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# PROCESSING AND PROPERTIES OF Ag-CLAD BSCCO SUPERCONDUCTORS

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## ABSTRACT

Long lengths of mono- and multifilament Ag-clad BSCCO conductors with critical current densities of  $>10^4$  A/cm<sup>2</sup> at 77 K were fabricated by the powder-in-tube technique. High-T<sub>c</sub> magnets were assembled by stacking pancake coils fabricated from long tapes and then tested as a function of applied magnetic field at various temperatures. A magnet that contained  $\approx 2400$  m of high-T<sub>c</sub> conductor generated a field of 3.2 T at 4.2 K. In-situ tensile and bending characteristics of the Ag-clad conductors have been studied. Multilayer Ag/superconductor composites have been fabricated with a novel chemical etching technique. Preliminary results with multilayer tapes show that continuous Ag reinforcement of the BSCCO core improves strain tolerance of the tapes so they can carry 90% of their initial I<sub>c</sub> at 1% bend strain despite a higher superconductor/Ag ratio than that of unreinforced tapes.

## 1. Introduction

The powder-in-tube (PIT) process for the Bi-Sr-Ca-Cu-O (BSCCO) system of superconductors, with silver (Ag) as a sheathing material, is a promising technique for fabricating long-length conductors from high-transition-temperature superconducting (HTS) materials. Although significant progress has been made in the past few years in fabricating PIT tapes and enhancing their critical current density (J<sub>c</sub>), the remaining critical issues impede the successful commercialization of HTSs. For many applications, as in electromechanical machinery, continuous lengths of tape, on the order of 1 km, with uniform electrical properties are necessary.<sup>1-5</sup> The electrical properties of these conductors under strain is another important engineering issue.

## 2. Conductor Fabrication

### 2.1 Fabrication of long-length conductors

Powder-in-tube fabrication of Ag-clad BSCCO conductors by our group is described in ref.4. High transport current properties in short samples have been achieved by a combination of uniaxial pressing and heat treatment. Critical current values above 40 A were typically attained at 77 K, the highest of which was 51 A.

Implementing a carefully designed two-step rolling and heat-treatment procedure, we have fabricated mono- and multifilament conductors several hundred meters in length.<sup>4,6</sup> A consistent J<sub>c</sub> of  $1.2 \times 10^4$  A/cm<sup>2</sup> has also been achieved in 850-m-long, and recently in 1260-m-long, 37-filament tapes at 77 K in self fields, as shown in fig.1. Short lengths from a recent 100-m-long 37-filament tape carried critical currents as high as 50 A at 77 K. The transport properties of both short and long mono- and multifilament tapes are shown in Table 1 with corresponding superconductor/Ag (sheath) ratios (superconductor fill factor).

Table 1. Summary of transport current properties of short and long mono- and multifilament Ag-clad BSCCO conductors.

Conductor	Length (m)	$I_c$ (A)	Core $J_c$ (A/cm <sup>2</sup> )	Overall $J_c$ (A/cm <sup>2</sup> )	Fill Factor (%)
Monofilament					
Short Pressed	0.03	51	45,000	9,000	20
Short Rolled	0.03	51	29,000	7,800	27
Long Length	70	23	15,000	3,500	24
Long Length	114	20	12,000	3,200	27
Multifilament					
Long Length	20	42	21,000	6,800	32
Long Length	90	35	17,500	5,600	32
Long Length	850	16	10,500	2,500	24
Long Length	1,260	18	12,000	3,500	30

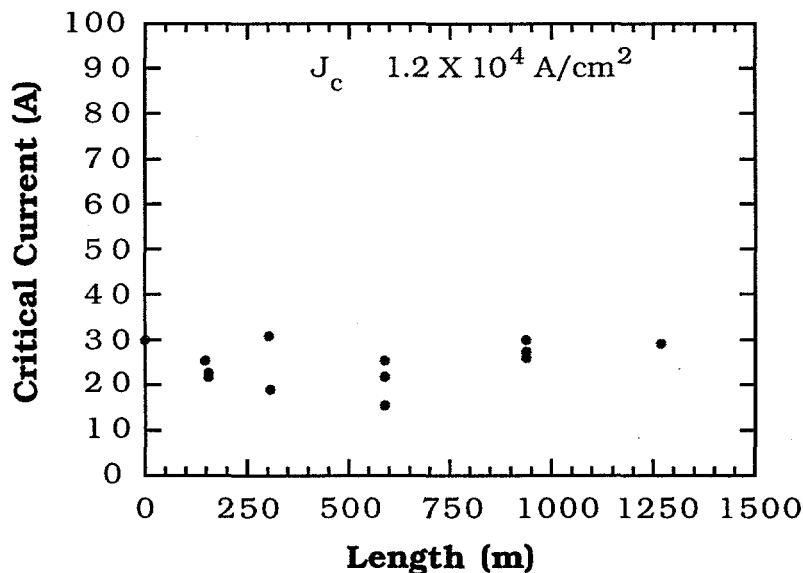


Fig. 1. Critical current vs. length of 1260-m-long 37-filament conductor at 77 K

## 2.2 Fabrication of prototype magnets and transformers

A test magnet fabricated by stacking 20 pancake coils, with a total conductor length of 2400 m, generated a record-high field of  $\approx 3.2$  T at 4.2 K in zero applied field. Another test magnet, generated a field of 1 T at 4.2 K and 0.6 T at 27 K, in a background field of 20 T. Total length of the conductor in this magnet was 770 m. The racetrack-wound solenoid was used to develop a 0.25 kVA high- $T_c$  superconducting transformer that has an iron core and can operate at liquid nitrogen temperature. The primary end of the transformer was made of  $\approx 85$  m of high- $T_c$  conductor, and the secondary end was 31 m long. Turns in the primary and secondary winding were 140 and 40, respectively.

