Examination of Current Limiting Mechanisms in Monocore $Bi_2Sr_2Ca_2Cu_3O_x$ Tape with High Critical Current Density

A. Polyanskii*, D.M. Feldmann*, S. Patnaik*, J. Jiang*, X. Cai*, D. Larbalestier*, K. DeMoranville**, D. Yu**, R. Parrella**

***Abstract*— Magneto-optical imaging, electromagnetic measurements and SEM have been used for the characterization of a monocore BSCCO tape made by oxide powder-in-tube process which had a transport J_c (77K, 0T) of 37kA/cm^2. Our study evaluates the connectivity between superconducting grains and reconstructs the local current distribution at <10 μm scale. Some local regions are found to carry up to 180 kA/cm^2 at 77 K, a new record for BSCCO wires.**

***Index Terms*—BSCCO tape, Magneto-optical imaging, current reconstruction, connectivity of grains**

I. Introduction

At present $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO–2223) tapes are the most promising conductors for electric power applications. However there are several current limiting factors in these tapes, which restrict their effective cross section and prevent their overall current density being even higher. For example, the achieved zero field critical current density in short length tapes at 77 K ($J_c \sim 7\text{x}10^4$ A/cm^2) [1] is still far below their potential capability ($J_c \sim 10^5$-10^6 A/cm^2) [2]. Therefore understanding the sources of current limitations is critical to achieving higher J_c in the future. Actually, many of these defects are well known and are produced during manufacturing. Intermediate deformation densifies the grain structure, leading to better connectivity and a higher density BSCCO core but also produces many unhealed cracks. The presence of cracks has been verified by the magneto-optical imaging (MOI) technique that shows many quasi-periodic, flux-leaking channels crossing filaments transverse to the rolling direction [3]. The existence of significant porosity and impurity phases has also been confirmed. At the present time, one very important question is still open, i.e. how high can the local J_c be on scales smaller than those accessed up to now (~100 μm) while still being representative of polycrystalline transport? Müller et al. [2] have estimated this value to be $8\text{x}10^5$ - $6\text{x}10^6$ A/cm^2 by calculating that a monocore tape with J_c (77K, 0T) = $2\text{x}10^4$ A/cm^2 has only 3% connectivity of the BSCCO core. The purpose of this present work is to investigate the local connectivity of a high J_c monocore tape (J_c(77K,0T) = $3.7\text{x}10^4$ A/cm^2) using Müller's electromagnetic method and to correlate it with the local current distribution measured using Magneto-Optical (MO) imaging.

Manuscript received September 19, 2000. This work was supported in part by the DOE-EERE and by facilities supported by the NSF-funded MRSEC on nanostructured materials.

*Applied Superconductivity Center, University of Wisconsin-Madison, Madison WI 53706 USA (telephone: 608-265-5455, e-mail: polyansk@engr.wisc.edu).

**American Superconductor Corporation, 2 Technology Drive, Westborough, MA 01581 (e-mail: rparrella@amsuper.com).

II. Experiment

This study is based on a silver sheathed monocore Bi-2223 tape with J_c (77K, 0T) = $3.7\text{x}10^4$ A/cm^2, which was fabricated by American Superconductor Corporation using the powder-in-tube (OPIT) process. The transport current was measured by the dc four-probe technique with a 1μV/cm criterion. A Quantum Design SQUID magnetometer was used for magnetization measurements. Bi-substituted garnet films with planar magnetization were used for the MO imaging [3]. Two different sample orientations were investigated in the MO experiment. In one case the face of the tape (H ~ || c-axis) was imaged, and in the other, a longitudinal cross section of the tape (H ~ || ab-plane) was studied. The latter geometry enabled us to quantitatively estimate the local current distribution. Scanning electron microscopy was used to study the growth related defect structure and secondary phases. For mass density measurements, the core was cut with a laser into several slices. Each slice was weighed and its cross-section and length measured so as to calculate the density of that slice.

