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BSCCO-2212 WIRE AND CABLE STUDIES

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ABSTRACT

BSCCO-2212 round wires are being studied at Fermilab for possible use in accelerator magnets. Several billets were produced by OST with various fill factors in a diameter range between 0.7 mm and 1 mm. To allow for cabling the strands, a modified process was implemented as opposed to the regular process with oxygen anneal. Rutherford-type cables were fabricated and the performance of extracted strands was compared with that of virgin samples. Cables were also tested using a superconducting transformer.

KEYWORDS: High temperature superconductor, BSCCO, DC measurement.

INTRODUCTION

The continued progress toward higher magnetic fields holds significant potential for general advances in science and technology [1]. For the past twenty years there have been steady increases in the field strength of superconducting magnets due to continued advances in Nb_3Sn conductor and magnet technology [2, 3]. The most recent internal tin Nb_3Sn conductors have enabled a commercial 22.3 T magnet for 950 MHz NMR spectroscopy [4, 5]. While Nb_3Sn can possibly enable 23.5 T for 1 GHz NMR, it is quite unlikely that this material can enable fields above 25 T.

TABLE 1. Strand Description

Strand ID	Billet No.	Diameter, mm	Total length, m	Fill factor, %	Peak J_c, A/mm^2	Peak J_E, A/mm^2	Passed bending test
A	PMM050518	1.02	248	22.3	-	-	Y
B	PMM050419	0.81	371	22.4	-	-	Y
C	PMM060505	0.7, 0.81, 0.9	357	28.2	4070	1148	N
D	PMM060508-1	0.7, 0.81, 0.91	360	26.4	3678	971	Y

$Bi_2Sr_2CaCu_2O_{8-x}$ (BSCCO-2212) is one of a large number of copper-oxide high temperature superconductors (HTS), which in addition to much higher critical temperatures also have very high critical fields compared with LTS [6, 7]. However BSCCO-2212 is the only copper oxide material which can be easily melt processed, which enables it to be fabricated in a wide variety of shapes, including conventional round multifilamentary wire. Some tens of kilometers of 2212 wire have been cabled, most of it coming from Showa Electric Wire Company in Japan [8, 9]. Several cabling trials have been made using OST's 2212 wire, the earliest being among the first made from this material [10].

The OST wire fabrication process uses a Ag0.2%Mg alloy sheath which is dispersion strengthened by oxidation of the Mg during heat treatment [11]. The best performance is usually obtained by oxygen preannealing of the AgMg sheathed strand. However, the hardened sheath which results from this preanneal severely restricts the diameter around which the wire can be bent without cracking. To enable cabling of Bi-2212 round stands, for this work OST produced billets with different O_2 anneal processes. Those that passed the bending test were used to fabricate a number of Rutherford-type cables. Samples were heat treated at OST according to an optimized schedule. The transport performance at 4.2 K of round and extracted strands was measured up to 15 T, and a number of cables were tested at self-field. To better explain the results, SEM/EDS analysis was also performed.

EXPERIMENTAL SETUP

Strand Description

The 2212 strands that were studied are described in Table 1, and a cross section is shown in Figure 1 (left). Strands A, B, and D passed the bending test, as shown in Figure 1 (right), and were therefore used for cabling.

