MAGNETIC SHIELDING BY SUPERCONDUCTING Y-Ba-Cu-O HOLLOW CYLINDERS

J. O. Willis, M. E. McHenry, M. P. Maley, and H. Sheinberg
Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Abstract

We have measured the magnetic field H' at the center of a hollow tube of sintered Y-Ba-Cu-O superconductor as a function of applied field H, temperature, tube length, and tube wall thickness. The maximum field that can be shielded H_{sh} agrees with the value calculated from the critical state model using the measured critical current density J_c. The maximum trapped field H_{tr} in the tube upon decreasing H to zero exceeds H_{sh} by as much as a factor of two, and large enhancements in J_c are observed in decreasing field. These phenomena are identified with intragranular flux pinning present only after H has exceeded H_{c1} of the grains. Finite tube length does not affect the H_{tr}/H_{sh} ratio appreciably. H_{sh} depends approximately on the square root of the wall thickness.

Introduction

As a means of determining critical current density J_c information on a specimen in a contactless way, the "flux tube" experiments of Kim et al.,[1] first performed on Nb-based superconductors in the 1960's, is a classic technique. A probe in the center of a hollow superconducting tube measures the internal magnetic field H' as a function of the applied field H. The difference of these values M = H'-H is attributed to supercurrents in the tube. In the critical state model, extremely useful for analyzing such experiments, every region of a sample is assumed to carry a critical current density determined only by the local value of the magnetic field B in the sample. For the case of the maximum shielded field H_{sh} upon increasing H from zero for which H' is zero, one obtains:

$$H_{sh} = k\, w\, J_c^* \cos\Theta, \qquad (1)$$

where H_{sh} is in G, $k = 0.4\pi$ G-cmA^{-1}, w is the wall thickness in cm, J_c^* is the average current density in Acm^{-2}, and $\cos\Theta$ is the opening half-angle of the tube. For a known dependence of J_c on B, the internal field H' can be calculated from (following Kim et al.):

$$k\, w = \int_H^{H'} dB/Jc(B). \qquad (2)$$

The granular, weak link nature[2] of sintered $YBa_2Cu_3O_7$ (Y123) might be expected to produce different features from those commonly observed in the traditional hard type II superconductors, and Cimberie et al.[3] have reported new phenomena in very short (diameter smaller than length) cylinders. We report here on tube magnetization and transport J_c measurements and attempt to interpret the data in terms of a model that includes the granular aspects of these new materials.

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Experimental

Samples were prepared from commercial [4] $YBa_2Cu_3O_7$ powder of average grain size 10 µm cold-pressed to 50,000 psi (3.4 kbar) and then fired in oxygen. The annealling cycle consists of a ramp to 965°C at 200°C/hour, holding at 965°C for 10 hours, cooling to 400°C at 25°C/hour, holding at 400°C for 20 hours, and then cooling to room temperature at 25°C/hour. The inside diameter of the tube was bored out to 0.7 to 0.9 cm. Final tube density was about 70% of the theoretical 6.38 gcm^{-3}.

The room temperature resistivity of this material is about 2600 µΩ-cm with a midpoint of 92 K, a 10 to 90% width of 2.5 K, and zero resistance near 89 K. dc susceptibility measurements in a 100 Oe field showed a 93 K onset, a 74 K midpoint, and 95% of $4\pi\chi$ flux exclusion at 7 K. The Meissner effect in 100 Oe was 24% of $4\pi\chi$ at 7 K.

Magnetometer magnetization M vs. magnetic field H loops were made at 7, 65, and 75 K. Hysteresis in these data is indicative of intragranular critical currents. Values of J_c determined using the Bean model,[5] $J_c = 15\Delta M/R$ where ΔM is the hysteresis in gauss, R is a typical particle size in cm, and J_c is in Acm^{-2}, are 1.8×10^6 at 7 K, 6.8×10^3 at 65 K, and $3.4\text{X}10^3$ at 75 K, all at H = 0. These values are similar to those measured in single crystals[6], although with a more rapid fall off with increasing temperature.

