Study on Novel Jointing Technique of Soldered-stacked HTS Wires

Gang Qian¹, Meiying Yin², Mingyang Wang¹, Zhuyong Li¹, Shufeng Guan¹ and Zhijian Jin¹

¹ Department of Electrical Engineering, Shanghai Jiao Tong University, No.800 Dongchuan Road, Minhang District, Shanghai, 200240, China
² Sino-Korean School of Multimedia Design, Shanghai University of Engineering Science, Shanghai, China

E-mail: zjjin@sjtu.edu.cn

Abstract. In high temperature superconducting (HTS) applications, joining two HTS wires is considered as an essential process for extending the available length. Many soldering and diffusion joints have been designed in recent years, but these joints mainly focused on joining two HTS virgin tapes with 4mm width and 0.15mm thickness. As for the recently developed soldered-stacked (SS) HTS wire, it does not have applicable methods of joining. In this paper, we proposed a novel technique to join two SS wires by soldering and stacking, and measured the joint resistance to demonstrate its feasibility of engineering. First, we join separate layers in SS wires using spot-welding machine. Second, we coat these layers in the solder bath. This method allows making joints and manufacturing SS wires simultaneously. This work will introduce the specification of this jointing method for SS wire, and the related experimental results will provide a reference for the SS wire joint fabrication in the future.

1. Introduction

With the rapid development of 2G HTS tapes, different jointing techniques to extend tape lengths have been proposed, such as, directly soldered joints[1], soldered joints using customized mold[2], soldered bridge joints[3], soldered joints with Ag layers face-to-face with each other[4]. And there are also diffusion joints using In as filling medium[5], diffusion joints using Ag as filling medium[6]-[8].

Different from cases mentioned above, in this paper, a novel jointing technique is proposed. Such a jointing technique is designed to joining two soldered-stacked (SS) HTS wires which are a stacked structure of HTS tapes. It is a key step to slice virgin tapes into customized width (often 1 mm or 2 mm) in the fabrication of SS wires[9]. And since all the previous joints cannot provide good mechanical and electrical performances after slicing, we do not use HTS tapes which already have joints to make SS wires. The entire design and fabrication process are introduced and three types of joint structures were tested to prove the feasibility of engineering applications.

2. Design and fabrication

All HTS tapes used in this study to fabricate the soldered-stacked (SS) HTS wire is produced by Superconductor, Nano & Advanced Materials Co., Ltd. (SuNAM) in Korea. Main parameters of three
different types of SS wire joints (wire A, wire B and wire C) we fabricated in this study are listed in table 1.

| Table 1. Main parameters of soldered-stacked (SS) HTS wire |
|-----------------------------------------------------------|
| Width and thickness of wire A and B                       | 2.0 mm × 0.6 mm |
| Width and thickness of wire C                            | 2.0 mm × 0.8 mm |
| Width and thickness of HTS tape                           | 2.0 mm × 0.15 mm |
| Critical current of HTS tape, self-field                   | 104 A at 77 K   |
| Thickness of superconducting layer in HTS tape            | ~1 µm           |
| Thickness of copper layer in HTS tape, each side          | ~20 µm          |
| Width and thickness of copper tape                         | 2.0 mm × 0.15 mm |

Figure 1(a) shows the diagrammatic sketch of the design and fabrication of the joint for SS wires. The entire process contains mainly two steps: welding process and stacking process. A sample of SS wire fabricated using this method is shown in Figure 1(b), and the red part is where the joint is.

In the welding process, we use the spot-welding technique to join two face-to-face HTS tapes by manually trigging the discharge of the power source. The Joule heat produced by the spot-welding electrode will melt the corresponding spots on the surface of the HTS tapes, and will then join the sperate tapes together. In this process, three factors need to be considered.

2.1. Number of the welding spots
The maximum axial tension that the joint can bear has a positive correlation with the number of the welding spots. Therefore, it is ideal to have more welding spots so that the joint can bear larger axial tension.
force. However, areas that go through the welding process are harder, crisper and thus more vulnerable to the bending force and the torque force. As a result, increasing the number of welding spots will increase the bending diameter and the twist pitch of the joint. Moreover, because high temperature produced by the electrode will degrade the electrical performance of the superconducting layer in HTS tapes, the welding process will increase the local resistance in the welding area. With such considerations, we find that choosing four welding spots is a good balance among the factors that mentioned before.