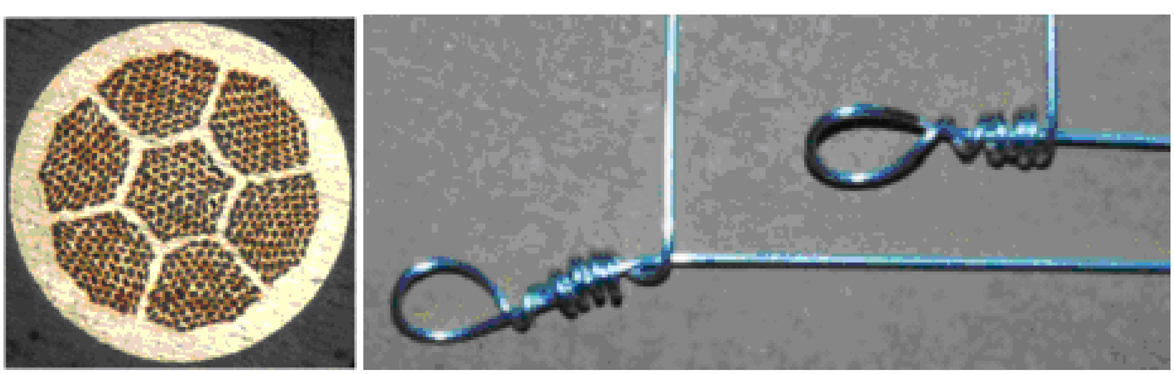


FIGURE 1. BSCCO-2212 strand cross section (left), and example of successful bending test (right).

TABLE 2. Cable Description

Cable ID	No. strands	Strand size, mm	Strands used	Ave. thickness, mm	Average width, mm	PF, %	Tested
1	19	1.02	A	1.938 ±0.003	9.992 ±0.050	82.6	Y
2	"	"	"	1.883 ±0.007	9.987 ±0.031	85.1	N
3	"	"	"	1.848 ±0.009	10.008 ±0.022	86.5	Y
4	24	0.81	B	1.554 ±0.008	9.921 ±0.072	82.7	Y
5	"	"	"	1.51 ±0.010	9.928 ±0.035	85.0	N
6	"	"	"	1.485 ±0.014	9.896 ±0.051	86.7	Y
7	27	0.692	D (24), copper (3)	1.309 ±0.011	9.876 ±0.059	81.0	N
8	24	0.81	D (20), B (4)	1.551 ±0.022	9.921 ±0.056	82.8	Y
9	21	0.911	D	1.711 ±0.007	9.959 ±0.082	82.8	Y

Cable Parameters

The cables were all rectangular and made in one pass. They were fabricated at FNAL using the same mandrel and a forming fixture made of two vertical rolls with variable gap, and of two thin horizontal rolls [12]. About 40 meters of cable were made, producing nine samples with packing factors (PF) ranging between 81% and ~87%. This was done by varying the cable mean thickness. The lay angle of all cables was 14°. Table 2 details the cable parameters, and Figure 2 shows some cross sections. In a couple of cases (cables 7 and 8) the cable map included different strands (see Table 2) to comply with lack of material.

Sample Preparation and Measurement Procedure

Virgin (round) strands, strands extracted from each cable and cable samples with welded ends were heat treated at OST in Oxygen atmosphere as shown in Figure 3. Critical current measurements were performed at Fermilab Superconductor R&D lab. Voltage-current (VI) characteristics were measured in boiling He at 4.2 K, in a transverse magnetic field, B, as described in [13]. The critical current I_c was determined using the 1 μV/cm criterion, with the usual measurement uncertainties [13]. Critical currents have not been corrected for self field effects which can be substantial at low fields. The cables were measured at self-field with a SC transformer equipped with a Rogowski coil to measure the secondary current [14].

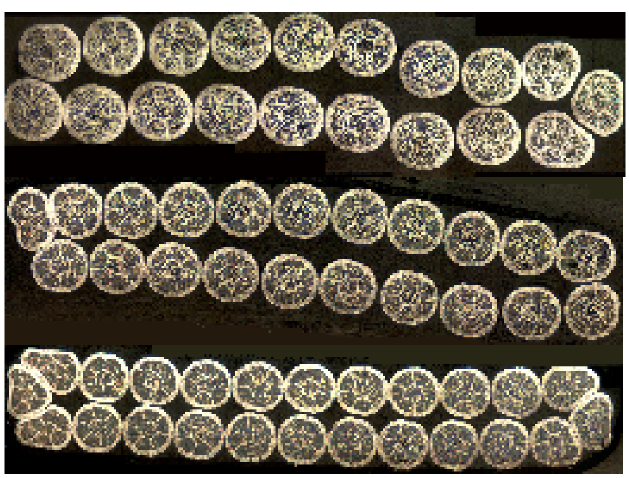


FIGURE 2. Cross section of 19-strand cable ID 1 (top), 21-strand cable ID 9 (middle), and 24-strand cable ID 4 (bottom).