III. Result and Discussion

A. Temperature Dependent Anisotropic Current Flow

Figure 1 illustrates plane-view MO images of a BSCCO monocore tape taken at T=12 K in different magnetic fields. The evolution of magneto-optical images of this tape with gradually increasing magnetic field elucidates the excellent electromagnetic property of the tape. An area with a bright contrast corresponds to higher magnetic field, where magnetic flux has penetrated into the tape. Accordingly the dark

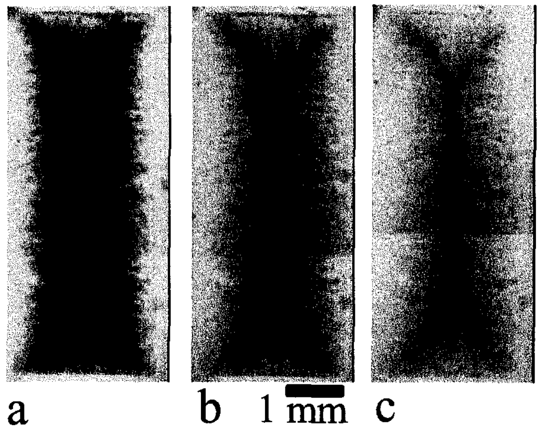


Fig.1. The plane-view magneto-optical images of the BSCCO monocore tape taking at T=12K and magnetic field a) H=40mT, b) H=80mT, c) H=120mT

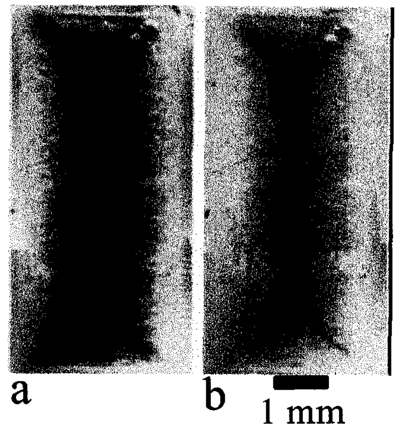


Fig.2. The plane-view magneto-optical images of the BSCCO monocore tape taken at T=77K and magnetic field a) H=5mT; b) H=8mT

regions demonstrate very good shielding property of this tape. The front of flux penetration is very smooth (the boundary between bright and dark area) and its depth increases progressively with the magnitude of the magnetic field. At a field of 120 mT (Fig.1c) magnetic flux has entered the tape from all edges and a well-demarcated "roof" pattern can be seen at the center and along diagonals. Such MO patterns of the flux distribution indicate that a significant long-range current is flowing around the whole tape. We see that the angle between diagonals is less than 90^0 (about 83-85^0), which means that the critical current density along the tape axis is higher than that across the tape. We can also see a characteristic flux penetration pattern that reflects structural non-uniformity in the BSCCO core, presumably due to microcracks, porosity and impurity phases. At liquid nitrogen temperature (Fig. 2), flux penetration into the BSCCO core takes place much more quickly than at 12 K, and full flux penetration is already observed at H = 8 mT. It is interesting to note that the angle between diagonals goes up to 88-89^0 and points to the fact that the role of different obstacles is more significant at 77K and thereby reduces the critical current density along the tape axis.

B. Investigation of Connectivity in BSCCO Core

It is well known that poor connectivity among superconducting grains is one of the prime hindrances for achieving higher critical current density in BSCCO tapes. To better understand the electrical connectivity of this tape we have subjected it to different forms of mechanical deformations and have checked the resulting defect structure by MO imaging. Fig. 3 demonstrates three MO pictures taken on the tape after three types of mechanical deformations have been applied: hammering, 50% reduction by rolling, and by bending the tape around a 1mm-diameter drill. It is very clear from these MO patterns that hammering or a 50% rolling reduction introduce the densest network of defects. At the

