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ORIGINAL PAPER

# Electrical and Superconducting Properties in Lap Joints for YBCO Tapes

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**Abstract** The joint process between tapes of coated conductors is a critical issue for most applications of high temperature superconductors (HTSs). In this work several lap joints using different techniques were prepared for three different types of commercially available YBCO-coated conductor tapes, with and without copper stabilizer or stainless steel reinforcement layers. Lap joints with effective lengths in the range of 3 to 20 cm were prepared using low melting point In–Sn and Sn–Pb alloys as soldering materials. The electrical resistance, the critical current, and the $n$-index of the joints were calculated from the electric field *vs.* current ($E \times I$) characteristic curves under DC current tests and by further subjecting the same samples to tensile stresses. The results showed that the reinforced tape is the more robust tape for the joint-making process, whereas the copper-stabilized tape presented the lowest joint resistivity but with a relatively smaller mechanical strength against tensile stress.

**Keywords** YBCO-coated conductor · Low resistance lap joint · Critical current degradation · Mechanical properties of lap joint

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## 1 Introduction

For several applications of high temperature superconductor (HTS) tapes in power devices the need to make joints between short lengths of tape is unavoidable because of the limited production capacity of the manufacturers. The joint can define the performance of the whole unit because the electrical and mechanical properties are affected by irreversible critical current degradation. There are mainly three types of joints between superconducting tapes: superconducting joints, non-superconducting joints (using low melting point soldering materials), and diffusion joints. Due to the present tape architecture, especially for applications in coils, transformers, rotary machines using YBCO tapes with copper as a stabilizer, and fault current limiters without a stabilizer layer, many designs considering resistive joints are reported [1–3]. The reliability of the joint technique is strictly dependent on the application because a simple joint fixture must be used during coil assembly.

In high magnetic field applications the coils are constructed using several lengths of YBCO tapes, and a larger number of joints are required. For these applications all joints have to be evaluated in order to achieve a reliable process with a low value of the joint resistance. For copper-stabilized tapes conductor joints using different soldering materials are reported with a resistance joint in the range of 2–300 $n\Omega\,cm^2$ measured at 77 K [4–7].

Diffusion joint techniques are applied for tapes without stabilizers or after removal of the Cu layer, with or without an Ag tape inserted in between. The diffusion process has been carried out at 400 °C in a flowing oxygen atmosphere from 3 up to 7 h under pressure during the heat treatment to obtain a good contact between the Ag surfaces [8].

For fault current limiter applications, in which mechanical strength and a high resistivity matrix are necessary, when a stainless steel reinforcement is used, it has the additional function of stabilizer. Usually during transition to the normal state part of the current flows through the stabilizer, thus providing shunt protection until the HTS material recovers its superconducting characteristics [9, 10].

In this work lap joints were prepared with YBCO tapes as received from suppliers without any surface treatment. The joints were soldered with two types of solder alloys having different melt points (Sn–In, m.p. 116 °C and Sn–Pb, m.p. 183 °C). Conventional four-contact method voltage-current measurements were made, and a further tensile test was applied for evaluating the electrical and superconducting characteristics of the lap joints as well as for determining the critical current $I_c$ degradation.

## 2 Experimental Details

For the evaluation of the transport properties of lap joints, YBCO commercial tapes supplied by *American Superconductor Corp.* (AMSC) and *SuperPower, Inc* (SP) were used. The tape characteristics are presented in Table 1.

The resistive lap joint was prepared using the as-received YBCO tapes from the supplier without any special preparation. The fixture to prepare the joint was designed to apply controlled pressure and temperature during the joining process. For heating the sample holder a cartridge resistance was used, and for a long length lap joint a hot air blower was employed, as shown in Fig. 1. The two lengths of YBCO tapes received a smooth layer of low melting point soldering material (Sn–In or Sn–Pb) in the joint area, without any friction on the tape surface, with a soldering iron. The tinned surfaces were adjusted face to face and aligned in the fixture, stacked together between two parallel steel sheets where the pressure was applied by screws. In order to control the torque ($N$) applied on the screw, the pressure ($P$) resulting in the joint can be obtained by $2\pi N = SPL$, where $L$ is the length per revolution of the screw and $S$ is the joined area. During the joining process the screw is tightened to adjust the thickness of the soldering layer to 5–10 µm.

