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P. Haldar, J.G. Hoehn, Jr.
Intermagnetics General Corporation
Guilderland, NY 12084

L.R. Motowidlo
IGC Advanced Superconductors, Inc.
Waterbury, CT 06704

U. Balachandran
Energy Technology Division
Argonne National Laboratory
Argonne, IL 60439

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Intermagnetics General Corporation
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Energy Technology Division
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ABSTRACT

Long lengths (30 to 100 m) of silver-sheathed Bi-2223 tapes with high current densities were fabricated by the conventional powder-in-tube technique and used to make compact and robust coils by the wind-and-react approach. The tapes were insulated, co-wound in parallel, and heat treated to produce a fused conductor of larger cross section in the form of pancake coils. The coils were stacked in series to make test magnets. The coils and test magnets were characterized at liquid nitrogen (77 K) and liquid helium (4.2 K) temperatures. The highest field generated by the test magnets was measured to be 0.36 T at liquid nitrogen and 2.6 T at liquid helium temperatures Progress in the prototype manufacturing of long lengths of HTS tape conductor is also discussed. 30 to 100 m lengths are now being made and 70 m lengths were measured to carry 23 Amps (J_c ~15,000 A/cm^2) when immersed in liquid nitrogen.

INTRODUCTION

The powder-in-tube (PIT) process has proved to offer the greatest advances towards exhibiting long length high temperature superconductor (HTS) wire manufacturing potential as well as improvements in current carrying ability.[1-4] The $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ compound (Bi-2223) is particularly suitable for the PIT approach since it can be readily deformed, textured, and densified by a sequence of thermo-mechanical operations. Another advantage of the PIT technique is its similarity to the industrial processes used in the manufacture of low temperature superconductors such as NbTi and Nb_3Sn.

In addition to low-field applications at liquid nitrogen temperature, the high temperature superconductors provide the potential of operating electric power devices and high-field magnets at temperatures (above 4.2 K) and fields (above 20 T) beyond the current capability of low temperature superconductors. This is possible if long lengths of HTS conductor with high current densities can be fabricated economically on an industrial scale. In this paper we report critical current data for long length (up to 70 m) tapes, and progress made in improving the manufacturability of these brittle materials. Long lengths of these materials were also processed, wound into small pancake coils, and used to construct test magnets. Parameters of these test magnets and their critical current data at liquid nitrogen (77 K), and liquid helium (4.2 K) are also presented.

EXPERIMENTAL

Long lengths of silver-clad Bi-2223 HTS tapes were fabricated by the powder-in-tube technique as described earlier.[3-4] Pre-reacted precursor powders were initially prepared from a mixture of high purity (>99.99%) Bi, Pb, Sr, Ca and Cu oxides and carbonates. These were carefully mixed, heat treated, ground, and packed into high-purity silver tubes. The packed billets were lightly swaged, drawn through a series of dies, and then rolled to final size. A series of intermediate heat teatments were performed between 800 to 840 °C to enable growth and alignment of the Bi-2223 phase in the tape core. Long (30 to 100 m) monofilament tapes have been processed this way. In some cases short samples were cut from the long lengths and subjected to an additional series of uniaxial pressing and heat treating operations.

Test magnets were made by stacking and connecting in series a set of double pancake coils. Each double-pancake coil set made by the 'wind-and-react' approach. Moreover, each pancake coil was comprised of three to five lengths of monofilament tape, co-wound in parallel to form a larger monolith conductor with ceramic insulation seperating each turn. Two coils wound on a single form were seperated by ceramic insulation and heat treated together to make a set of double-pancake. Epoxy resin provided the necessary structural strength and rigidity. The double-pancakes were then stacked to form the test magnet.

Short and long lengths of the tape samples were measured for their critical current using the four-probe technique. The measurements were performed at liquid nitrogen, 77 K. Longer tapes (up to 70 m) were also characterized by the four-probe technique by spirally winding them on large mandrels and immersing them in liquid nitrogen (77 K).

The test magnets were measured by placing them in a cryostat. Critical currents of the test magnets were measured at 4.2 K (liquid helium in the crysostat) and at 77 K (liquid nitrogen in the cryostat). Voltage taps were placed at the ends of each pancake coil to determine their performance individually.

The criterion for critical current was 1 μV/cm and critical current densities (J_c's) were determined for the superconducting and overall cross-sectional areas. Note that the high aspect ratio of the tape combined with the irregularities of the superconducting core make it extremely difficult to obtain an accurate value for the core cross-sections.[5] For example, techniques such as weighing the sample before and after etching the core, weighing of cut micrographs, measuring of enlarged optical micrographs, and measurements from an image analyser provide a wide range of values, from 8 X 10^{-4} cm^2 to 1.7 X 10^{-3} cm^2. Thus there can be a large range in core J_c, depending on a measurement technique used. Although it is useful to determine the value of core J_c, it is more useful to know overall or engineering J_c, because the overall J_c provides a design base-line for magnets and devices. In this paper we also report overall J_c's of the composite to elucidate the problems associated with enhancing core J_c.

