High Field Insert Coils From Bi-2212/Ag Round Wires

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***Abstract*—Bi-2212/Ag round wire is a promising and practical material for extending high field superconducting magnets beyond the limits of Nb_3Sn. Efforts to develop superconducting magnets in the 25 to 30 T range include fabrication and test of practical size insert coils using this wire. Recent studies have focused on improvements in wire performance, wire insulation, and coil fabrication for wind-and-react coils. Continued improvements in the engineering critical current density (J_E) and the critical current density (J_c) performance have been achieved by optimizing the starting precursor composition, and the heat treatments. The highest J_E of 1580 A/mm^2 at 4.2 K, 0 T and 420 A/mm^2 at 4.2 K, 31 T were obtained in 0.81 mm wire. In particular, significant progress on braided insulation has been made for enabling a robust procedure for wind-and-react Bi-2212 solenoid coils. Performance of three of these coils has been measured in background fields up to 19 T, showing good prospects for high field magnet application of this conductor.**

***Index Terms*—Bi-2212 round wire, high temperature superconductors, superconducting magnets, superconducting materials.**

I. Introduction

The 2005 U.S. COHMAG report emphasizes that continued progress toward higher magnetic fields holds significant potential for general advances in science and technology [1]. One specific recommendation this report makes for high field technology development is the goal of a 30 T superconducting magnet for NMR. Commercial high field superconducting magnets for NMR, made with Nb_3Sn wires, are available with fields up to 22.5 T at 2.2 K [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 probably enable 23.5 T for 1 GHz NMR, it is unlikely that such Nb_3Sn magnets can be pushed higher than 25 T because of limits on the upper critical field (B_{c2}).

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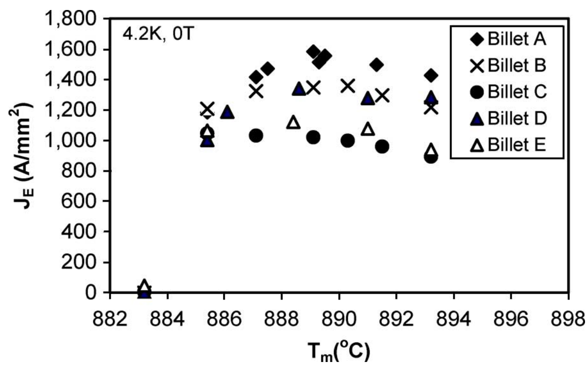

Fig. 1. Optimization of 1.0 $\mu V/cm$ J_E vs. the partial melting temperature for 5 recent billet wires.

Efforts are underway to develop alternate materials with higher B_{c2} values and thus greater high field critical current density (J_c); these efforts are mainly focused on ceramic high-T_c superconductors (HTS) because of their extraordinarily high irreversibility field $(B_{irr}$-) at 4.2 K [6], [7]. Based on performance, available lengths, and potential for further improvement, the most likely material to enable superconducting magnets in the 25–30 T range is $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) [3], [8]–[11]. The COHMAG report specifically mentions the potential for driven superconducting magnets up to 30 T using this material [1].

At Oxford Superconducting Technology, there is continued development activity aimed at using Bi-2212 conductors for high field magnet applications. Round wires are preferred because of strong advantages over tape, such as no anisotropy, ease of layer winding, and enablement of conventional cabling methods. Our recent work focuses on improving J_c and J_E in long length Bi-2122 round wires to enable magnet applications [12]. In particular we explore new insulation materials that enable wind-and-react Bi-2212 coils. In this paper, we report recent progress toward a practical magnet Bi-2212 conductor.

II. Round Bi-2212/Ag Wires

The round wires were manufactured using a powder-in-tube process. The wire fabrication details were described in [8], [13]. We have been developing Bi-2212 round wire typically in an 85×7 filament configuration. The average filament size is about 14 μm when the wire diameter is 0.8 mm and ceramic fill factor (determined by metallography) is 25–30%. The material is heat treated in a flowing oxygen atmosphere using a partial melt-solidification process. The maximum temperature is between 880 and 895°C and the cooling rate between 1 and 10°C/h. Fig. 1

