

VOLTAGE DISTRIBUTION AND MECHANICAL STRENGTH IN SPLICE JOINTS MADE FROM AS-MANUFACTURED YBCO COATED CONDUCTORS*

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ABSTRACT

With recommendations from wire manufacturers as a starting point, a series of solder joints were fabricated and characterized to determine the best method to produce repeatable, low-resistance and high-mechanical-strength splices in as-manufactured, stabilized YBCO coated conductors. From the 2.54 cm long splice joints that were fabricated, parameters such as solder material, stabilization material, fabrication method, and conductor geometry were varied to determine the impact of each on splice joint properties. Results indicate that the lowest resistance splice joints were influenced primarily by the tape orientation in the joint and the stabilization material. The lowest resistances were between $2 \times 10^{-8} \Omega$ and $1.0 \times 10^{-7} \Omega$ in 4-mm wide tapes and were obtained from pure copper stabilized tapes oriented with the YBCO layers in closest proximity. The voltage drop along the splice length indicated that only a fraction of the splice length contributes to the splice joint resistance. Mechanical characterization of splice joints showed that the joint resistance remained unchanged under axial stress up to a stress level at which the critical current of the tapes forming the joint degrades irreversibly.

KEYWORDS: YBCO coated conductors, splice joints, voltage distribution.

INTRODUCTION

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Progress has been made in the commercial production of second-generation $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) coated conductors with lengths reaching or exceeding 1 km and critical currents approaching that of first-generation $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ (BSCCO) tapes [1]. While these lengths are practical for many applications, there will always be a need by either the wire manufacturer or the end-user of these materials to fabricate a coated conductor splice joint. This splice joint will either utilize shorter sections of conductor or repair a conductor damaged during device manufacturing or in the field. Development of methods to fabricate coated conductor splice joints from as-manufactured YBCO coated conductors with low resistance and high mechanical strength is needed to minimize the impact of these splice joints on the performance of a given superconducting device.

Previous work in the area of splice joints has focused on a specific splice joint fabrication with a specific YBCO coated conductor and a specific solder. Park [2] examined splice joints that were fabricated with copper-stabilized 344 superconductors from American Superconductor (AMSC) and used a 67%Bi-33%In solder. It should be noted that unless otherwise specified, the components of the solder are expressed in terms of percentage mass. A splice joint with a length of 5 cm and with the tape faces closest to the YBCO soldered together showed a resistance of $0.138 \mu\Omega$. The resistance was $3.24 \mu\Omega$ when the tape faces farthest from the YBCO were soldered together. This group then looked at the impact of stabilizer removal on splice joint resistance [3] and found that the resistance with a 60%Sn-40%Pb solder could be lowered to between $4.52 \text{ n}\Omega$ and $29 \text{ n}\Omega$ depending on the technique used to remove the stabilizer. Others [4,5] have looked at methods to fabricate low-resistance splice joints on silver-coated YBCO tapes with no stabilizer and with thickness of silver between $1 \mu\text{m}$ and $5 \mu\text{m}$ and have produced similar resistances as found in ref. 3. Within the work in the area of splice joint fabrication, only Sugano [4] considered the tensile properties of the joint in addition to its resistance and observed degradation in performance while tensile load was applied, which occurred at a value less than the tensile limit of the coated conductor.

In this study, the coated conductor splice joints were characterized in terms of their resistances and mechanical strength with respect to a broad spectrum of splice fabrication parameters. Specifically, the splice fabrication parameters that were investigated included solder material, conductor stabilization, tape orientation, and method of fabrication. The investigation took into account not only the manufacturer's splice joint fabrication recommendations from AMSC [6] and SuperPower [7] but also the variations in materials and processing that could simplify the splice joint fabrication process. In addition, a given joint fabrication was repeated with several separate splice joints to determine the variability of the electrical and mechanical properties.

