Investigation of HTS CrossConductor Joints, Connectors and Terminations

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***Abstract*—The HTS CrossConductor (HTS CroCo) is a modified stacked-tape arrangement, aiming for high current density and easy long-length fabrication to be used as a strand for a high current cable aiming for industrial DC application or large high-field magnets. In order to allow for an economical operation, terminations, joints, and connector parts need to be sufficiently low-resistive to minimize the heat generation and thus the cooling cost. On the other hand, industrial applicability requires reliable and easy-to-use concepts.**

In this paper, three approaches to fabricate soldered joints and terminations for HTS CrossConductors are presented and assessed based on resistance measurements at *T* = 77 K, sf. Termination resistances of some tens of nano-Ohms were achieved for the best termination concepts. Additionally, four types of low-resistive HTS CroCo connectors with bending radii of less than 5 cm are introduced and assessed. For the best connector types, some tens of nano-Ohms were achieved giving rise to a heat generation of less than one Watt at operating conditions.

Index Terms—High Temperature Superconductivity, high current cable, HTS CroCo, HTS CrossConductor, REBCO, stacked conductor, joint, termination, connector, solder, soldering

I. Introduction and Previous Work

High temperature superconductors (HTS), in particular Rare Earth Barium Copper Oxides (*RE*BCO) are promising candidates for high-current DC applications, where currents of several tens of kilo-Amperes are requested. Applications include large high-field magnets, e.g. for fusion magnets, as well as high current cables for DC power transmission, e.g. for power transfer from wind parks, bus bars in big data centers, or for aluminum smelters [1]. In order to meet the demands of both fields of application, a modular cable solution is beneficial. Over the last years, several approaches to form high-current cables from individual *RE*BCO tapes were suggested [2], including conductor on round core (CORC) cable [3], [4] Roebel cable [5], and several versions of Twisted-stacked-tape conductor (TSTC) [6], [7], [8]. Due to the full transposition of the Roebel cable, terminations can easily be formed by soldering the Roebel cable over one transposition length to a terminal block [9], whereas for the other conductor concepts, terminations are more difficult to fabricate due to the cables' partial transposition. Recently, trimming of the individual layers of *RE*BCO tapes in a CORC to form low-resistive terminations was suggested and tested [10]. Staggering of the individual tapes of a TSTC cable was used in [11] to form the terminations of a 60 kA conductor comprising 320 *RE*BCO tapes in 20 strands. For the original, typically unsoldered, TSTC conductor, termination concepts based on the use of BSCCO tapes or a wrapping with REBCO tapes were shown in [12]. Recently, a soldered, compact so-called "folding-fan" termination was introduced and showed very low-resistive terminations [13]. Jointing of high-current, stacked-tape conductors based on a staggering of the tapes and the use of an additional, staggered bridge-type connector piece, was suggested [8], [14] for a modular assembly of heliotron coils.

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The HTS CrossConductor (HTS CroCo) is a modified TSTC arrangement with high current density and easy long-length fabrication [2], [15], [16] and consists of a cross-shaped HTS tape arrangement (HTS CroCo core) fabricated in a single step plus an outer seamless tube. HTS CroCo can be used as a strand for a high current cable for industrial DC applications or large high-field magnets. One important feature is the use of *RE*BCO tapes with thick electroplated copper of 50 - 55 µm thickness encapsulating the conductor completely in order to facilitate the current transfer into the stack.

One key aspect of this work is the investigation of termination concepts that are both, low-resistive and also easy and fast to fabricate.

HTS CroCos used in this study were fabricated from 10×4 mm and $20 - 22 \times 6$ mm wide *RE*BCO tapes and soldered with Sn63Pb37 solder in the fabrication setup described previously [15]. Some cross-shaped *RE*BCO stacks were encapsulated by a copper tube of 0.5 mm wall thickness. Critical currents of the HTS CroCos are around 3 kA at T = 77 K, sf.