TABLE I
TEST COIL PARAMETERS AND GENERATED FIELD

Name	ID (mm)	OD (mm)	Height (mm)	No. Turns	No. Layers	Wire Length (m)	Self Field J_E (A/mm^2)	Self Field (T)	19 T Field J_E (A/mm^2)	19 T Field (T)
W2	53.2	62.5	73.0	202	4	37	353	0.8	--	--
W3	53.1	71.2	73.0	425	8	83	289	1.27	109	0.47
W4	53.0	81.9	73.0	628	12	133	375	2.3	170	0.99
D1	25.5	81.8	74.0	1332	24	224	--	--	--	--
D2	25.5	74.8	74.0	1534	24	242	--	--	--	--
D4	25.5	44.6	200.0	1201	8	132	260	1.5	127	0.74

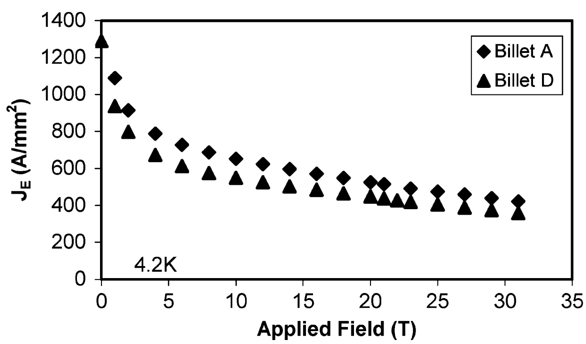

Fig. 2. Comparison of 0.1 $\mu V/cm$ $J_E(B)$ at 4.2 K for two 1 m long coil samples. The difference in J_E with the starting compositions is evident.

Fig. 3. Photographs of ceramic braided and reacted 1.0 mm diameter wires for breakdown voltage test.

shows the optimization of J_E versus the partial melting temperature for five recent billets A-E with different powder compositions. The figure shows that the peak J_E of 1580 A/mm^2 was achieved in billet A having the composition of $Bi : Sr : Ca : Cu = 2.17 : 1.94 : 0.89 : 2.00$.

Fig. 2 compares J_E versus applied magnetic field up to 31 T at 4.2 K in two 1 m long coil samples (0.8 mm diameter). These two samples, cut from two billets A and D that had the same fabrication process but different starting powder composition, had independent heat treatment optimization. The difference between J_E in these two wires is attributed to the starting powder compositions. The higher J_E of 420 A/mm^2 at 31 T was obtained in billet A. However, it is observed that they have similar behavior with respect to applied magnetic fields.

III. INSULATION

To fabricate wind-and-react coils from these strain sensitive Bi-2212 wires, an insulation is required that can withstand the heat treatment conditions of nearly 900°C in pure oxygen. At OST, various glass insulations have been used to braid Nb_3Sn conductors for commercial wind-and-react coils. We have tried these glass braids as insulation on Bi-2212 wires, but these all suffered from various problems, primarily insufficient temperature rating to survive the heat treatment, and chemical interactions with the Bi-2212 melt. At the NHMFL, sol-gel coated zirconia was used for the wind-and-react coils from Bi-2212 tapes [14]. However these coils suffered from a high failure rate due to chemical interactions between the coatings and the Bi-2212 melt [15].

We have recently experimented with several ceramic yarns from different sources as insulations. A series of preliminary experiments compared I_c and chemical interaction between braid insulations and Bi-2212 wires in a range of wires (using several precursor powders) with and without insulation. No effect on I_c in single strands was observed in the wires with the two braided insulations, but others suffered the I_c degradation because of chemical interactions between the insulation and wires. After consideration of the availability and cost, one ceramic yarn was chosen and successfully braided on these round Bi-2212 wires. With proper machine setup, the ceramic yarn could be braided in a manner comparable to glass braid on Nb_3Sn except for the thickness. The braid thickness obtained was about 125 μm. As shown in Fig. 3, high voltage breakdown testing has been done on braided and reacted 1.0 mm strands in accordance with IEC standard 60851-5. Five samples were tested and the average measured breakdown voltage was 1679±19 V. Note that in a coil the braid is infiltrated with epoxy, and the breakdown performance may exceed this value.

