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YBCO and Bi2223 Coils for High Field LTS/HTS NMR Magnets: HTS-HTS Joint Resistivity

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Abstract

This paper presents our latest experimental results on high-temperature superconducting (HTS) splice joints for HTS insert coils made of YBCO and Bi2223, that comprise a 1.3 GHz low-temperature superconducting/HTS nuclear magnetic resonance magnet currently under development at Francis Bitter Magnet Laboratory. HTS splice joint resistivity at 77 K in these insert coils must be reproducible and $< 100 \text{ n}\Omega \text{ cm}^2$. Several YBCO tape to YBCO tape (YBCO-YBCO) splice joint samples were fabricated, and their resistivity and I_c were measured at 77 K. First, we describe the joint splicing setup and discuss the parameters that affect joint resistivity: pressure over joint surface, solder, and YBCO spool batch. Second, we report results on YBCO-YBCO joints at 77 K in zero field. Measurements have shown that spool batch and solder are primary sources of a wide range of variation in YBCO-YBCO joint resistivity. By controlling these parameters, we expect to reproducibly achieve HTS-HTS resistive joints of resistance $< 100 \text{ n}\Omega \text{ cm}^2$.

Index Terms—

Coated YBCO conductor and Bi2223; high-temperature superconducting (HTS) magnet; HTS tape to HTS tape splicing technique; HTS-HTS splice resistivity

I. INTRODUCTION

THIS paper presents our latest results on an HTS tape to HTS tape (HTS-HTS) splice technique devised for the 700 MHz HTS insert (H700) coils of a 1.3-GHz LTS/HTS NMR magnet currently being developed at FBML [1]. The H700, to be incorporated in our new 1.3 GHz LTS/HTS NMR magnet, is made of two stacks of double-pancake coils (DPs), 26 DPs in the inner YBCO coil and 40 DPs in the Bi2223 coils [1]. Adjacent DPs within each coil are electrically spliced, by means of YBCO tape to YBCO tape (YBCO-YBCO) splice joints in the inner coil and Bi2223-YBCO-Bi2223 joints in the outer coil. (In addition, there is one YBCO tape to Bi2223 tape joint connecting inner and outer coils.) In developing an HTS-HTS resistive joint technique, our goal was to achieve a reproducible joint (or contact) resistivity at 77 K of $<100 \text{ n}\Omega \cdot \text{cm}^2$ in zero field. Here, it is assumed that a 77 K, zero-field resistivity will remain constant, or will not be increased too much, at 4.2 K and in $\sim 25 \text{ T}$ (inner coil joints) and $\sim 16 \text{ T}$ (outer coil joints); this assumption has been validated through earlier research on magnetoresistive effect of solders [2], [3]. For example, for a joint resistivity of $100 \text{ n}\Omega \cdot \text{cm}^2$, a 10-cm long (thus a contact area of 6 cm^2) YBCO-YBCO splice joint (for 6-mm wide YBCO [1]) would dissipate $\sim 1.4 \text{ mW}$ at the designated operating current of 257 A [1]. This dissipation rate includes a $\sim 25\%$ magnetoresistive increase at 4.2 K in joint resistivity from 0 to 25 T, the highest field at joint sites-note that this $\sim 25\%$ increase is based on an assumption that a linear extrapolation, valid up to 5 T [3], holds up to 25 T. This Joule heat dissipation rate results in a total joint dissipation of $<150 \text{ mW}$ for H700, which translates to an additional LHe evaporation rate of $\sim 200 \text{ cm}^3/\text{hr}$, an acceptable level to maintain a stable cryogenic environment for H700 [3]. Good reproducibility is also important to decrease the risk of obtaining bad joints. Replacement of a bad joint shortens the overall conductor length in the DP that in turn jeopardizes its field magnitude and field homogeneity capability [4]. This paper reports results on YBCO-YBCO splices at 77 K. Included are resistivity and critical current (I_c) data for variables that include spool batch, solder, and joint length. We also discuss key variables that affect reproducibility and joint resistivity.

