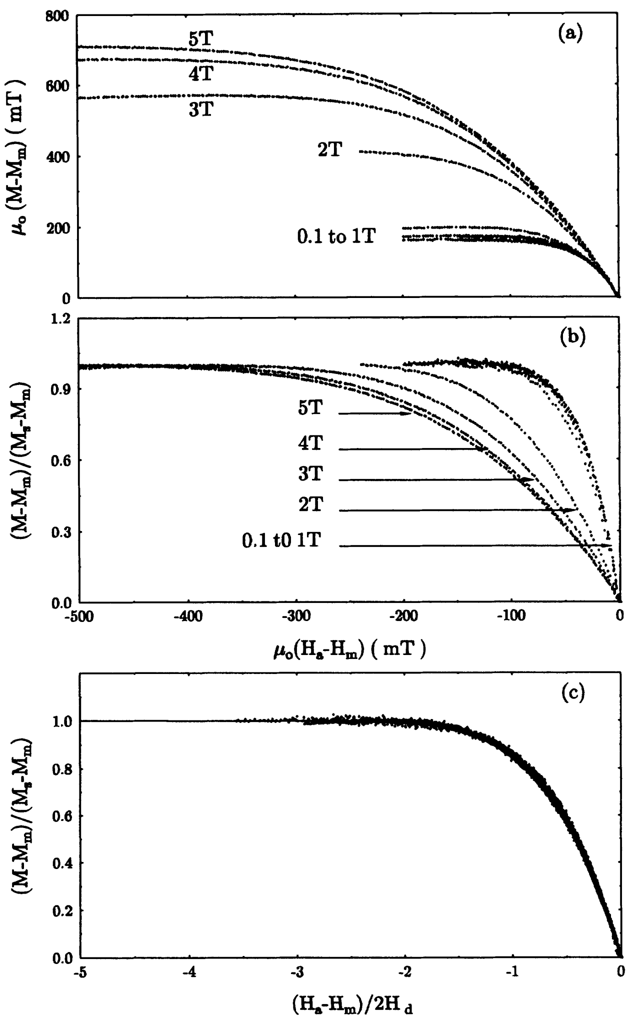

FIG. 2. (a) Magnetic reverse legs at 60 K and at maximum fields $\mu_0 H_m$ from 0.1 to 5 T (from bottom to top) with steps of 0.1 T below 1 T and with steps of 1 T up to 5 T; (b) same as above but the magnetization has been normalized and the maximum field $\mu_0 H_m$ goes from 0.1 to 5 T from right to left; (c) fitted data to theoretical curve in solid line.

written conveniently as follows

$$\frac{M-M_m}{M_s-M_m}=\frac{4}{\pi}xS(x)\ , \tag{4}$$

where $x=(H_a-H_m)/2H_d$.

In their calculations, Clem and Sanchez[12] have assumed J_c constant. At high temperature, this assumption is certainly not valid as the magnetization, and therefore J_c, are field dependent in the crystals investigated. However, as the field variation ΔH needed to reverse completely the magnetization is much smaller than H_m, we can suppose that J_c is constant during the reversing process. In addition, since the M-H loop is symmetrical around the field axis then $M_s=-M_m$. We have found that we can use Eq. (4) to fit our data at all temperatures. To perform the fit, we started from the experimental curves similar to those of Fig. 2(b); we divided H_a-H_m by $2H_d$ where H_d is a value that gives the best fit to the theoretical curve. The experimental results are represented in Fig. 2(c); data result from a fit applied to reverse legs measured at different temperatures up to 70 K and at reversal fields μ_0H_m up to 10 T, for crystal 2 as well as crystal 1; the solid line is the theoretical curve of Eq. (4). Hence at all values of reversal field up to 10 T and temperatures up to 70 K, the reverse leg follows closely the shape given by Eq. (4). According to these results, the shape effect is still important even at high magnetic field and high temperature, where the magnetization is much smaller than the applied field. First, the critical state always occurs through the thickness. Second, in the raw M-H data [as in Fig. 2(a)], the initial slope of the reverse leg is determined by an ideal response keeping the flux change zero. Hence this initial slope is only determined by the shape (the two crystals have shown different initial slopes) and is independent of temperature and field. Correcting the data similar to those of Fig. 2(a) by replacing $[H_a-H_m]$ by $[H_a-H_m-NM(H_a-H_m)]$, where N is the corresponding demagnetizing factor for each crystal, leads to the same initial slope for the two crystals. Note the difference with magnetic materials, where the shape effect or demagnetizing factor becomes irrelevant when the magnetization is much smaller than the applied field.

