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Effect of crossed flux on flux pinning in YBCO superconductor

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We have conducted magnetization experiments on melt-texture grown YBCO superconductor at 77 K. The magnetic anisotropy and its effects on flux pinning and remanence have been investigated using two pickup coil measuring systems. The remanence along the *c*-axis decreases as the field in the *ab*-plane increases, and the crossed flux magnetization curves merge with the uncrossed one. The decrease of the remanence and flux pinning along the *ab*-plane are discussed in terms of rotation and expulsion of flux, and the possibility of flux cutting.

Key words: *superconductivity; anisotropy of magnetization; flux pinning*

1. Introduction

High-T_c superconductors (HTS) represent an interesting group of substances for both theoretical and experimental investigations. Anisotropy is perhaps the most interesting aspect of the HTS. The layered crystal structure of HTS produces anisotropy in many of their physical properties, such as electrical resistivity, critical magnetic field and magnetization [1–3].

The magnetic properties of the Cu-O layered superconducting compounds are known to reflect the pronounced crystallographic asymmetry. As observed in $Y_1Ba_2Cu_3O_{7-x}$ crystals, not only are the lower and upper critical fields much larger and smaller, respectively, for external fields applied parallel rather than perpendicular to the *c*-axis, but the vortex pinning is also anisotropic, being stronger by far for the vortex line along *c*-axis [4].

The purpose of this study is to observe the effects of crossed remnant flux on the magnetization and hysteresis in a transverse direction using bulk-textured high-T_c material. The study carried out at 77 K, the temperature higher than that in Refs. [4]

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and [5]. Thus we may expect drastic differences in the behaviour of crossed flux, due to the weakening of flux pinning and smaller elastic moduli of the vortex lattice at elevated temperatures [6, 7]. Using two coil arrangement, we monitor the changes in both the longitudinal ($M \parallel H$) components as the field is varied, and compare the hysteresis loops in the crossed and uncrossed conditions.

2. Experimental

The experiments were performed on a family of melt-textured-grown $Y_1Ba_2Cu_3O_{7-x}$ samples. The sample was prepared by the standard method [8] of very slow cooling (not faster than 2 $K \cdot h^{-1}$) through the paratactic temperature, after a partial melting at 1100 °C, for about 30–40 min. After oxygen annealing at 600 °C for 48 h, the sample was cut out in a suitable size, typically 1×4×4 mm^3. The texturing was checked by SEM and XRD. Large, clear grain growth was visible. The sample had a zero-resistance temperature close to 89 K and a sharp diamagnetic transition between 90 and 89 K. All dc magnetization measurements were made at 77 K using a commercial vibrating sample magnometer (VSM). While the longitudinal moment (M_x) was measured with the commercially obtained set of pickup coils, the transverse moment (M_y) was measured with a self-wound set of coils, designed according to Ref. [9]. Each component was measured using a separate lock-in amplifier. The sample vibration was along the z direction, while the field applied along the x direction. By rotating the sample around the z-axis, the c or ab direction can be made parallel to the applied field. The rotational head of the VSM allowed a 1° resolution of orientation. The sample was field cooled at a particular angle Φ with respect to the c-axis in field cooling condition (FC) and also the sample was cooled down at zero field (ZF). The details of the experimental procedure are brought in Chap. 3 for better understanding.

3. Results and discussion

The following chapter is divided into two parts. Section 3.1 describes basic anisotropy effects characterizing the sample, Section 3.2 discusses the effect of a crossed remnant flux on hysteresis curves.