EXPERIMENTAL SETUP AND PROCEDURES

Electrical Characterization of Splice Resistance

To characterize the splice joint resistance of a large number of samples, a sample holder, shown in FIGURE 1, was designed and fabricated. This configuration allowed the voltage to be measured along the length of a given splice while minimizing sample handling. This was accomplished through the use of solid copper blocks with indium foil to introduce current into the splice and the use of spring-loaded pins to measure the voltage. Because no soldered voltage taps were used, reheating of a splice joint was avoided. Splice handling was minimized because it was important to establish a connection between

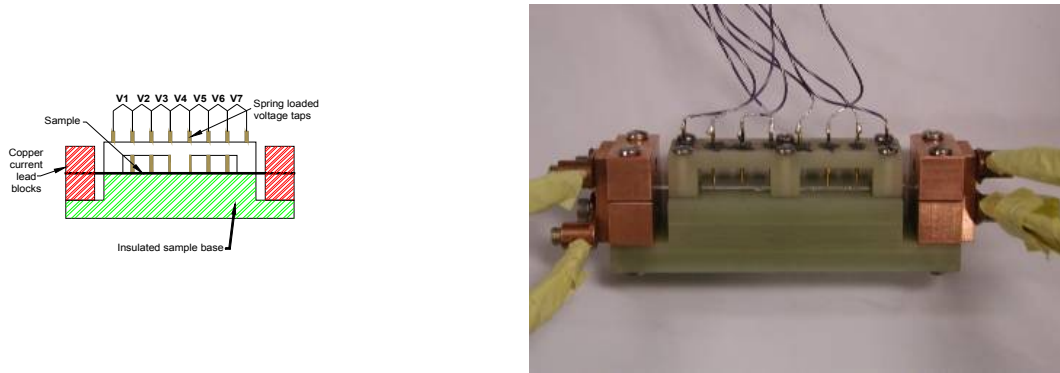


FIGURE 1. Schematic (left) and photograph (right) of the sample holder used to measure voltage distribution along the length of YBCO coated conductor splice joints.

electrical and mechanical properties because it allowed mechanical characterization to be conducted on the same splice joint after the initial electrical characterization was completed.

After the sample and the sample holder were cooled in an open bath of liquid nitrogen, the voltages were measured differentially down the length of the sample while current was increased until the $1 \mu\text{V}/\text{cm}$ criteria was reached in one or more sections of the sample. The resistance in each section was found by taking a linear fit of the voltage as a function of current as shown in FIGURE 2, and the sum of the resistances was used to determine the total resistance of the splice joint. Based on the sensitivity of the equipment used in this measurement, the estimated uncertainty in the splice joint resistance is $0.01 \mu\Omega$.

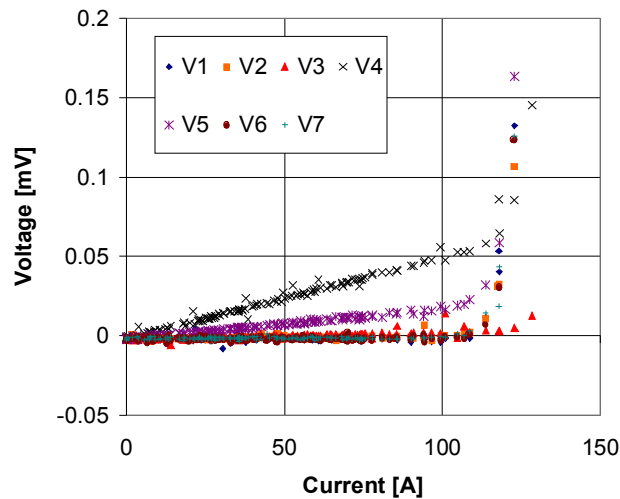


FIGURE 2. Example of voltage profile as a function of current for a 2.54 cm long YBCO coated conductor splice joint made using In-Sn solder from 4 mm wide SuperPower tape with $20 \mu\text{m}$ of surround copper stabilizer

Mechanical Characterization of Splice Joint

Within each group of solder fabrications, a representative set was screened for mechanical strength under tensile load. The resistance of the splice joints was measured as a function of axial stress, where stress was applied to the sample by use of a servo-hydraulic actuator. Copper lugs were soldered to the stabilizer on the YBCO side, at the end of both

coated conductors that were spliced together. The lugs were connected to the tensile tester and at the same time acted as current contacts. Two sets of voltage contacts