The flux tube experiments were carried out using a calibrated axial Hall probe in the center of the hollow superconducting tube which is itself coaxial with a 2.5 cm inner diameter by 10 or 15 cm long copper solenoid. The Hall probe and tube were both centered vertically within the solenoid to ± 1 mm. The external field H produced by the solenoid was increased in steps with the Hall probe determining the internal field H' at each step. The field range is ± 1000 Oe, and the Hall probe resolution is ± 0.5 Oe. During the runs the experiment was immersed in a bath of liquid N_2 or liquid He to assure isothermal conditions.

Transport critical current measurements were made with a short sample immersed in a cryogen and with the current direction perpendicular to H. A 1 µV criterion was used for defining J_c; this corresponds to about 10 µV/cm or about 10^{-4} of the normal state resistance. The current is swept and the voltage across the sample is monitored with a nanovoltmeter. The contacts to the sample are made by soldering Ag wires to plasma-sprayed Ag pads 0.2 cm in diameter and 0.01 cm thick. Contact resistivities are in the 10^{-8} Ω-cm^2 range and cause no observable joule heating.

Results and Discussion

Typical flux tube magnetization data are shown in Fig. 1 for a tube of 0.9 cm inside diameter, 0.33 cm wall thickness, and 5 cm long. The internal field H' remains zero up to an applied field H equal to H_{sh} above which H' climbs rapidly. The value of H_{sh} for this tube is 28 Oe at 75 K, corresponding to an average J_c of 69 Acm^{-2} using Eq. 1.

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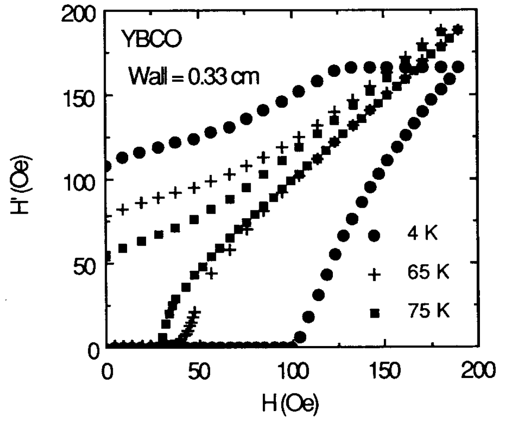

Figure 1. Internal magnetic field H' vs. applied field H for a 0.33 cm wall tube at the temperatures indicated.

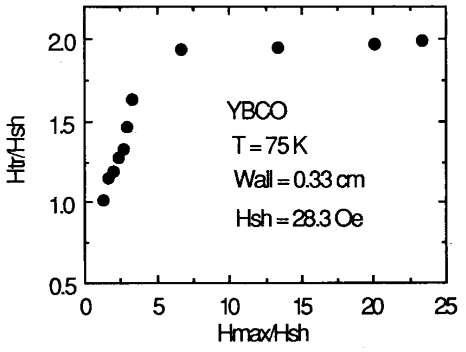

Figure 2. Ratio of the trapped field H_{tr} to the shielding field H_{sh} vs. the maximum field in the cycle H_{max} divided by H_{sh} for a 0.33 cm wall tube at 75 K.

By using the measured transport $J_c(H)$ values, Eq. 2 can be integrated and a value of 24 Oe is obtained, in reasonable agreement with the directly measured H_{sh}. At 65 and 4 K H_{sh} and the magnitude of the hysteresis is larger than at 75 K concomitant with increases in J_c at those lower temperatures. The thickness dependence of H_{sh} is roughly as $\sqrt{w}$ expected for a $J_c(H)$ that is proportional to $(H + H_0)^{-1}$, where H_0 is small, that is, a very rapid fall off of J_c with H.

One remarkable feature of the data shown in Fig. 1 is the asymmetry in the shielding value H_{sh} and the larger trapping field H_{tr} upon reducing H from its maximum value H_{max} to 0. In addition, H_{tr} monotonically increases with H_{max}. Figure 2 shows the ratio H_{tr}/H_{sh} versus H_{max}/H_{sh} for the same tube as in Fig. 1. Clearly H_{tr}/H_{sh} increases and saturates at high H_{max} to values much greater than the value of 1 expected from the critical state model.

