PROGRESS IN DEVELOPMENT OF TAPES AND MAGNETS MADE FROM Bi-2223 SUPERCONDUCTORS

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Abstract

Long lengths of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ tapes made by powder-in-tube processing have been wound into coils. Performance of the coils has been measured at temperatures of 4.2 to 77 K, and microstructures have been examined by X-ray diffraction and electron microscopy and then related to superconducting properties. A summary of recent results and an overview of future goals are presented.

Introduction

Powder-in-tube (PIT) processing has been used by several research groups to obtain very high critical current density (J_c) in short lengths of Ag-clad Bi-Sr-Ca-Cu-O (BSCCO) superconductors. Sato et al. and Yamada et al. reported J_c values of 5.4 x 10^4 A/cm^2 and 3.3 x 10^4 A/cm^2, respectively, at 77 K and zero applied field. The NKT Research Center in Denmark reported J_c values as high as 6.9 x 10^4 A/cm^2.[1-9] Because the J_c values of BSCCO tapes at 4.2 K and in high magnetic fields are significantly higher than those of low-T_c superconductors such as NbTi and Nb_3Sn, BSCCO can be used to replace presently used low-T_c superconductors. Additionally, BSCCO conductors can be used well beyond the temperature and field capability of low-T_c superconductors. The success in short-length tapes has not only helped researchers better understand the PIT process, but has also encouraged them to develop techniques for fabricating long lengths of robust conductors.

The high J_c values of BSCCO tapes can be attributed to the strong c-axis orientation of its grains. Good grain alignment improves intergrain connectivity, thereby increasing the current–carrying capacity of the material. Alignment and texturing of the BSCCO grains can be obtained very easily by the PIT process, compared to various other conventional techniques such as sinter forging, hot isostatic processing, and jelly roll.[3-4,8,10-11] At 77 K, the transport properties of conventionally consolidated and sintered BSCCO samples are very low. On the other hand, tapes fabricated by the PIT process seem to exhibit very high J_cs.[1,8-12] The silver sheath used in the PIT process provides good thermal, mechanical, and electrical stability. Additionally, because the PIT process is analogous to the current manufacturing technology for fabricating low-T_c superconductors, it can be very easily modified to fabricate high-T_c superconductors at the industrial level.

The high–J_c values mentioned above were obtained by subjecting the short-length tapes to a series of uniaxial–pressing and heat–treatment schedules. Potential applications of high-T_c superconductors include power transmission cables, current leads, motors, generators, magnetic resonance imaging (MRI), and superconducting magnetic energy storage (SMES) systems. Most of these applications require that long lengths of robust and flexible conductors, with uniform and reproducible properties, be manufactured.[5,8,12-14] Because it is impossible to meet these goals with uniaxial pressing, considerable effort is being expended to overcome this problem. Employing a two-step rolling and heat-treatment procedure, Intermagnetics General Corporation and Argonne National Laboratory successfully fabricated long lengths of Ag-clad BSCCO conductors. These tapes were cowound into prototype pancake-shaped coils by the "wind-and-react" approach. Test magnets were then fabricated by stacking the pancake coils and connecting them in series. The coils and magnets have been characterized at various temperatures and magnetic fields.

During fabrication and service, the tapes are subjected to significant axial and bending stresses. Additionally, the temperature gradient and magnetic field generated induces additional stresses in the material. These factors could lead to degraded transport properties. Because the mechanical properties of Ag are inadequate to withstand all stresses, considerable effort is being focused on improving the strain tolerance of the tapes.[15-22] Techniques such as addition of Ag to the superconducting powder, use of alloy sheath material such as AlNiMg and Ag-Al_2O_3 as an alternative to Ag, and fabrication of multifilament conductors have been used to improve the mechanical characteristics of the Ag-clad BSCCO tapes.[1,17-22]

Singh et al. reported that strain tolerance of the tape can be improved, without much loss in J_c, by addition of Ag to the superconducting core. They observed that for a 1.2% applied strain, 90% of the original J_c was retained in the BSCCO-Ag composite, compared to only 40% in the monolithic tape.[17] Although the role of Ag is not yet fully understood, it is known to reduce the melting temperature and alter the reaction kinetics of the superconductor core. Additionally, it helps to prevent crack growth and assists in the texturing of the superconductor grains.[11] Sato et al. developed a 1296-filament BSCCO superconducting wire with a much better strain tolerance (1.2%) than that of monocore tapes (0.2%).[1] Dou et al. studied the mechanical properties of monocore and multifilament conductors containing 19 filaments. The critical bend strain and tensile strain of the multifilament conductor was found to be 0.8% and 0.65%, respectively, compared to 0.2% for the monocore conductor.[19] Intermagnetics General Corporation fabricated a 61-filament BSCCO-2212 conductor with sheathing of both pure Ag and Ag-Al_2O_3. Using the principle of dispersion strengthening, they obtained improved mechanical properties in the sheath material.[18,22] This paper discusses some of the issues of fabrication and characterization of long lengths of mono- and multifilament Ag-clad BSCCO conductors.

