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ADVANCES IN FABRICATION OF MONO- AND MULTIFILAMENT Ag-CLAD BSCCO SUPERCONDUCTORS

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ABSTRACT

Fabricating long lengths of robust and high-quality conductors is imperative for various applications of high-T_c superconductors. Long lengths of mono- and multifilament Ag-clad Bi-Sr-Ca-Cu-O conductors have been fabricated by the powder-in-tube technique. High values for critical current density (J_c) have been achieved in both short- and long-length conductors. J_c values up to 12,000 A/cm^2 have been achieved in an 850-m-long multifilament conductor. Pancake-shaped coils and test magnets fabricated from long-length conductors were characterized at various temperatures and applied magnetic fields. A magnet containing 770 m of high-T_c conductor generated a record high field of ≈ 1 T at 4.2 K in a background field of ≈ 20 T. In-situ tensile and bending characteristics of both mono- and multifilament conductors have also been studied. Multifilament conductors exhibited better axial strain tolerance ($\varepsilon \approx 1\%$) than that of monofilament conductor ($\varepsilon \approx 0.2\%$), while retaining 90% of their initial critical current. An analysis of the results is presented, along with effects of parameters such as thickness, superconductor/Ag ratio, and microstructural details.

INTRODUCTION

Significant effort has been expended over the past few years on the development of superconducting wires and tapes for possible electric power and high-field magnet applications. Potential commercial applications of high-T_c superconductors include motors, generators, and transmission cables. Fabricating robust and high-quality conductors is important for the various applications envisaged for high-Tc superconductors. Long lengths of Ag-clad Bi-Sr-Ca-Cu-O (BSCCO) superconductors have been successfully fabricated by the powder-in-tube (PIT) technique. The process appears to be promising for economically fabricating long lengths of flexible high-T_c superconductors because it utilizes a processing technique similar to that currently used in the manufacture of low-T_c superconductors. The goal is to apply the technology to devices that currently use low-T_c

superconductors, or to new devices capable of operating at higher temperatures and/or in higher magnetic fields.[1-6]

Several research groups have reported high critical current density (J_c) in short-length Ag-clad BSCCO samples that were fabricated by the PIT technique and subjected to cycles of uniaxial pressing and heat treatment. In addition, J_c values of tapes fabricated from BSCCO are significantly higher than those exhibited by low-T_c superconductors, such as NbTi and Nb_3Sn, at 4.2 K and in high applied magnetic fields.[1-3,5,7-9] However, because uniaxial pressing is not appropriate for fabricating long lengths of conductors, a more practical approach, such as rolling, must be adopted to meet the stringent requirements of the various applications envisaged for high-T_c superconductors.[5]

Using a modified processing technique, Intermagnetics General Corporation(IGC) of Latham, NY, in collaboration with Argonne National Laboratory (ANL), have fabricated high quality mono- and multifilament BSCCO conductors in lengths of up to several hundred meters. At 77 K, J_c values of $\approx 1.2 \times 10^4$ A/cm^2 have been achieved in a 125-m-long monocore conductor. Similar results have been obtained in long lengths of multicore conductor containing several monocore filaments. The conductors have been co-wound in parallel to form prototype pancake-shaped coils. High-T_c superconducting magnets were then assembled by stacking the pancake-shaped coils and connecting them in series.[5,10,11]

During fabrication of coils and magnets, the tapes are subjected to both tensile and bending stresses. In addition, during service, they are subjected to large electromagnetic hoop stresses that develop because of Lorentz forces. At times, these stresses could even reach the ultimate strength of the material. Because high-T_c superconductors are soft materials consisting of a ceramic compound and silver, which is widely used as the sheath material in the PIT process, they are unable to withstand these stresses. Cracks induced in the superconducting core because of the above mentioned stresses could lead to degradation of the current transport properties of the tapes.[2,4,5,12-17] Much effort is being expended to improve strain tolerances of the tapes, either by addition of Ag to the superconductor core, or by using alternative sheath materials such as AgNiMg, AgMg, Ag-10 at% Cu, or AgAl, or by developing multifilament conductors.[18-22] This paper discusses the fabrication and characteristics of long-length conductors, high-T_c magnets, and the mechanical properties of Ag-clad BSCCO superconductors.

EXPERIMENTAL PROCEDURE

The Ag-clad BSCCO tapes were prepared by the conventional PIT technique. Appropriate amounts of Bi_2O_3, PbO, $SrCO_3$, $CaCO_3$, and CuO were mixed and calcined at 800-850 °C in air for $\approx$50 h to obtain a partially reacted mixture of BSCCO-2212, calcium cuprate, and other secondary phases. The characteristics of the powders were carefully monitored by differential thermal analysis, X-ray diffraction (XRD), and wet chemical analysis. To obtain a more homogeneous powder, intermittent grinding was used during calcination.

