PHYSICAL REVIEW B VOLUME 36, NUMBER 4 1 AUGUST 1987

Flux pinning and critical current density in $YBa_2Cu_3O_{6+y}$ and $EuBa_2Cu_3O_{6+y}$ superconductors

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(Received 6 May 1987; revised manuscript received 9 June 1987)

We have studied the magnetic characteristics of the critical states of Y-Ba-Cu-O and Eu-Ba-Cu-O high-T_c superconductors. Magnetization data at various temperatures have revealed a very large magnetic hysteresis. The highly irreversible behavior was found to exist both in bulk samples and in well-isolated particles. These effects are consistent with the existence of large pinning forces caused by the structural defects in these materials. By analyzing the hysteretic magnetization data, the critical current density J_c as a function of the external magnetic field has been obtained at several temperatures. The variation of the trapped flux with temperature (up to T_c) has also been measured.

Discovery of the high-T_c superconductor[1,2] Y-Ba-Cu-O has attracted tremendous attention. The single-phase $YBa_2Cu_3O_{6+y}$ system[3] has a T_c in excess of 90 K.[3] The critical current density is at least 1100 A/cm^2 in zero applied field at 77 K.[3] The upper critical field was estimated to be about 180 T (Ref. 1) at low temperature. It has also been found that substitution of Y with many of the 4*f* rare-earth elements barely affects the transition temperature.[4,5] The causes of the high T_c, the extremely large H_{c2}, and the critical current density are of particular importance and deserve detailed theoretical and experimental studies. An understanding of these attractive characteristics must be achieved.

In this Rapid Communication, we present magnetic studies for two systems, $YBa_2Cu_3O_{6+y}$ and $EuBa_2Cu_3O_{6+y}$. The latter is typical of the rare-earth-substituted superconductors. We have found an extremely large magnetic hysteresis, independent of sample morphology. Large critical current densities at different external fields and temperatures have been deduced from the magnetization data in the critical state.

The samples were made using solid-state reaction methods. High-purity powders of $BaCO_3$, CuO, Y_2O_3, or Eu_2O_3 were mixed in the appropriate proportions and pressed into pellets under a pressure of 2×10^5 psi. The samples were sintered at 930 °C in an oxygen atmosphere for over 40 h with two intermediate grindings and pressings. X-ray diffraction shows that the samples consist of a single perovskite-type phase as reported by Cava *et al.*[3] A standard four-probe resistivity measurement technique was used to determine T_c. $YBa_2Cu_3O_{6+y}$ has a midpoint T_c of 94.5 K and a transition width of 1 K. In $EuBa_2Cu_3O_{6+y}$, $T_c=94$ K and the transition width is about 1.5 K. Magnetic measurements were carried out on a commercial superconducting quantum interference device (SQUID) magnetometer, which has a magnetic field range of 0–50 kOe and a temperature range of 1.5–400 K.

Figure 1 shows the magnetization curves of $YBa_2Cu_3O_{6+y}$ and $EuBa_2Cu_3O_{6+y}$ at 2.3 K with magnetic fields varying between −50 and 50 kOe. The samples were initially cooled down in zero external field. After a reversible region in small external fields, both samples display extremely large reproducible magnetic hysteresis. The completely closed loops have a twofold rotational symmetry about the origin. We have also observed similar behavior in other *R*-Ba-Cu-O compounds (*R* represents a rare-earth element). We believe that it is a common characteristic of this type of superconductor.

The observed magnetic hysteresis curves in Fig. 1 are consistent with the metastable critical states of an imperfect type-II superconductor.[6,7] In such critical states, the penetrated flux lines are pinned on the structural defects of chemical inhomogeneities. Therefore, movement of the flux line lattice is impeded, and the superconductor is able to sustain a supercurrent up to a critical current density (J_c), which can be orders of magnitude larger than that of a defect-free type-II superconductor. The critical current density is thus a measure of the interaction between the magnetic flux lines and the lattice defects.

