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TRANSPORT AND MAGNETIZATION CURRENTS IN BSCCO/Ag TAPES#

M.E. McHenry, [a, b] P.J. Kung, [a, b] M.P. Maley, [a] J.O. Willis, [a] and J. Y. Coulter [a]
[a] Superconductivity Technology Center, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.
[b] Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, U.S.A.

Abstract-- A (Bi,Pb)SrCaCuO-2223/Ag tape has been produced by thermomechanical processing. Transport J_c's have been measured between H = 0 and 7 T and T = 7 to 75 K. Magnetization currents, J(H,T), have been determined for similar temperatures and fields (0 to 5 T) oriented parallel and orthogonal to the thickness of the tape. Dimensional scaling arguments show that flux penetrates most quickly along the tape thickness direction (for fields parallel to the tape plane and therefore the ab planes of the textured BSCCO grains). This implies that the anisotropy ratio of J_c and J_{ab} is reduced in tapes as compared with single crystals consistent with predictions of the brick wall model. Also measured were the H dependence of magnetization currents, $J^{H\perp c}{}_{ab}$ and $J^{H\|c}{}_{ab}$, and effective pinning potentials, $U_{eff}(J)$, for similar field orientations. Fast magnetic relaxation causes an exponential field dependence, $J/J_c\ \alpha\ \exp(-H/H_0)$ of transport and magnetization currents consistent with a divergent $U_{eff}(J)$ as $J \Rightarrow 0$. Temperature dependences for H_0 for transport and magnetization measurements are interpreted in terms of different time scales (or voltage criteria); for H_0 in two field orientations are explained by a directionally dependent $U_{eff}(J_{ab})$.

I. INTRODUCTION

The development of high temperature oxide superconducting materials for large current carrying applications has met with challenges posed by granularity (weak links) [1], as well as the problem of thermally activated flux motion [2]. Dissipation due to the latter is associated with weakly pinned fluxons. Weak link behavior is a manifestation of granularity, which is exacerbated by short coherence lengths and anisotropy. In the recent past, significant progress has been made in overcoming the weak link problem in BSCCO/Ag tapes produced through a thermomechanical processing route [3,4]. In these materials it appears that a highly textured and dense superconducting material with c-axis texture (parallel to the tape thickness) allows for the predominant flow of transport currents along favorable directions parallel to ab planes. This texture and the plate-like morphology of the BSCCO grains also allow for large contact areas between grains so that currents can be effectively shunted from grain to grain along the c-axis to bypass weak links normal to the current path. This point of view has recently been developed in the so-called "brick wall" model [5,6] of critical current densities.

As applied to superconducting tapes, this brick wall model views the individual superconducting grains as being coupled by Josephson currents through the grain boundaries. The grain to grain shunting of current along the c-axis is seen as the bottleneck to current flow in the tape. A consideration of current continuity leads to the conclusion that the tape's ab critical current density is in fact limited by the c-axis J_c as: $J_c{}^{ab} = f\,(l/t)_g\, J_c{}^c$, where$(l/t)_g$ is the nominal length to thickness aspect ratio of the grains and f is the fraction of the c-axis grain boundary area available for current transfer (l may exceed the grain length if all ab grain boundaries are not weak links). With typical aspect ratios on the order of 100:1 the brick wall model predicts a reduced $J_c{}^{ab}$ for the tape as compared with values for single crystals even if the full single crystalline value of $J_c{}^c$ is maintained in the tape. Therefore, the ab to c-axis anisotropy ratio is reduced in tapes as compared with single crystals.

At higher temperatures a steep decline in $J_c{}^{H\|c}{}_{ab}$ and increasing anisotropy with respect to field orientation is observed, which suggests that the decay of intragranular currents is important in determining transport properties of the tapes [7]. This decline is typically so severe as to limit the use of these materials at 77 K in even modest fields. It is commonly held that high temperature degradation of transport properties is a consequence of thermally activated motion of 2D pancake vortices and a shallow magnetic irreversibility line in BSCCO materials [8]. It appears that the brick wall model needs to be modified to reflect thermally activated flux motion's influence on transport properties.