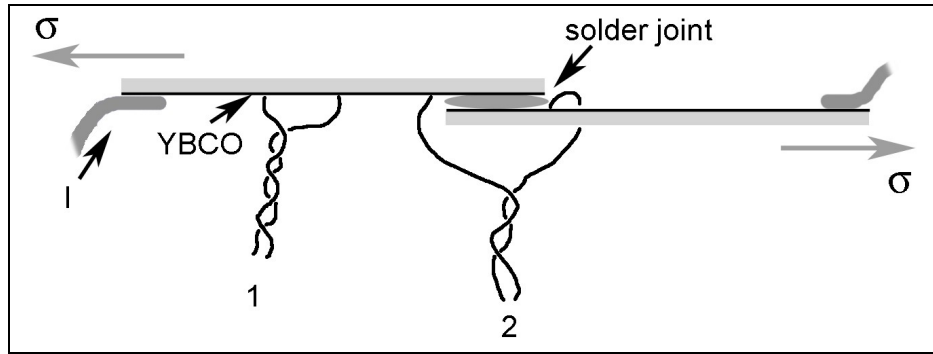


FIGURE 3. Schematic of two coated conductors that were spliced, showing the voltage contact configuration used during mechanical testing.

were soldered onto the YBCO side of the samples (FIGURE 3). One set was soldered about 1 cm apart on one of the coated conductors (contacts numbered 1 in the figure) to determine the critical current of the conductor. The other set was soldered across the splice joint (contacts numbered 2 in the figure) to measure the joint resistance. The axial stress was calculated with 5% uncertainty by dividing the applied load by the area of the cross section of the coated conductor. The critical current was determined with an electric-field criterion of $1 \mu\text{V}/\text{cm}$ and an uncertainty of about 0.5%. The splice resistance and the critical current of one of the coated conductors were determined as a function of axial stress, by stepwise increasing the applied load to the sample. Ideally, the splice resistance remains constant with increasing stress, up the stress where the critical current of the coated conductor degrades irreversibly (σ_{irr}).

SAMPLE SPECIFICATION AND SPLICE JOINT FABRICATION

The splice joints that were fabricated utilized commercially available, as-manufactured YBCO coated conductors. The as-manufactured YBCO coated conductors used in this study were produced by AMSC and SuperPower. The coated conductors from AMSC were representative of their three-ply conductor architecture. This architecture consisted of a silver-coated, 4 mm wide YBCO insert tape, grown on a buffered $75 \mu\text{m}$ thick Ni-5at%W substrate and laminated between either two pieces of 4.4 or 4.8 mm wide, $50 \mu\text{m}$ thick copper strip or two pieces of 4.4 mm wide, $110 \mu\text{m}$ thick brass strip. These YBCO coated conductors will be referred to as 344 (4.4 mm) AMSC and 348 (4.8 mm) AMSC to distinguish between the two tape widths used. The as-manufactured YBCO coated conductor from SuperPower consisted of a silver-coated YBCO tape grown on a buffered $50 \mu\text{m}$ thick Hastelloy substrate and with $20 \mu\text{m}$ of surround copper stabilizer plated around the entire tape structure. The YBCO coated conductor from SuperPower will be referred to as SCS4050.

In addition to the solders recommended by the manufacturers, solders with similar melting point and properties were chosen for evaluation. TABLE 1 lists the properties of the solders used in the fabricated splice joints. As mentioned earlier, the composition of the solders are specified with respect to percentage mass. All splice joints made with 344 AMSC and 348 AMSC used a solder with a melting point below 179°C , which is recommended by the manufacturer [6]. Note that these values are lower than the irreversible stress limit (σ_{irr}),

where the superconducting film starts to crack. Specifically, the tensile strength of the YBCO coated conductors, which can be defined as the retention of 95% of sample critical current, is 200 MPa for 344 AMSC and 348 AMSC, and 500 MPa for SCS4050.