II. HTS CroCo Terminations

Fig. 1 shows the three different types of terminations A-C that were investigated in this study. Sn63Pb37 solder is used for the soldering processes unless otherwise stated. All terminations are 120 mm long and made of copper, the cross-sections of A and B are $10\,\mathrm{mm} \times 30\,\mathrm{mm}$, and $20\,\mathrm{mm} \times 20\,\mathrm{mm}$, for C. Termination A is known as a "staggered" or "stair" termination, where the individual *RE*BCO tapes of the stack are cut shorter subsequently by a certain length, here by 4 mm, and then soldered to the inclined copper terminal part. In order to simplify the fabrication of the copper termination piece, it was decided not to mill a stair with 30 steps of 0.175 mm step height but an oblique groove of 7 mm width at an angle of ~3° into the copper terminal piece. Termination type B is formed by soldering the HTS CroCo to a 7 mm wide and 6.3 mm deep groove. Two orientations of the tapes with respect to the connector plane were tested, in configuration B1, the

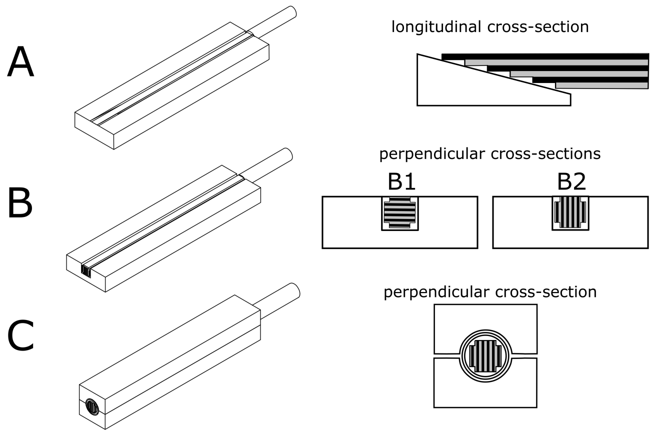

Fig. 1. Schematic overview and cross-sections of the investigated termination types

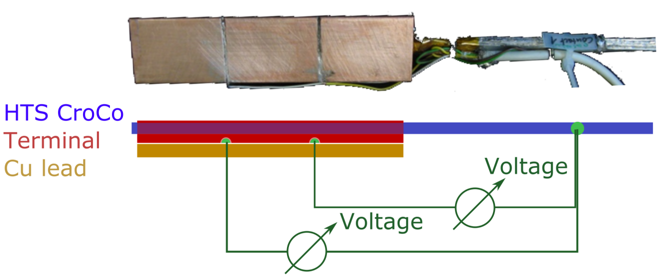

Fig. 2. Photograph and schematical representation of the measurement setup and positioning of voltage taps. (color version available online)

tapes are parallel oriented to the connecting plane, whereas in configuration B2, the tapes are oriented perpendicularly as it can be seen from the cross-sectional drawings of Fig. 1. Termination C is formed by soldering a HTS CroCo including the surrounding copper tube with low-melting In52Sn48 solder to the terminal. This type was already discussed in [15] at a slightly different geometry.

Voltage-Current-Characteristics were measured up to the expected critical current of the HTS CroCos at $T = 77\,\mathrm{K}$ and self-field conditions in an open liquid nitrogen bath. The samples' terminations were clamped to L-shaped copper current leads of the same length as the terminations to ensure a uniform current injection to the terminations. Two voltage taps were soldered to small grooves in the connector side at 4 cm from both ends of each terminal block as it is shown in Fig. 2. Voltages were measured towards a reference voltage tap on the superconductor several centimeters away from the termination. The termination resistance is determined by fitting the V(I) curves to a linear function for currents up to 1.5 kA where no contributions of the superconducting transitions of the HTS CroCo are visible. The displayed termination resistance is calculated as the mean value of both voltage measurements on the same termination, the uncertainty is indicated as well.