II. EXPERIMENTAL DETAILS

Samples were produced by an oxide-power in tube (OPIT) process as detailed in [8]. The final dimensions of the monofilament tape were 0.3 by 0.016 cm^2. The superconducting core was 0.24 cm wide and 0.01 cm thick. A 2-cm-long piece was used for transport measurements. A piece 0.35 cm long was cut for magnetization measurements and later sectioned (halving the length) to examine critical state scaling. The thickness and width were determined from SEM photographs of the cross-section.

Transport J_c measurements were performed over the temperature range 20-77 K in a flow through cryostat in magnetic fields up to 7 T. The sample was attached with vacuum grease to a copper block containing a calibrated carbon-glass thermometer. Tests showed negligible heating for currents less than 30 A. A voltage criterion of 1.0 μV/cm was used to define I_c from I-V curves. $J_c(B,T)$ was determined with H||c (normal to the tape surface).

Magnetic M(H) measurements were carried out on the 0.35 cm segment of tape in a Quantum Design SQUID magnetometer. A 3-cm scan was used and the field was swept in the no-overshoot mode. Hysteresis measurements

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were made for fields between ± 5 T and at temperatures of 7 to 75 K with fields oriented parallel to and orthogonal to the tape thickness. The hysteretic measurements required ~2.5 hours each. J(H) was determined from the magnetization loop width using a Bean model [9] expression adapted for an orthorhombic sample: $J(H) = 20\Delta M(H)/(a\,(1 - a/3b))$ [10]. Here a and b are the width and length dimensions, J is in A/cm^2, ΔM in emu/cm^3, and a and b are in cm. The effective flux creep activation energy [11], $U_{eff}(J)$, was determined from measurements of magnetic relaxation, M(t), for T < 50 K. M(t) was measured starting at times of ~120 s and extending to 2-3 hours. We use the model of reference 11 to determine a non-linear dependence of $U_{eff}(J)$. $U_{eff}(J)$ was determined for both field orientations.

III. RESULTS AND DISCUSSION

Figure 1 shows transport critical current densities as a function of field at temperatures of 20-75 K, for our BSCCO/Ag tape samples with the applied field oriented parallel to the tape thickness. Notable in this response is a nearly exponential field dependence for $J_c(H)$ at all temperatures. Although current densities exceeding 10^4 A/cm^2 are observed at low temperatures, this dramatic decay of J at high fields and temperatures restricts the H-T phase space for which these would be useful conductors.

Comparison of transport and magnetization currents is complicated both by different experimental time constants [8] as well as the possibility of different length scales for the two experiments. A granular sample which exhibits zero transport current density can still exhibit hysteretic response due to currents which circulate in individual grains of the samples. A technique for determining the length scale over which the magnetization currents flow involves sectioning of samples and examining whether critical state scaling of the magnetization with sample size can be observed. For macroscopic currents the magnetization should scale linearly with the sample dimension(s). As depicted in Figure 2, with H||c the magnetic response reflects the current density J_{ab}. For the field oriented in the ab plane, the current flows in a circuit partly in the ab plane and partly along the c-axis. It is thus ambiguous as to whether the ab or c-axis current densities or both control the magnetic response in this field orientation. This is another reason for employing sectioning experiments and critical state scaling arguments to determine the important current paths in our samples.

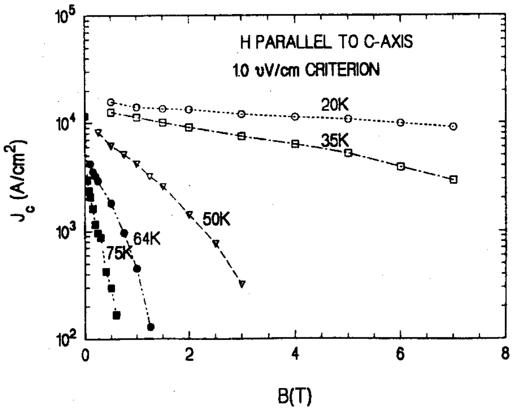

Fig. 1: (a) Transport critical current densities for a BSCCO/Ag tape for a field oriented along the tape thickness (c-axis) for T = 20, 35, 50, 64 and 75 K.