There are a few ways to obtain the critical current den-

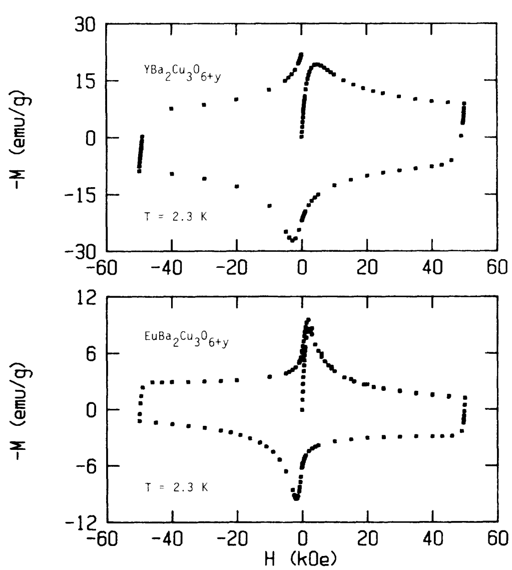

FIG. 1. Magnetization curves at $T=2.3$ K for $YBa_2Cu_3O_{6+y}$ and $EuBa_2Cu_3O_{6+y}$.

sity.[7] The most straightforward measurement is made by passing an increasing current through a superconducting wire in a transverse field until a voltage ($\sim 1\ \mu V$) is detected. It requires a very fine wire for a superconductor with large J_c, which cannot be easily accommodated in Y-Ba-Cu-O ceramic materials. However, J_c can also be determined by measuring the magnetization of a sample with regular geometry (e.g., flat sheet, cylinder) in a parallel field. This method imposes less stringent requirements on the preparation of samples. It is generally assumed that J_c is a function of the local magnetic induction B with a few adjustable parameters,[8] such as $J_c = \alpha/B^n$ or $J_c = \alpha/(B+B_0)$. This, along with the relation $\nabla\times\mathbf{B} = (4\pi/c)\mathbf{J}_c$, enables $\mathbf{B}(\mathbf{r})$ to be calculated at different positions in the sample. By integration, the average magnetization $4\pi M$ of a sample can be obtained.

For the particular case of a large flat plate with thickness d, J_c and the reversible magnetization M_e can be obtained, to first approximation, through the following relations:[9]

$$4\pi(M^+ - M^-) = \frac{8\pi}{10} dJ_c(H) , \qquad (1)$$

$$4\pi(M^+ + M^-) = 2(4\pi M_e) , \qquad (2)$$

where M^+ and M^- are the magnetization of the decreasing and increasing field branches. Fietz, Beasley, Silcox, and Webb[9] have shown that $J_c(H)$ obtained by magnetization measurements through relation (1) is in good agreement with that obtained by direct critical current measurements.

We have determined $J_c(H)$ at different temperatures using relation (1). A rectangular Y-Ba-Cu-O sample with area $6.3\times3.65\ mm^2$ and thickness 0.155 mm was measured in the magnetometer with field parallel to the sample plane. The magnetization curves at $T=2.3$, 15, and 40 K are shown in Fig. 2. The broken lines represent the reversible magnetization M_e, calculated using relation (2). The critical current density as a function of external field is shown in Fig. 3. The general shape of $J_c(H)$ is typical of an imperfect type-II superconductor.[6,7,9] J_c attains a value of 130000 A/cm^2 at $T=2.3$ K and $H=5$ kOe. It should be noted that in the critical states, J_c is almost completely determined by imperfections in the superconducting material. The large J_c values indicate the existence of strong flux pinning in this type of high-T_c superconductor.[7] A point of special interest is that the J_c values as obtained from electrical transport measurements[3] are generally much lower than those from magnetization measurements. This is caused by the porous structure of the solid-state reacted materials. Superconducting grains loosely contact with each other in such a way that the point contacts behave like weak links. That limits the current path, hence reducing the current-carrying capacity.