The electrical characterization of the sample was carried out by the conventional four-contact method. The electric field vs. current characteristics curves were obtained using a Power Ten DC current supply to produce a current ramp rate of 1.2 A/s, up to 140 A for the AMSC tapes and up to 260 A for the SP tapes. A Keithley 182 Sensitive Digital Voltmeter was used to measure the voltage drop in the lap joint region. The data was acquired by using a National Instruments GPIB interface and a computer program written in MATLAB. All $E \times I$ characteristics curves were analyzed by using the following equation below [5, 6]:

$$E = \frac{R_J I}{L} + E_c\left(\frac{I}{I_c}\right)^n \quad (1)$$

**Table 1** Main characteristics of YBCO-coated conductor tapes

| | Tape manufacturer | | | | |
|---|---|---|---|---|---|
| | SP | SP | SP | AMSC | AMSC |
| Type | SF 12100 | SCS 12050 | SCS 4050 | 344S | 344C |
| Size (mm) | $12.1 \times 0.13$ | $12.1 \times 0.14$ | $4.0 \times 0.14$ | $4.3 \times 0.15$ | $4.3 \times 0.21$ |
| Substrate | Hastelloy | Hastelloy | Hastelloy | Ni–W | Ni–W |
| Stabilizer | – | Copper | Copper | – | Copper |
| Reinforcer | – | – | – | Stainl. steel | – |
| $n$-index | 36 | 30 | 30 | 28 | 28 |
| Critical current $I_C$ (A) | 223 | 254 | 103 | 88 | 79 |

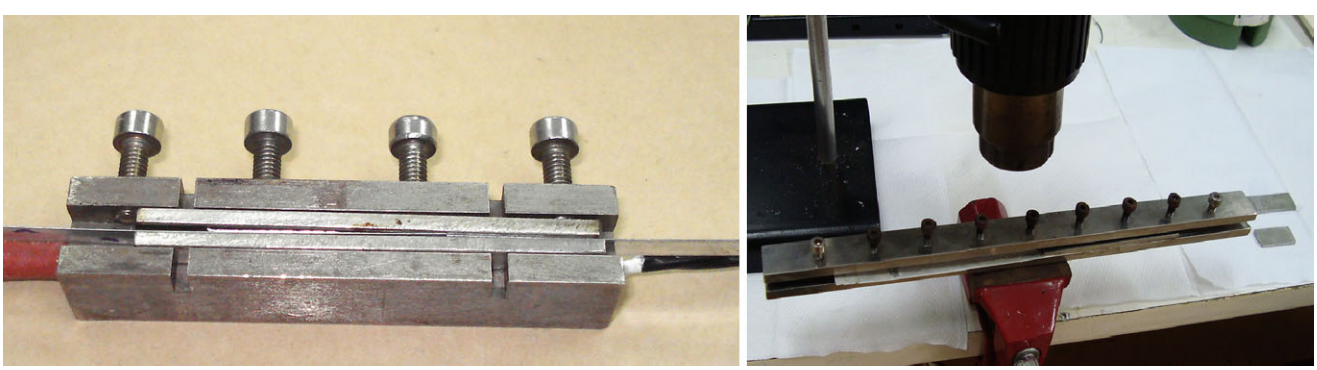

**Fig. 1** Joint fixture with cartridge resistance and thermocouple and blowing hot air system

**Table 2** Joint characteristics for the superpower SF 12100 tape

| Joint length (cm) | Resistance $R_j$ (nΩ) | $R_j A_j$ (nΩ cm$^2$) | $I_c$ (A) | $n$-index |
|---|---|---|---|---|
| 3.2 | 47.7 | 190 | 219 | 27.0 |
| 4.9 | 55.4 | 335 | 220 | 23.9 |
| 7.2 | 38.5 | 338 | 217 | 26.7 |
| 10.1 | 50.4 | 614 | 216 | 24.2 |
| 15.0 | 37.1 | 671 | 210 | 26.9 |

