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# AC MAGNETIC FIELD LOSSES IN BSCCO-2223 SUPERCONDUCTING TAPES

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## ABSTRACT

The AC magnetic losses at power frequencies (60 Hz) were investigated for mono- and multifilament Ag-sheathed (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_y$ (BSCCO-2223) tapes with similar transport critical current ($I_C$) values at 77 K. The multifilament sample exhibited higher losses than the monofilament under the same conditions. Loss peaks are discussed in terms of intergranular, intragranular and eddy current losses. Because of BSCCO's anisotropy, field orientation has a large effect on the magnitude of these peaks, even at relatively small angles. Losses for fields applied parallel to the c-axis of the textured BSCCO grains are larger by more than one order of magnitude than those applied perpendicular.

## INTRODUCTION

High-temperature superconductors, such as BSCCO-2223, have shown promise for use in applications such as AC power transmission cables. To be of practical use, power losses must be sufficiently lower than those of conventional materials so that the savings exceed the cost of maintaining the low temperatures required for operation. Multifilament tapes have been developed in an effort to increase the performance of superconducting tapes. Compared with monofilament tapes, the magnitude of AC losses in these geometries are important since they represent ongoing operational costs.

The imaginary part, $\chi''$, of the complex magnetic susceptibility, $\chi = \chi' + \chi''$, is associated with hysteretic AC losses [1-3]:

$$P_h = \int M \, dH = (\chi'' H_0^2) / (2 \mu_0). \tag{1}$$

According to the Bean critical state model, hysteretic losses per cycle of AC magnetic field applied parallel to the slab thickness D are predicted by [4,5]:

$$P_h = (4 W H_0^3) / (3 \mu_0^2 J_c) \qquad \text{for } (H_0 \leq H^*) \tag{2}$$

$$P_h = D^2 W J_c H_0 (1 - (2 H^*/3 H_0)) \text{ for } (H_0 > H^*), \tag{3}$$

where W is the slab width, $H_0$ is the amplitude of the applied magnetic field, H* is the magnetic field at which flux completely penetrates the sample, and $\mu o$ is the magnetic permeability of free space. It follows from Eqs. 2 and 3 that $P_h$ is characterized by $H_0^3$ dependence when the applied magnetic field does not fully penetrate the sample and by $H_0$ dependence in the regime where the applied magnetic field is greater than the field required for full penetration.

It is widely accepted that AC losses in BSCCO tapes are frequency-independent at frequencies < 1000 Hz [5-7]. The losses at power frequencies are predominantly hysteretic, with negligibly small eddy current losses [8]. Loss peaks in $\chi''$ have been attributed to several different mechanisms. Eddy current losses are due to excitation of normal electrons, intergranular losses are due to flux penetration of the weak-link grain boundaries, and intragranular losses are due to the depinning of Abrikosov vortices [3,6,7]. Intergranular and intragranular peaks shift to lower temperatures with increasing DC magnetic field, while the intrinsic peak shows little dependence on temperature or field intensity.

In this paper, AC losses have been measured for two tapes with similar 77 K transport critical current ($I_C$) values. Measurements were done for a 10 (Oe) AC field ($10^{-3}$ T) and at power frequencies. Losses were investigated as a function of temperature, field orientation, and applied DC magnetic field.

## EXPERIMENTAL PROCEDURE

Mono- and multifilament Ag-sheathed BSCCO-2223 tapes were made by a powder-in-tube (PIT) technique using $Bi_{1.8}Pb_{0.4}Sr_{2.0}Ca_{2.2}Cu_{3.0}O_y$ powder [9,10]. Before packing into Ag tubes, the powder had an average particle size of $\approx$15 µm, and X-ray analysis showed BSCCO-2212 peaks. The tubes were drawn and rolled to a tape that was $\approx$250 µm thick. The cross-sectional area of each sample was observed by scanning electron microscopy (SEM); compositional analysis was accomplished by energy-dispersive spectroscopy (EDS).

Figure 1 is a low-magnification (20x) SEM image taken in the back-scattering (BS) mode of cross sections of mono- and multifilament tapes.

The tapes were cut into 4-cm lengths, and heat treatments were carried out in an atmosphere of 7% $O_2$ - 93% Ar under the following schedule:

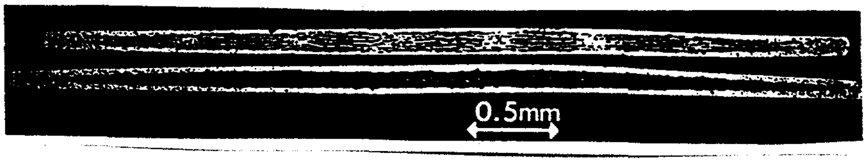

**Figure 1.** SEM micrograph showing cross sections of BSCCO-2223 multifilament (37) and monofilament tapes.

1. heating to 830°C at a rate of 1°/min,
2. holding at 830°C for 48 h, and
3. cooling at a rate of 2°C/h to 800°C and then 20°C/h to room temperature (RT).