### 3. Strain tolerance of Ag-clad BSCCO conductors

#### 3.1. Mono- and multifilament conductors

Ag-clad BSCCO tapes are susceptible to damage due to axial, bending, and magnetic stresses that come into play during fabrication and operation of devices made from such tapes. Cracks induced in the superconducting core because of these stresses could lead to degradation of the superconducting properties. Therefore, the importance of understanding the strain tolerance of these tapes as a function of their transport properties cannot be overstated.<sup>2-4</sup>

Axial strain tolerance of mono- and 61-filament conductors (reported in Ref. 5) was evaluated by subjecting the tapes to an in-situ tensile test. We obtained bending characteristics of the conductors in-situ, with a custom-designed test fixture.<sup>4</sup> The irreversible strain limit ( $\epsilon_{irr}$ ) is defined as that strain beyond which a decrease in  $I_c$  is irreversible. Bending tests conducted on both mono- and 61-filament conductors at 77 K and zero applied field revealed that multifilament conductors exhibit better strain tolerance than monocore tapes.

#### 3.2. Multilayer conductors

Strain tolerance of Ag-clad BSCCO tapes can be improved by using Ag addition, alternative sheath materials, or multifilament conductors.<sup>4</sup> Singh et al. showed that the strain tolerance of tapes can be improved without much loss in  $J_c$  by adding Ag to the superconductor powder.<sup>6</sup> In addition, as reported by several researchers,<sup>4</sup> the interfacial region between the BSCCO core and the Ag sheath with well-aligned BSCCO grains is believed to be responsible for high  $J_c$ . Our work on the influence of Ag showed that the strain tolerance of the tapes increased with increasing Ag (sheath) content. Thus, Ag addition should not only enhance  $\epsilon_{irr}$ , but the increased Ag/BSCCO interfacial area should also increase the  $J_c$ .

Cracks initiated on the outer side (tensile side) of a bent tape eventually propagate through the thickness of the core to the inner side (compressive side) and impede the flow of current. Because ceramics withstand much higher compressive strains than tensile strains, if Ag reinforcement is included in the core to isolate the cracks in the tensile side of the bent tape, current can still flow unimpeded through the part that is under compression. However, it is critical to control the geometry of the additional Ag in the core because in powder or particulate form, the Ag may not provide the same reinforcement provided by a continuous filament. On the other hand, a continuous filament may produce a break in the superconducting core by fusing with the sheath.

Employing an etching technique that was developed to join Ag-clad BSCCO tapes,<sup>4</sup> we have fabricated tapes with a multilayer structure that incorporate Ag foil or wire in the core. The Ag sheath from one side of a pair of tapes was etched while the other side was kept intact. The exposed cores were then aligned and joined with either a single filament of 25- $\mu$ m-thick Ag foil or 25- $\mu$ m-thick Ag wires sandwiched between them.<sup>4</sup> The joined tapes were pressed and subjected to the same thermomechanical treatment that was used for regular tapes. Preliminary observations of such tapes indicate enhanced strain tolerance, as shown in fig. 2. A multilayer tape with a fill factor of 40% exhibited higher strain tolerance than did monofilament conductors with fill factors of 23, 30, and 38%; and the multilayer tape retained 90% of its initial  $I_c$  at a bend strain of 1%. Work is in progress to understand the influence of the geometry and

processing of the sandwiched Ag layer on the electrical and mechanical properties of multilayer tapes.

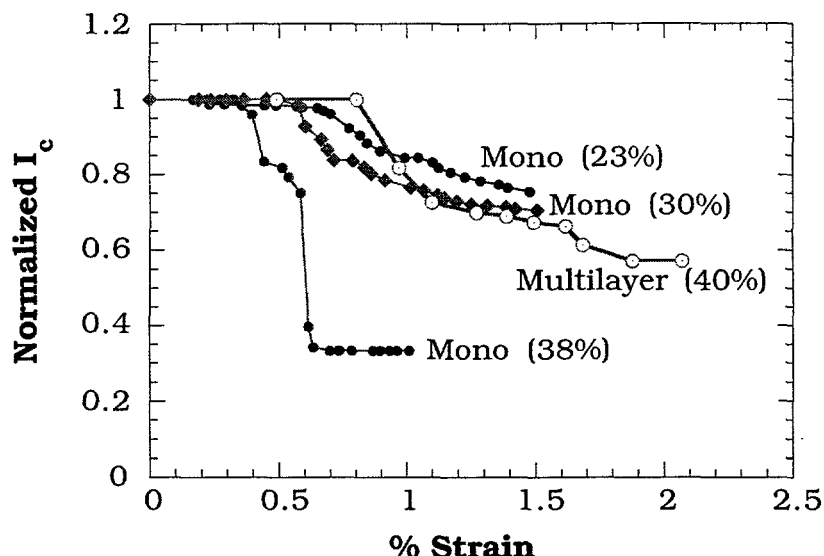


Fig. 2. Strain tolerance of Ag-clad BSCCO mono- and multilayer (foil) tapes with various superconductor fill-factors (in parentheses)

#### 4. Summary

Long-length mono- and multifilament Ag-clad BSCCO-2223 tapes with a consistent  $J_c$  of 12000 A/cm<sup>2</sup> at 77 K have been fabricated. High- $T_c$  magnets and a prototype 0.25 kVA transformer have been constructed from such long tapes. In-situ strain tolerance tests were conducted with a custom-made test fixture. Multilayer Ag/BSCCO composite tapes were fabricated by sandwiching Ag foil/wires between the cores of two tapes. Continuous reinforcement provided by the sandwiched Ag appears to enhance the strain tolerance of such tapes in spite of increased superconductor/Ag ratios.

#### 5. Acknowledgments

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