

Fabrication and Prototype Testing of a Strain-Tolerant Bi-2212 Cable

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Abstract—We have successfully manufactured and tested prototypes of a mechanically stabilized $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_x$ (Bi-2212) 6-on-1 cable-in-conduit (CIC). The superconducting wire in the cable is reinforced with Inconel X-750 tubes to provide improved strain tolerance and greater ease of handling. We are providing a detailed description of the manufacturing process. We have wound test coils from the cable, and we are reporting on the preliminary testing of the coils.

I. INTRODUCTION

The strain sensitivity of $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_x$ (Bi-2212) [1-4] is a significant obstacle for its application in high-field magnets. We have successfully developed a 6-on-1 cable-in-conduit (CIC) that is mechanically stabilized with Inconel X-750 tubes for improved mechanical properties and strain resistance. The cable is intended for wind and react (W&R) use. We have previously described the design, material evaluation and short sample testing of the first batch of cable that used an earlier generation of Bi-2212 wire and stainless steel tubing for the outer sheath [5,6]. The cable made for the test coils described here uses an improved wire design with 427 filaments in a double restack design, as well as Inconel X-750 for both inner and outer tubing. This paper describes the manufacturing and testing of the cable and of small coils made from it. One of the coils is shown in Figure 1.

II. PRACTICAL ISSUES

Two peculiarities of Bi-2212 in particular make the heat treating of the material non-trivial: The critical current depends heavily on the maximum temperature T_m during melt processing [7,8], a deviation of only 2°C causes a loss in critical current of 25-40%. The melt processing consists of sintering the conductor, then transforming it into

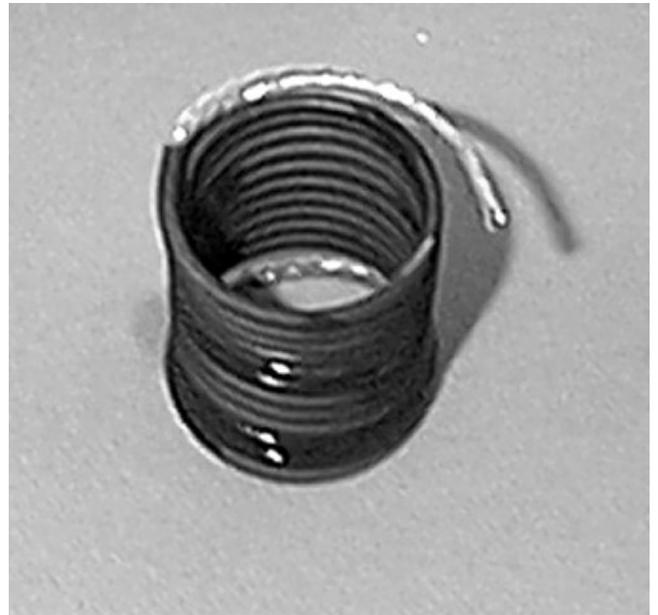


Figure 1. Picture of the test coil

the partial melt, and finally annealing it. Furthermore, oxygen is released and reabsorbed as the material melts and solidifies and the oxygen partial pressure is a crucial variable in the phase diagram [9-12].

The close tolerances required in heat treating Bi-2212 make the transformation from the conductor manufacturer to the user doing his own heat treatment non-trivial. Platinum/Platinum-Rhodium (Type S) thermocouples are very accurate and are commonly used in high-temperature furnaces. But at best, they have a limit of error of .1% in the relevant temperature range (880°C - 900°C) [13], so that the readings from two perfectly good thermocouples can differ from each other by 2°C already. In addition, the relative location of the thermocouple to the coil or sample and the calibration of the readout can introduce more small deviations. For this reason, most cable development programs prefer to have the wire manufacturer heat treat the material. We decided for an in-house heat treatment program because it will ultimately lead to shorter turn-

around times. To reproduce the heat treatment supplied by IGC, we did several heat treatment runs in which we increased T_m by 1°C to find the optimum furnace settings for processing.

The oxygen release can lead to problems in a confined geometry, where gas flow is restricted. If oxygen is released into a constricted area, its partial pressure increases. Conversely, the reabsorption of oxygen can cause a lowered partial pressure if flow is restricted. The melting point of Bi-2212 is dependent on the oxygen partial pressure, and so is the phase assemblage in the melt [14]. Any CIC design will restrict gas flow around the superconducting wires. To allow for gas flow around the wires inside our cable, we laser-drilled the inner tubing of our cable as described below.