**Table 3** Joint characteristics for the AMSC 344S tape

| Joint length (cm) | Resistance $R_j$ (nΩ) | $R_j A_j$ (nΩ cm$^2$) | $I_c$ (A) | $n$-index |
|---|---|---|---|---|
| 3.0 | 667 | 880 | 72 | 26.0 |
| 7.0 | 191 | 588 | 72 | 26.0 |
| 10.0 | 158 | 695 | 73 | 25.8 |
| 15.0 | 87 | 574 | 73 | 25.9 |
| 19.9 | 73 | 642 | 73 | 26.0 |

in which the first term $R_J I/L$ is the contribution in the voltage of the resistive region of the lap joint and $E_c(I/I_c)^n$ is the contribution in the voltage of the superconducting-to-normal transition.

An electrical measurements test was performed to determine the $E \times I$ characteristics curves. Two pairs of voltage taps were located within the region without the joint, with a sample length of 70 mm, and the other voltage tap was within the region containing the lap joint (30 mm length), in order to measure both $E-I$ curves simultaneously.

## 3 Results and Discussion

### 3.1 Electrical Characterization

The lap joints prepared with YBCO tape SF 12100 (stabilizer free) with joint lengths from 3 to 15 cm were measured in order to evaluate the joint resistance, the $n$-index, and $I_c$. The results are summarized in Table 2. The results show that this joint resistance does not depend on the joint length and that no $I_c$ degradation and $n$-index reduction were observed.

For the joint prepared with YBCO tape AMSC 344S, also without Cu stabilizer but including reinforcement with stainless steel tape (25 µm each side), the results for joint resistance are presented in Table 3. The results show that the joint resistance presents a strong dependence on the joint length determined by the stainless steel tape resistivity.

The joints using YBCO tapes with Cu as stabilizer were prepared with SP tapes SCS 12050 (12 mm width) and SCS 4050 (4 mm width), and with the AMSC 344C tape (4 mm width). The joints were prepared with a joint length of 6.3 cm, and their electrical characteristics are presented in Table 4.

**Table 4** Joint characteristics for the YBCO tapes with Cu stabilizer

| Type of YBCO tape | Resistance $R_j$ (nΩ) | $R_j A_j$ (nΩ cm$^2$) | $I_c$ (A) | $n$-index |
|---|---|---|---|---|
| SCS 4050 | 16.2 | 41.8 | 93 | 17 |
| SCS 12050 | 2.3 | 17.4 | 245 | 14 |
| AMSC 344C | 30.5 | 73.0 | 88 | 18 |

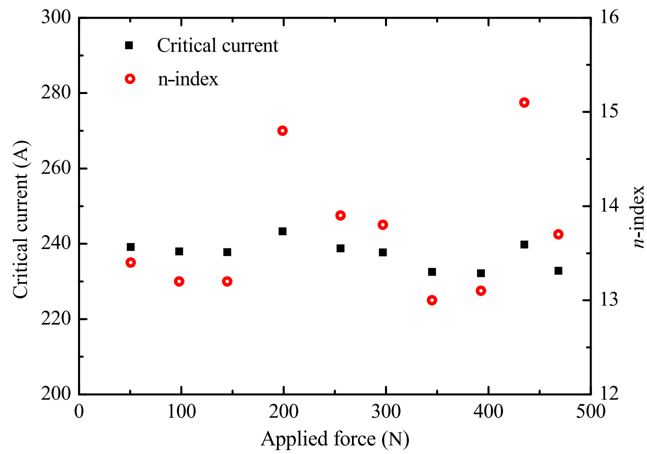


**Fig. 2** Critical current and $n$-index as a function of applied force for the SCS 12050 tape

The joints prepared with copper-stabilized tapes presented the lowest joint resistance with the largest $I_c$ and $n$-index reduction.