After the initial 48-h heat treatment, samples were pressed with a 2.2 x $10^6$ N load. Samples were heat treated again for 48 h. The $I_C$ values were measured by a conventional four-point probe method with a 1 μV/cm criterion at 77 K under self-field. Table 1 summarizes specific characteristics for the two samples.

**Table 1.** Specific characteristics for two tapes

| | Multifilament | Monofilament |
|---|---|---|
| Number of Filaments | 37 | 1 |
| $I_C$ (A @ 77 K) | 33 | 32 |
| Cross-sectional ratio (BSCCO/Ag) | 0.52 | 0.89 |
| $J_C$ (A/m$^2$ @ 77 K) | 1.29 x $10^8$ | 8.57 x $10^7$ |
| Width (m) | 5.00 x $10^{-3}$ | 5.30 x $10^{-3}$ |
| Length (m) | 5.00 x $10^{-3}$ | 5.30 x $10^{-3}$ |
| Thickness (m) | 1.50 x $10^{-4}$ | 1.50 x $10^{-4}$ |
| Total Mass (g) | 3.27 x $10^{-2}$ | 3.66 x $10^{-2}$ |
| BSCCO Mass (g) | 6.73 x $10^{-3}$ | 1.32 x $10^{-2}$ |

Magnetic measurements were made in a Quantum Design Physical Properties Measurement System (PPMS) magnetometer which has a sensitivity of 2 x $10^{-8}$ emu at 10 kHz and a temperature stability of 0.01 K at 5 K [11]. Samples were centered in an AC magnetic field amplitude of 10 Oe ($10^{-3}$ T) and a frequency of 5 kHz at 80 K. The imaginary part of the complex magnetic susceptibility, $\chi$", associated with hysteretic AC losses, was measured at various temperatures and applied DC magnetic fields. All measurements were performed with an applied AC magnetic field of 10 Oe at a frequency of 60 Hz.

Magnetic measurements were performed with samples placed in different orientations with respect to the applied magnetic field, as shown in Figure 2. The vertical (V) orientation denotes an applied field perpendicular to the c-axis, while the horizontal (H) orientation denotes an applied field parallel to the c-axis of the BSCCO grains.

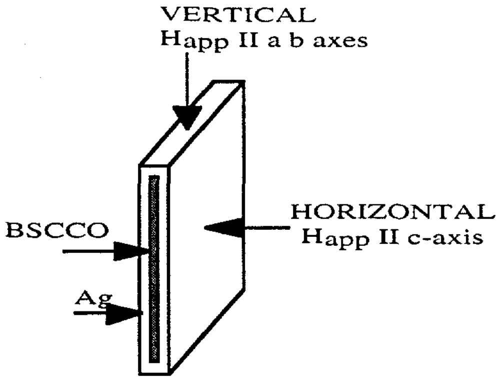

**Figure 2**. Schematic presentation of magnetic field orientations.

## RESULTS AND DISCUSSION

### Effect of Tape Geometry (Monofilament vs. Multifilament)

Figure 3 shows the imaginary part of the complex magnetic susceptibility, χ", for the monofilament and multifilament tapes in the vertical orientation for an applied AC field of 10 (Oe) (1 x $10^{-3}$ T) and background DC fields of 500, 1000 and 5000 (Oe) (0.05, 0.1 and 0.5 T). First, results for the monofilament tape in the 0.05 T DC field are discussed. As the temperature increases, the applied magnetic field becomes greater than the critical field to nucleate vortices along grain boundaries. These intergranular Josephson vortices began to penetrate the sample, causing an increase in χ". With further increases in temperature, the applied field exceeds the critical field for grains and vortices began to penetrate into the grains. χ" exhibits a peak at temperatures below $T_c$ indicating complete penetration through the sample volume [3,12]. Further increases in temperature lead to a decrease in χ". Increasing the DC magnetic field from 0.05 to 0.5 T shifts $T_c$ from 105 to 95 K. Also, the peak temperature for χ" shifts from ≈ 95 to ≈ 82 K.

The multifilament tape exhibits significantly larger losses (≈2.7 times larger) than that of the monofilament tape. This is attributed to magnetic coupling between the individual filaments of the multifilament tape [1-3]. As a screening current develops on each strand, a local magnetic field is created and impinges on neighboring filaments. This creates local magnetic fields on the individual strands that are higher than the applied field alone, resulting in larger losses. Loss peaks of the multifilament sample appear at temperatures lower than the corresponding peaks of the monofilament sample.