TABLE 1. Properties of solders used in YBCO coated conductor splice joint fabrication

Solder	Composition (% Mass)	Melting Point (°C)	Resistivity at 300 K ($\mu\Omega\text{-cm}$)	Shear Strength at 300 K (MPa)
In-Bi	67%Bi 33%In	109		
In-Sn	52%In 48%Sn	118	14.7	11.2
In	100%In	157	7.2	6.1
Sn-Pb-Bi	43%Sn 43%Pb 16%Bi	163	21.0	44.1
Sn-Ag	96.5%Sn 3.5%Ag	221	10.7	18.6

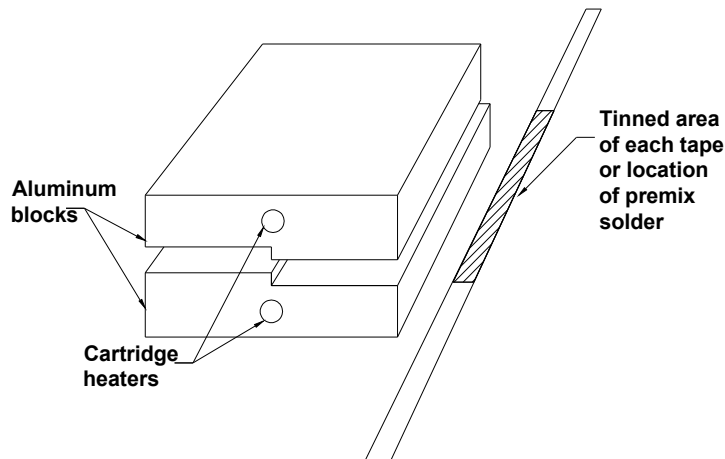


FIGURE 4. Aluminum heater fixture used to fabricate YBCO coated conductor solder joints with premixed solder paste.

Two methods for fabricating the 2.54 cm long splice joints were examined. The first was a bench-top method where a temperature-controlled soldering iron with a spade tip was used to tin each tape over a 2.54 cm (1 in.) length. The temperature of the soldering iron was set to about 5–10°C above the melting point of the solder and periodically monitored by a thermocouple during the splice joint fabrication. The tinned YBCO coated conductor tapes were soldered together at the same temperature, with the same temperature-controlled soldering iron under compression at both ends with wooden dowels. The second method for fabricating the splice joints used the fixture shown in FIGURE 4 and premixed solder paste. The paste, which is a mixture of a given solder and flux, was applied over a 2.54 cm length between two YBCO coated conductors, and the two conductors were then secured in an aluminum heater fixture. The entire fixture was heated with cartridge heaters up to approximately 5–10°C above the melting point of the solder, which typically took 2–3 minutes. This method was investigated because the use of a paste could reduce the number of steps in a splice joint fabrication. With respect to the overall length of the splice joint, the length was accurate to within 1 mm of the 2.54-cm long length.

RESULTS AND ANALYSIS

Voltage Distribution Along Splice Length

FIGURES 5 and 6 show voltage distributions along the length of two YBCO coated conductor splice joints. Both joints used the same SCS4050 YBCO coated conductor and In-Sn solder, but the orientation of the tapes in the joint differed. In FIGURE 5 the tape faces closest to the YBCO were soldered together (HTS-HTS), whereas in FIGURE 6 the tape face closest to the YBCO was soldered to the tape face closest to the substrate side of the second tape (HTS-Sub).

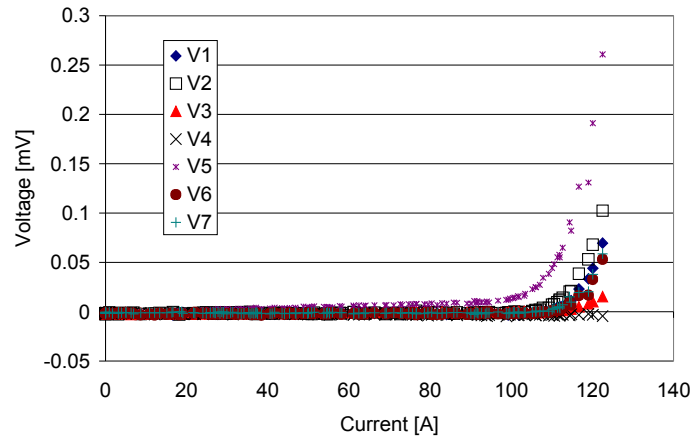


FIGURE 5. Voltage distribution along the length of a 2.54 cm long YBCO coated conductor splice made from 4 mm wide SuperPower tape with 20 μm of surround copper stabilizer and In-Sn solder. The tape orientation in this joint was HTS-HTS, with the tape faces nearest the YBCO soldered together.