IV. WIND-AND-REACT COILS

Several kilometers of 0.8 mm and 1.0 mm strand were braided to use in a series of wind-and-react test coils. Table I compares parameters for six coils. Coils W2 through W4, D1, and D2 were intended to provide progressively thicker winding sections, having 4, 8, 12, and 24 layers. Coil D4 was to provide

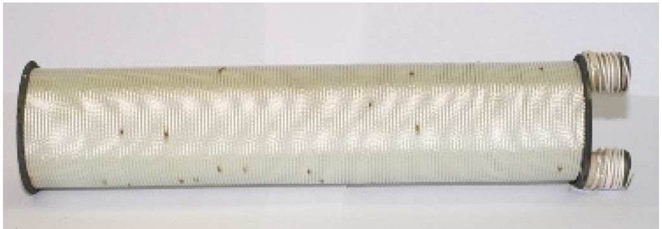

Fig. 4. Coil D4 (height 200 mm) after heat treatment.

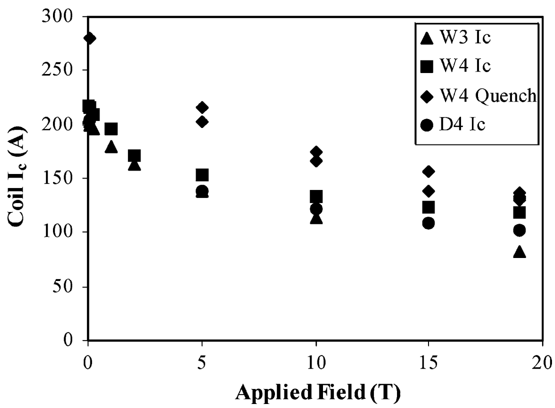

Fig. 5. 0.1 $\mu\mathrm{V/cm}$ $\mathrm{I_c(B)}$ performance for coils W3, W4 and D4. The upper curve is initial quench current data of coil W4.

larger coil height with 8 layers for satisfying a commercial design. Note that coils W2 and W3 used wire from the same billet; others used wire from billets with the same design but higher performance as a result of better precursor powders [12]. After winding, all coils were heat treated using a schedule identical to that used for short sample I_c optimization. Fig. 4 shows coil D4 after heat treatment. There is some spotting in the braid after heat treatment, which is likely due to slight leaking of the 2212 melt. The heat treated coils were epoxy impregnated using procedures established for our 5 T 2212 insert coil which reached 25 T [11], and then tested in background fields using the NHMFL 20 T, 200 mm bore resistive magnet. Critical current was determined using a criteria of 0.1 $\mu\mathrm{V/cm}$. For the three larger coils, a calibrated cryogenic Hall probe was used to directly measure axial field. Coil constants were calculated for these coils using a standard short solenoid model, and the Hall probe data agreed with these calculations to within a few percent, indicating no shorted turns and verifying the integrity of the insulation.

In previous work [16], we reported I_c measurement results of coils W2 through W4. Here we provide more data for the coils with thicker or larger sections. Whereas coil W4 quenched at the very start of the V(I) transition during the first several current ramps in the field test, D4 was well behaved, with stable V(I) transitions and an I_c value of 100 A at 4.2 K, 19 T. However, the I_c values in coils D1 and D2 with thicker section were very low, as discussed below. Fig. 5 shows the in-field $\mathrm{I_c(B)}$ data obtained at 4.2 K and 0.1 $\mu\mathrm{V/cm}$ for coils W3, W4 and D4. The top curve in Fig. 5 shows the quench currents obtained. In a 19 T background field coil W3 added 0.47 T, W4, 0.99 T, and D4, 0.74 T at I_c (0.1 $\mu\mathrm{V/cm}$).

