FABRICATION AND CHARACTERIZATION OF HIGH- T_c TAPES AND COILS MADE FROM Ag-CLAD Bi-2223 SUPERCONDUCTORS*

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Fabrication and characterization of high- T_c tapes and coils made from Ag-clad Bi-2223 superconductors

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Prereacted Pb-doped Bi-Sr-Ca-Cu-O powders were packed into Ag tubes, drawn, rolled, and given intermediate heat treatment to prepare long lengths of Ag-clad Bi-2223 superconductor tapes. With the use of improved process conditions, transport critical current density (J_c) values exceeding 10^5 A/cm² at the temperature of liquid helium (4.2 K) and liquid neon (27 K), and greater than 4×10^4 A/cm² at liquid nitrogen temperature (77 K), were obtained in zero applied field with short tape samples. Detailed microstructural analysis and J_c measurements in applied fields up to 20 T are reported. Rolled tapes were cut into lengths of up to 10 m, and several such tapes were used in parallel to fabricate small superconducting pancake coils by the "wind-and-react" technique. Recently, we fabricated a test magnet with six pancake coils, each containing three 10-m lengths of rolled tapes and tested at 4.2, 27, and 77 K as a function of applied fields up to 14.5 T. A maximum generated field of 1.25 T was measured in zero applied field at 4.2 T. Detailed measurements made on the pancake coils and test magnets are reported in this paper.

1. INTRODUCTION

Much effort has been made over the last few years to improve the properties of Ag-clad Bi-2223 superconductor wires and tapes fabricated by the powder-in-tube technique [1-5]. Because this approach utilizes processing similar to that currently used in the manufacture of low-temperature superconductors, it appears to be a promising industrial method for fabricating long lengths of flexible high-temperature superconductors. The goal is to apply the technology to devices that currently use low-temperature superconductors, or to new devices capable of operating in higher temperatures and/or magnetic fields. Bi-2223 superconductor tapes show significantly higher transport critical current density (J_c)

values than those of NbTi and Nb₃Sn superconductors at 4.2 K in high applied magnetic fields. Recently, we reported J_c values of $>4 \times 10^4$ A/cm² in short pressed Bi-2223 samples, and $\approx 3 \times 10^4$ A/cm² in short rolled tape samples, at 77 K [6]. Control of the thermomechanical process makes it possible to obtain a high degree of uniformity, texture (grain alignment), density, and phase purity, thus achieving high J_c s over long lengths of composite tapes. Using a two-step rolling and heat-treatment procedure, we have processed long lengths of Ag-clad Bi-2223 tape conductors and fabricated small prototype pancake coils and a test magnet. In this paper, we report on the fabrication of the tapes, coils, and magnets and on their properties.

2. EXPERIMENTAL

Ag-clad tapes were prepared by the conventional powder-in-tube 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 ≈ 50 h, with intermittent grindings. The partially reacted precursor powders were then packed into Ag tubes, lightly swaged and drawn through a series of dies, and then rolled to a final thickness of ≈ 0.1 mm. Tapes longer than 30 m have been produced by this technique. Short lengths (≈ 4 cm) of tapes were cut and heat treated at $\approx 850^\circ\text{C}$ in air with intermittent uniaxial pressings. Although uniaxial-pressing and heat-treatment cycles produced the highest J_c s in the short samples, this procedure is not suitable for fabrication of long tapes.

Unlike pressing, repeated rolling of dense composites introduces cracks in the ceramic core due to nonuniform stresses imparted to the superconductor. By carefully monitoring the rolling parameters, however, we can achieve homogeneous compression similar to that achieved by uniaxial pressing. Pancake coils were fabricated from long lengths of rolled tapes. An intermediate heat treatment at $\approx 850^\circ\text{C}$ was performed prior to the final rolling step. One to six tapes were cowound in parallel on alumina mandrels with insulation (used to separate each turn) and heat treated by the "wind-and-react" approach. A test magnet was made by stacking and connecting in series a set of three double pancake coils. Each pancake consisted of three 10-m lengths of tape.

Transport J_c values of the tapes were measured by the standard four-probe technique with a $1\text{ }\mu\text{V/cm}$ criterion in the temperature range of 4.2–77 K and magnetic fields up to 20 T. The magnetic field was applied parallel or perpendicular to the tape surface. The J_c was determined for the superconducting cross-sectional areas.

3. RESULTS AND DISCUSSION

For the short samples that were uniaxially pressed and heat treated in steps, critical current (I_c) values ranged from 40 to 50 A, corresponding to a J_c of $>4 \times 10^4\text{ A/cm}^2$ at 77 K in a self-field. By using a repeated uniaxial pressing and heat-treatment operation, we were able to improve the transport properties of the short tapes.