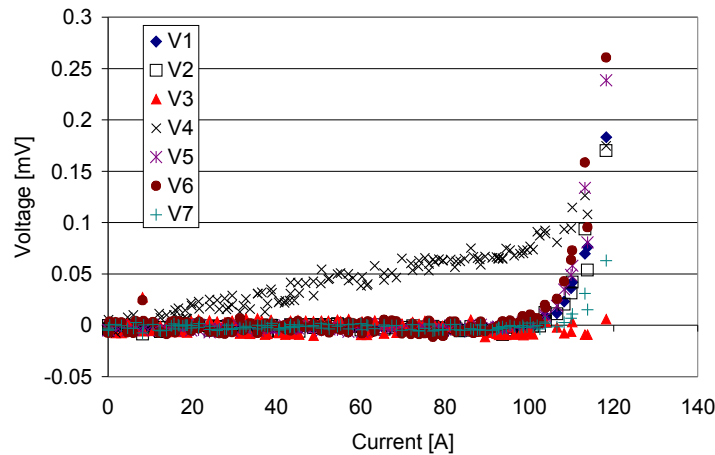


FIGURE 6. Voltage distribution along the length of a 2.54 cm long YBCO coated conductor splice made from 4 mm wide SuperPower tape with 20 μm of surround copper stabilizer and In-Sn solder. The tape orientation in this joint was HTS-Sub, with the side nearest the YBCO soldered to the substrate side of the other conductor.

It was observed that the splice joint resistance increased from $0.12 \mu\Omega$ to $0.78 \mu\Omega$ when the joint orientation was changed from HTS-HTS to HTS-Sub. However, from FIGURES 5 and 6, it is clear that the voltage along the splice joint appeared over the same 1.2 cm long interval, which the spacing of the voltage taps in FIGURE 1 and was not influenced by the joint orientation. This localized voltage was also observed in splices fabricated with 344 AMSC and 348 AMSC conductors. This independence with respect to joint orientation is the result of the fact that the superconducting films where the voltage pins were located are an equipotential surface. In the samples shown in FIGURES 5 and 6, the voltage pins for V3 through V4 are on the same coated conductor tape and the voltage does not appear until the voltage taps are located on separate parts of the splice joint.

Splice Joint Resistance

TABLE 2 summarizes the average splice joint resistances for the splice joints that were fabricated and characterized. The method of joint fabrication denoted in the table as “soldering iron” refers to the use of a temperature-controlled soldering iron to tin the YBCO tapes and solder the tapes together, whereas “heater block” refers to the use of premixed solder with the aluminum heater block shown in FIGURE 4. The average splice joint resistances and their corresponding standard deviations shown in TABLE 2 were calculated from the measured splice joint resistances from six splice joints fabricated by the same method.

A few conclusions about solder joint resistance can be drawn from TABLE 2. First, splice joints fabricated with copper stabilization had lower resistance than splice joints fabricated with brass stabilization. For example, assuming a laminated structure for the 344 AMSC tapes with 15 μm of solder between the stabilization and the silver cap layer, the presence of brass should have increased the joint resistance by a factor of 2–3 as compared with copper. While the standard deviation was higher for the case with the brass lamination and the In-Bi, the resistance was about 3.7 times higher than the copper lamination case. Of the six brass-laminated splice joints, one had a significantly higher splice joint resistance (1.64 $\mu\Omega$) than the average splice joint resistance (0.62 $\mu\Omega$). If this data point is removed, the average splice joint resistance is 0.37 $\mu\Omega$, and the brass lamination case would be 2.2 times higher than the copper lamination case and in better agreement with the change in splice joint