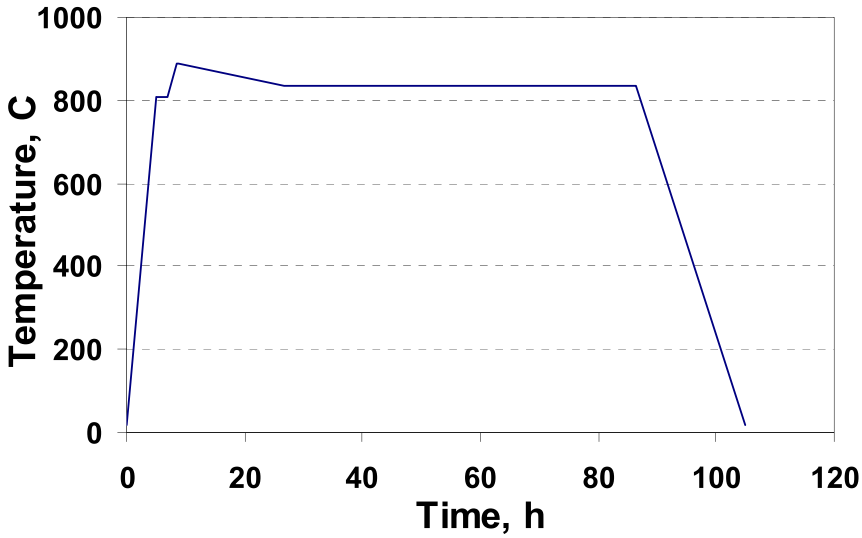


FIGURE 3. Optimized heat treatment schedule used for all the Bi samples.

RESULTS AND DISCUSSION

Round Strand

The critical current density, J_c, at 1 T and 12 T is shown as a function of size for strands C (regular O_2 anneal process) and D (modified process) in Figure 4. In this case, not much difference in J_c was found between the two different annealing processes used.