Fig. 3(a) shows the voltage-current-characteristics of the best sample of each investigated type of terminations, (b) displays the obtained termination resistances on a semi-

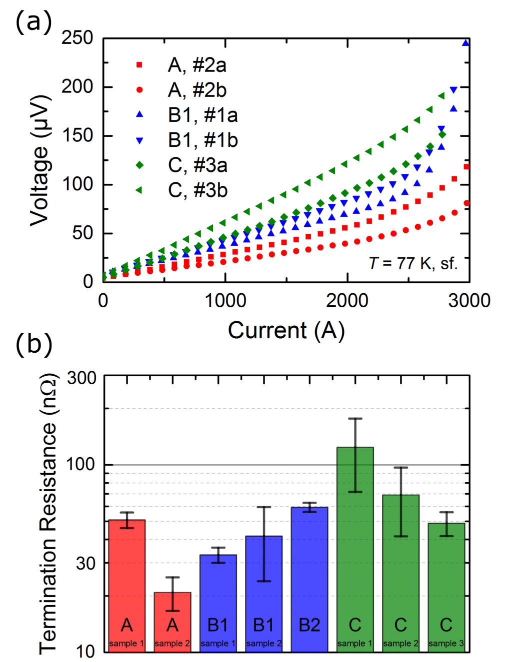

Fig. 3. (a) Voltage-Current-Characteristics of the best samples of the investigated three types of terminations, (b) termination resistances of all investigated samples. Different colors indicate the different termination concepts. (color version available online)

logarithmic scale for all investigated samples. One can conclude from these measurements that lowest resistance values are achievable with the staggered "stair" terminations (A) with $21 \pm 6\,\mathrm{n\Omega}$ for sample A#2. However, this comes at the cost of cutting each tape to individual lengths. In particular for the HTS CroCo, whose tapes are already soldered during the fabrication process, this is time-consuming, as the stack has to be desoldered first, then cut, and finally soldered to the termination. Termination type B results in second-best resistance values with $33 \pm 4\,\mathrm{n\Omega}$ for sample B1#1. Taking into account that the current can be injected into both sides of the *RE*BCO tapes for the parallel configuration B1, compared to only one edge for the perpendicular configuration B2, it is reasonable that the resistance value of sample B2 is higher than both samples B1. On the other hand, the difference in obtained termination resistance between termination type B and A is reasonably small such that the soldering of whole HTS CroCos can be considered as an option for terminations where not ultimately low termination resistances are required.

For termination type C, best resistance values of $49 \pm 10\,\mathrm{n\Omega}$ for sample C#3 are observed. Its resistance is slightly higher than for the other terminations, as expected due to the increased number of interfaces and solder layers.

The measured resistance values stem from two parts, solid-state resistances of the copper termination and solder layers, and interface resistances, basically to the *RE*BCO tape stack. Simulations of the actual terminal cross-section and of the solid-state resistivities of the materials at $T = 77\,\mathrm{K}$ resulted in a contribution of $13\,\mathrm{n\Omega}$ for termination types A and B and $22\,\mathrm{n\Omega}$ for termination type C. In order to allow for a better comparison to literature values, one can calculate specific

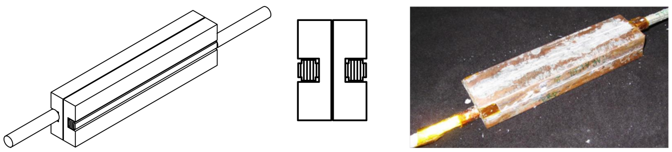

Fig. 4. Concept, cross-section and image of the Double-Termination-Joints (color version available online)