Monofilament and multifilament samples in the horizontal orientation are compared in Figure 4. The peak temperature maximum for χ" for monofilament tape shifts to ≈104 K for a zero DC field to ≈ 75 K for a 0.5 T DC field. Also, the critical temperature decreases to ≈ 82 K with increase in DC field to 0.5 T. The multifilament tape showed broad peaks for the horizontal orientation, indicating that low fields (10 Oe AC and zero DC field) began to penetrate the sample at temperatures of ≈ 40 K. For 0.5 T DC field, peak loss maximum occurs at ≈ 55 K, well below the liquid nitrogen range. Again, the multifilament sample exhibits larger losses, suggesting magnetic coupling between filaments. The loss ratio $\chi''_{\mathrm{Multi}} / \chi''_{\mathrm{Mono}}$, for this orientation was ≈ 2.2, while the ratio for the vertical orientation was 2.7. This result might be due to filament geometry and

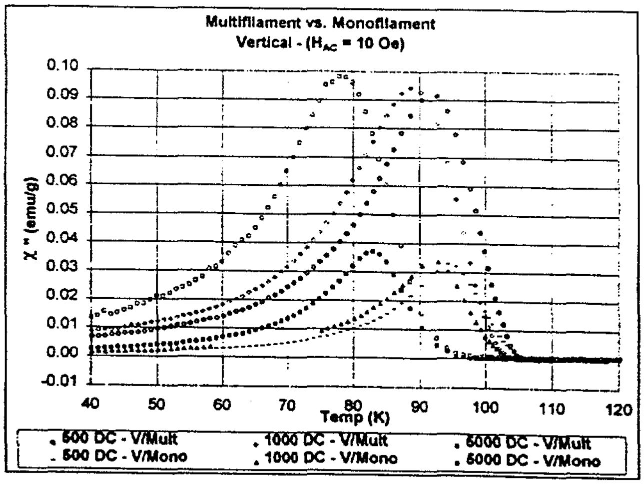

**Figure 3.** Measurement of $\chi$" vs. temperature for monofilament and multifilament tapes in a vertical position with respect to the applied magnetic field.

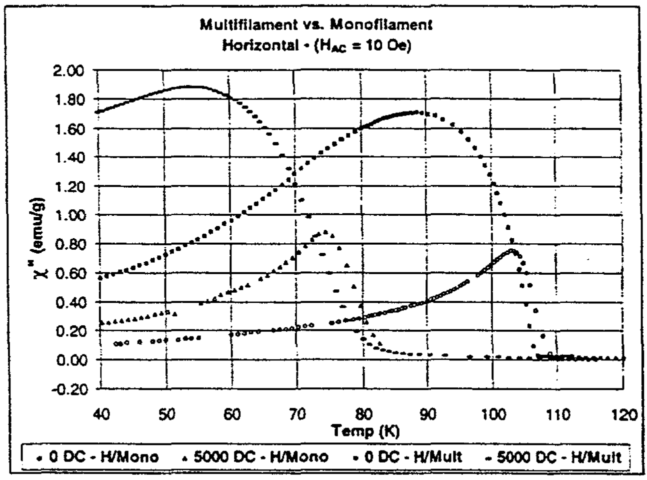

**Figure 4.** Measurement of $\chi$" vs. temperature for monofilament and multifilament tapes in a horizontal position with respect to the applied magnetic field.

field orientation. Since each filament is roughly slab-shaped, it presents a larger profile to the applied magnetic field in the horizontal position than it does in the vertical position. Thus in the horizontal orientation, the outer filaments provide shielding of the inner filaments from the applied field. However, losses in this orientation are still much larger than in the vertical orientation due to the anisotropic nature of the BSCCO superconductor.

Magnetic coupling between filaments in a BSCCO tape supports the work of Oota *et al.* [4] and Yang *et al.* [12] in that there is a strong interaction between filaments, which increases AC losses. However, Oota *et al.* [4] suggested that the increased AC losses observed for multifilament tapes versus monofilament were due to increased eddy currents. Rather, it appears that these losses are caused by magnetic coupling between filaments. Since field orientation is important, filaments within the tape should be arranged so as to minimize the effect of mutually induced fields.

## Effect of Applied Field Orientation

The effect of applied magnetic field orientation on the multifilament tape is shown in Figure 5. The slight rise in $\chi''$ at low temperatures (<20 K) is indicative of a loss peak caused by eddy currents in the Ag sheath.