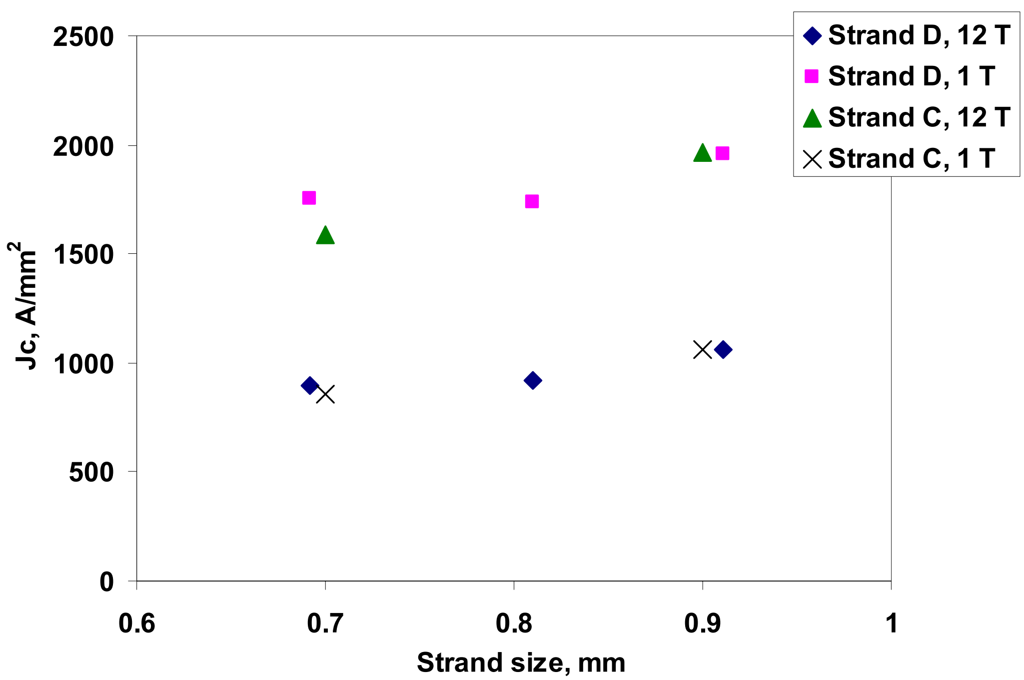
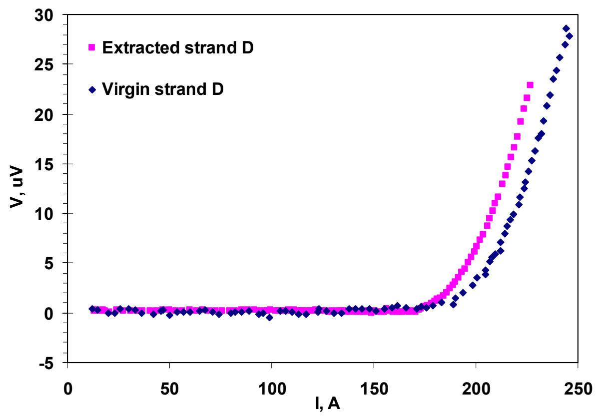


FIGURE 4. J_c at 4.2 K as a function of strand size for round strands C and D.



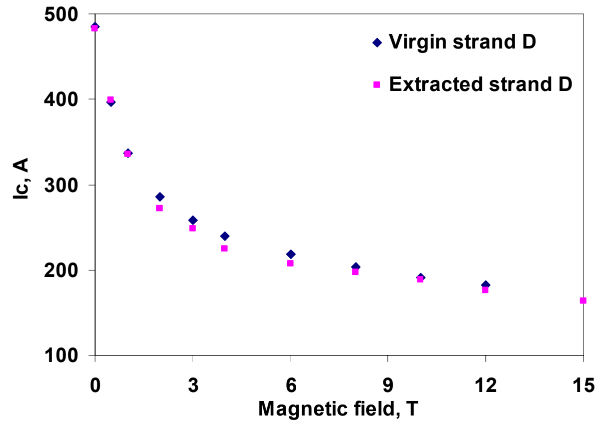


FIGURE 5. V-I curve at 12 T (left), and I_c(4.2 K) as a function of field (right) for the 0.91 mm virgin and extracted Bi-2212 strand (strand D from cable ID 9).

Extracted Strand

Figure 5 (left) shows an example of V-I characteristics for a 0.91 mm round and extracted Bi-2212 strand (strand D from cable ID 9). At right the I_c at 4.2 K of these strands is shown as a function of field. The plot in Figure 6 of the normalized I_c(4.2 K) and that in Figure 7 of the normalized n-value, both as a function of cable packing factor, summarize the results obtained for all the extracted Bi-2212 strands. There is no noticeable dependence on magnetic field for either I_c or n-value. As can be seen, besides for one single case, which however was found to be reproducible, the I_c degradation of the extracted strands is reasonable and typically less than 20% at least up to 85% of packing factor. The n-value dependence with packing factor is stronger than for the I_c. Strands of different designs behave differently to cabling. For instance the I_c degradation is larger for strand B, which is an old design that had not been optimized for cabling.