TABLE 2. Splice joint resistance for different 2.54 cm long YBCO coated conductor splice configurations

Coated Conductor	Stabilization Material and Thickness	Joint Orientation	Solder	Joint Fabrication	Average Splice Joint Resistance ($\mu\Omega$)	Standard Deviation in Resistance ($\mu\Omega$)
348 AMSC	Copper; 50 μm	HTS-Sub	In-Sn	Soldering iron	0.060	0.02
344 AMSC	Copper; 50 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	1.040	0.28
344 AMSC	Brass; 110 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	1.010	0.31
344 AMSC	Brass; 110 μm	HTS-Sub	Sn-Pb-Bi	Heater block	2.720	0.29
344 AMSC	Copper; 50 μm	HTS-Sub	Sn-Pb-Bi	Heater block	0.150	0.03
344 AMSC	Copper; 50 μm	HTS-Sub	Sn-Pb-Bi	Heater block	0.180	0.02
344 AMSC	Copper; 20 μm	HTS-Sub	In-Sn	Soldering iron	0.190	0.06
344 AMSC	Copper; 20 μm	HTS-Sub	In-Sn	Soldering iron	0.620	0.58
344 AMSC	Copper; 20 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	0.070	0.06
344 AMSC	Copper; 20 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	0.720	0.06
344 AMSC	Copper; 20 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	0.060	0.03
344 AMSC	Copper; 20 μm	HTS-Sub	Sn-Pb-Bi	Soldering iron	0.520	0.11
344 AMSC	Copper; 20 μm	HTS-Sub	Sn-Pb-Bi	Heater block	0.030	0.01

resistance with respect to stabilization.

Finally, the average splice joint resistance and the standard deviation of the splice joint resistance were lower for the heater block method of joint fabrication than for the soldering iron method. While this result indicates a preference for the heater block method, which did

simplify the fabrication process, additional work is needed to determine the usefulness of this method to end users because the number of available premixed solder pastes is limited, especially for 344 and 348 AMSC tapes, which can be soldered only at temperatures below 179°C.

Mechanical Integrity of Splice Joints

The results of the mechanical tests on a number of splice joints made with AMSC tape are shown in FIGURE 7, and of splice joints made with SuperPower tape, in FIGURE 8. The results of one sample per configuration are presented in each figure, although multiple splice joints were measured for each splice joint configuration. Two types of AMSC splice joints were tested under axial stress—one splice joint with copper laminated tapes soldered with In-Bi solder and one splice joint with brass laminated tapes soldered with In-Sn solder. The critical current of the tapes only degraded reversibly by a few percent up to the irreversible stress (σ_{irr}) of about 400 MPa for the copper laminated sample and up to a stress of 600 MPa for the brass laminated sample. The brass laminated sample was stronger due to the higher strength of the brass laminates as compared with the copper laminates.

The resistances of the splice joints remained constant up to σ_{irr} in both cases, showing that the splice joints with 2.54 cm overlap were mechanically stronger than the superconductors spliced together. Splice joints that were fabricated from SuperPower tape with 20 μm of surround copper stabilizer showed similar behavior (FIGURE 8). The resistance of the splice joint remained unchanged as well, under axial stress up to the irreversible strain limit at which the superconducting film started to break (between 650 and 800 MPa, depending on the sample batch).

The results also showed that in splice joints made from either AMSC or SuperPower tapes with a splice joint overlap of 2.54 cm, the splice was mechanically stronger than the tapes themselves despite the low shear strength of the soldering materials in bulk form. The solder used to splice the tapes had no direct influence on the mechanical strength of the 2.54 cm long splice joints.