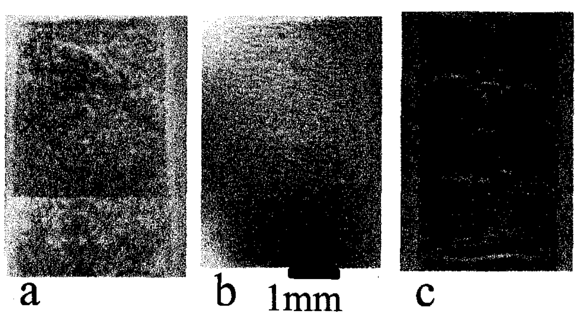
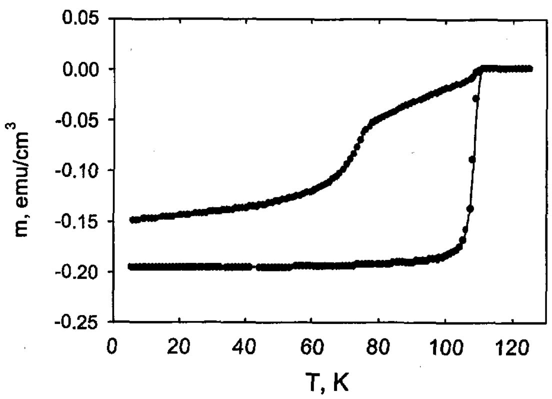


Fig.3. MO images taken at T=11K and H=40 mT for different method of deformation: a) hammering; b) 50% reduction by rolling and c) bending around the 1mm diameter drill.



Fig,4. The temperature dependence of magnetization curves taken on fully processed tape (bottom) and after hammering deformation (top) by SQUID magnetometer.

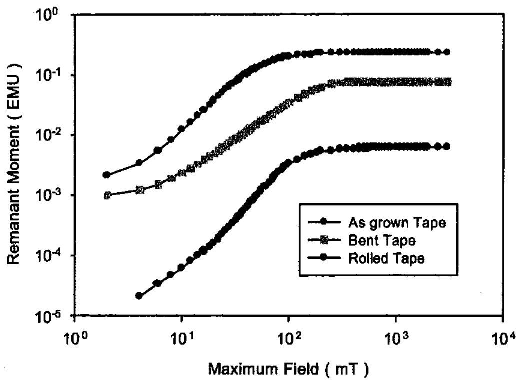


Fig. 5. Remnant magnetic moment as a function of the maximum applied field at T=10 K for the as-grown, bent and rolled tapes. The external field is applied perpendicular to tape plane.

same time bending over a 1mm diameter drill does not generate a network of cracks on as small a length scale. The MO images of these crushed samples do not show macroscopic bulk current circulating on the scale of the sample size and for this reason, the "roof" patterns are absent on each one. Thus these extrinsic defects prevent any large-scale bulk intergrain critical current flow. The magnetic flux penetrates in each sample in an unrestricted way along numerous mechanical defects, well visible in the MO image. The temperature dependence of magnetization for the hammered tapes measured with magnetic field applied perpendicular to the c-axis shows a clear transition at 80 K (Fig. 4). This transition can be attributed mostly to 2212 intergrowths within the 2223 grains. Such intergrowths are often found in 2223 tapes by TEM [4] and their presence in these particular samples was confirmed by XRD [5].

Recently Müller et al. have showed [2] that the tape core connectivity can be extracted from the ratio of intergrain and intragrain critical current density which can be derived from the remnant magnetic moment in as-grown and crushed tapes. In our magnetic experiments we compared two crushed tapes with different kinds of deformations: 50% reduction of thickness by rolling (Fig. 3b) and bending around the 1 mm diameter drill (Fig. 3c). As is well visible from MO pictures in Fig. 3, the rolled sample, with 50% reduction, has the highest density of microcracks than the other two tapes and the MO image is entirely due to intragranular contributions. Thus by studying the as-grown and crushed tapes we can obtain both intergrain and intragrain contribution to critical current density.

The magnetization measurements were done by using the SQUID magnetometer to progressively increase field and measure the remnant moment on a zero field-cooled sample. Fig. 5 shows the remnant moment for various maximum fields for the as-grown, rolled and bent tapes at the fixed temperature of 10 K. All three tapes show saturation at ~ 0.3 T external field. This implies that both intergrain and intragrain regions in these tapes saturate around the same field and that the as-grown tape is very well connected. From the analysis of Müller et al. [2] the tape connectivity C = J_c (intergrain)/J_c (intragrain), is dependent on the geometry of the sample, the superconducting volume fraction and the ratio of intergrain and intragrain remnant moment. It is important to note that bending around 1 mm diameter drill does not create defects of the order of grain size, which is evident from the MO images, and therefore the bent tape cannot be used to extract the intragranular remnant magnetic moment. From our measurements on the bent tape we found C ~ 0.034 while on the rolled tape C is 0.2. This means that local critical current can be ~ 5 times higher than long range critical current. Clearly better connectivity C = 0.2 has resulted in very high critical current density in this particular BSCCO tape.