Figure 1 shows the temperature dependence of J_c for a short tape sample in magnetic fields that are perpendicular to the surface. At low temperatures (<40 K), J_c values of $>10^5\text{ A/cm}^2$ have been measured. Moreover, with the application of high magnetic fields, field-independent behavior was observed. Detailed J_c measurements were also carried out at 77 K and at pumped liquid nitrogen (64 K) temperatures in applied fields up to 3 T (Fig. 2). These measurements were made at Brookhaven National Laboratory on samples fabricated in a joint project between Argonne National Laboratory and Intermagnetics General Corporation. By pumping liquid nitrogen down to 64 K, J_c in the field parallel to tape surface increased by one order of magnitude at 2 T over that at 77 K. This shows that practical devices can be made with Bi-2223 tapes operated at temperatures obtainable by pumping liquid nitrogen.

Long lengths of rolled Bi-2223 tape conductors were tested by winding them into pancake coils. One to six tapes were cowound in parallel on alumina formers with ceramic insulation (used to separate each turn) and heat treated by the "wind-and-react" approach. The J_c of coils containing one and two 1.0-m lengths of conductor approached 10^4 A/cm^2 at 77 K in self-field and exceeded 10^4 A/cm^2 at 4.2 K in fields up to 13 T [5]. These J_c values were ≈ 60 –80% of those of the short, rolled samples at 77 K; the difference is probably due to inhomogeneities and microcracks along certain regions of the

Figure 1. Temperature dependence of J_c - H measurements for a Bi-2223 short tape sample with field applied perpendicular to the tape surface.

tapes. Moreover, the coils are subjected to large self-fields during testing, whereas the short linear tapes generate very little self-field.

Figure 3 shows an example of a wind-and-react pancake coil that was wound from three lengths of 10-m-long rolled tapes onto a 2.5-cm-diameter alumina mandrel, resulting in a coil of 57 turns and a 7.5 cm outside diameter. With a $1 \mu\text{V}/\text{cm}$ criterion, I_c for this coil was $\approx 22 \text{ A}$ at 77 K and $\approx 280 \text{ A}$ at 4.2 K. The coil exhibited ≈ 1250 ampere-turns at 77 K and $\approx 16,000$ ampere-turns at 4.2 K. Generated fields were 330 G (77 K) and 4200 G (4.2 K). Recently, we fabricated six such pancake coils, each containing three 10-m lengths of rolled Bi-2223 tapes [6]. Figure 4 is a photograph of a test magnet assembled by stacking six individual pancake coils.

The six pancake coils were connected in series. The height of the test magnet was 5.33 cm. Measurements were made on the test magnet at liquid helium (4.2 K) and liquid neon (2 K) temperatures in applied fields up to 14.5 T. Because the individual pancake coils of the test magnet performed differently, a range of critical current values was determined. At 4.2 K, the stack carried a maximum I_c of 190 A and a minimum of 109 A in self-field, and 100 A (maximum) and 60 A (minimum) in a field of 14.5 T. A maximum generated field of 1.25 T was measured in zero applied field. At 27 K, the maximum and minimum I_c s were 125 A and 78 A in zero applied field and 69 A and 42 A in an applied field of 14.5 T [6]. At 77 K, a maximum generated field of 0.11 T was measured at the critical current of the

Figure 2. J_c vs. applied magnetic field for short-length samples at liquid nitrogen (77 K) and pumped liquid nitrogen (64 K) temperatures.

best-performing single pancake coil. With the complete test magnet in the superconducting state, the minimum field generated was 0.08 T.

4. SUMMARY

Using the powder-in-tube method, we have processed long lengths of Bi-2223 tape conductors. By improving process conditions, it is possible to improve transport critical current density (J_c) in short lengths of Ag-clad Bi-2223 tape. Practical J_c levels have been achieved ($>10^4$ A/cm²) at 77 K and low magnetic fields and at 20 K in fields up to 20 T. The mechanical-deformation operation had important implications for the

integrity of the conductor tapes. Long lengths (≈ 180 m) of conductors have been processed and fabricated into pancake coils having properties approaching practical levels. The results presented here indicate that high- T_c materials are promising for high-field magnets and electric power devices operating at temperatures below ≈ 30 K.

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Figure 3. Pancake coil cowound with three 10-m lengths of rolled Bi-2223 conductors.

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Figure 4. Test magnet assembled with six single-pancake coils.

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