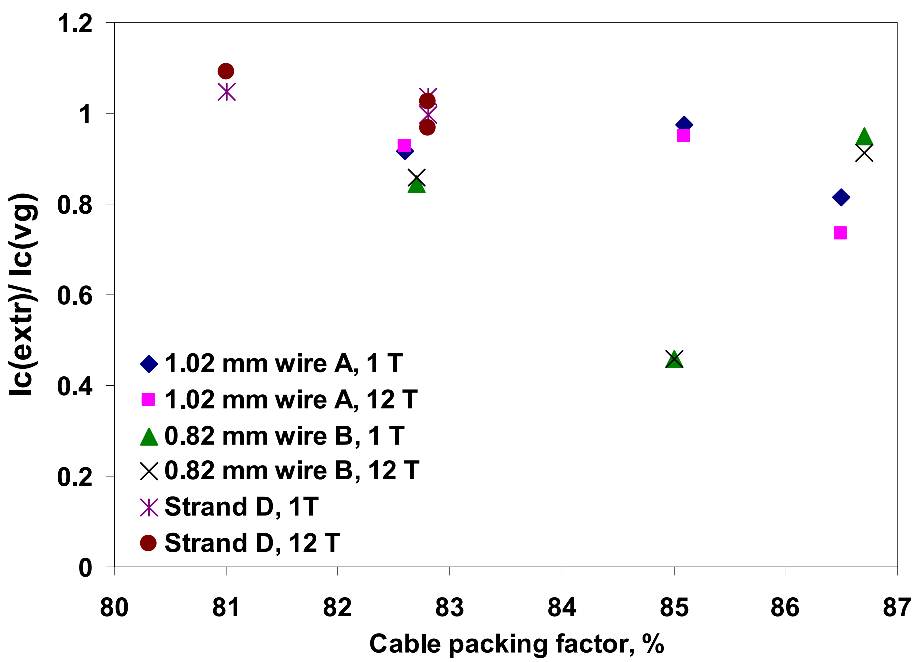


FIGURE 6. Normalized I_c at 4.2 K as a function of cable packing factor for the extracted Bi-2212 strands.

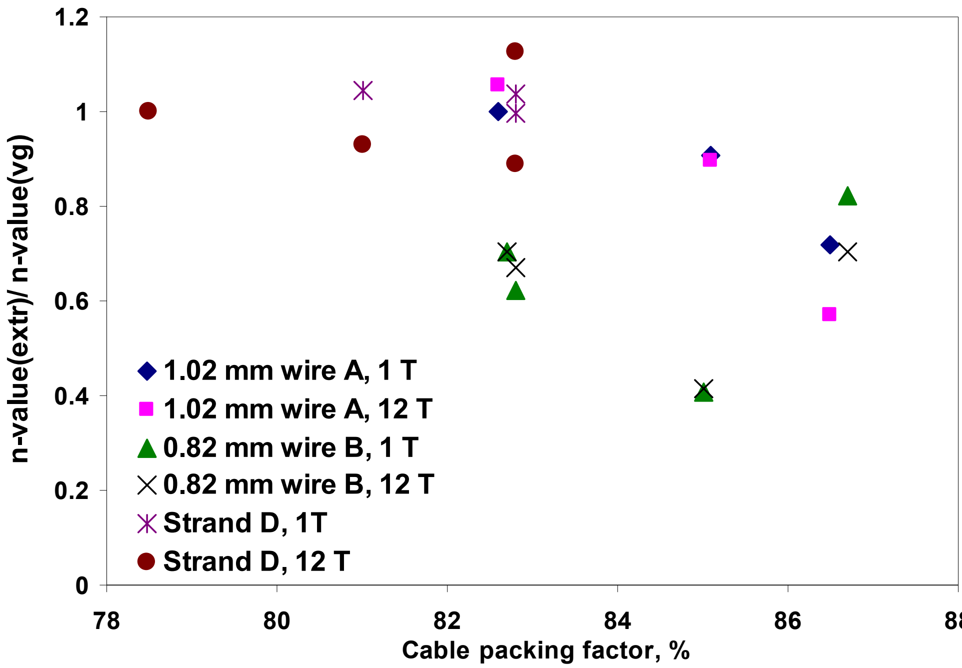


FIGURE 7. Normalized n-value at 4.2 K as a function of cable packing factor for the extracted Bi-2212 strands.