3.1. Anisotropy effects of the sample

The magnetization of HTS is well known to be anisotropic. The effect of this anisotropy can be observed in melt textured sample with well defined directionality of the grains. To quantify the anisotropy, we define the anisotropy ratio as $M^c_{\rm rem}/M^{ab}_{\rm rem}$, where $M^c_{\rm rem}$ is the value of remnant magnetization for a field applied (and later removed) along the *c*-axis and M_{rem}^{ab} is the remnant magnetization for the field along the *ab*-plane. The procedure of determining this ratio was as follows. First, the sample was cooled down to 77 K in zero field (ZF) conditions, then the external field along the *c*-axis was raised to about 4 kOe and then cycled to zero and the remnant magnetization (i.e., the magnetization which is present when $H \to 0$) along this axis was measured. The same procedure was repeated for the *ab*-plane. ure 1 shows the $M(H)$ loops along these respective directions, where curve (a) refers to the *c*-axis and curve (b) to the *ab*-plane. To obtain the anisotropy ratio we divided the value of M_{rem}^{c} at the point A by the value of M_{rem}^{ab} at the point B when $H = 0$. We obtain the anisotropy ratio of about 3.6, while a number close to 4 is reported by Song et al. [10]. The value of 3.6 indicates that our sample is characterized by a high anisotropy of structure and magnetization M_{rem}.

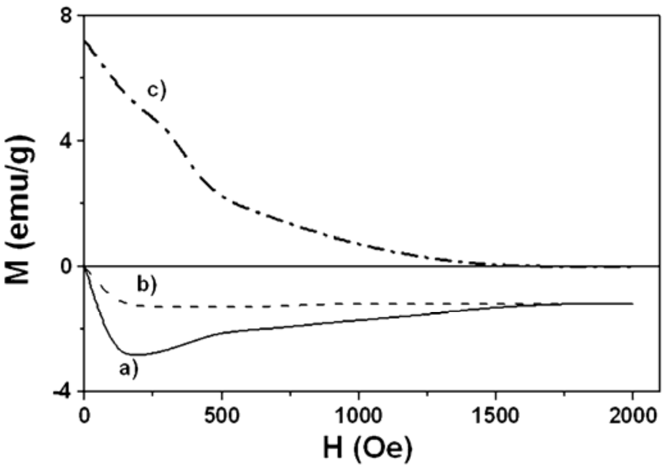

Fig. 1. M(H) loops of $YBa_2Cu_3O_{7-x}$ at T = 77 K in zero field cooling condition: a) along *c*-axis, b) along *ab*-plane

Flux trapping can also show anisotropy of the sample. In order to study the effect of anisotropy on flux trapping, we carried out the following experiment. The sample was cooled down to a low temperature (77 K) in an FC condition for field applied parallel to the *c*-axis ($\Phi = 0$) and for field applied perpendicular to the *c*-axis (parallel to *ab*-plane), $\Phi = 90°$. Then the field was turned off and M_{rem} was recorded. In Figure 2, we have plotted M_{rem}^{c} ($\Phi = 0$) and M_{rem}^{ab} ($\Phi = 90°$) at 77 K as a function of the applied cooling field.

We see that M_{rem}^{c} and M_{rem}^{ab} increase with the increasing magnetic field until the saturation level is reached. This occurs at the field H_{c}^{sat} of about 400 Oe for $\Phi = 0$ and H_{ab}^{sat} 200 Oe for $\Phi = 90°$, i.e. the remanence for $H \parallel c$ attains the maximum value at the field higher than for $H \perp c$. This has been reported by Song et al. [10] on the

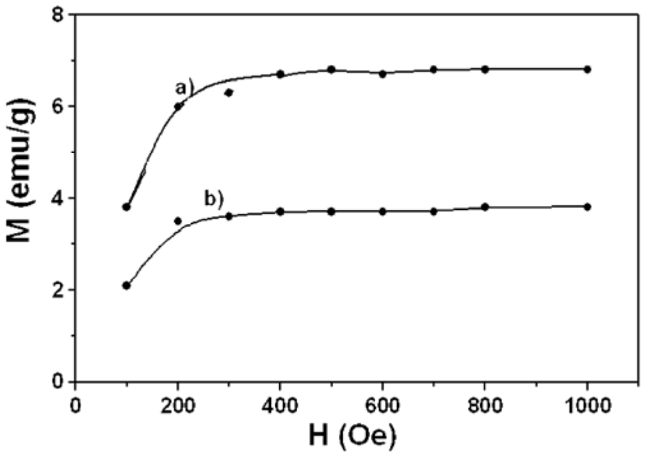

Fig. 2. Remnant moment against cooling field H_{FC} for the field along: a) the c-axis (M^{c}_{rem}), b) along the ab-plane (M^{ab}_{rem})