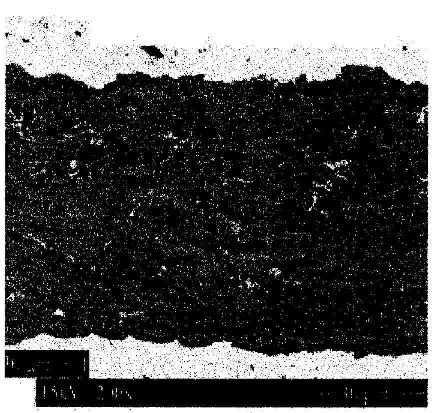


Fig.6. SEM image of a longitudinal section of BSCCO monocore tape. White color is Pb-rich phase (3221), black color is $(Ca,Sr)_2CuO_3$- impurity phases and some Bi-2212 are presented.

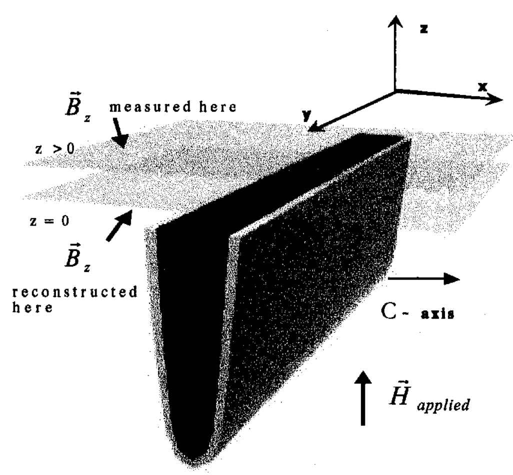


Fig.7. The slab geometry of MO experiment. The tape thickness is 55-60 μm and the half of the width is 1mm (vertical direction).

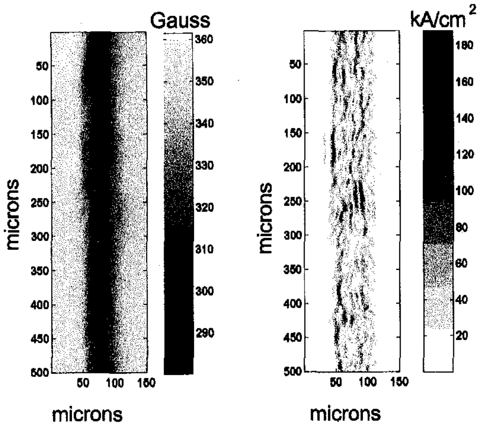


Fig.8. MO image (left) taken at T = 77 K in H=36mT (360G) on the longitudinal section of the monocore tape and reconstructed map of the critical current distribution (right). The darker regions correspond to higher values of critical

C. Current Reconstruction

For the current reconstruction, a half width of tape was prepared by mounting the 2-mm piece of tape in carbon-filled bakelite. This mount was ground with SiC up to the centerline of the tape width and was polished with 0.05 μm Al_2O_3 powder in methanol, so as to reveal the longitudinal face. Fig. 6 shows a scanning electron microscope (SEM) image of representative part of the longitudinal section of the tape. Some amount of Pb-rich phase (3221), $(Ca,Sr)_2CuO_3$ and Bi-2212 were found in this tape. The center plane mass density was 6.3 g/cm^3 (theoretical value is 6.35 g/cm^3) and goes down to 5.0 g/cm^3 towards the edge of tape.