The precursor powders were packed by mechanical agitation into high-purity Ag tubes, lightly swaged, drawn through a series of dies, and then rolled to a final thickness of $\approx$0.1 mm. Short lengths of tapes were cut and heat treated at $\approx$850°C in air with intermittent uniaxial pressing. After each thermomechanical step, the tapes were characterized by XRD, scanning electron microscopy (SEM), and critical current (I_c) measurements. Transport properties of the tapes were measured by the standard four-point probe technique with a criterion of 1 μV/cm.

Although uniaxial pressing and heat treatment cycles produced short-length tapes with the highest J_c values, the procedure is not suitable for fabricating long length conductors. Because distribution of stresses is not uniform, repeated rolling of ceramic composites introduces cracks in the ceramic core; this, in turn, leads to degradation of transport properties. However, by carefully monitoring the rolling parameters, long-length conductors with uniform cross sections and improved transport properties have been fabricated. These conductors have been co-wound in parallel to form pancake-shaped coils by the "wind-and-react" or "react-and-wind" approach. Test magnets were fabricated by stacking together and connecting a set of the pancake coils in series . The magnets were characterized at 4.2, 27, 64, and 77 K in background fields up to 20 T. Multifilament conductors containing 37 and 61 filaments were fabricated by stacking monocore wires in larger Ag tubes and then drawing and rolling them to final size.

Axial strain tolerance of mono- and multifilament (61 filaments) conductors was evaluated by subjecting the tapes to an in-situ tensile test. Retention of I_c as a function of applied strain was measured at 77 K and in applied fields of 0 and 0.5 T. In-situ bend characteristics of the conductors were obtained with a custom-designed test fixture. The tape was fixed between two movable arms mounted on a lead screw. The tapes were bent into a bath of liquid nitrogen by moving the arms toward each other by means of a crank-shaft mechanism. The correlation between the number of turns of the crank-shaft and the radius of curvature to which the tapes were bent was pre-established at ambient temperature. The bend strain (ε) was determined from the relationship

$$\varepsilon = t/2R \qquad (1)$$

where t is the total thickness of the tape and R is the radius of curvature. The irreversible strain limit ε_{irr} is defined as that strain beyond which the decrease in the I_c is irreversible. Bend tests were conducted on both mono- and multifilament (61 filaments) conductors at 77 K and zero applied field. The effect of superconductor/Ag ratio (superconductor fill factor) on the bend characteristics of monofilament conductors was also studied; monofilament conductors with fill factors of 23, 30, and 38% were used.

RESULTS AND DISCUSSION

We have used PIT technique to successfully fabricate long-length conductors with uniform cross sections and improved transport properties. At 77 K and zero applied field, a J_c of $\approx 1.6 \times 10^4$ A/cm^2 has been achieved in a 125-m-long monofilament conductor. Figure 1 shows I_c along the length of an 850-m-long multifilament (37 filaments) conductor. The I_c of the conductor was 16 A, corresponding to a J_c of 1.2×10^4 A/cm^2 at 77 K and zero applied field. Consistent results have been obtained from long-length mono- and multifilament conductors, indicating that considerable progress has been made in their development.

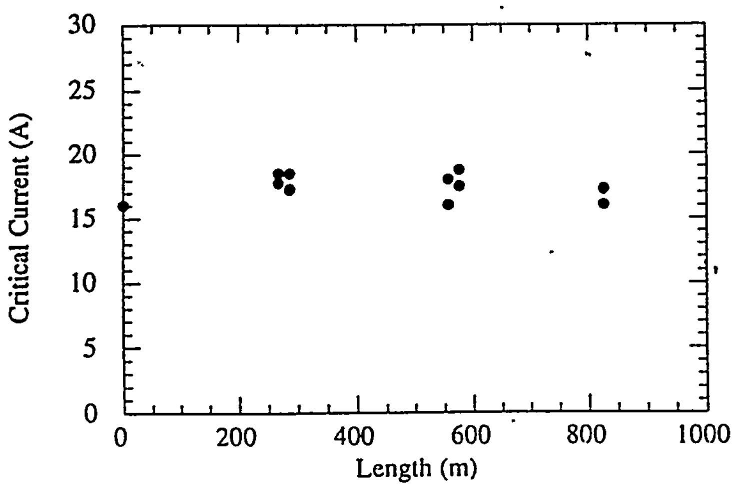

Figure 1. I_c vs. length at 77 K of multifilament (37 filaments) conductor. J_c of an 850-long conductor was $\approx 1.2 \times 10^4$ A/cm^2.