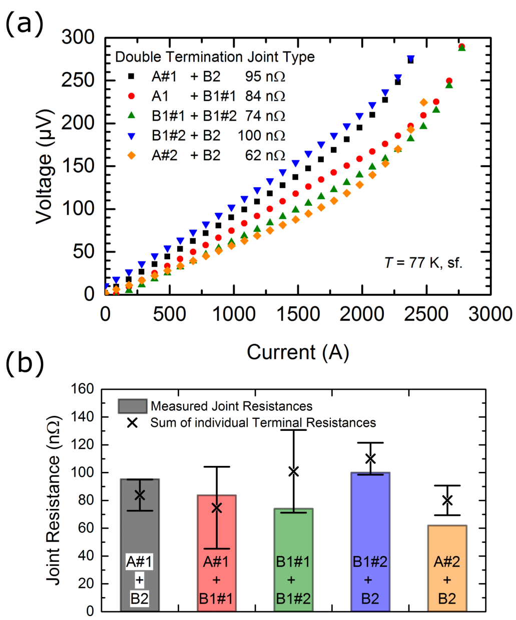

Fig. 5. (a) Voltage-Current-Characteristics and (b) joint resistances of the Double-Termination-Joints (color version available online)

termination resistance $R \cdot A$ using the contact area A. As most joint resistivity data stems from tape-to-tape lap joints, the calculated solid-state contributions are subtracted first. For sample A#2, one obtains $51 \pm 38\,\mathrm{n\Omega cm^2}$ for current injection into the tape planes of *RE*BCO tapes, in good agreement with a recent study on soldered *RE*BCO tape joints [17] and other staggered TSTC terminations [11], [18]. For sample B1#1 one calculates $288 \pm 58\,\mathrm{n\Omega cm^2}$. This value is more difficult to assess as tape data for side-injection into *RE*BCO tapes is not available.

III. Double-Termination-Joints

Fig. 4 shows schematics and an image of a Double-Termination-Joint, which is formed by soldering the base planes of two terminations A and B using low-melting ($T_M = 118\,°\mathrm{C}$) In52Sn48 solder. Soldering was performed on a temperature-controlled hot plate at temperatures below the melting temperature of Sn63Pb37 solder (T_M =183 °C) used for the terminations. Voltage taps were soldered to the HTS CroCos several centimeters away from the joint.

Five pairs of double-terminations were measured, the resulting V(I) characteristics are shown in Fig. 5(a). Panel (b) displays the measured joint resistivities and compares them with the sum of the individual terminal resistances. For four out of five measurements, the joint resistance agrees with the sum of the termination resistances within the uncertainty of the individual termination resistances. For the last measurement, the observed joint resistivity is by $\approx$ 10 nΩ smaller. These measurements confirm hitherto the positioning and analysis of the measurement concept used for the termination resistance measurements.

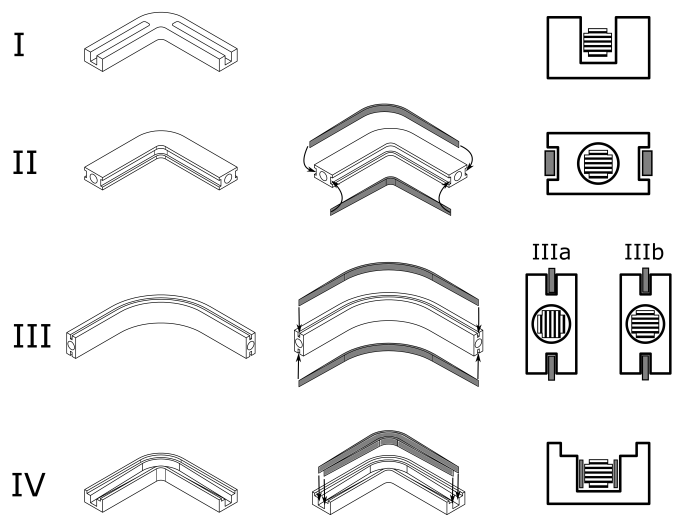

Fig. 6. Schematics of the investigated four types of 90° angular connectors

IV. Angular HTS CroCo connectors with small bending radius

Angular connectors are important for industrial application of soldered TSTC conductors. The rigidity due to the soldering of the tapes is useful for mechanical and electrical stability, but prevents the bending of these conductors at small bending radii. Therefore, a modular approach of a straight cable parts and angular connector sections is envisaged for applications in existing installations or narrow ducts. Without loss of generality, we will discuss connectors with an angle of 90° between the connecting HTS CroCos, only. With the results on terminations at hand, it was decided to use the termination concept B as basis for the design of angular HTS CroCo connectors, as it provides sufficiently low resistances at minimal efforts for the fabrication.