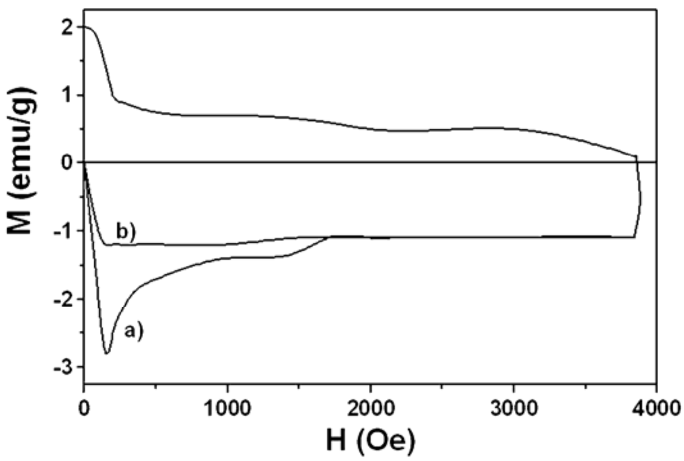

Fig. 3. $M(H)$ loops along the ab-plane: a) single flux state, b) two flux state for $\Phi = 0$, $H_{FC} = 1$ kOe and $T = 77$ K (see the text for details)

single crystal sample. We can explain this behaviour as follows. Figure 2 clearly shows the anisotropy of flux trapping and the difference between the pinning strengths in the two different directions. Note that M_c saturates at 6.8 emu/g and M_{ab} at 3.5 emu/g, i.e. $M_c^{\text{sat}}/M_{ab}^{\text{sat}} = 1.9$. This behaviour has been attributed to the anisotropic nature of H_{c1} (lower critical field). The point of deviation from linearity of $M(H)$ loop, H_{c1} is almost 80 Oe for H parallel to the c-axis and is approximately 35 Oe for H perpendicular to the c-axis (parallel to the ab-plane) [10]. Thus $H_{c1}^{c}/H_{c1}^{ab} = 2.3$. At the same time we note that the ratio of saturation field for remnant magnetizations $(H_c^{\text{sat}}/H_{ab}^{\text{sat}})$ is equal to 2.

3.2. Crossed flux conditions

We show first the effect of the crossed flux on the magnetization loops. The procedure for making these experiments was as follows. The sample was cooled down to low temperature in the field H_{FC} = 1 KOe along the c-axis, then the field was turned off, the sample was rotated by θ = 90° and the $M(H)$ loop was taken along the ab-plane (Fig. 3b). Figure 3a shows the corresponding $M(H)$ loop taken without crossed flux (i.e., the sample cooled down to low temperature in a zero field and then the field cycled along the ab-plane without remnant flux along the c-axis). It is apparent that the magnetization in the ab-plane shows a higher flux penetration in Fig. 3b. M_{ab} at the cusp is less than half the value for the curve in Fig. 3b. The initial slope of the loop (b) is also significantly lower than of loop (a), depicting the case of flux entry in the former case. For low fields (H < 1.5 kOe), the total width of loop (b) is less than the width at corresponding field values in the single flux loop (a). It is quite evident that in the crossed flux mode large amount of the flux penetration reduces the shielding currents (leading to lower diamagnetic signal). Furthermore, the flatness of the curve after the cusp indicates that higher initial flux penetration leads to slowing down of subsequent flux entry as the field along the ab-direction is increased. The points of merger of the curves (a) and (b) are found to depend on the cooling field, e.g. for a lower field H_{FC} = 400 Oe the curves merge at about 800 Oe, while for H_{FC} = 200 Oe they merge at about 600 Oe (not shown here). Clearly, the higher the cooling field and the remanence along the c-axis, the greater the persistence of the effect on the ab-plane moment.