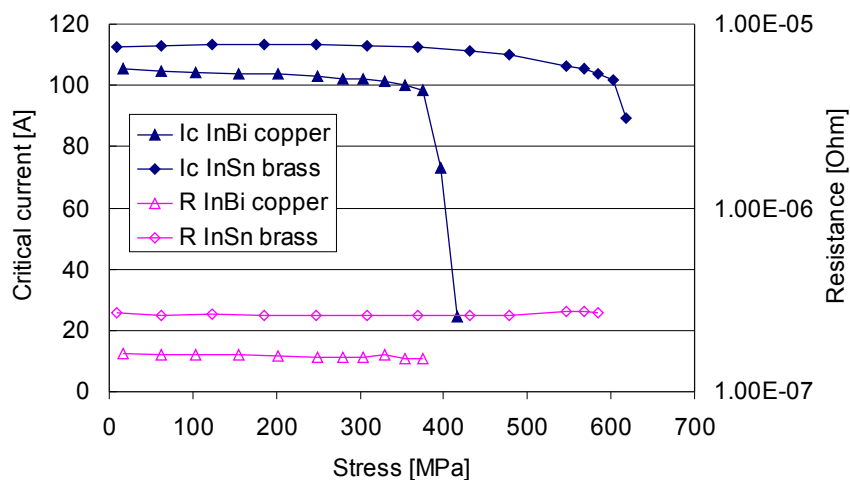


FIGURE 7. Critical current and splice resistance as a function of axial stress for splice joints made from AMSC tape with either copper or brass laminates. The splice joints were prepared with either In-Bi or In-Sn solder. The data represented by one type of symbol shows the critical current (closed) or the resistance (open) of a single sample.

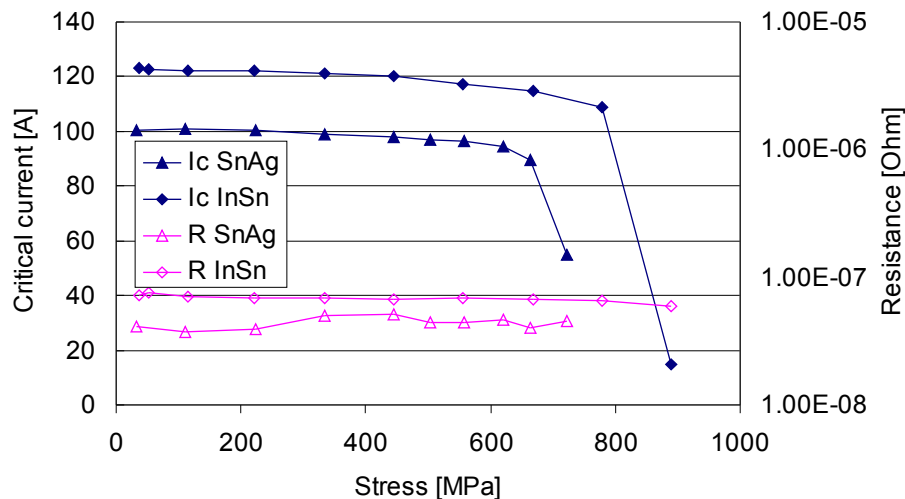


FIGURE 8. Critical current and splice resistance as a function of axial stress for splice joints made from SuperPower tape with 20 μm of surround copper stabilizer. The splice joints were prepared with either Sn-Ag or In-Sn solder. The data represented by one type of symbol shows the critical current (closed) or the resistance (open) of a single sample.

CONCLUSIONS

The electrical and mechanical properties of splice joints fabricated with as-manufactured YBCO coated conductors were characterized with respect to splice joint fabrication materials and methods. It was found that the stabilization material impacted splice joint resistance; switching from copper to brass increased the resistance by about a factor of 3. In addition, the tape orientation caused the most significant change in splice joint resistance. This change in resistance, however, did not correspond to a change in the voltage distribution, as the voltage distribution along the splice length was localized within a 1.2 cm length independent of the YBCO coated conductor, tape orientation, stabilization, or solder material used. The use of premixed solder paste during joint fabrication reduced variation in splice joint resistance in the cases examined. Additional testing is needed to confirm the usefulness of premixed solder pastes to different applications as there are currently only a limited number available commercially. The resistance of the 2.54-cm long splice joints remains unchanged under axial stress up to a stress level at which the critical current of the tapes that form the joint degrades irreversibly. The effective mechanical strength of the splice joints is determined by the strength of the superconductor, not the splice joint itself.

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