To better understand the behavior of the extracted strand with larger degradation (strand B from cable ID 5), SEM/EDS analysis was performed on the surface of tested samples of both this strand and strand D from cable ID 9. It was found that both samples had MgO precipitates on the surface of the silver sheath consistently with its original Ag0.2%Mg alloy composition. However, the distribution density of the fine MgO precipitates in strand D was smaller than that in strand B (Figure 8). In addition, many abnormally large MgO precipitates were found in this strand, whereas strand D did not have any. These large precipitates may be caused by irregular grain growth, possibly due to heat treatment temperature inhomogeneities, but additional SEM studies of the cross section of the extracted strands should be performed to understand whether this effect is consistently reproducible.

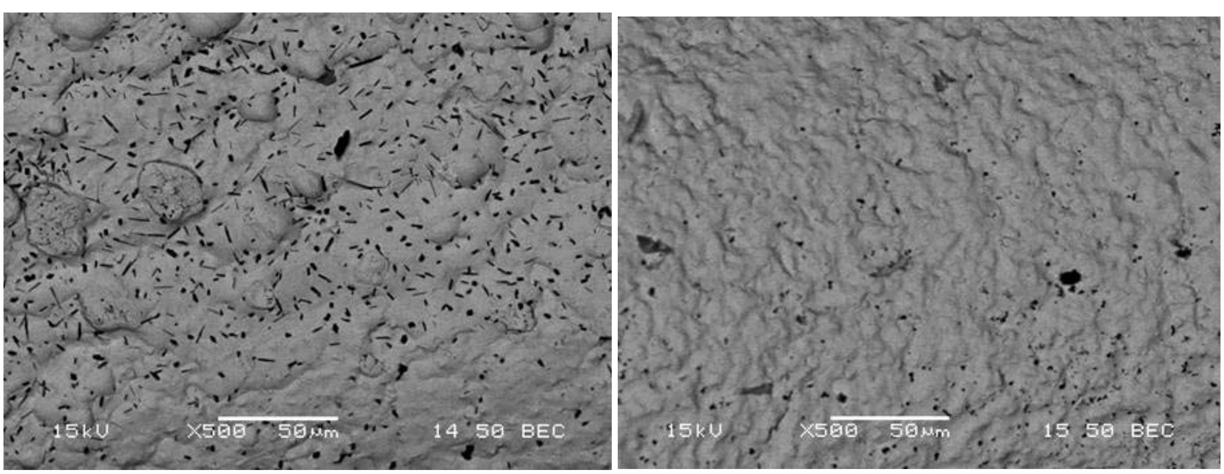


FIGURE 8. Distribution of the fine MgO precipitates in poorly performing strand B (left), and in good performance strand D (right).