We have considered several possible explanations for this asymmetry. The first of these deals with finite length corrections from the magnetic field distribution along the tube. Because of the large field dependence of J_c, demagnetizing effects might be expected to allow significant flux penetration of the sample ends for H less than or equal to H_{sh}. To test this hypothesis, tubes of the same wall thickness but different lengths with aspect ratios (length to outside diameter) of 1.7 to 6.7 were measured. No qualitative differences were seen in the measurements, i. e., both H_{sh} and H_{tr} are reduced for the shorter tubes, but there always exists a large enhancement of H_{tr} over H_{sh} even for tubes with small demagnetizing factors (large aspect ratios). To further study this behavior, we measured the axial dependence of H' at 75 K for the tube of Figs. 1 and 2; the data and several model calculations are shown in Fig. 3. The experimental curves are for $|H-H'(z)|/|H-H'(0)|$ vs. the reduced half-length z (z is 0 at the tube center and 1 at the tube end) at $H = H_{sh}$, $H = 1.07H_{sh}$, and for H = 0 (trapping state) after cycling up to 200 Oe. The z dependence of the magnetic field for a finite length solenoid with the same dimensions as the tube are shown for three $J_c(z)$ dependences of the form $J_{co}(1 - az)$ with a = 0.1, 0.5, and 1 approximating the effects of demagnetization. A value of a of 0.5 corresponds to a reduction in the central field by only 10%. The measured z dependences are not too different from the calculation with a equal to 0.1 and differ by no more than about 15% from one another, and thus cannot be responsible for the large observed ratio (a factor of 2) between H_{tr} and H_{sh}. We conclude that finite length effects are not responsible for the enhanced H_{tr} values.

One of the major differences between sintered Y123 and the classical type II superconductor is the granular nature of the new materials. These systems consist of grains with essentially single crystal properties weakly coupled to other randomly oriented grains. These "weak links" manifest themselves through a very strong dependence of J_c on H, characteristic of Josephson junctions. The granular material may be characterized by two sets of parameters, following Clem,[2] one for the grains and one for the Josephson junctions, denoted by subscripts G and JJ, respectively. Intragranular current densities measured in a

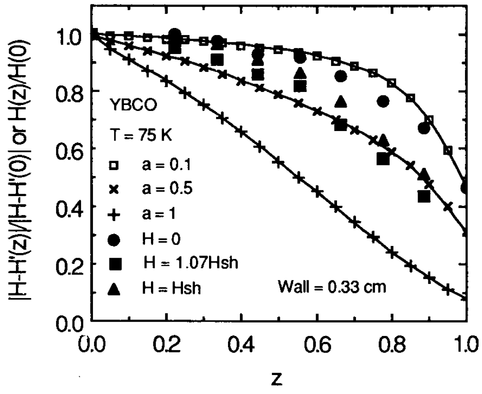

Figure 3. Measured (isolated points) and calculated (connected points) axial dependence of the magnetic field for a 0.33 cm wall tube. The values of a correspond to the axial current distribution $J_c = J_{co}(1 - az)$. See text for more details.

dc magnetization experiment determine J_{cG}, whereas transport critical current is limited by currents flowing through the weak links and is designated as J_{cJJ}. In a flux tube experiment, only the macroscopic currents are expected to produce shielding and trapping of flux. Measurements were made on a cold pressed but unsintered tube, with presumeably weak or no links between grains, using the same starting material as the sintered tubes. The data show no hysteresis, i. e., H' = H between within the measurement accuracy for H between +200 and -200 Oe, implying no net transport current in the tube. Thus J_{cG}'s do not directly contribute to the enhancement of H_{tr}.

There is another mechanism by which the grains may contribute to the flux pinning in these sintered materials that is described in the generalized critical state model (GCSM).[7] At low magnetic fields flux travels through the weak link network and J_c is determined by intergranular pinning. Above $H_{c1G}(T)$, the lower critical field for the grains, flux begins to penetrate the grains where the pinning is much stronger than in the intergranular regions. This extra pinning along some parts of the vortex lines, which is not present in the field sweep up to H_{sh}, but is present on decreasing H back to zero thus may be expected to increase H_{tr} over H_{sh}. From Fig. 2 it is evident that the enhancement of H_{tr} saturates above about 125 Oe at 75 K, a field value near the peak in the magnetometer M vs. H virgin trace that is normally identified with complete flux penetration of the grains. According to the GCSM, above this field there should be no further enhancement to J_c caused by intragranular pinning. The field H_{max} required to saturate H_{tr} increases with decreasing temperature and is consistent with the magnetometer determined values for full flux penetration.