Experimental Procedure

The precursor powder for the PIT process was obtained by the solid-state reaction of high-purity oxides and carbonates of Bi, Pb, Sr, Ca, and Cu. The powders were mixed and calcined at ≈800-850°C for ≈50 h. To obtain a more homogeneous powder, intermittent grinding was employed during the calcination stage. For some of the best results, the cation ratio was Bi:Pb:Sr:Ca:Cu = 1.8:0.4:2:2.2:3. The powders were then packed into high-purity Ag tubes by mechanical agitation. The tubes were swaged, drawn through a series of dies to a final diameter of ≈2 mm, and then rolled at the rate of about 10% reduction per pass to a final thickness of ≈0.1 mm. Short lengths of tape were cut and subjected to a series of thermomechanical treatments consisting of uniaxial pressing and heat treatment. Several parameters are involved in the PIT process, including powder composition, homogeneity, reduction ratio, heat–treatment temperature, time, and atmosphere. All should be carefully controlled in order to obtain the desired properties.

Although very high J_c has been obtained in short-length tapes by uniaxial pressing, the process is not useful for fabricating long length conductors. A more practical approach such as rolling is required. Using two-step rolling and intermediate and final heat treatments, we have manufactured long lengths of Ag-clad BSCCO conductors. Conductors up to several meters in length (30 to 100 m) and as thin as ≈0.1 mm have been processed. Pancake-shaped coils were formed by the "wind-and-react" approach, wherein the tape is first cowound on an alumina former and then heat treated. Ceramic insulation was used to separate each turn in the coil. Test magnets were fabricated by stacking together and connecting in series a set of the pancake-shaped coils. The magnets were characterized at 4.2, 27, and 77 K in background fields up to 20 T.

For the multifilament conductors, several sections of monocore Ag-clad conductors were assembled into a second Ag tube with an outer diameter (OD) of 12.70 mm and an inner diameter (ID) of 9.36 mm. Using a drawing schedule similar to that used for monocore conductor, we drew the tubes to a diameter of ≈2.5 mm. Finally, with a special shape-forming technique, the tubes were rolled into tapes with a final thickness of ≈0.5 mm. Multifilament BSCCO-2212 conductors have also been fabricated using Ag and Ag-Al_2O_3 as the sheath material. The conductor tapes were first heat treated at 885°C for ≈0.3 h, followed by slow cooling to 850°C. The tapes were held at this temperature for ≈111 h. The multifilament conductor with Ag-Al_2O_3 sheathing was given periodic annealings at ≈350°C to relieve work-hardening of the sheath.

Results and Discussion

Short-length samples that had been subjected to a series of uniaxial-pressing and heat–treatment schedules exhibited J_c values of >4 x 10^4 A/cm^2 at 77 K and zero-applied field, and 2 x 10^5 A/cm^2 at 4.2 K and zero-applied field. Haldar et al. showed that by increasing the superconducting fraction of the BSCCO tapes, the current–carrying capacity of the tapes can be enhanced considerably.[12] In addition to J_c measurement, the short samples were characterized by X-ray diffraction and scanning electron microscopy. Qualitative analysis of J_c as a function of number of thermomechanical treatments reveals that J_c initially increases, reaches a peak, and then finally decreases. This variation has been reported by several groups and has been attributed to the variation in degree of texturing and local inhomogeneities present in the tape.[23-25] The short tapes have been characterized at various temperatures and applied magnetic field. Figure 1 shows J_c, as a function of applied field up to 3 T, at 77 K and at pumped liquid nitrogen temperature (64 K). These measurements were made at Brookhaven National Laboratory. At 64 K, J_c in the field parallel to the tape surface increased by one order of magnitude at 2 T over that at 77 K.