With the aim of finding the origin of the very large flux pinning and the associated critical current density, we have performed the measurements on a sample with completely different morphology. The sample consisted of a well-ground Y-Ba-Cu-O superconducting powder dispersed in a fine powder of insulating boron nitride. The

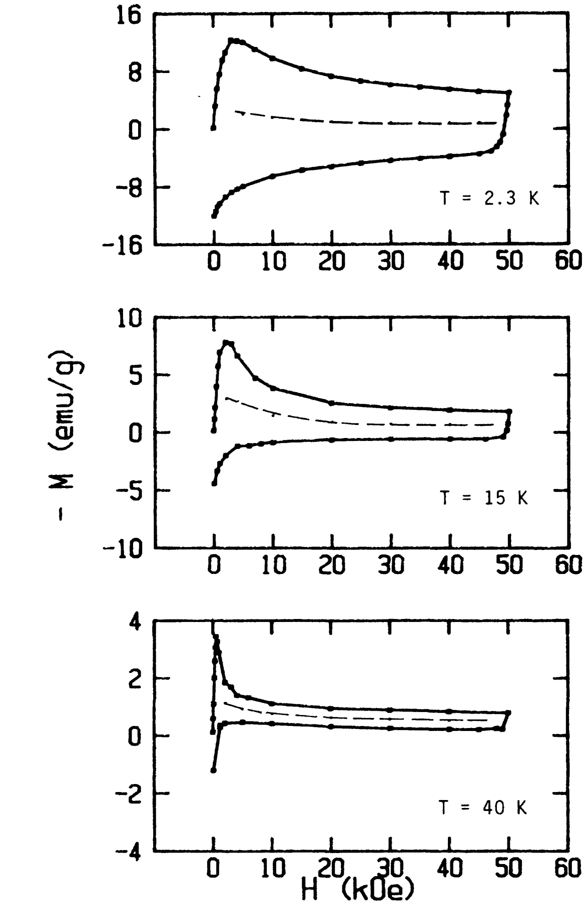

FIG. 2. Magnetization vs applied magnetic field for the $YBa_2Cu_3O_{6+y}$ sample at $T=2.3$, 15, and 40 K. The broken line is the reversible magnetization.

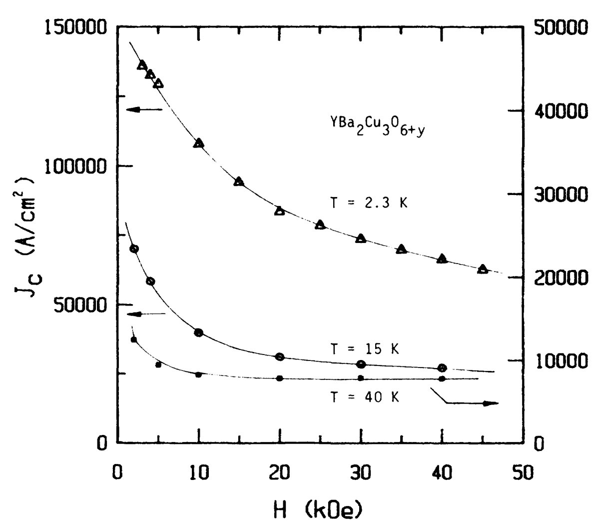

FIG. 3. Critical current densities vs applied field at $T=2.3$, 15, and 40 K for $YBa_2Cu_3O_{6+y}$.

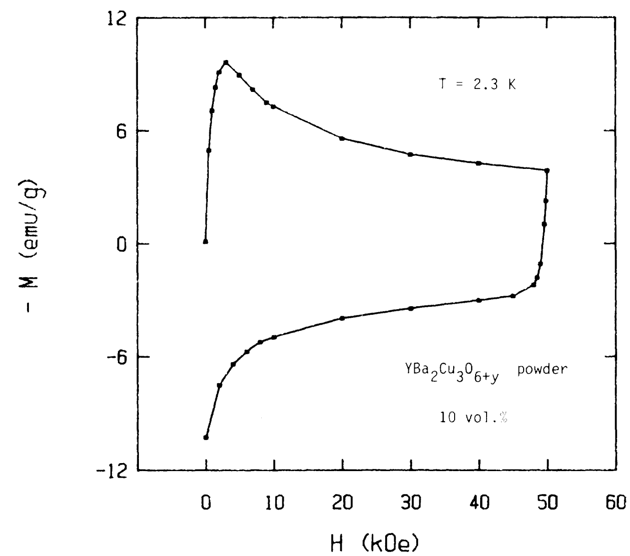

FIG. 4. Magnetization curve at $T=2.3$ K for the $YBa_2Cu_3O_{6+y}$ powder dispersed (with a volume fraction of 10%) in boron nitride powder.