There is, however, some magnetization data that does not appear to fit into the GCSM. If a complete hysteresis loop is traversed from 0 to H_{max} to $-H_{max}$ to $+H_{max}$ two possible discrepancies appear: on the final quarter cycle form 0 to H_{max}, the H' values are coincident with the virgin trace for H greater than H_{sh}; and the value for which H' goes from positive to negative when H decreases from zero toward $-H_{max}$ is exactly $-H_{sh}$. Within the GCSM both zero crossings should occur at larger absolute values of H because of the extra flux pinning within the grains that is not present on a virgin sweep up to H_{sh}.

On the other hand, strong support for the GCSM comes from direct transport J_c measurements on a 0.15 x 0.15 x 1cm^3 bar cut from the sintered tube stock. Measurements at 75 K shown in Fig. 4 and similar results at 65 K show a large hysteresis of J_c with H. This is also qualitatively consistent with the enhancement of pinning above H_{c1G} predicted by the GCSM. Self-field effects, calculated to be a maximum of 8 Oe for a uniform current distribution in the sample at zero applied field, can affect the value of J_c at fields less than about 10 Oe, but the self field is much smaller at finite fields (H > 20 Oe) and seems insufficient to produce the very large J_c enhancements observed.

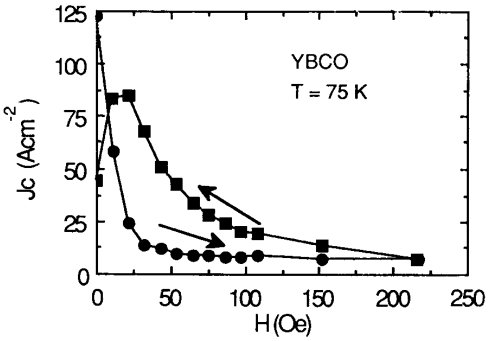

Figure 4. Transport critical current density J_c at 75 K measured on a bar cut from the sintered tube stock illustrating the large hysteresis with field H.

Summary and Conclusions

We have performed flux tube magnetization, dc magnetization, and direct transport critical current measurements on sintered Y123 superconducting material. The results generally fit within the critical state model in that the H_{sh} values are in agreement with the values calculated directly from the transport J_c measurements. The granular, weak link nature of these materials is apparent in the strong dependence of J_c on H and the lack of shielding for the unsintered tube of isolated superconducting particles. H_{tr} values larger than H_{sh} and increasing monotonically with the maximum field H_{max} as well as the large hysteresis in J_c with H do not fit within the theory. Extension to the generalized critical state model, which considers the two component granular nature of the system, gives a better approximation to the $J_c(H)$ and H_{tr}/H_{sh} results with the inclusion of additional flux pinning within the grains for H greater than H_{c1G}. There are still some features of the data that are difficult to reconcile with either of these models and that warrant further study.

Acknowledgements

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References

[1] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, "Magnetization and Critical Supercurrents," Phys. Rev., vol. 129, pp. 528-535, 1963.

[2] J. R. Clem, "Granular and Superconducting-Glass Properties of the High-Temperature Superconductors," Physica C, vol. 153-155, pp. 50-55, 1988.

[3] M. R. Cimberie, C. Ferdeghini, G. L. Nicchiotti, M. Putti, A. S. Siri, C. Rizzuto, C. A. Costa, M. Ferretti, C. L. Olcese, F. C. Matacotta, and E. Olzi, "Magnetization Measurements on Tubular Samples of $YBa_2Cu_3O_{7-y}$," Superconductor Science and Technology, vol. 1, pp. 30-35, 1988.

[4] W. R. Grace & Co., Columbia, MD 21044.

[5] C. P. Bean, Phys. Rev. Lett., vol. 8, pp. 250-252, 1962.

[6] T. R. Dinger, T. K. Worthington, W. J. Gallagher, and R. L. Sandstrom, "Direct Observation of Electronic Anisotropy in Single-Crystal $Y_1Ba_2Cu_3O_{7-x}$," Phys. Rev. Lett., vol. 58, pp. 2687-2690, 1987.

[7] L. J. Campbell, "Generalized Critical State Model," presented at the International Conference on Critical Currents in High-Temperature Superconductors, Snowmass Village, CO, August 16-19, 1988.