The sample was mounted in slab geometry in order to calculate local critical current and its distribution at the BSCCO core (Fig. 7.). The MO indicator film was placed on the polished longitudinal face of the tape. For this geometry [6], the current flow in the sample can be found by

$$J_x = \frac{2}{\mu_0}\frac{\partial B_z(z=0)}{\partial y} \quad and \quad J_y = -\frac{2}{\mu_0}\frac{\partial B_z(z=0)}{\partial x} \quad (1)$$

if the Z component of the magnetic field in the plane Z = 0 ($B_z(z=0)$) is known. However, when the field is sampled it usually occurs at a height z>0 above the sample surface. A modified technique takes this measured field, $B_z(z>0)$, and reconstructs the field on the surface of the sample, $B_z(z=0)$. Once $B_z(z=0)$ is known, Eq.(1) can be applied. In our previous work [6] $B_z(z>0)$ has been used directly as an approximation to $B_z(z=0)$, but this results in an underestimation of the true critical current density. The calculation (1) is fair only with the next two approximations: if current has 2D flow in the plane of MO observation and the sample is infinite in Z direction. Mathematical calculations have shown that a monocore tape with half width of 1mm and thickness 55-60 μm mounted as shown in Fig. 7 is a good approximation to the slab geometry. Two magnetic field maps for current reconstruction were taken in the magnetic field H = 36 mT and 45 mT. The MO image and corresponding current distribution taken at 36 mT are shown in Fig. 8. It is clearly visible that a few local spots on the current map have a critical current value much higher than the surrounding area. The maximum value of J_c recovered is about 180 kA/cm^2. This result is in excellent agreement with our remnant moment experiment where we showed that the local J_c can be ~ 5 times larger than the bulk J_c. Essentially the same value of J_c was taken at H=45 mT. The average value of the critical current calculated from the current reconstruction (J_c=34-35 kA/cm^2) in these fields agrees well with critical current density calculated independently from the macroscopic transport and SQUID magnetization measurements. The depression of bulk critical current at 77 K for this tape (J_c=37 kA/cm^2 in zero magnetic filed) points towards the existence of wide spread weak links even in this state-of-the-art tape.

IV. CONCLUSION

Using three different experimental techniques such as MO imaging, transport and magnetization measurements, we have been able to correlate the current limiting defect structures in a high quality BSCCO tape to the critical current density. Intergrowths, misalignment and grain boundaries lead to poor connectivity among superconducting grains and severely restrict the current flow. Both the current reconstruction and magnetization study point to the fact that the local maximum critical current density can be as high as 5 times the local bulk current density (~180 kA/ cm^2) at liquid nitrogen temperature.

REFERENCES

[1] M.W. Rupich, Q. Li, R.D. Parrella, M. Teplitsky et al., "Critical current density enhancement in Bi-2223 composites," The 1998 Int. Workshop on Supercond., pp. 147-150, Okinawa, 12-15 July, 1998.

[2] K.-H. Müller, C. Andrikidis, J. Du, K.E. Leslie, C.P. Foley, "Connectivity and limitation of critical current in Bi-Pb-Sr-Ca-Cu/Ag tapes," Phys. Rev. B, vol. 60, pp. 659-666, 1999.

[3] J. W. Anderson, X. Y. Cai, M. Feldman, A. Polyanskii, J. Jiang, J. A. Parrell, K. R. Marken, S. Hong, D. C. Larbalestier, "The influence of intermediate roll characteristics on the residual crack density and critical current density in multifilamentary ($Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ tapes," Supercond. Sci. Technol., vol 12, pp. 617-623, 1999.

[4] T.G. Holesinger, J.F. Bingert, M. Teplitsky, Q. Li, R. Parrella, M.P. Rupich, G.N. Riley, "Spatial variations in composition in high-critical-current-density Bi-2223 tapes," J. of Material Research, vol. 15, pp. 285-295, 2000.

[5] M.O Rikel is with the Applied Superconductiviry Center, University of Wisconsin-Madison, Madison WI 53706 USA (e-mail: mrikel@facstaff.wisc.edu), private communication.

[6] A.E. Pashitski, A. Polyanskii, A. Gurevich, J.A. Parrell, D.C. Larbalestier, "Magnetic granularity, percolation and preferential current flow in a silver-sheathed $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O_{8+x}$ tape," Physica C 246, pp. 133-144, 1995.