Title

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Fabrication and Test Results for Rutherford-type Cables Made From BSCCO Strands*

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Abstract — **Wires based on the Bi-2212 HTS superconductor are becoming available commercially, with current densities that are attractive for some applications. We report here on our success in using these Bi-2212 wires to fabricate multistrand, kiloamp conductors that can be used to construct dipole and quadrupole magnets for particle accelerator applications. Multistrand cables have been made from several types of Bi-2212 wire supplied by two manufacturers. These cables were made with cores of various compositions and dimensions in order to optimize the fabrication process. In addition, cables have been made from aspected strands as well as round strands. Cable critical currents will be reported and compared for the various cable parameters investigated in this study.**

I. INTRODUCTION

HTS superconductors based on the BSCCO compositions are now available in the form of wires that can be made in several hundred meter lengths, and with J_c values that are becoming attractive for high field accelerator magnet applications [1]. However, several issues remain to be resolved before we can be confident that these materials will fulfill all the requirements for this application. The critical current of these wires is on the order of several hundred amps. In order to produce a high dipole field in a 10 meter long magnet, the operating current must be in the range of several kiloamps. This means that these wires must be assembled into a parallel current array. The most common method used for accelerator magnet applications has been the so-called Rutherford cable, where the wires are twisted and flattened to produce a flexible, transposed, high current conductor that can be bent around a small diameter to accommodate the ends of the magnet. This paper reports on the development of a Rutherford-type cable using multifilamentary Bi-2212 wires with a Ag/Ag alloy matrix, produced by Intermagnetics General Corp. (IGC) and Oxford Superconducting Technology (OST).

II. STRAND FABRICATION AND OPTIMIZATION

OST strand was fabricated by conventional powder in tube and multifilament restack techniques. Starting 2212 powder with controlled characteristics was packed in a pure silver tube. The powder billet was drawn and hexed; then 121 hex wires were restacked in an alloy tube. The multicore billet was drawn to 0.8 mm final size, resulting in an average filament diameter of 40 μm. Strands were fabricated with two different metal/ceramic ratios, 2.3/1 and 3/1. The ratio was varied by changing the thickness of the tube used for the powder billet.

J_c optimization was performed using a matrix of heat treatment trials. The parameters varied were, melt temperature, time and cooling rate from the melt. I_c in the strands at 4.2 K, self field, varied from a low of 40 A to a high of 179 A. With optimum heat treatment parameters, I_c values greater than 140 A were achieved reproducibly in these strands.

IGC multifilament BSCCO-2212 round wires were fabricated using the powder-in-tube approach. Wire designs included filament numbers from 84 to 310 with corresponding final average filament diameters ranging from 60 to 20 μm. The superconductor volume fraction ranged from 15 to 25%. The conductor sheath included a Ag-0.1%Al matrix between the filaments with an outer jacket of pure silver. Processing was performed using standard LTS reduction schedules and final lengths were typically 200 to 300 meters. The wires were processed to a final diameter of 0.808 mm. During the course of the program the critical current, I_c, of these wires was significantly improved from about 55 A to over 200 A in self field at 4.2 K (see Table I). The I_c enhancements were obtained as a result of introducing wire fabrication improvements and optimization of heat treatment parameters. The I_c's of one meter long helical wire samples were about 65 Amps at 12 T (at 1 μm/cm criteria), using the standard four point method, with voltage taps 25 cm apart. The corresponding J_c in the superconductor is about 520 A/mm^2.

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III. CABLE FABRICATION

Previously, two types of Rutherford cables have been fabricated successfully from LTS wires—cored and coreless cables. For example, a core of stainless steel is used in order to provide a high resistance between the strands on each wide face of the cable and thus reduce the coupling losses in the cable [2],[3]. We decided to use a core in these HTS cables for two reasons: (1) to provide high interstrand resistance, and (2) to provide for a more gentle bending of the wire at the edge of the cable. Two thicknesses of cores were investigated—0.390 mm and 1.092 mm. Several candidate materials were tested for compatibility with the Bi-2212/Ag wires and we found that a Ni-Cr alloy with a low Fe-content was the best [4]. A series of cables were made from strand material provided both by IGC (Table I) and by OST (Table 2).

TABLE I.
IGC WIRES USED IN THIS STUDY

Sample No.	Fil. No.	Fil. Diam., (microns)	S.C.vol. (%)	Anneal State*	Ic(A) (4.2 K,0T)	Remarks **
SN 240	294	23	15	CW	55	N2 atm
SN 320	90	60	24	CW	75	N2 atm
SN 251	84	60	20	CW		
SN 260	84	60	21	CW	10	
SN 340	120	45	25	CW	25	
SN 380	293	23	25	CW	200	vac
SN 410	310	20	25	CW/ann.	225	vac
SN 430	310	20	25	CW/ann.	135	vac
SN 440	310	20	25	CW/ann.		vac

**N2 denotes billets packed under a nitrogen atmosphere; vacuum denotes billets evaluated before sealing.

TABLE II.
OST WIRES USED IN THIS STUDY

Sample No.	Fil. No.	Fil. Diam. (microns)	S.C. vol. (%)	Anneal State*	Ic(A) (4.2K,0T)	Remarks
PM040997	121	40	30	CW	80-179	Improved
PM041797	121	40	30	CW/ann.	40-149	heat treatment
PM082897	121	40	25	CW		

*CW denotes wire drawn to final size without annealing; ann. refers to wire given a final or intermediate anneal at 350 C.