Pancake-shaped coils and high-T_c test magnets, fabricated from long-length conductors, were characterized at various temperatures and applied magnetic fields. A test magnet fabricated by stacking 10 pancake coils, with each coil containing three 16-m lengths of BSCCO conductor, generated a record high field of 2.6 T at 4.2 K and zero applied field. At 27, 64, and 77 K, the generated fields were 1.8, 0.53, and 0.36 T, respectively. Total conductor length in the magnet was ≈480 m. Recently, another test magnet was fabricated with eight double pancake coils. Each coil contained three 16-m lengths of BSCCO conductor co-wound together; total conductor length was ≈770 m. The 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.

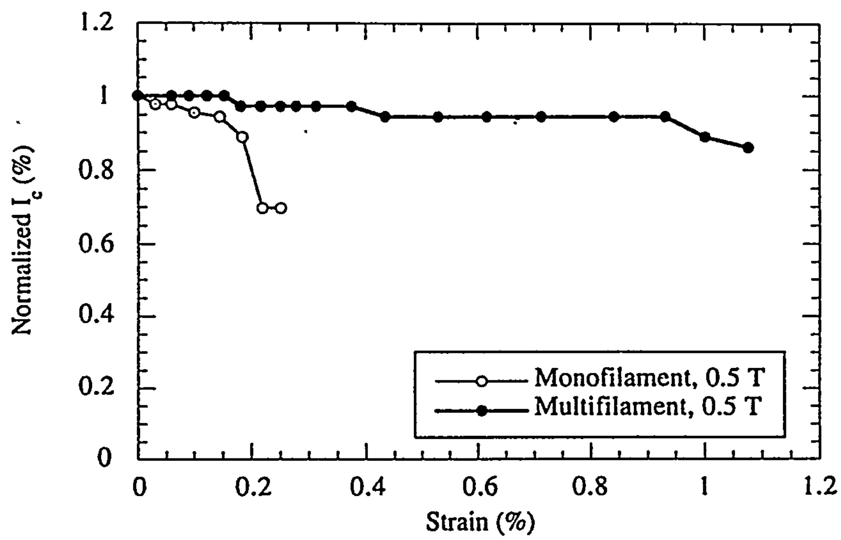

Figure 2. Normalized I_c vs. strain of mono- and multifilament conductors at 77 K and 0.5 T applied magnetic field

The results for normalized I_c as a function of applied axial strain in an applied field of 0.5 T for mono- and multifilament (61 filaments) conductorsis shown in Figure 2. As seen in Figure 2, multifilament conductors appear to have better strain tolerance than monofilament conductors, retaining more than 90% of their initial I_c at ≥1% strain. Whereas ε_{irr} for the multifilament conductor was ≈1%, that for the monofilament conductor was ≈0.2%. Microscopic examination of the longitudinal cross section of the monofilament conductor (Figure 3) shows fracture and delamination of the superconductor core from the Ag sheath. In addition, bloating of the superconductor tape, which can be attributed to the thermal gradient that is set in the material when it is removed from liquid nitrogen, was also observed. Figure 4 shows the normalized I_c of mono- and multifilament (61 filaments) conductors as a function of bend radius. As observed by several other research groups, the drop in I_c with decreasing bend radius is more profound in monofilament conductors than in multifilament conductors. Figure 5 shows preliminary results of the effect of superconductor/Ag ratio (superconductor fill factor) on the bend characteristics of the monofilament conductor. The plot shows that the ε_{irr} for the monofilament conductor increases as superconductor fill factor decreases. For commercial development of high-T_c superconductors it is important to know the strain characteristics of the tapes. The results we obtained are encouraging because they show that further improvement in mechanical properties can be achieved without compromising current transport properties. At present, effort is underway to further study the effect of superconductor/Ag ratio, alternative sheath material, Ag doping, and packing density on the strain tolerance of BSCCO tapes.

Figure 3. SEM photomicrograph of monofilament conductor subjected to in-situ tensile testing. Microscopic examination shows fracture and delamination of superconductor core from Ag sheath.