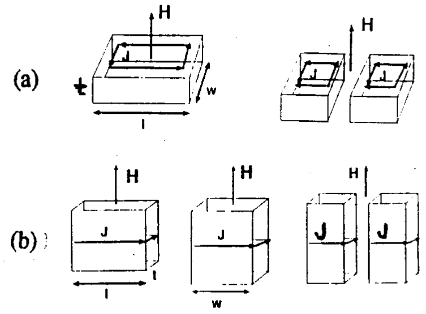

Fig. 2: Tape geometry (a) H||c (b) H||ab before and after cutting showing length l, width w, and thickness t.

Fig. 3 compares the hysteretic response for the tape with H||c before and after cutting the tape in half (Figure Two (a)). Prior to cutting a = 0.24 cm and b = 0.35 cm, and after cutting $a' = 0.18$ cm and $b' = 0.24$ cm. According to critical state scaling arguments the ratio of the hysteresis should be: $\Delta M^{un}/\Delta M^{cut} = 1.40$. Fig. 3 shows that at 20 K, the hysteresis loop obtained for the two cut pieces when scaled (by 1.4) is nearly identical to that of the uncut piece. This agreement suggests the validity of the Bean model dimensional scaling for an orthorhombic sample and implies that the sample is well coupled at low T (i.e. the sample dimension is the appropriate length scale for the magnetization currents). A slight but progressive discrepancy in the scaling law can be observed at higher temperatures. This breakdown has been used to suggest that higher temperatures induce granularity in the sample if the scaling factor is progressively reduced [12]. We note that our data require larger scale factors and do not support the idea that the sample is more granular at higher temperatures. Since BSCCO is a fast relaxing system, and given an implicit scaling of the magnetic diffusion equation with sample dimension, a faster decay of the magnetization in the smaller sample is a viable explanation of breakdown of dimensional scaling at high temperatures.

The results of cutting experiments for H||c allow us to conclude that magnetization currents flow over a length scale equivalent to the sample size. We now examine dimensional scaling for H||ab. Fig. 4 compares hysteretic magnetic response at 20 K, with H||ab for a BSCCO/Ag tape sample and two pieces obtained after lengthwise halving the original. Notable in this figure is that data for the halved samples are unscaled. For these data and at 7, 35, 50, 64 and 77 K (not shown) there are no differences in the hysteresis for the cut and uncut pieces. In a similar experiment prior to cutting, it was noted that there was also no difference in the hysteretic response when H was oriented along the length or width directions of the tape. These

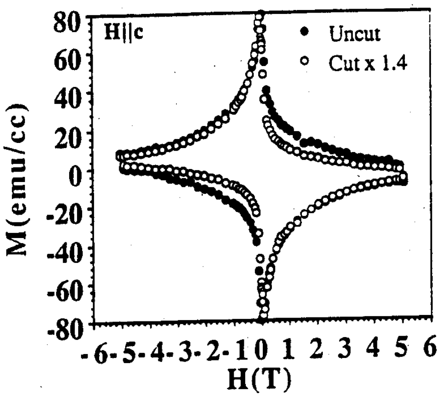

Fig. 3: Comparison of 20 K hysteretic response with $H\|c$ for tape sample and 2 pieces obtained after lengthwise halving. Halved pieces M(H) is scaled by 1.4.

experimental observations allow us to conclude that neither the length or width dimensions are pertinent for scaling of the magnetization currents, and that the critical state is controlled by the thickness dimension for $H\|ab$. This implies that the hysteretic response for $H\|ab$ in the tapes is controlled by the J_{ab}; therefore both for $H\|c$ and $H\|ab$ the J_{ab} tape current density is being probed for temperatures between 7 and 75 K. We surmise that differences in pinning, hysteretic response and dissipation for these field orientations can be attributed to the underlying interactions between J_{ab} and intrinsically pinned vortices ($H\|ab$) and pancake vortices ($H\|c$). It should be recognized that some response of pancake vortices is inevitably also observed with $H\|ab$ since the tape does not possess perfect texture.