We fabricated long conductors (≈30-70 m), wound them into pancake-shaped coils, and tested the coils. J_c values were ≈60-80% of the short rolled samples at 77 K. The difference in J_c values between the short and long conductors can be attributed to inhomogeneities and microcracks along the length of the tapes. Additionally, the coils are subjected to large self-fields

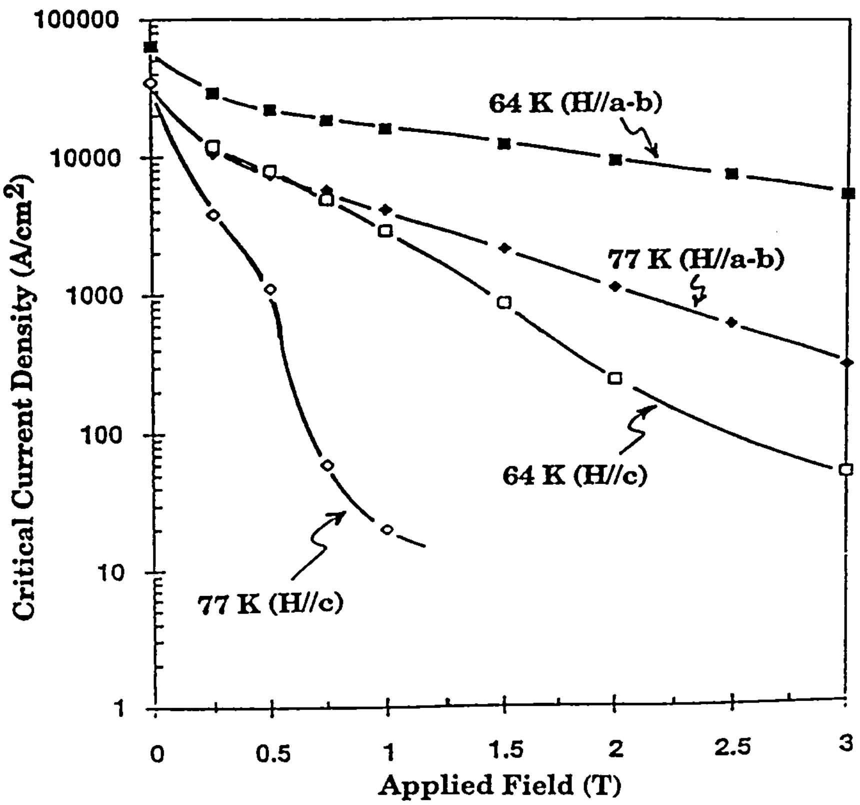

Fig. 1. Critical current density, as a function of applied magnetic field, of short samples at liquid nitrogen (77 K) and pumped liquid nitrogen (64 K) temperatures.

during testing, whereas the short tapes do not generate much self-field. A test magnet was fabricated by stacking together and connecting in series 10 pancake coils, each containing three 16–m lengths of BSCCO-2223 conductor. Total length of the conductor used in the magnet was ≈480 m. The magnet was characterized at 4.2, 27, and 77 K. At 77 K, the maximum field generated was 0.36 T, while at 27 and 4.2 K it was 1.8 and 2.6 T, respectively. Figure 2 shows another test magnet fabricated with eight double–pancake coils, each containing three 16–m lengths of BSCCO conductors. Total length of the conductor was 768 m. Figure 3 shows the characteristics of this magnet at 4.2 and 27 K, in background fields up to 20 T. The magnet generated a field of ≈1 T in a background field of 20 T at 4.2 K. These results are very encouraging because they show not only the robustness of the high-T_c superconductor magnet but also that it can generate substantial field in a very high background field. The results also show that the high-T_c coil can be used as an insert to generate a very high field in a hybrid magnet containing low-T_c superconductors. Additionally, the high-T_c magnet can be used to meet the stringent requirements of field–sensitive applications such as MRIs.

Multifilament conductors containing 37 filaments of up to 230 m in length have also been fabricated. Figure 4 shows I_c as a function of length; the consistent results demonstrate the considerable improvement in development of multifilament conductors. J_c of a multifilament BSCCO-2212, with Ag-Al_2O_3 as the sheath material, was ≈1-3 x 10^3 A/cm^2 at 77 K, 4.5 x 10^4 A/cm^2 at 4.2 K and zero applied field, and 2.5 x 10^4 A/cm^2 at 4.2 K and 12 T. The tensile properties of the BSCCO-2212/Ag and BSCCO-2212/Ag-Al_2O_3 have also been studied. Figure 5 shows the stress/time relationship of the yield strength of multifilament conductors. At room temperature, yield strength of the Ag–Al_2O_3–sheathed BSCCO-2212 was greater by a factor of 4 than that of Ag–sheathed BSCCO. These results indicate that long lengths of multifilament conductors with improved mechanical properties can be fabricated with alternative sheathing material.