II. EXPERIMENTAL SETUP

A. Joint Implementation

Fig. 1 is a picture of our splicing setup, composed of a stainless steel strip heater, curved aluminum sample holder, load-applying structure, temperature sensors, and heater power supply. An 8-mm wide, 0.252-mm thick stainless steel strip is used to apply a uniform pressure on the joint over the curved aluminum holder, machined to match the outer curvature of either HTS coils. Although the heater is currently 8-mm wide, i.e., designed for 4-mm wide YBCO tape, its width may readily be increased to 12 mm for a new H700 coil wound with 6-mm wide YBCO tape [1]. Two temperature sensors, one on the center of the holder and the other at 90° (counter-clock-wise) from the center, are used to protect the joint samples from overheating. The load structure, connected under the heater, and load cells are prepared to apply load at the moment when the temperature reaches the solder melting point.

B. Joint Procedure and Details

We made each YBCO-YBCO joint sample through the following steps: 1) prepare two YBCO tapes and clean HTS side surface of each tape with Scotch-Brite sponge and acetone, 2) apply soldering flux on the HTS side of each tape, 3) place two YBCO tapes on the holder with a piece of solder in between, 4) place the heater over the joint and turn on the power supply to charge the heater current, 5) apply an 8-kg load (~90 kPa), right before the joint temperature reaches the solder melting point, and 6) turn off the power supply and let the joint cool down to room temperature. Table I lists information on joint procedure, HTS conductor, cleaning pad, soldering flux, and solder. We hand-scrub (15–20 times) the tape surface with Scotch-Brite to remove the oxidation layer on the tape, then cleanse the residue with acetone. In this paper, all the joint samples were fabricated with one pen-type soldering flux which can dispense a controlled amount of flux.

With a constant heater current of 20 A, we used two different temperatures decided by melting point of solders, one for Tix/Indalloy, and the other for Kester 44. The former took about 5 minutes to raise the temperature to 155 °C whereas the latter took about 10 minutes to raise it to 185 °C. These temperatures are the melting points of respective solder. For each solder, we applied a load when the solder was about to melt, 5–10 °C below its melting point. This process is designed to avoid sharp edges, possible on some part of solder layer, so that we can protect HTS tapes from mechanical damage during the load-applying process. After loading, a slight pendular motion was applied to the joint implementation to ensure a uniform pressure over the joint sample. To protect the joint sample from thermal damage, we turned off the power supply within 10 seconds after the temperature reached the solder's melting point or exceeded by 5–10 °C. By blowing room-temperature nitrogen gas over the joint sample for ~10 minutes, we cooled it down to below 50 °C.

C. Conductor and Solder

SuperPower 4-mm wide YBCO tape was used to make YBCO-YBCO joint samples. As shown in Table I, 5- μm thick copper layer (10- μm thick in total), 15 μm less than standard thickness provided by the vendor, was coated around the YBCO tape to satisfy our design requirements [5], [6]. To test reproducibility, we made at least 3 joint samples for each set of the same joint parameters: solder, conductor spool ID (batch #), and joint length. The vendor slits 12-mm wide YBCO tape into three spools, each of 4-mm wide tape. The last two capital letters, MS, FS, and BS, of each spool ID identify the original location of the 4-mm wide tape. Here, MS, FS, and BS, stand for middle-slit, front-slit, and back-slit, respectively. We made one group of joint samples that were made of the conductors having the sample spool ID number, M3-745-2, but different slit IDs. Joint length was also varied from 2.5 cm to 10 cm to test the reproducibility of our joint technique, i.e., if reproducible, HTS-HTS joint resistance should be inversely proportional to joint length [7], [8].

Three different types of solder, listed in Table I, were examined: two round wire solders, each requiring pre-tinning the copper layer of the YBCO tape and a 0.05-mm thick Indalloy solder ribbon of optional pre-tinning. The joint resistance and joint resistivity were calculated from the V-I curve measured by standard 4-point method as the current was

increased from 0 A to 50 A. Critical current I_c was determined based on a $1\text{-}\mu\text{V}/\text{cm}$ criterion after the resistive voltage of the joint resistance was deducted.

III. RESULTS

A. Conductor Spool ID

The most surprising, and unexpected, discovery of our results is that joint resistance depends critically on conductor spool ID (batch #). Fig. 2 shows joint data, resistivity (solid squares) and I_c (open circles), sorted out by conductor spool ID (Batch #). The joint samples, each 2.5-cm long, were made with Indalloy ribbon solder. From the same batch, 3–5 joint samples were made. Table II, including all the joint samples depicted in Fig. 2, presents joint resistivity and I_c of 17 different sample sets, grouped by pre-tinning process, spool ID, and solder. In the 4th column of Table II, three abbreviations, SnPb, Tix, and Ind, are assigned for different solders, Kester 44, Tix solder, and Indalloy solder in Table I, respectively. The experimental results of joint resistivity and I_c are summarized in four different values, minimum-average-maximum in columns 6 and 8, and coefficient of variation (CV) in columns 7 and 9. CV, defined as the ratio of the standard deviation to the mean, quantifies deviations of joint sets of different averages. Similar to standard deviation, the smaller the CV, the less dispersion in the data set. Therefore, $\text{CV} < 1$ in all joint resistivity data in Table II implies a close correlation between joint resistivity and spool ID.