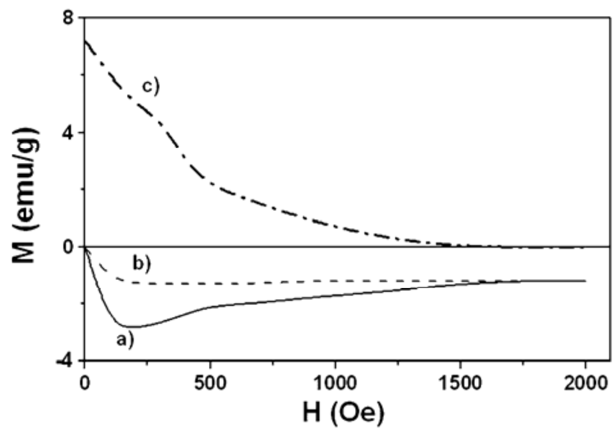

Fig. 4. Simultaneous measurement of two components (M_x and M_y) vs. applied field: a) M_x (single flux state) along the x-direction (ab-plane), b) M_x (two flux condition) along the x-direction (ab-plane), c) M_y (two flux condition) along the y-direction (c-axis), H_{FC} = 1 kOe and T = 77 K

Similarly we recorded $M(H)$ loops for the Φ = 90° case, i.e. the hysteresis of the c-axis moment in the presence of remnant flux along the ab-plane. The effects in this case are much weaker, as expected for a much smaller remanence of the *ab*-plane moment, particularly after turning on the field along the *c*-axis.

A question related to the above experiments remains unanswered: what happens to the remnant flux when we turn on the transverse field. In order find the answer, we carried out other set of experiments. The procedure was identical to that of the previous one: after rotating the sample, the $M_x(H)$ loops as well as the variation of the remnant moment on Y-coil were recorded in this experiment, M_x corresponds to the moment along the applied field direction while M_y is the remanence now rotated perpendicular to the *x*-direction. Figure 4 shows this variation when the field is applied along the *ab*-plane at a very slow rate. We can see that the remanences along the *c*-axis decrease with increasing H and become zero at about the merge point of two $M(H)$ loops along the *x*-direction. Thus it is clear ($\Phi = 0$ case) that the differences in the loops persist as long as $M_y \neq 0$, and that the application of H (along the *x*-direction) decreases M_{rem} continuously. The data however does not clarify what is the cause of decreasing of M_{rem}. This is addressed in the next section.

4. Conclusion

We have shown that in the higher temperature region in which we have worked, the effect of the crossed flux is to reduce shielding currents and enhance depinning effects. This is in contrast to the data of Park et al. [4] where the *c*-axis remanence stabilized the *ab*-plane flux. There are two possible causes for such effects:

1. Mutual repulsion between vortices called *depinning torque* acts on one magnetization M_1 trying to align it along the field due to the other one. In this rotation (caused by the torque), the vortices M_1 may get deppined and be expelled leading to lowering of remanence as observed.

2. The other process, so-called the flux cutting process, takes place when flux families at some mutual angles are made to traverse each other. This results in cutting of a part of one vortex and joining up with a part of the other one. The cut vortices are freed, being able to be expelled and depinned. In our case this may also be a significant source of reduction of pinning, due to a crossed flux.

The results of our experiments at this stage cannot unambiguously indicate which of the two effects is active or predominant. To identify the process unambiguously, a careful examination of temperature and field dependences of the effects is required, or a helical field setup should be used.

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