Summary

By carefully controlling the various parameters involved in the PIT process, we have obtained very high J_cs in Ag-clad BSCCO superconductors. Pancake–shaped coils and test magnets have been fabricated from long–length conductors and characterized at various temperatures and magnetic

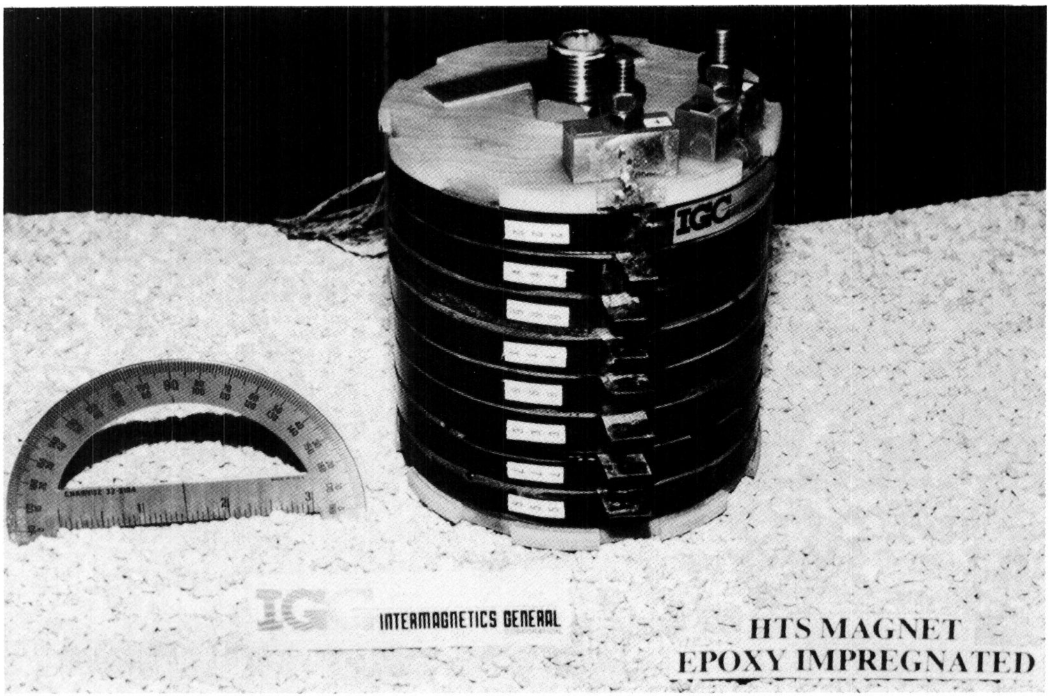

Fig. 2. Test magnet assembled by stacking eight double–pancake coils in series.

fields. The results indicate that devices capable of operating at higher temperatures and magnetic fields could now be fabricated from high-T_c superconductors. The issue of conductor strain tolerance has also been addressed.

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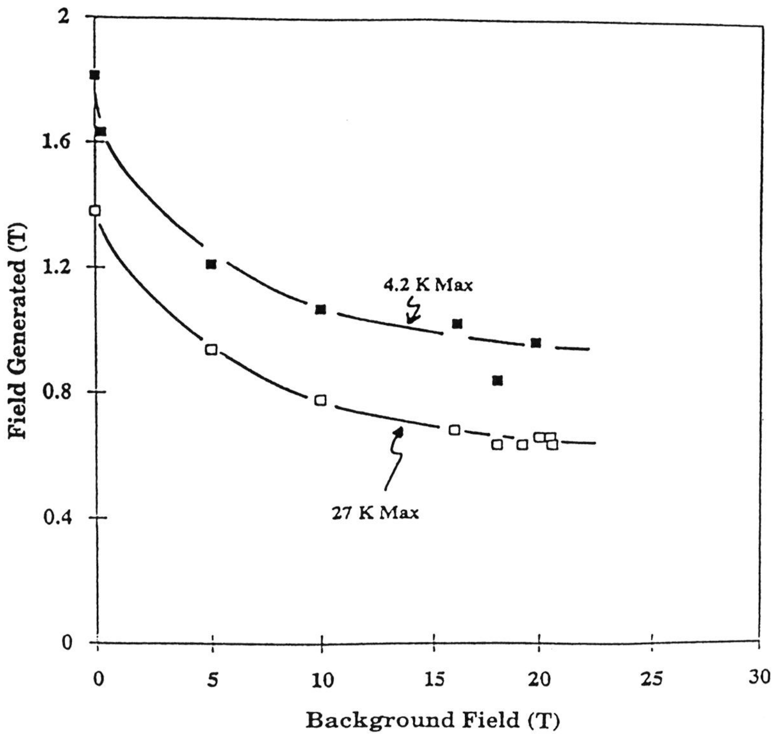

Fig. 3. Field generated by high–T_c magnet vs. background field at 4.2 and 27 K.