Based on Fig. 2 and Table II, we conclude that conductor batch is a critical parameter of joint resistivity. With some batch conductor, for example, it was impossible to achieve a joint resistivity of $< 100\text{ n}\Omega \cdot \text{cm}^2$. Similar results have also been reported by another group [9]. Note that the joint resistivity and I_c of joint samples from the same spool ID tend to be related to each other.

The joint data from the same spool ID but different slits are also compared in this paper. Fig. 3 presents joint resistivity and I_c data for three groups of 4-mm wide joint samples, NP01, NP02, and NP03, made respectively with BS, FS, and MS tapes. The joint resistivity values are in the range of $220\text{--}310\text{ n}\Omega \cdot \text{cm}^2$, i.e., there seems to exist no close relation between slit and joint resistivity. This result is confirmed by two other sample sets, NP04 and NP05, whose average joint resistivity were 586 and $516\text{ n}\Omega \cdot \text{cm}^2$, respectively. These two sample sets were made of conductor from same spool, M3-747-2, but from different slits, BS and MS. The resistivity data from two different spool IDs agree quite well regardless of slits.

B. Solder

Three different solders were statistically compared by CVs of joint resistivity and I_c in Table II. We associate a low CV with an indication of good reproducibility, as discussed below.

First, the CVs of pre-tinned sample sets tend to be higher than those of un-pre-tinned sample sets, which can be interpreted as a higher uncertainty of pre-tinning scheme on both joint data, joint resistivity and I_c . This tendency is most likely caused by uncertainty of pre-tinning process. Because the pre-tinning process was carried out by conventional soldering station which made it hard to control factors involved, such as pre-tinning pressure, the amount of pre-tinned solder, and the surface condition of the pre-tinned conductor.

Comparison between P04 and NP08 typically holds for this assumption. These two sample sets have identical splicing conditions except the pretinning process, but the CVs of joint resistivity of P04 and NP08 show a large difference, 0.229 and 0.087, respectively. For the H700 insert, non-pre-tinned, Indalloy solder ribbon will be used to splice DPs with our joint implementation.

Second, three joint sample sets made either with solder Kester 44, or SnPb in Table II, showed degraded I_c to well below 100 A. With P05, I_c of one joint samples was degraded to 53 A, less than half of their average I_c , 108.6 A. Degradation of I_c was most likely caused by excessive heating of the YBCO layer, because Kester 44 requires a longer period of heating to reach its melting point of 185 °C. Because of higher possibility on overheating by the heating process and our joint implementation, solders of lower melting points are better suited to splice DPs.

C. Joint Resistance Versus Joint Length

As stated earlier, joint resistance is inversely proportional to joint length. Fig. 4 shows joint resistance data for 4 selected lengths: the data seem to verify this simple correlation between joint resistance and length. We used two different spool IDs, M3-753 BS and M3-747-2 BS, to validate this correlation with spools having different joint resistivity. The data points in left section of Fig. 4 are from spool ID M3-753 BS (solid shapes) and the other data points in right section are from M3-747-2 BS (hollow shapes). The different symbol shapes are used to distinguish different joint length in Fig. 4. Although sample numbers 54 and 74 have lower joint resistances than the rest of joint samples for the same joint length, joint resistance and joint length appears to be corrected in Fig. 4.

IV. CONCLUSION

Through measurements of ~90 HTS joint samples, all prepared with SuperPower YBCO 4-mm wide tapes, originally slit from 12-mm wide tape, we have found a strong correlation between 4-mm wide YBCO spool ID (Batch #) and HTS joint resistivity. Namely, two otherwise identical joints, except for conductor batch numbers, produce two clearly different joint resistances, for example, one is within an acceptable limit, lower than $100 \text{ n}\Omega \cdot \text{cm}^2$, while the other shows joint resistivity of higher than $100 \text{ n}\Omega \cdot \text{cm}^2$. We have also found that ribbon solder results in most reproducible HTS joint resistance. Solders of low melting points prevent overheating of the YBCO layer, resulting in a joint sample with a good and reproducible critical current.