RESULTS AND DISCUSSION

Short tape samples (3.5 to 4.0 cm in length) that had been subjected to several cycles of uniaxial pressing and heat treatment always carry the highest currents. Values above 40 A were typically attained at liquid nitrogen temperature, with the highest being 51 A. Data for short samples that were uniaxially pressed and heat treated as well as those that were cold-rolled and heat treated are presented in Table 1 and compared with those of a long (34 m and 70 m) tapes. The long monofilament tape was processed by a two-cycle cold-rolling and heat treatment operation. Overall, or engineering, J_C, determined from the cross-sectional area given by thickness times width (not considering taper of the tape edges), is also indicated in Table 1 for all samples. Also provided for are the approximate superconductor fractions for each sample type for comparison. It can be noted from this table that short samples that were subjected to rolling still perform considerably below those that were pressed. Highest superconductor J_C's in rolled short samples have more recently begun to approach ~30,000 A/cm^2 although the overall J_C compares well with a pressed sample with a lower superconductor fraction (27 % vs 20 %) We have also been able to improve on the superconductor fraction, thereby increasing the overall critical current density. Billets are now being processed with thinner silver sheaths and undergo a total reduction of 100 in overall area without any problems in mechanical deformaion.

Continued progress is being made in fabricating long lengths of tape. Recent measurements on a 70 m length with a 24 % superconductor fraction carried 23 Amps at liquid nitrogen, corresponding to a core J_C of ~15,000 A/cm^2 and an overall conductor J_C of 3,500 A/cm^2. This does show considerable improvement from earlier measurements made on a 34 m length of tape with a similar composite configuration that carried 16 Amps (see Table 1).

Table 1. Critical current densities of short and long tapes at 77 K

	I_C (A)	Core J_C (A/cm^2)	Overall J_C (A/cm^2)	SC (%)
Short Sample (Pressed)	51	~45,000	9,000	20
Short Sample (Rolled)	33	~21,000	5,000	24
Long length (34 m)	16	~11,000	2,500	24
Long Length (70m)	23	~15,000	3,500	24
Short Sample	51	~29,000	7,800	27

Shown in Figure 1 is critical current data at 77 K for several billets that were processed to ultimately yield 30 to 35 m long HTS mono-filament tape. The billets were all processed similarly. Several short samples were sectioned from various regions of the final conductor lengths and measured. The average values of these samples is plotted to compare the performance of each length of tape. This average value is typically representative of the performance of the entire length. The superconductor fraction for these billets is nominally 24 %. The bar cnart indicates continued improvement in the critical current data with billet number. Earlier measurements ranged from 5 to 15 Amps while more recent lengths typically carried 20 to 25 A. Occasionally, a few lengths could be fabricated with Ic's exceeding 30 A. Additional work is being performed to fabricate longer lengths of conductor with a reduced fraction of silver sheath. We have successfully processed 100 m of continuous lengths of mono-filament composite tapes.

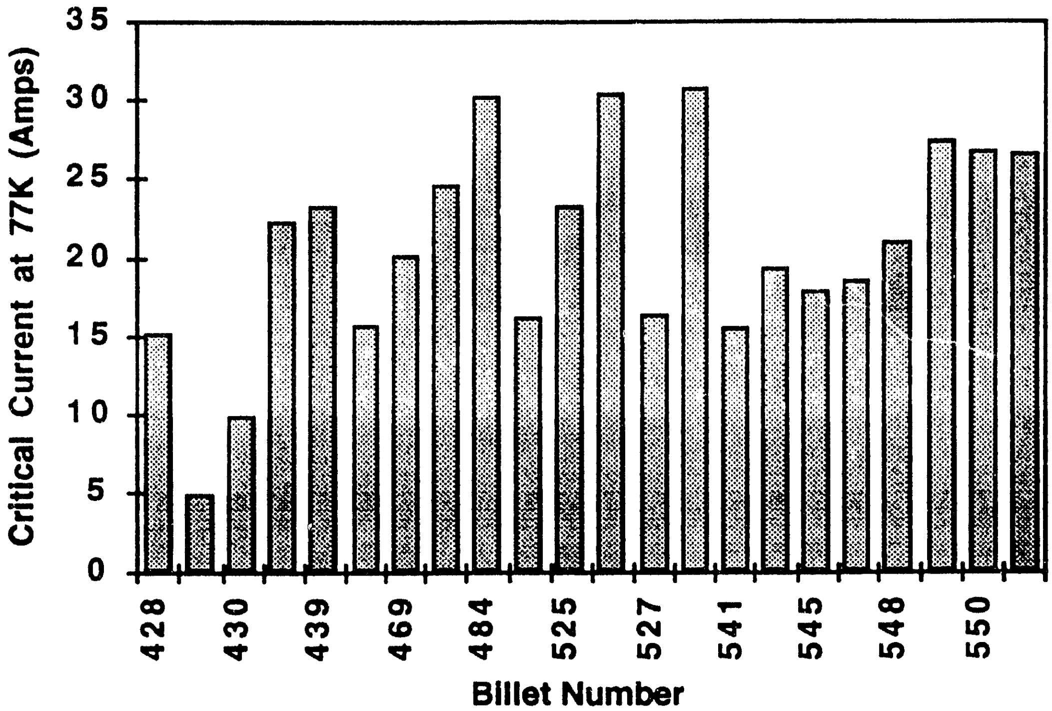

Figure 1. Critical current (Ic) at 77 K for several long (30 to 35m) lengths of monofilament tape conductor manufactured at IGC.