III. MANUFACTURING

A. Wire

The Bi-2212 wire was manufactured by IGC-AS using the oxide-powder-in-tube (OPIT) process [15] and, along with a detailed heat treat schedule, delivered to Texas A&M University. The first batch of wire delivered was a 300 filament design, all the work described here was done with the improved 427 filament double restack design.

B. Tubing

Both the inner and outer tubing is made of Inconel X-750 and was manufactured by Uniform Tubes, Inc. of Colleagueville, PA. Inconel X-750 is a Nickel-Chromium alloy that is commonly used in high-temperature oxidizing atmospheres but also in cryogenic applications.

The inner tubing has a nominal outer diameter of .81 mm and a nominal wall thickness of .04 mm. The tubing was supplied annealed in single straight pieces of 1-1.5 m length and is fed into the middle of the 6 Bi-2212 wires during cabling. We have used a laser trimmer (Electro Scientific Industries, Model 44) to perforate the tubing. The holes were cut about 2.5 mm apart and have a diameter of approximately .05 mm. The tubing was subsequently annealed in air and also subjected to a spring-tempering heat treatment.

The outer tubing (nominal outer diameter 3.2 mm, nominal wall thickness .13 mm) was supplied as drawn in long coils. The pieces used in the cable were annealed in air before drawing.

C. Cabling

The cabling operation is done on a 6-on-1 cabling machine that was retrofitted so that the smallest bend diameter during cabling was 15 cm. Six spools hold the superconducting wire. The superconducting wires are silver-soldered to copper lead wires to minimize the superconductor waste. Once the cabling process is started and the cabling tension in all wires is equal, the inner tubes are consecutively fed into the center of the cable. The length of the cable made this way is only determined by the

available wire; as the inner tubes are fed continuously they do not limit the length of cable.

The cable pieces that are used for short samples or coils are then cut out of this long length of cable.

D. Drawing

The appropriate length of unsheathed cable (which at this point has an outer diameter of 2.4 to 2.5 mm) is then inserted into the outer tube of Inconel X-750 (2.94 mm i.d.). One end is swaged to a diameter that is smaller than the die diameter, and the tubing is drawn onto the 6-on-1 cable configuration using a .104 inch (2.64 mm) drawing die. Dish Soap is used as a drawing fluid. During the drawing process, the wall thickness of the outer tubing stays constant while the tube is elongated. The die diameter is chosen so that the drawn tubing has a snug fit on the wire and inner tube.

E. Sample Preparation and Coil Winding

The coils were made of longer lengths (~ 1.5 m) of cable that was wound onto a 2.54 cm mandrel. In the process, the originally round cable (26.4 mm diameter) shaped itself into an oval with major and minor diameters of 27.6 and 25.2 mm, respectively. The coil was not captured as winding tension was released at the end of the coil winding process, so that the coils sprung back to an inner diameter of 3 cm. The ends were exposed by carefully grinding away part of the sheath with a Dremel tool, and then breaking the remaining piece off.

SEM images of part of the cable that was bent into a coil are shown in Figures 2 and 3. Both figures illustrate the ovalization of the cable. Figure 2 gives a frontal view of the cable, while Figure 3 shows a cross-section, which can be seen by the 'virtual' distortion of the image. The inner and outer tubes are also visible. The diameter of the wire is .81 mm, the twist pitch 1.7 cm.