The absence of scaling with $H\|ab$ should be contrasted with similar observations for BSCCO-2212 single crystals, having similar aspect ratios as that of our tape, in which dimensional scaling with the crystal width was observed [13]. This indicates that $(J_c^c w) < (J_c^{ab,H\|ab}\, t)$ and allows for determination of J_c^c. Biggs et al. [13] found $J_c^{ab,H\|c}$ to be ~0.7 x 10^6 A/cm^2 for H = 0 at 7 K, with a large drop of nearly an order of magnitude by 15 K. They also measured J_c^c to be ~3 x 10^4 A/cm^2 for H = 0 at 7 K again dropping rapidly with temperature. The experiment put a lower bound on $J_c^{ab,H\|ab} > 2 \times 10^6$ A/cm^2 for the crystals measured.

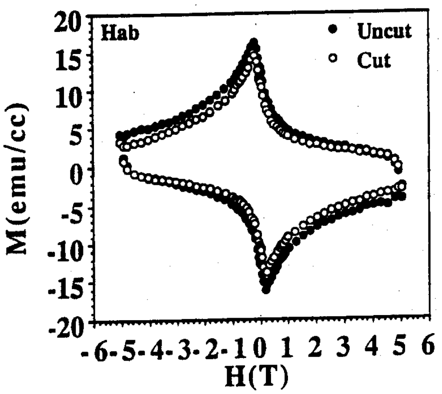

Fig. 4: Comparison of 20 K M(H) for $H\|ab$ for a tape sample and 2 pieces obtained after halving (unscaled).

For our tapes, the absence of dimensional scaling allows us to measure $J_c^{ab,H\|ab}$ from the hysteretic response. Further, the converse condition, $(J_c^c\, w)_{tape} > (J_c^{ab,H\|ab}\, t)_{tape}$ must be true if dimensional scaling is not observed. We observe $J_c^{ab,H\|c}$ to be ~2 x 10^4 A/cm^2 in zero field at 5 K and $J_c^{ab,H\|ab}$ to be ~8 x 10^4 in zero field at 5 K. We can thus set a lower bound on the critical current density along the tape thickness, $J_c^c > 6 \times 10^3$ A/cm^2. Using this lower bound for the tape's J_c^c and given an ~100:1 aspect ratio of the grains it is possible to conclude that the fraction, f, of grain boundary area available for current transfer is less than ~0.1. An important conclusion is that while single crystal anisotropy ratios for the ab plane to c-axis critical current densities exceed 25 and by some estimates are as high as 10^2-10^3, the anisotropy ratio in our tape is less than ~18. This argues for the validity of the brick wall model, which predicts a reduction in the anisotropy ratio primarily due to the suppression of the ab current density because of the bottleneck for shunting current along the c-axis.

Fig. 5 shows magnetization currents derived from the hysteretic response for (a) $H\|c$ and (b) $H\|ab$. Notable is the fact that in both cases J(H) exhibits a nearly exponential field dependence, J(H) ~ exp(-H/H$_0$). In the case of $H\|ab$, however the values of the decay field, H_0, are significantly larger. This is consistent with a difference in potentials for intrinsically pinned and pancake vortices. The values of H_0 are also smaller for the $H\|c$ magnetization currents as compared to the similar transport currents shown in Fig. 1. We view this as reflecting different time constants of the two experiments, or alternatively different effective voltage

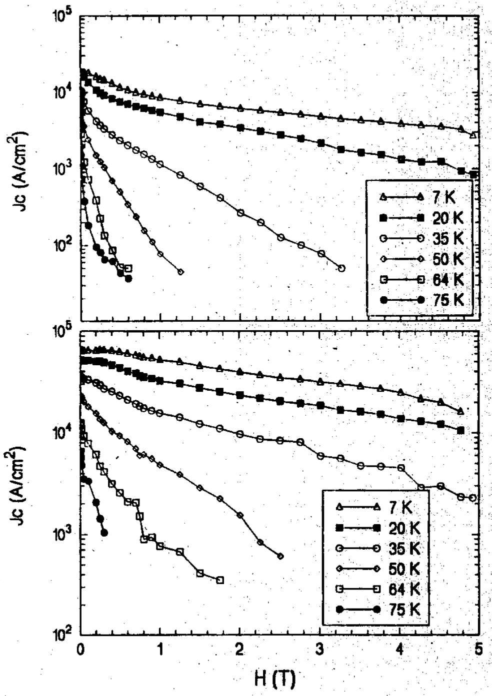

Fig. 5: Magnetization J(H) for (a) $H\|c$ and (b) $H\|ab$

criteria [8]. Similar exponential J(H)'s have also been observed in fast relaxing oxide superconductors and attributed to a diverging pinning potential, $U_{eff}(J)$ [14] as $J \Rightarrow 0$. Recently, both diverging power law, $U(J) = U_c((J/J_c)^{\mu}-1)$ and logarithmic, $U(J) = U_1 \ln(J_c/J)$, potentials have been proposed for HTSC materials.