As the magnitude of the applied DC magnetic field is increased, the loss peak shifts to lower temperature and broadens, similar to that of the YBCO sample investigated by Silva and McHenry [11]. However, no clear separation of the intergranular and intragranular loss peaks is seen within the range of the applied DC fields ($\leq 0.5$ T). The small depression at the top of the loss peak at 0.5 T suggests that the intergranular and intragranular peaks overlap and that a separation should be seen at higher DC fields. Thus, the single broad loss peak observed is a superposition of the two component loss peaks, intergranular and intragranular. As fields are applied at angles further from the c-axis perpendicular (i.e., more parallel to the c-axis of the superconducting grains), the loss peaks shift to lower temperatures and the interval between peaks for different DC fields (e.g., between 0 and 0.5 T) increases. More important, the magnitude of the loss peak increases dramatically as the field orientation strays from the c-axis perpendicular. This dependence on field orientation is so crucial that the magnitude of the loss peak of a 0.5 T DC field applied perpendicular to the c-axis (5000 DC-V) is more than one order of magnitude lower than for a zero DC field applied parallel to the c-axis (0 DC-H); $\chi''$= 0.0982 and 1.60 emu/g, respectively at 80 K.

The monofilament tape also showed this dependence on field orientation. This can be seen by comparing the magnitude of the loss peak for a 0.5 (T) DC field applied perpendicular to the c-axis (5000 DC-V in Figure 6) with that of a zero T DC field applied at a slight angle ($\approx 8^{\circ}$) from perpendicular (zero DC-S in Figure 6), where the values are 0.037 and 0.113 emu/g, respectively. This reflects the anisotropic nature of BSCCO and demonstrates the importance of considering field orientation when working with these types of superconductors, even under low-field conditions.

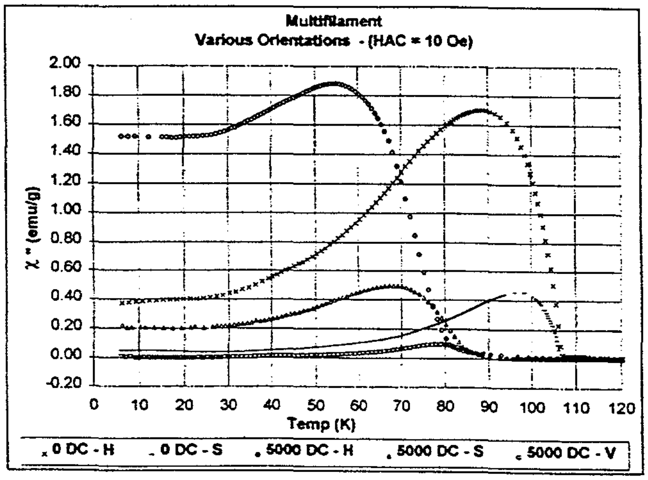

**Figure 5.** Measurement of $\chi''$ vs. temperature for a multifilament tape in various positions with respect to the applied magnetic field. The angular (S) orientation refers to a magnetic field applied at an angle of $\approx 24^{\circ}$ to the a-b axes.

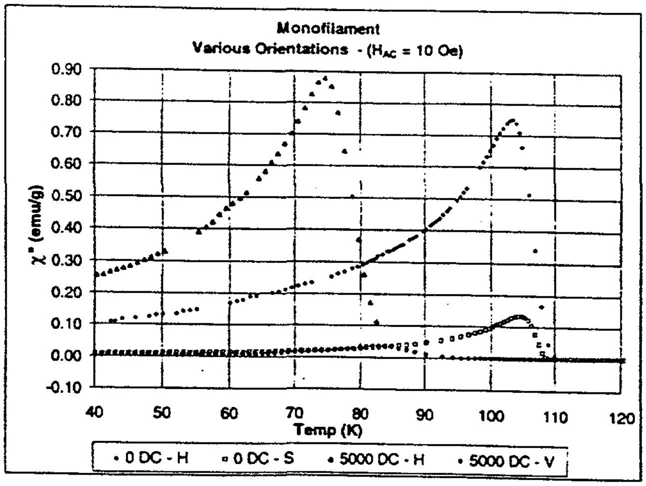

**Figure 6.** Measurement of χ" vs. temperature for a monofilament tape in various positions with respect to the applied magnetic field. The angular (S) orientation refers to a magnetic field applied at an angle of ≈8° to the a-b axes.

## CONCLUSIONS

AC losses for monofilament and multifilament BSCCO-2223 tapes were investigated as a function of temperature, applied DC magnetic field, and field orientation. The multifilament sample exhibited higher losses than the monofilament tape under similar conditions. Losses for fields applied parallel to the c-axis of the textured BSCCO grains are larger by more than one order of magnitude than those applied perpendicular to the c-axis. Loss peaks shift to lower temperature and broaden with fields applied at increasingly greater angles from the c-axis perpendicular. Losses due to eddy currents in the Ag sheath were observed at low temperatures. Intergranular and intragranular loss peaks were not resolved for applied DC magnetic fields ≤ 0.5 T (5000 Oe). Rather, they appeared as a single loss peak that broadens and shifts to lower temperatures with increasing applied DC fields. Field orientation proved to be very important, even at small angles, due to BSCCO anisotropy.

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