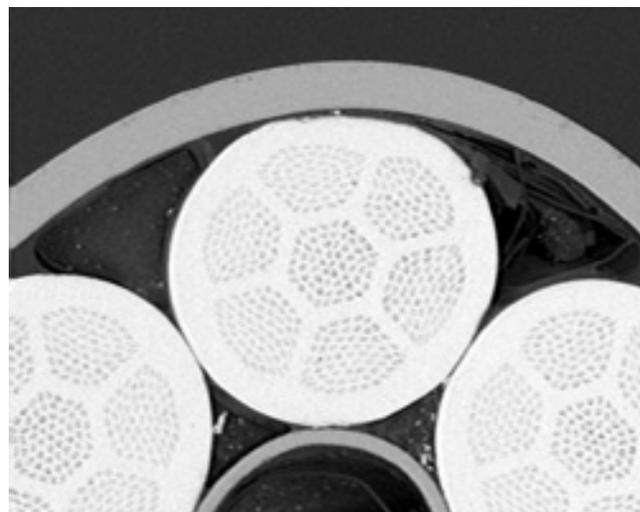


Figure 2: Frontal View SEM of bent cable

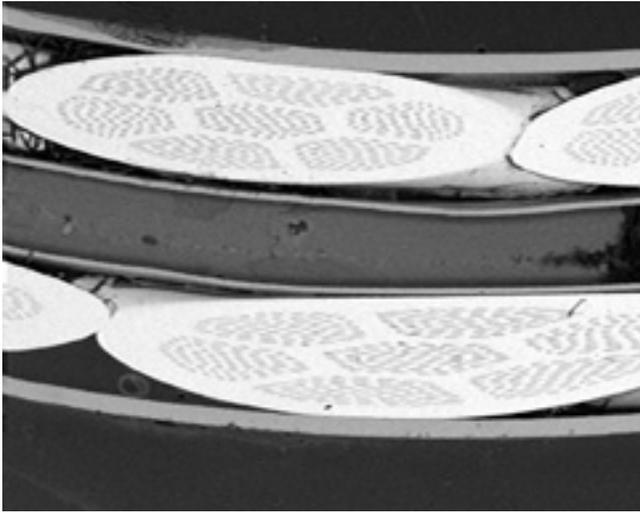


Figure 3: Side View SEM picture of bent cable

F. Heat Treatment

The heat treatment is done in a converted three-zone Bruce Diffusion Furnace, which offers a large uniform temperature zone. However, due to its size the furnace has a comparatively large thermal mass. This makes it necessary to pull the samples to the front end of the furnace once the final anneal stage is completed, since low cooldown rates have been associated with a decomposition of the 2212 phase [16].

IV. TEST RESULTS

We heat treated a batch of 4 reference wires, 2 short samples (about 10 cm overall length) of the cable and 2 coils as shown in Figure 4. The coils were approximately 1.2m and 1.1m long. During the heat treatment of the sample batch we experienced a 30 minute power failure during the ramp from the partial melt to the final anneal. The furnace temperature dropped by approximately 150C before power was restored and as a result the critical current I_c in the reference wires was lower than for previous heat treatments. Also, the only power supply available at the time had a maximum current of 600 Amperes, so that we

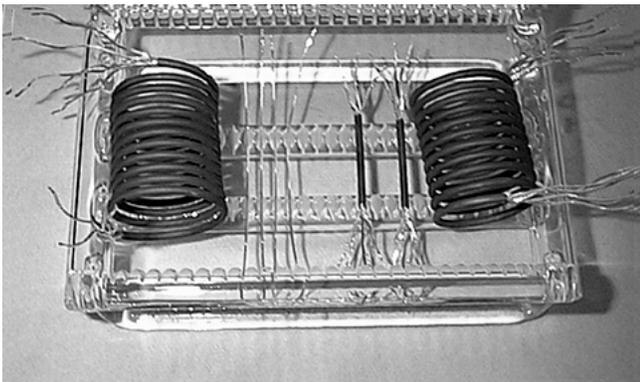


Figure 4: The test batch

decided to only connect one wire within the cable and look for the onset of the resistive transition in the superconductor. We will have a bigger power supply available for subsequent testing.

Table 1 gives the approximate onset current for the superconducting-resistive transition at 4.2K in self-field. The results show that the transition happens at similar currents for the wires and one of the coils, whereas the other coil shows a significantly lower onset current. We believe that the lower onset current of the second coil is due to mishandling of the coil while it was mounted to the short sample test rig. We are in the process of fabricating and testing more coils to confirm this. The new samples will then also be tested under compression. The fixturing for those tests has been designed and machined and the tests will be carried out in October.

Table 1. Onsets of resistive behavior in Samples

Sample	Resistive Onset
Wire 1	128 A
Wire 2	128 A
Coil 1	128 A
Coil2	72 A

V. CONCLUSIONS AND OUTLOOK

We have successfully fabricated short samples and test coils of the cable. From our preliminary tests, it appears that there is no degradation of critical current in the coils, although additional testing is required to confirm this. The cable can be wound into coils with an inner diameter of 2.54 cm, thus making it suitable for applications where small bending radii are important.

We have succeeded in doing in-house heat treating of the Bi-2212, a task made difficult by the narrow window of the partial melt temperature required for maximum I_c .

We are preparing to test the behavior of the cable under compression. To that end, we have built a compression test fixture and we are expecting to test the compression behavior of the cable in October.

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