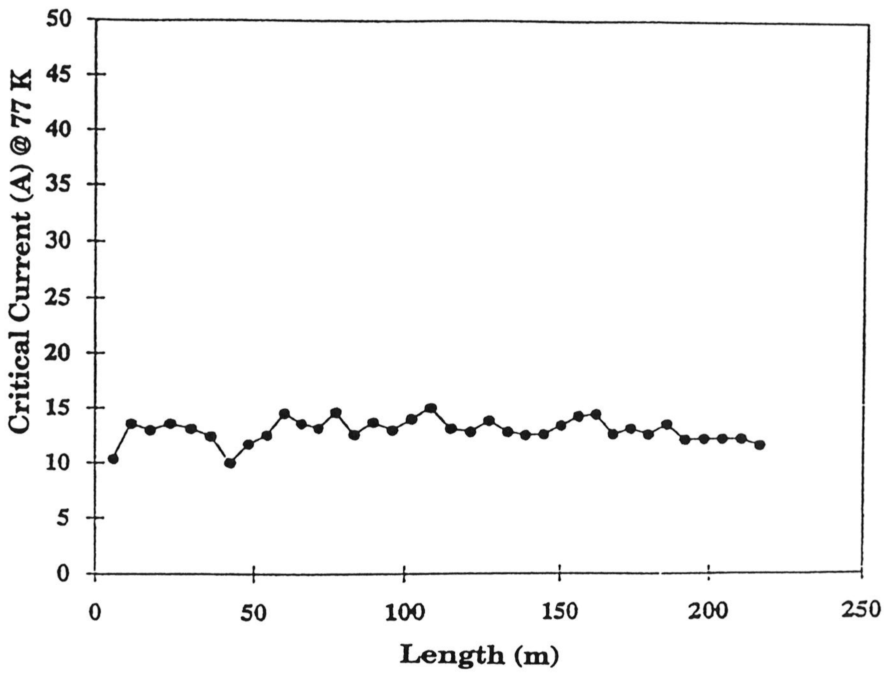

Fig. 4. I_c at 77 K of multifilament conductor containing 37 filaments.

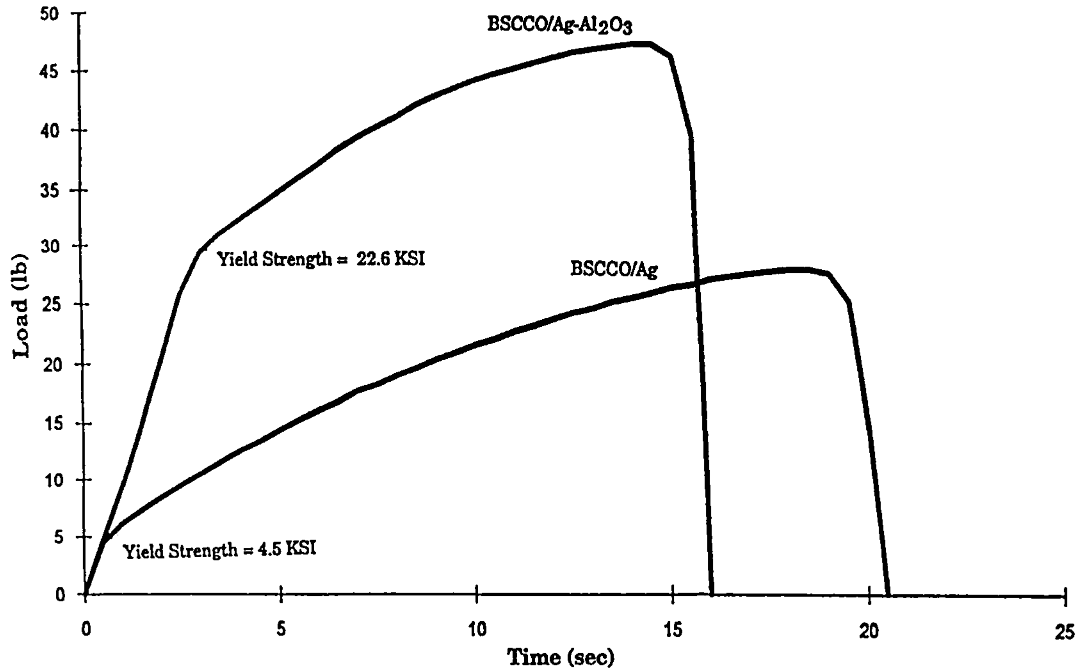

Fig. 5. Stress/time curves of BSCCO–2212/Ag and BSCCO–2212/Ag–Al_2O_3 multifilament conductors.

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