Cables were made with the two thicknesses of cores, and the cable parameters are listed in Table II. Several parameters were changed in comparison to those used in LTS cables. First, the strand tension was reduced from the 5 kg used for NbTi to about 1.5 kg. Second, the degree of compaction was reduced from around 90% to 85%. Finally, no attempt was made to twist the strands. After these changes were made, cables could be fabricated without excessive wire breaks with both the IGC and OST wires. However, occasional wire breaks occurred with both types of wires. The tendency for wire breaks increased as the Bi-2212 powder content was increased from around 15 to 25%. Cables were made with both thin cores (18 strands) and thick cores (19 strands) and sent to IGC or OST for heat treatment and I_c testing. Cross sections of the thin core and thick core cables made from OST wire are shown in Fig 1 .

TABLE III.
CABLES MADE FROM IGC WIRES

Cable #	Strand I.D.	Strand #	Core Mat'l Thick. (mm)	Ic(A)@ T (4.2 K)
613	SN 380	18	Nichrome 0.390	1080@0T 650@8T
614	SN 380	19	Nichrome 0.390	2100@0T
614A	SN 380	19	Nichrome/ MgO tape 1.092	3400@0T 1650@4T
640	SN 410	19	Nichrome/ MgO tape	
641	SN 430	19	Nichrome/ MgO tape	

TABLE IV.
CABLES MADE FROM OST WIRES

Cable #	Strand I.D.	Strand #	Core Mat'l Thick. (mm)	Ic(A)@ T (4.2 K)	Remarks
607	PM040997	19	Nichrome 1.092	950	
608	PM040997	18	0.390	920	
643	PM041797	19	Nichrome 1.092		Strand annealed

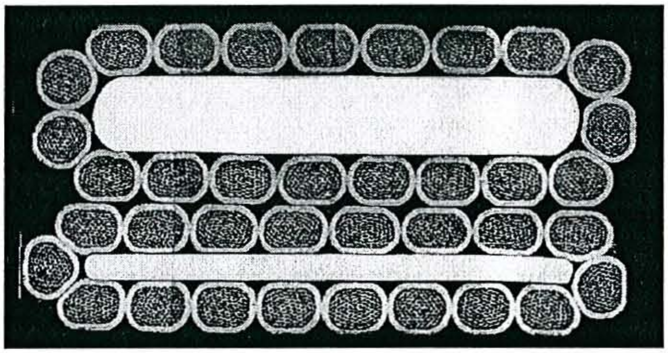

Fig. 1 Oxford HTS (Bi-2212) with Ni-Cr core; Top #607;Bottom #608

IV. TEST RESULTS

In order to investigate the possibility of cabling degradation and/or core contamination, the following sequence of tests were performed. I_c measurements were made on (1) uncabled wires, (2) wires removed from the cable, and (3) the cables with cores in place. Slightly different methods are used at IGC and OST for the heat treatment and cable testing. At OST, the cable is wrapped on a 100 mm diameter mandrel (1.25 turns, 400 mm long), heat treated, and transferred to the test mandrel which is 95 mm in diameter. The sample is soldered to the test mandrel with a voltage tap spacing of about 360 mm. The test fixture is then placed in a solenoid with a background field of 5 T and with a testing current limit of 1000A. The I_c is then measured and reported at a 1 microvolt/cm criteria. The results for one series of OST cables are shown in Fig 2. In addition to the data for the full cable, data are also shown for the wires before cabling and for wires removed from the cable and tested individually.

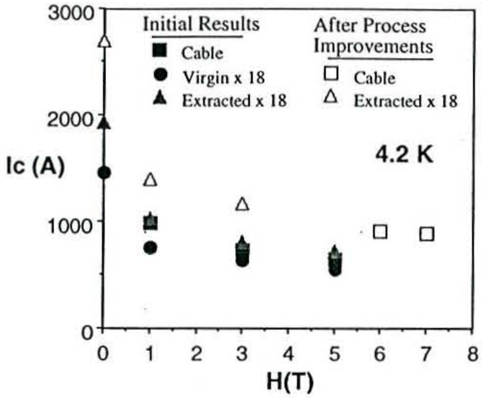

Fig. 2 Critical current vs. field for Cable 608 (OST wire)

The data points labeled "Initial Results" show that the I_c results for both the full cable and the extracted strands are in close agreement. These results indicate that there is little degradation, either by the cabling operation or by contamination by the core, for this particular heat treatment and strand combination. Following the initial tests, the heat treatment was modified to improve the strand J_c. This produced a significant increase in the cable critical current, to 820A ($J_c = 345$ A/mm^2)at 7 T. Data could not be taken below 6 T due to the 1000 A power supply limitation.