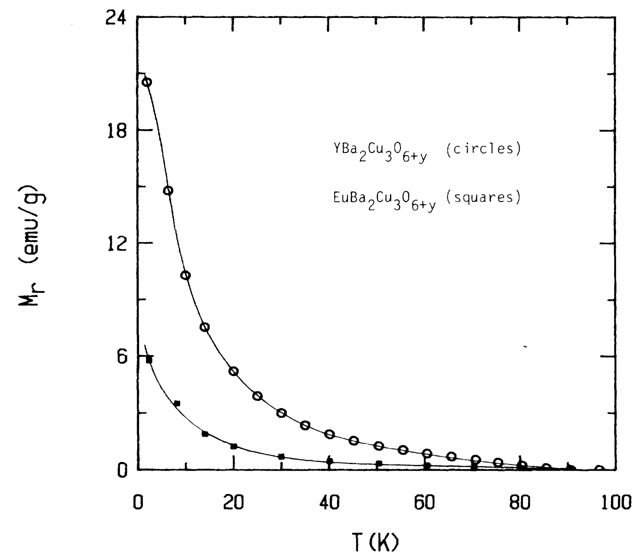

FIG. 5. Magnetic remanence vs temperature for $YBa_2Cu_3O_{6+y}$ (circles) and $EuBa_2Cu_3O_{6+y}$ (squares).

volume fraction of Y-Ba-Cu-O was 10% so that the superconducting particles were well isolated from each other. The cold-pressed sample was cut into a strip approximately $7\times1.2\times0.29$ mm^3. The magnetization curve of this sample is shown in Fig. 4. The large hysteresis remains intact, indicating that the flux pinning is not confined to either the surface or the voids of the bulk material, but rather is caused primarily by the superconducting grains themselves. We feel that the internal structural defects (dislocations, vacancies, stacking faults, etc.) and grain boundaries in these superconducting materials play the main roles in providing the large flux pinning force. It has long been known[6,7] that superconducting alloys show considerable magnetic hysteresis and trapped flux if a high density of defects is generated by extreme cold work, neutron irradiation, or other means.

Recently, a high-resolution electron microscopy study[10] has shown that there exists a considerable amount of structural defects such as dislocation, stacking fault, and vacancies in the Y-Ba-Cu-O materials. There is speculation[10] that the defects provide strong coupling between electrons and the underlying lattice, thus increasing T_c. The large magnetic hysteresis observed in the present study is consistent with the microscopy result. It is a manifestation of the extensive structural defects existing in this type of superconductor.

In order to study the variation of flux trapping with temperature, we have measured the remanent magnetization M_r as a function of temperature for Y-Ba-Cu-O and Eu-Ba-Cu-O. The results are shown in Fig. 5. At each temperature, the sample was magnetized to 50 kOe and then the field was reduced to zero, after which the trapped magnetization was measured. Again, both systems display similar behaviors. The trapped flux decreases as temperature increases, but hysteresis persists all the way to T_c.

In summary, we have investigated the magnetic response of $YBa_2Cu_3O_{6+y}$ and $EuBa_2Cu_3O_{6+y}$. The samples displayed an extremely irreversible behavior in the critical state. By analyzing the hysteresis of these samples, we have obtained the reversible magnetization and the critical current density as a function of temperature and applied magnetic field. At the lowest temperature (2.3 K), $J_c(H)$ varies from 130000 A/cm^2 to 50000 A/cm^2 as the field is increased from 5 to 50 kOe. The irreversible behavior of the samples was not found to vary markedly with sample morphology. The observed large flux pinning is a manifestation of the extensive structural defects and grain boundaries.

This work is supported in part by National Science Foundation Grant No. DMR86-07150 and Office of Naval Research Contract No. N0001485-K-0175.

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