Without ruling out the possibility that intergranular relaxation may be important in the tape samples, we note that the magnetic relaxation behavior for several HTSC crystals [14] is adequately described by a $\ln(J_c/J)$ dependence over a range of J. U(J) has been empirically described as: $U(J) = \frac{U_1\, g(T/T_x)}{(kT)\, H^n} \ln(J/J_c(T))$, where U_1 is a material dependent energy parameter, $g(T/T_x)$ a thermodynamic scaling function and T_x a scaling temperature. In fast relaxing and anisotropic systems, including LSCO and BSCCO single crystals, $n \sim 1$, and T_x is approximated from the irreversibility line, $T_{irr}(H)$. For these systems, noting that $U_{eff} = kT \ln(\nu_0\tau)$, (with $\nu_0 = v_0/a$, where v_0 is a prefactor for the thermally activated fluxon velocity and τ the experimental time constant) we observe that hysteretically determined magnetization currents (at fixed T) have an exponential H dependence: $J/J_c = \exp[-H/H_0]$ where $H_0 = \left[\frac{U_1\, g(T/T_x)}{kT \ln(\nu_0\tau)}\right]$. An exponential H dependence is commonly observed in BSCCO/Ag tapes, as shown above. H_0 values offer a means of comparing different field and temperature dependent current densities obtained by techniques with different time constants [15] as is the case for our transport J_c's and magnetization currents. The comparison of values of H_0 for different samples or field orientations allows comparison of the activation energy scales at fixed times.

We have performed magnetic relaxation experiments in fields of 1 and 2 T for H||c and H||ab from 4-40 K to determine $U_{eff}(J)$. We will discuss details of these measurements in a forthcoming publication. We have considered both power law and logarithmic fits to $U_{eff}(J)$ and found that the ln(J) fits are adequate below ~20 K. Power law fits with the 3D collective pinning exponent of 3/2 yielded excellent fits over the entire temperature range, though more work is clearly necessary to determine whether this is a relevant microscopic model for tapes. We summarize the result of these measurements in Table 1. $U_{eff}(J)$ is determined from M(t) data using a formalism [8] in which an integrated 1D diffusion equation is inverted to yield:

$$\frac{U_{eff}(J)}{kT} = -T \ln\left(\frac{d\langle M\rangle}{dt}\right) + T \ln\left(\frac{2H_s v_0}{a}\right)$$

where <M> is the average magnetization, H_s the surface field, v_0 the fluxon velocity, and a the sample dimension. Notable are energy scales which exceed those observed for BSCCO-2212 single crystals [16]. Energy scales for H||ab and H||c are consistent with observed anisotropy in J_{ab}. Values of v_0 much lower than previously seen in single crystals can be explained in part by lower J_c values.

Table 1: Results of fitting $U_{eff}(J)$ to logarithmic and power law potentials, $C = \ln(v_0 H/a)$.

Field Dir.	H (T)	J_c x10^4 (A/cm^2)	U_1 [ln]	U_c [power]	C	T_x [K]	v_0 x10^{-3} (cm/s)
H||ab	1	9.0	450	210	7	95	~1-10
	2	7.5	350	180	7	95	~1-10
H||c	1	1.3	300	130	5	72	~3-50
	2	1.0	200	90	5	60	~3-50

IV. CONCLUSIONS

Dimensional scaling of hysteretic response of BSCCO/Ag tapes reveal magnetization currents to flow over the entire sample. The absence of scaling for H||ab implies that that the J_{ab}:J_c anisotropy does not exceed ~18 consistent with the ideas of the brick wall model. The decline of Jab as a function of field and temperature is consistent with fast relaxation. Transport and magnetization current differences can be interpreted in terms of different time scales for these experiments. J_{ab} for H||c and H||ab differ in a way consistent with differences in pinning of intrinsic and pancake vortices.

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