At IGC, the cables were heat treated on a 100 mm diameter mandrel and transferred to a 90 mm diameter mandrel for testing. A cable length of 2.27 meters was used, with 100 mm between the primary voltage taps. I_c values are reported using a 1 microvolt/cm criteria. The cable I_c vs. field for the initial tests are shown in Fig. 3, labeled 614.

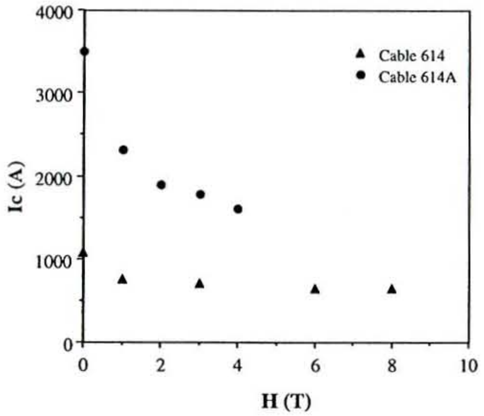

Fig. 3 Critical current vs. Field for cable 614 and 614A

In addition to the primary voltage taps over a 100 mm sample length, secondary voltage taps were placed on strands in the straight, flat sections of the cable and also at the edges of the cable. Although the sensitivity of the measurement is reduced compared to the total sample length measurements, the results show a systematic difference between the I_c measured on the flats and the edges. The I_c values (4 K, 0T) of the straight section are 195 A, whereas the values at the edges are 164 A, e.g. similar to the values measured for the entire wire length of 166 A. Although the IGC test results on I_c measurements at the cable edges compared with the cable flat faces showed that some cabling degradation was present, in general the cable I_c degradation appeared acceptable.

IGC and Showa made significant improvements in the cable I_c during this program by changing the wire fabrication, cable core, and heat treatment parameters. The best I_c value for the cables made from IGC wire, heat treated and tested at Showa, are labeled 614A. Several changes were made in the processing of this cable. In order to insure that contamination was not occurring in the low Fe content nichrome cores, Showa removed the core, wrapped the core with MgO insulation, and reassembled the cable. In addition, a modified heat treatment was employed, and the sample was tested as a 50 mm straight sample, with 10 mm voltage tap spacing, instead of a coil. The cable I_c for this test represents the highest I_c obtained to date in this study ($I_c = 1650$ A; $J_c = 760$ A/mm^2, 4 T).

Although cables of sufficient length for these tests could be made routinely, attempts to make cables in tens of meter lengths resulted in an unacceptable level of strand breakage. This problem was overcome by annealing the wire before cabling. A significant change in mechanical properties of the wires occurred as a result of this annealing step. The yield stress was reduced from approximately 210 Mpa to 66 Mpa and the elongation increased from about 2% to over 5%. After annealing was introduced, no strand breakage has been observed in the fabrication of 5-10 m lengths of cables.

V. CONCLUSIONS

A number of challenges have been met and overcome during this program aimed at developing HTS cables for accelerator magnet applications. First, the wire I_c values have been increased from the early wires, which had values in the range of 10-75 A to the present where greater than 200 A is the norm. Cable I_c degradation and ac losses have both been minimized by use of a core [4]. Possible contamination of the Bi-2212 wires by the core has been reduced by the use of low-Fe nichrome ribbons. It appears that contamination can be reduced further by coating these ribbons with MgO. Most importantly, strand breakage has been eliminated by annealing the strands before cabling. The best cables in this series have an I_c exceeding 1650 A at 4.2 K and 5.0 T. When extrapolated to 30 strand cables and to 16 T, these Bi-2212 J_c values are comparable to the values being obtained at present for Nb_3Sn cables. However, several significant challenges remain. First, the matrix: superconductor ratio should be reduced from the present 3:1 to a value sufficient for magnet protection, i.e. nearer to 1:1. In addition, the I_c vs. strain characteristics must be measured and the strain limits established for the HTS cables.

VI. FUTURE PLANS

The next phase of this program is the fabrication of 100 m lengths of cable. The effect of strain on the I_c will be evaluated in measurements both parallel and perpendicular to the wide face of the cable. Small racetrack coils will be fabricated and tested in the background field produced by LTS racetrack coils [5]. The billet size used in strand fabrication will be increased in order to reduce the unit costs. React and wind racetrack coils will be made in order to evaluate the utility of this process for accelerator dipole magnets.

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