Values for the parameter H_d have been derived from these fits and in Fig. 3(a) we have shown $H_d(H_m)$ at 60 K for both crystals. In this figure we have used different y axis to represent data of crystals 1 and 2 to make it clear that both crystals lead to the same field dependence of μ_0H_d and differ only by a proportional factor. If the crystals have same value of J_c, this factor would be equal to the ratio of the thicknesses d_2/d_1. According to Fig. 3(a), this ratio is equal to approximately 10. The calculated ratio using the thicknesses leads to $d_2/d_1=11$; the agreement with the previous value is very good. Hence the pinning properties are indeed very similar as we predicted earlier. It is worth mentioning that the shape of the curve in Fig. 3(a) is similar to that of the hysteresis loops at 60 K and as $H_d=J_cd/2$, the so-called fishtail shape of the M-H loops at high temperature effectively results from an increase of the critical current density, J_c, with the applied magnetic field H_a.

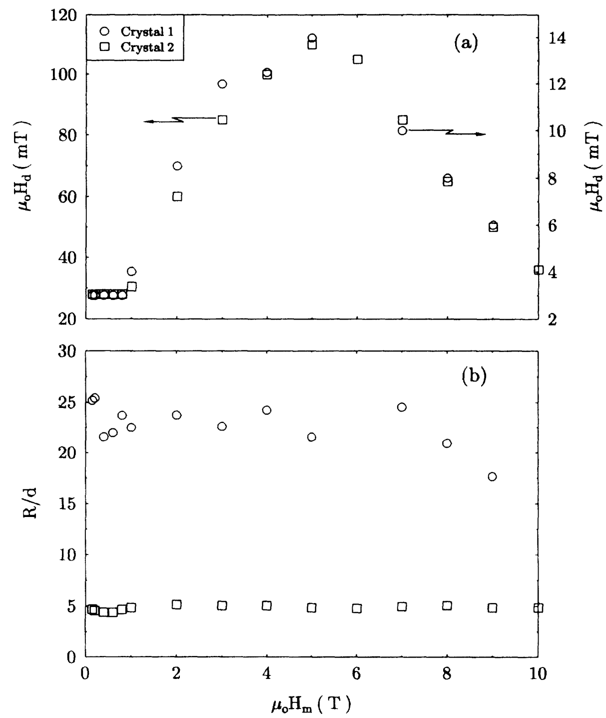

FIG. 3. (a) The fitting parameter H_d as a function of μ_0H_m obtained from reverse legs at $T=60$ K; (b) the parameter $\alpha=R/d$ deduced from data of (a) and Eq. (5) as a function of the maximum field μ_0H_m for both crystals.

In Fig. 3(b) we have given the parameter $\alpha=R/d$ found for different H_m using the fitting parameter H_d and the following relation valid for thin crystals:[12]

$$M_s-M_m=\frac{2}{3}J_cR=\frac{4}{3}\frac{R}{d}H_d\ . \tag{5}$$

We have found α to be field independent as expected and has the value 22 for crystal 1 and 5 for crystal 2. These values are in reasonable agreement with the calculated ones: $\alpha_1=R_1/d_1=27$ for crystal 1 and $\alpha_2=R_2/d_2=3.5$ for crystal 2.

Our measurements clearly demonstrate that flux penetration takes place through the thickness of thin YBCO crystals at all temperatures up to 70 K and magnetic fields up to 10 T. The thickness of single crystals characterized by a large value of the parameter α is shown to play a prominent role: The full penetration field H_p and the magnetic reverse legs are found to depend on d rather than R. The experimental results give strong support to the Bean model calculations for thin disks, performed by Clem and Sanchez. The full penetration field as well as the reverse legs measured at different temperatures up to 70 K, and at reversal magnetic fields μ_0H_m up to 10 T, follow closely the functional dependence predicted in their work.

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