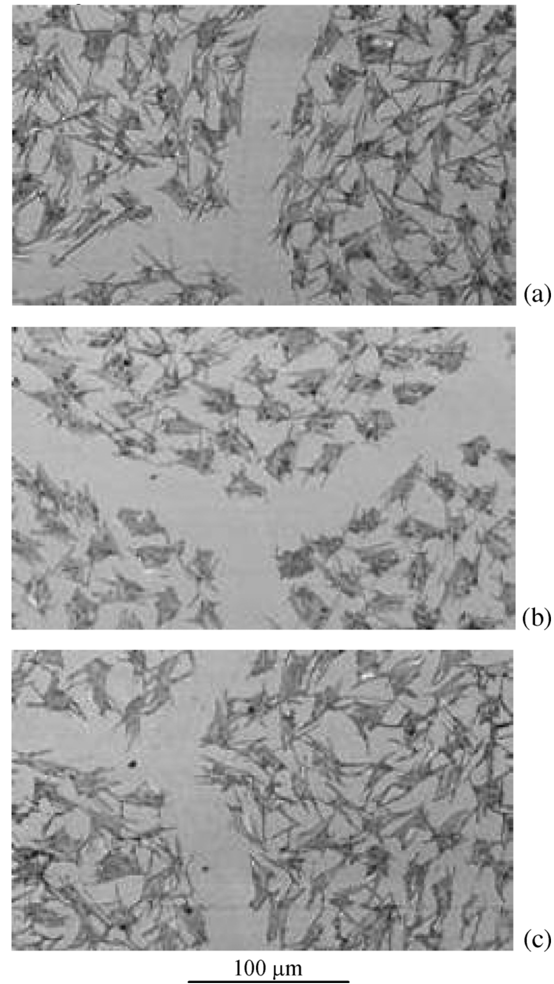

Fig. 6. The filament morphology from three different areas (a) outer, (b) central and (c) inner layers of coil D1 after heat treatment and test.

Microstructure observation was performed on the cross-section of coil D1 cut after I_c test. Fig. 6 compares the filament morphology from three different areas (outer, central and inner layers) of coil D1 after heat treatment and test. The micrographs show many whiskers between filaments in the outer and inner layers. This morphology corresponded with the good I_c in our previous work [8]. But, a significant difference in filament morphology was found in the central layers, where there were fewer whiskers. This difference in filament morphology indicates re-crystallization under different conditions, possible differences include the peak temperature and/or the oxygen content. I_c measurement from layer to layer from coil D2 confirms the lower I_c values occurred in several central layers. This difference, observed only in the thicker coils, indicates a remaining problem for uniform melting in the thick coil sections. Note that all wire coils made with 12 layers or fewer have given good I_c performance. Further study of this problem is required.

For practical application of Bi-2212 coils, the Lorentz force induced strain on the coil is a significant factor for coil design. Therefore, several strain gauges were attached at midpoint on the outer layer of coil D4 in the hoop and axial direction to allow characterization of the mechanical state of the coil. Fig. 7

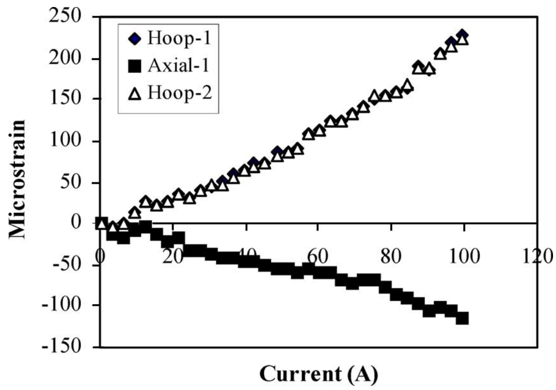

Fig. 7. Strain-current characterization of coil D4 in 19 T background field.

compares the microstrain-current measurement data obtained on coil D4 in a 19 T background field. Data shows a microstrain of 250 (0.025% strain) in hoop carried at 100 A, 4.2 K, 19 T. Axial strain is about half of the hoop strain. As prior studies have shown, Bi-2212 round wire is capable of strain tolerance up to 0.5% strain [9]. Such strain-current performance in the now demonstrated wind-and-react coils, makes this round Bi-2212 wire a promising material for continued high field coil development.

V. SUMMARY

We have described progress in the development of multifilament Bi-2212/Ag wires for magnet applications. In summary, continued improvements in multifilament wire have enabled demonstration of J_E of 1580 A/mm^2 at 4.2 K, 0 T and 420 A/mm^2 at 4.2 K, 31 T. Braided ceramic yarn has enabled layer wound, wind-and-react coils with up to 24 layers. All coils made with 12 layers (15 mm thick sections) or fewer have given good I_c performance. A successful wind-and-react coil technique has produced a 1 T insert in a 19 T background, and shows good potential for future high field insert coils. Further study of thicker section coils is required.

