YBa₂Cu₃O_{7-δ} SINGLE CRYSTALS INVESTIGATED BY TORQUE AND MAGNETOMETRY

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Abstract. – Magnetic critical current densities of an YBaCuO single crystal have been investigated using both magnetometry and torque. For currents along the *C* axis, J_c is estimated to be 10^3 and 10^5 A/cm² respectively from the two techniques, compared to 10^5 and 10^6 A/cm² for currents in the *AB* plane. Differences between the two estimates are ascribed to the intrinsic inhomogeneity of the flux pinning.

Direct critical current measurements on massive samples of oxide superconductors such as single crystals and sintered blocks are difficult to perform, because of contact resistances. For this reason, magnetic hysteresis measurements are frequently used, and interpreted through Bean and related models. We want to point out that torque measurements provide complementary information on the critical currents and flux pinning. The following measurements were done on a large YBaCuO single crystal ($1 \times 0.7 \times 0.5$ mm³) prepared by a flux method [1].

We recorded the magnetic hysteresis loops of figure 1 at 4.2 K (corrected for demagnetizing effects)

Fig. 1. – Magnetization loops for field along and perpendicular to the *C* axis.

using a vibrating sample magnetometer for fields along or perpendicular to the *C* axis. The difference in the magnetization amplitude between the two orientations is more than one order of magnitude and indicates stronger critical currents in the *AB* plane. The sample alignment in the perpendicular geometry is crucial and a 10° error results in a doubling of the signal, so that we consider loop (b) as an upper limit.

Using the Bean model [2], J_c is determined through:

$$J_c = 15 \Delta M(H) / R \quad (1)$$

where $\Delta M(H)$ (in emu/cm³) is the hysteresis between ascending and descending branches of the hysteresis loop and R the effective average sample radius in cm (Fig. 2).

The magnetization curves correspond to $J_c \approx 10^5$ A/cm² in the *AB* plane and $\approx 10^3$ A/cm² per-

Fig. 2. – Critical currents calculated from loops of figure 1.

pendicular to *AB*. Values in the literature [3-6] range from 10^5 to 10^6 A/cm² for currents in the *AB* plane, and the anisotropy ratio is found to be between 5 and 20, the higher values being associated with the lower estimates of the critical currents. Thus, our crystal exhibits relatively small critical currents and high anisotropy. This indicates less pinning than in average samples, which may be due to the annealing conditions [5].

Bean's formula (1) is a measure of the maximum flux line gradient in the sample allowed by the pinning force F_p . We can also write:

$$J_c \approx 2F_p / \Phi_0 \quad (2)$$

F_p was determined independently using the following torque technique, again at 4.2 K [1]. The sample is prepared with flux lines trapped parallel or perpendicular to *C* by zero field cooling, aligning the magnet in the appropriate direction and cycling the field up to a 9 kG maximum and back down to zero. The magnet is then turned by 90° and the field ramped up slowly in this perpendicular direction. The observed torque signal Γ is proportional to the product of the number of flux lines that remain trapped in the original direction times the applied field. As the field increases, the torque on the flux lines grows, causing more of these lines to be released and so the normalized torque signal Γ/H to decrease. As shown in figure 3, there is no well defined depinning field at which all the flux lines are released and the torque falls to zero; this indicates that all flux lines are not pinned equally. Taking the mean depinning field H_d as the field where half of the

Fig. 3. - Γ/H on vortices trapped a) along the C axis b) perpendicular to it. In this figure the torque signals are normalized to their initial low field values.

lines have been released, an average pinning force can be estimated using:

$$F_p \approx \Phi_0 H_d / (\pi L) \quad (3)$$

where L is the sample length along the initial flux line direction. Associated critical currents estimated using (2) and (3) are found to be a few times 10^6 A/cm² in the AB plane and a factor 10 less along C .

Though the trend of the anisotropy is the same for torque and magnetometry measurements, a discrepancy is observed between the absolute values estimated from the two techniques, particularly for currents in the C direction. The explanation may lie in the way the depinning field is defined. It appears that even in single crystals the flux pinning is inhomogeneous, as can be judged from the strong flux creep which shows up as relaxation effects. This means that the pinning strength and so the critical current deduced from different magnetic measurements may not be directly comparable. The hysteresis loops interpreted on the Bean model are related to the initial breakdown from perfect flux pinning at the critical field gradient. Our torque data on the other hand give information on the whole spectrum of pinning strengths; it appears reasonable that the average effective pinning strengths

we estimate from these measurements are distinctly higher than the initial breakdown pinning strengths estimated from the hysteresis loops on the same sample. Concerning the magnitude of the critical currents determined using one technique or the other, it should be kept in mind that we are not dealing with an intrinsic property of the crystal, but with its ability to pin flux lines, which varies from one sample to the other. Further measurements on different single crystal samples should give more information on the complex problem of flux pinning in the systems. A single parameter such as an effective F_p does not give a complete characterization of the flux pinning, and results from different complimentary techniques will be required to test models of pinning.

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