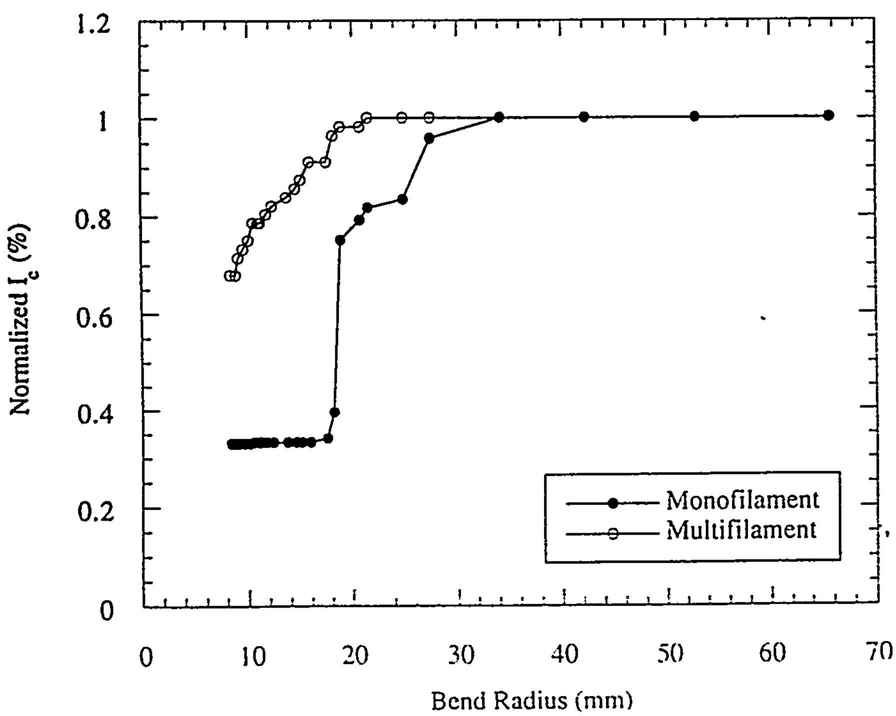

Figure 4. Normalized I_C of mono- and multifilament conductor as a function of bend radius.

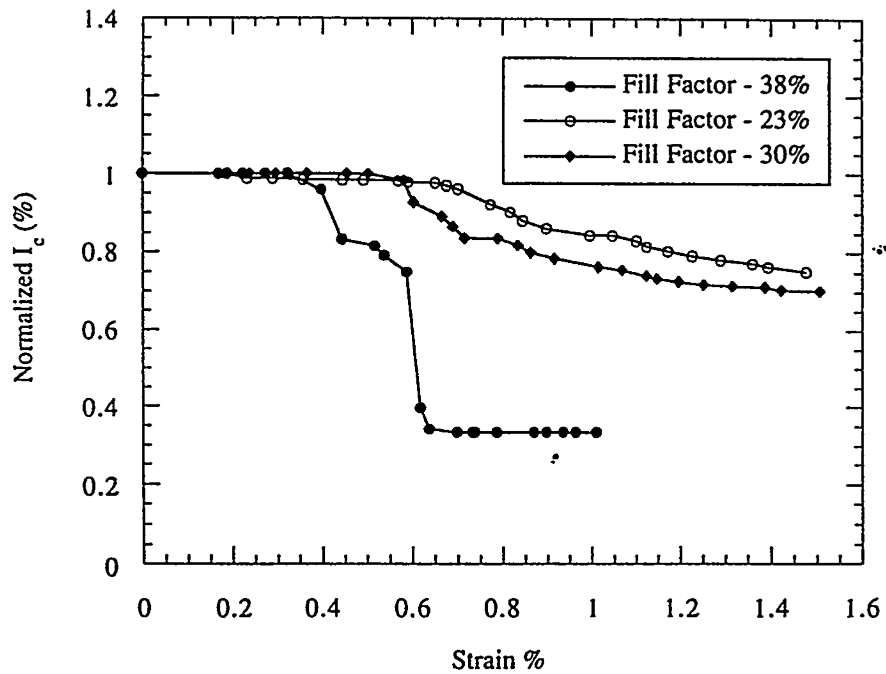

Figure 5. Normalized I_c vs. bend strain of monofilament conductors with three superconductor fill factors.

SUMMARY

High-quality mono- and multifilament conductors up to several hundred meters in length have been successfully fabricated by the PIT technique. High-T_c magnets were fabricated by forming pancake-shaped coils and connecting them in series. A high-T_c magnet containing 770 m of tape generated a field of ≈ 1 T at 4.2 K and in a background field of 20 T. The magnets can be used, along with low-T_c magnets, to form hybrid magnets for field-sensitive applications. Strain tolerance of the conductors was evaluated by subjecting them to in-situ tensile and bending tests. Tensile tests indicate that multifilament conductors exhibit better strain tolerance than monofilament conductors because they are able to retain 90% of their initial I_c at strains $\geq 1\%$. The effect of superconductor/Ag ratio on the bending characteristics of the conductors was also evaluated. Preliminary results indicate that the irreversible strain limit of the monofilament conductor increases with decreasing superconductor fill factor.

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