Fig. 6 shows four types of angular connector pieces for the connection of two HTS CroCo ends. The left column displays the copper connector pieces, the central one the position and way to install additional staggered *RE*BCO tapes and the right column shows a cross-section through the connectors with schematics of the HTS CroCo (including the orientation of the tapes) and the additional tape stacks (depicted in grey color). Apart from the cross-section, HTS CroCos are not shown for clarity.

Connector I is a copper angle of 15 mm bending radius at the mean plane and essentially serves as a reference. Its cross-sectional dimensions are $12\,\mathrm{mm} \times 20\,\mathrm{mm}$, the length of the channel for the connection of the CroCo ends is 60 mm.

Tpye II is of same outer dimensions but contains two notches on the inner and outer planes for the installation of two stacks of staggered, 6 mm wide *RE*BCO tapes. The *RE*BCO tapes were pre-tinned with Sn63Pb37 solder and cut into two

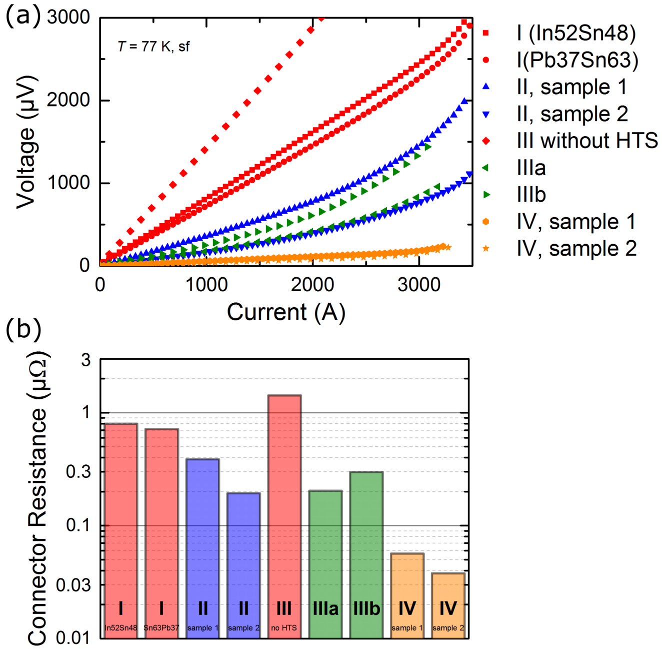

Fig. 7. (a) Voltage-Current-Characteristics and (b) connector resistances of the investigated angular (90°) connectors of small bending radii. Different colors indicate the different connector concepts. (color version available online)

sets of 15 pieces of individual length which were then soldered to the notches as it can be seen from Fig. 6. Thus the *RE*BCO tapes are bent in their easy bending direction.

Type III is a variation of II with slightly different outer dimensions: The bending radius is 50 mm, the copper piece is only 10 mm thick and the stacks of *RE*BCO tapes (here pre-tinned with In52Sn48) is assembled into 4 mm deep, 2 mm wide grooves. It turned out that the latter facilitates significantly the handling and installation of the staggered *RE*BCO tapes. For this connector, parallel (IIIa) and perpendicular (IIIb) orientations of the HTS CroCos with respect to the staggered stacks are investigated.

In Connector IV, two staggered HTS stacks (comprising each 15 tapes pre-tinned with Sn63Pb37) are installed on the inner sidewalls of the angular connector piece. Thus they are in direct contact with the HTS CroCo ends and current is not transferred through any copper piece but directly via the solder from one superconductor to another. The copper part essentially serves as a mold which is then filled with solder on a hot plate and covered with a lid (not shown in Fig. 6 for better visibility) to provide the electrical contact between the HTS CroCo ends and the staggered *RE*BCO tapes. One could even think of removing the outer part by making it of graphite instead of copper if the reduction of cross-sectional space is at a premium.