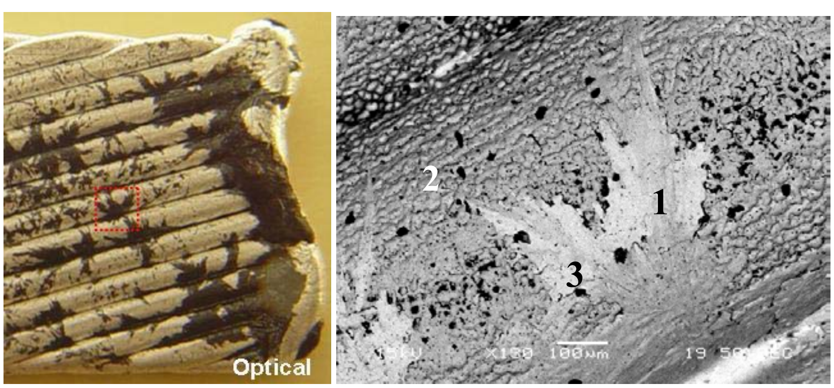
TABLE 3. Cable Test Results

Cable ID	Impregnation	Bending	No. strands	Strand I_c (0 T)	Strand I_c (0.5 T)	Cable I_c(self-field)	Cable n-value	I_c(meas)/ I_c(exp)
1	Y	N	19	397	327	3617±35	8.8	53%
3	N	N	“	445	295	3743±51	10.1	53%
4	I	N	24	186	133	2251±27	10.1	59%
6	N	Y	“	216	148	2300±200		53%
8	N	Some	24	357, 217	289, 163	3229±16	5.9	44%
9	I	N	21	483	399	5100±200		55%

Cable Performance

Table 3 shows the cable test results obtained at 4.2 K at self-fields of 0.1 to 0.3 T. For all the cables, an I_c degradation of about 50% was found. This current reduction on the cables was significantly and systematically larger than that of the extracted strands. To estimate the expected cable current, the average of the extracted strand critical currents at 0 T and 0.5 T was used, along with the cable strand composition in Table 2, because the self-field produced by the transformer secondary is 0.18 T to 0.29 T for cable currents between 3000 A and 5000 A. More accurate estimates could be performed in the future.

After reaction, the surface of all the cables showed black spots embedded in the silver coating as in Figure 9, left and center. SEM/EDS analysis performed on the surface of a cable showed that the composition of this black material was very close to that of Bi-2212 (Spectrum 1 in Table of Figure 9, at right), which must have come from the filament powder during heat treatment. In addition, a small crater was found at the edge of the sample. Analysis showed several oxide phases, with specific shapes and morphologies, such as Bi-2212 (needle like grains), Bi-2201 (step like grains), (1,0) phase (spherical grains) and others. Further analysis would be needed to obtain more accurate chemical compositions, but it is already clear that the performance of these cables has been drastically degraded because of changes in the microstructure and chemical composition due to the powder leaks during heat treatment. However, because no leaks were observed either at the naked eye or through SEM on the extracted strands, which performed well, the hypothesis can be made that this problem is not as much related to the strand ability to withstand deformation as to the heat treatment of the cables itself, i.e. oxygen distribution on hidden surfaces, temperature inhomogeneities, and such.



Spectrum No.	1	2	3
Element	At. %	At. %	At. %
Ag (L)	0	100	0
Bi (M)	14.91	0	3.59
Sr (L)	9.04	0	2.21
Ca (K)	5.53	0	0.78
Cu (L)	11.49	0	5.80
Mg (K)	0	0	29.33
O (K)	59.03	0	58.28
Totals	100.00	100.00	100.00

FIGURE 9. Bi-2212 cable after reaction (left), back scatter image of circled black spot (center), and composition Table in marked locations (right).

CONCLUSIONS

The focus of this work with OST was to produce Bi-2212 strands adequate for cabling. For this purpose, billets with different O_2 anneal processes were produced. These billets had very similar J_c's. The I_c degradation of the extracted strands was reasonable and typically less than 20% at least up to 85% of packing factor for all the cables, but in one reproducible single case. It was found that the poorly performing strand had more and larger MgO precipitates on its surface than a well performing one. This may be caused by irregular grain growth, possibly due to heat treatment temperature inhomogeneities.

The I_c degradation measured on the cable samples was significantly and systematically larger than that of the extracted strands. It was found that this was due to changes in the microstructure and chemical composition due to powder leaks during heat treatment. However, because no leaks were observed on the extracted strands, which performed well, this problem may not be as much related to the strand ability to withstand deformation as to the heat treatment of the cables itself. Given the excellent performance of the Bi-2212 strands after cabling, it is worthwhile to devote future resources to solve this cable heat treatment problem.

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