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REFERENCES

[1] U.S. National Research Council's Committee on Opportunities in High Magnetic Field Science, "Opportunities in High Magnetic Field Science," National Academies Press. Washington, D.C., 2005.
[2] A. Street, "Superconducting magnets: At the heart of NMR," *Spectroscopy Europe*, vol. 15, no. 1, pp. 10–13, 2003.
[3] S. W. Van Sciver and K. R. Marken, "Superconducting magnets above 20 tesla," *Physics Today*, vol. 55, no. 8, pp. 37–44, 2002.
[4] Oxford Instruments Superconductivity, "Oxford Instruments Announces the World's First 950 MHz Magnet for Nuclear Magnetic Resonance is at Field," press release, August 31, 2005.
[5] S. Hong, M. B. Field, J. A. Parrell, and Y. Zhang, "Latest improvements of current-carrying capability of Nb-Sn," *IEEE Trans. Appl. Supercond.*, vol. 136, p. 1146, 2006.
[6] H. W. Weijers, Q. Y. Hu, Y. S. Hascicek, A. Godeke, Y. Vouchkov, E. Celik, and J. Schwartz, "Development of 3 T class Bi-2212 insert coils for high field NMR," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 563–566, 1999.
[7] M. K. Okada, T. Tanaka, K. Wakuda, Ohata, J. Sato, H. Kumakura, T. Kiyoshi, H. Kitaguci, K. Togano, and H. Wada, "Fabrication of Bi-2212/Ag magnet for high magnetic field applications," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 920–923, 1999.
[8] H. Miao, K. R. Marken, M. Meinesz, B. Czabaj, and S. Hong, "Development of round multifilament Bi-2212/Ag wires for high field magnet applications," *IEEE Trans. Appl. Supercond.*, vol. 15, p. 2554, 2005.
[9] T. Hasegawa, T. Koizumi, Y. Hikichi, T. Nakatsu, R. Scanlan, N. Hirano, and S. Nagaya, "HTS conductors for magnets," *IEEE Trans. Appl. Supercond.*, vol. 12, p. 1136, 2002.
[10] H. W. Weijers, U. P. Trociewitz, S. H. Thompson, F. Trillaud, A. Mbaruku, Y. S. Hascicek, J. Schwartz, K. R. Marken, M. Meinesz, and H. Miao, "Development of a 5 T HTS insert magnet as part of 25 T class magnets," *IEEE Trans. Appl. Supercond.*, vol. 13, p. 1396, 2003.
[11] H. W. Weijers, U. P. Trociewitz, K. R. Marken, M. Meinesz, H. Miao, and J. Schwartz, "The generation of 25.05 T using a 5.11 T $Bi_2Sr_2CaCu_2O_x$ superconducting insert magnet," *Supercond. Sci. Technol.*, vol. 17, pp. 636–644, 2004.
[12] H. Miao, K. R. Marken, M. Meinesz, B. Czabaj, S. Hong, M. O. Rikel, and J. Bock, "Studies of precursor composition effect on J_c in Bi-2212/Ag wires and tapes," *Adv. in Cryogenics Eng.*, vol. 52B, p. 673, 2006.
[13] K. R. Marken, H. Miao, M. Meinesz, B. Czabaj, and S. Hong, "BSCCO-2212 conductor development at Oxford superconducting technology," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 3335–3338, 2003.
[14] H. W. Weijers, Q. Y. Hu, Y. Viouchkov, E. Celik, Y. S. Hascicek, J. Schwartz, K. Marken, and J. Parrell, "Development and testing of a 3 T Bi-2212 insert magnet," *Adv. in Cryogenics Eng.*, vol. 45A, p. 769, 2000.
[15] D. E. Weslowski, M. O. Rikel, J. Jiang, and E. E. Hellstrom, "Reactions between oxides and Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ conductors," *Supercond. Sci. Technol.*, vol. 18, p. 934, 2005.
[16] K. R. Marken, H. Miao, M. Meinesz, B. Czabaj, and S. Hong, "Progress in Bi-2212 wires for high magnetic field applications," *IEEE Trans. Appl. Supercond.*, vol. 136, p. 992, 2006.