### 3.2 Mechanical Tests

The mechanical behavior of the joined samples was tested at 77 K by a single static tensile test under transport current measurements. The sample holder was designed for easy assembly and correct alignment to avoid the onset of joint bending to contribute to $I_c$ degradation and $n$-index reduction.

Figures 2, 3, and 4 show the electrical characteristics of the joints when tensile force is applied along the tape length.

The critical current as a function of applied load can be calculated for 95 % of the $I_c$ value corresponding to an applied force $F = 345$ N for the SCS 12050 tape, $F = 123$ N for the SCS 4050 tape, and $F = 237$ N for the 344C tape. The $n$-index reduction observed can be attributed to the pressure applied during the joint preparation in order to reduce the thickness of the soldering materials.

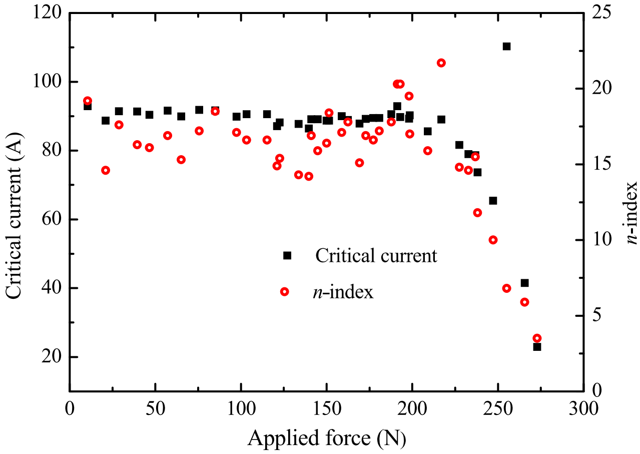


**Fig. 3** Critical current and $n$-index as a function of applied force for the SP SCS 4050 tape

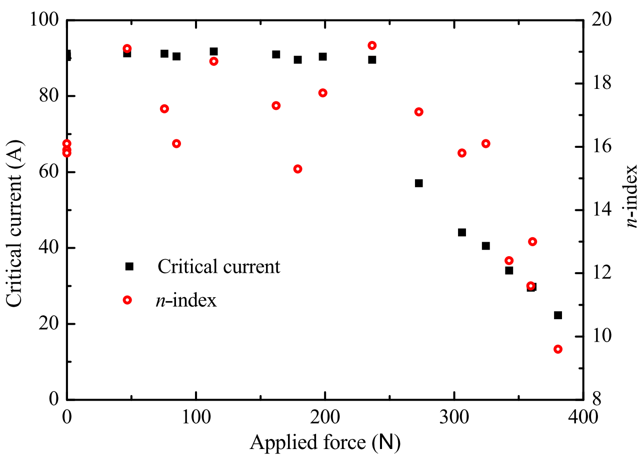


**Fig. 4** Critical current and $n$-index as a function of applied force for the AMSC 344C tape

## 4 Conclusions

Tape reinforced with stainless steel presented lower $I_c$ degradation as well as lower $n$-index reduction. However, the joint resistance is very sensitive to the joint length because of the reinforcement resistivity. The same behavior was observed in the stabilizer-free tape SF 12100, which also presented low $I_c$ degradation and $n$-index reduction.

The copper-stabilized tapes from both SP and AMSC presented the lowest joint resistivity and the largest $n$-index reduction (45 % for SCS tape, 64 % for 344C). The mechanical tests showed a 95 % $I_c$ reduction for the SCS 12050 tape withstanding a 345 N force, whereas the SCS 4050 showed the same $I_c$ reduction for a 123 N force, and the 344C tape supported a 237 N force.

In conclusion, the reinforced tape is the more robust tape for the joint-making process, whereas the copper-stabilized tape showed the lowest joint resistivity with a relatively smaller mechanical strength against tensile stress. Thus, in a joining tape procedure, if the mechanical strength is the main design parameter, it will require the use of reinforced tape to withstand the stresses during both the joining process and operation under a mechanical load.

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