Fig. 7(a) shows the V(I) characteristics of the investigated connectors, (b) displays the obtained connector resistances on a semi-logarithmic scale. For connector type I, resistances of $800\,\mathrm{n\Omega}$ and $720\,\mathrm{n\Omega}$ were obtained for soldering with In52Sn48 and Sn63Pb37 solder, respectively. This value stems mostly from the resistance of the copper part: Considering the distance only from the inner tips one HTS CroCo to the other, one calculates a copper resistance at $T = 77\,\mathrm{K}$ of $390\,\mathrm{n\Omega}$ and from the one outer end of the connector to the other of $1200\ \mathrm{n\Omega}$ (assuming being made completely from copper).

The addition of the *RE*BCO stacks at the inner and outer sidewalls (connector II) resulted in a significantly reduced connector resistance, $190\ \mathrm{n\Omega}$ was found for sample 2. This already indicates that the concept of adding additional *RE*BCO tapes in order to lower the connector resistances is effective.

In order to prove this directly, connector III was measured first without *RE*BCO stacks installed. Here a resistance of $1420\ \mathrm{n\Omega}$ is found, which agrees well with the calculated copper resistance of the connector piece ($850\ \mathrm{n\Omega}$ tip-to-tip, $1940\ \mathrm{n\Omega}$ end-to-end). After installation of the two staggered *RE*BCO stacks, the connector resistance reduces to $200\,\mathrm{n\Omega}$ for configuration IIIa and to $300\,\mathrm{n\Omega}$ for IIIb, which is a reduction by $86\,\%$ and $79\,\%$, respectively.

Finally, two nominally identical samples of connector IV were tested and showed a resistance of $57\ \mathrm{n\Omega}$ and $38\ \mathrm{n\Omega}$. Assuming that half of the resistance value stems from each end of the connector, one calculates a specific contact resistance of $205\,\mathrm{n\Omega cm^2}$ and $137\,\mathrm{n\Omega cm^2}$, respectively. These values are in good agreement with reported literature values on soldered *RE*BCO tape joints [17], [19]. With a critical current of one HTS CroCo of $\approx 3\,\mathrm{kA}$, one calculates a maximum Joule heating power of $0.5\,\mathrm{W}$ and $0.34\,\mathrm{W}$, respectively. In a real cable installation with LN_2 cooling, this value is significantly lower than other sources of losses, e.g. cryostat losses, [20] and in the range of other HTS cable joints [21].

V. Conclusions

We introduced and assessed three types of terminations for the HTS CroCo. Staggering of the tapes in the stack proved useful in minimizing the contact resistance, in fact, the lowest resistance value ($21\,\mathrm{n\Omega}$) was observed for this technique. However, the fabrication of this type of termination is time-consuming and not feasible for an in-field application. Soldering the HTS stack as a whole to a channel in the termination piece (terminal B) has proven to provide also low-resistive terminations of $33 - 59\,\mathrm{n\Omega}$ which are a lot easier to fabricate. These values are confirmed by measurements of double-termination joints, where the aforementioned terminations are soldered back-to-back. Considering these results, low-resistive angular connector pieces with bending radius below 5 cm were designed. It was shown that the addition of *RE*BCO tape stacks to copper connector blocks reduced the resistance by $\approx 80\,\%$ if the stacks are assembled in channels on the outer sides of the connecting copper pieces (connector type III) and by $\approx 95\,\%$, if the stacks are assembled to the inner sides of the connector blocks (connector type IV).

The heat generation of the best connector at the critical current of the HTS CroCo is $\approx 0.34\,\mathrm{W}$, making the application of a modular system with angular connector pieces and straight HTS CroCo cable sections feasible.

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