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Fig. 1.
Photograph of splicing setup, composed of a stainless steel heater, joint, load-applying structure, temperature monitor, and power supply. Load cell has a slit to be slid into load-applying structure in time of necessity.

Fig. 2.

Joint resistivity and critical current chart of 2.5-cm-long joint samples from different spool ID, distinguished by dashed vertical lines. The same amount of ribbon-form Indalloy solder, was used for all the samples.

Fig. 3.

Joint resistivity and critical current chart of different cutting slit from same original 12-mm-wide spool, M3-745-2. Table II includes more detailed values through NP01–03.

Fig. 4.

Joint resistance chart to present relation between joint resistance and joint length. All the joint samples were fabricated with Indalloy solder and four different joint lengths were chosen for comparison. Two samples from different spool ID, M3-753 BS and M3-747-2 BS, were distinguished by a dashed vertical line.

TABLE I.

GENERAL INFORMATION OF JOINT SAMPLES

Items	Specifications		
Conductor (Vendor)	SCS4050-AP (Superpower Inc.)		
Width; Thickness [mm]	4; 0.07		
Stabilizer (Thickness [μm])	Copper (5)		
I_c (self field, at 77K) [A]	> 100 A		
Joint length [cm]	2.5, 5.0, 7.5, 10		
Cleaning Pad (Vendor)	Scotch-Brite (3M)		
Type	Scouring pad No. 96		
Flux (Vendor)	CW8100 (ITW Chemtronics)		
Type	No clean dispensing pen (Rosin based)		
Solder	Tix	Kester 44	Indalloy
Material	Indium alloy	60Sn40Pb	80In15Pb-5Ag
Form	round wire	round wire	ribbon
Dimension [mm]	Φ0.9	Φ 1.3	25 × 0.05
Melting point [°C]	135	185	158

TABLE II.

JOINT SAMPLE DATA

Item	Set	Spool ID	Solder	Quantity	Joint Resistivity [nΩcm ²]	Min - Average - Max	CV	I_c [A] Min - Average - Max	CV
Pre-tinned samples	P01	M3-745-2 MS	SnPb	6	191.5-254.9-356.9	61-87.1-128.5	0.273		0.314
	P02	M3-747-2 BS	SnPb	3	629.5-820.9-1093.4	73-117.9-143	0.295		0.331
	P03	M3-753 BS	Tix	4	30.7-56.6-96.1	127.4-129.8-135.5	0.536		0.030
	P04	M3-753 BS	Ind	9	27.7-46.7-59.3	127.9-131.2-136.7	0.229		0.030
	P05	M3-765-1 BS	SnPb	11	51.6-67.90	53-108.6-129	0.172		0.223
	P06	M3-765-1 BS	Tix	3	86-118.7-150.8	102.1-107.5-113.5	0.273		0.053
	NP01	M3-745-2 BS	Ind	3	268.9-285-301.8	120.7-124.8-132.9	0.058		0.056
	NP02	M3-745-2 FS	Ind	3	216.7-238.4-256.3	110.1-119.3-124.4	0.084		0.067
	NP03	M3-745-2 MS	Ind	3	235.8-241.8-248.9	136.2-138.5-140.3	0.027		0.015
	NP04	M3-747-2 BS	Ind	4	520.4-586.4-690.1	133-137.4-140.7	0.134		0.028
	NP05	M3-747-2 MS	Ind	14	260.6-515.9-695.2	111.7-141.9-162.8	0.25		0.110
Not-pre-tinned samples	NP06	M3-748-2 FS	Ind	5	175.4-205.3-225.9	128.9-134.5-137.6	0.101		0.025
	NP07	M3-750-2 FS	Ind	4	302.4-370.4-473.6	113.6-121.2-128.6	0.198		0.054
	NP08	M3-753 BS	Ind	7	54.5-59.9-66.4	122.3-128.1-133.8	0.087		0.034
	NP09	M3-765-1 BS	Ind	4	105-116.5-129.3	119.2-121.4-125.5	0.098		0.023
	NP10	M3-772-1 BS	Ind	3	43.8-52.7-66.4	112.6-116.6-118.7	0.229		0.030
	NP11	M3-774-1 MS	Ind	4	35.7-38.8-44.1	119.1 - 120-121.5	0.097		0.009