Figure 2 shows a photograph of a recent test magnet, assembled by stacking five double-pancake coils. The dimensions and pertinent parameters of this and other previous magnets and their critical current data are presented in Table 2. At 77 K a Hall probe was placed in the bore of these magnets to obtain their field constant at the midplane. At 4.2 K the central field was calculated with the field constant determined at 77 K. The maximum value for the critical current corresponds to the highest critical current of a pancake coil in the assembly and the maximum field generated is that determined for the entire assembly using the maximum critical current for the best performing pancake coil. Similar determinations were made for the minimum critical current and the minimum field generated. By improving performance of the HTS conductor as well as coil winding techniques we have been able to improve the performance of our HTS magnets over the past few months (see Table 2). The most recent magnet was measured to generate a maximum and minimum self-field of 0.36 T and 0.21 T respectively, at 77 K. The values at 4.2 K correspond to 2.6 T and 1.8 T.

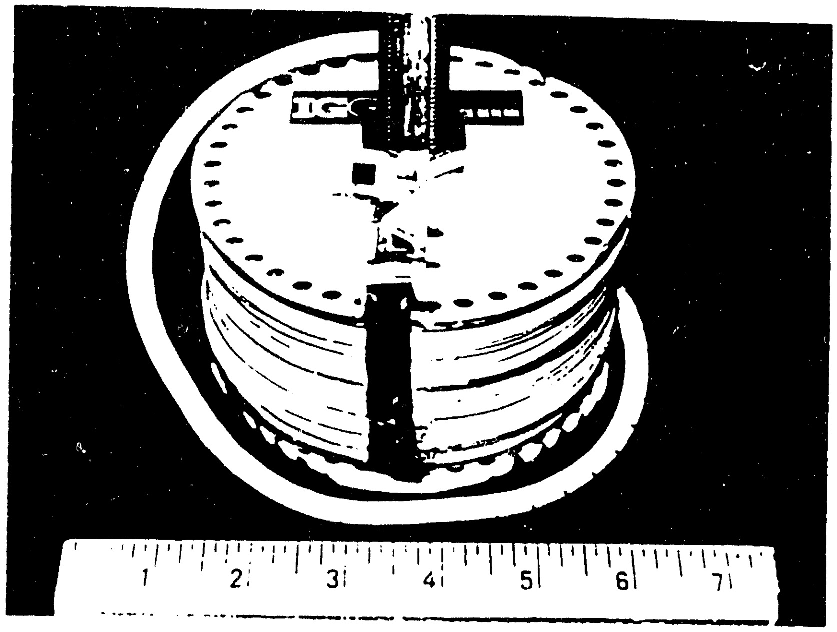

Figure 2. Photograph of a recent test magnet assembled with five double-pancake coils.

The set of results presented here indicates that considerable improvements are being made in improving the performance of HTS conductor and magnets. These materials are promising for high-field magnets and electric power devices operating at a temperature below ~ 30 K; operation at temperatures above 4.2 K could improve refrigeration efficiency and reliability. Higher temperature operation (above 30 K) is possible for applications requiring lower operating fields.

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Table 2. Parameters and critical current data of test magnets constructed at IGC.

	Magnet 1 (June 93)	Magnet 2 (Aug 93)	Magnet 3 (Sep 93)	Magnet 4 (Oct 93)
Winding Inner diameter (cm)	2.50	2.50	2.50	2.50
Winding Outer diameter (cm)	7.50	9.65	11.30	11.30
Coil Height (cm)	5.33	9.84	6.35	6.35
No. of co-wound tapes per pancake	3	5	3	3
Total length of tape in magnet (m)	153	570	480	480
Total no. of turns in magnet	330	612	700	700
Overall winding cross-section (cm^2)	0.0348	0.0532	0.0363	0.0363
No. of pancake coils	6	10	10	10
Magnet Constant (Gauss/Amp)	62.9	64.7	109.7	111.2
77 K				
Ic MAX	19 A	41 A	22 A	32 A
Bo MAX	0.12 T	0.26 T	0.24 T	0.36 T
4.2 K				
Ic MAX	170 A	255 A	167 A	234 A
Bo MAX	1.01 T	1.65 T	1.83 T	2.60 T

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