2.2. Joint length
The law of resistance in equation (1) describes the relationship between joint resistance and joint length when the current flowing through the joint is uniformly distributed. $R \cdot l \cdot \varphi \cdot t \cdot w \cdot S$ is the resistance, length, resistivity, thickness, width and the plane area of the joint, respectively.

$$R = \frac{\varphi \cdot t}{S} = \frac{t}{w \cdot l}$$

(1)

Equation (2) is the logarithmic form of equation (1). And as is shown in this equation, in the case where the current distribution is uniform in the joint, the relationship between $\log R$ and $\log l$ would be linear.

$$\log R = -\log l + \log \frac{\varphi t}{w}$$

(2)

However, due to the inadequate contact between two tapes in the micro level[5] and more importantly, the non-uniform current distribution in the joint, the joint resistance tends to approach a lower limit as the joint length increases[6]. This means the relationship between $\log R$ and $\log l$ in equation (2) would not be linear.

Based on this idea, we fabricate joints of different lengths without both copper tapes from the process of figure 1(a), and plot the relationship between the resistance and the length of these joints in figure 2.

![Figure 2. Joint length dependence of joint resistance without both copper tapes fabricated from the process of figure 1(a).](image)

As is shown in figure 2, the resistance of joints with lengths of 2 cm, 4 cm, 6 cm, 8 cm and 10 cm are 0.89 μΩ, 0.39 μΩ, 0.24 μΩ, 0.22 μΩ and 0.20 μΩ respectively. When joint length is smaller than 6 cm, $\log R$ and $\log l$ manifest a generally linear relationship so the resistance of joints manifest good formality. However, when joint length exceeds 6 cm, the relationship between $\log R$ and $\log l$ is no longer linear, which can be considered that joint resistance has reached the lower limit.
Therefore, a balance needs to be achieved between the resistance and the length of the joint, and we regard 4 cm a suitable length.

2.3. Position of the welding spots
J Sheng et al.[7] found that due to the nonlinear E-J characteristic of the YBCO layer in the HTS tape, the current density at both ends of the joint is greater than that in the middle. Therefore, the welding spots should stay in the middle of the joint in the ideal case so that less current will flow through the areas that are damaged by the welding process. And as a result, the joint will manifest lower resistance compared with the case where welding spots are at both ends. However, in the stacking process, liquid solder has no constraint force against the intrinsic tension in different parts of the tape, so that spots in the middle cannot guarantee good contact of two tapes, especially at both ends of the tapes. And this can increase joint resistance[6]. Consequently, we find that for a 4 cm joint, the first pair of spots should be 0.5 mm from the edge of joint and the second pair 1mm from the edge, as is shown in figure 3.

![Figure 3. The position of the welding spots](image)

In the stacking process, HTS tapes with joints along with other intact HTS tapes or copper tapes undergo stacking and soldering process in the solder bath simultaneously. In order to achieve lower resistance, the solder chosen to fill the gaps between adjacent tapes is Sn63Pb[2]. Its melting point is 183 degrees Celsius. Since the working environment for YBCO tapes has an upper temperature limit, the temperature in the solder bath is set at 200 degrees Celsius[2]. The stacking process is completed in a reel-to-reel machine, a solder bath and some reels to mount the tapes.

3. Results
In order to verify the performance of joints, we evaluate the resistance of three joint types that are often encountered in practical applications. Their schematic drawings are shown in figure 4.

Figure 4(a) shows the diagrammatic sketch of an HTS tape insert with one joint and copper tapes on both sides. In engineering applications, HTS tapes with joints close to each other are likely to appear, and its entire resistance should also be evaluated. Such a structure is shown in Figure 4(b). Moreover, if two adjacent HTS tapes have similar length and thus have joints close to each other, the position of the joints should be adjusted to a ladder-like structure shown in Figure 4(c). Such a ladder-like structure has many advantages; compared with joints that are lapped over each other, a ladder-like structure has relatively even thickness, larger contact areas with the working environment (liquid nitrogen, 77 K) and thus has better heat dissipation performance and higher quenching threshold.

![Figure 4. Lateral view of Soldered-stacked (SS) wires with three types of joint structures.](image)
We use the four-probe method for data sampling and resistances are obtained by linear fitting. And the experimental results of joint resistances mentioned above are shown in figure 5.

For wire A, figure 5(a) shows that the resistance is similar to what is shown in figure 2. This is reasonable because the resistance of copper layers is much bigger than that of the joint composed of HTS tapes. The resistance of a single 4 cm long copper tape we used in this study is 1.18 mΩ at 77 K, which is at least three orders of magnitude higher than that of the HTS joint shown in figure 2. This means the entire resistance is mainly composed of the joint resistance.

For wire B, figure 5(b) shows that the entire resistance equals to the sum of the respective joint resistances. This conclusion seems obvious but it verifies the fact that non-uniformly distributed current that flows through joints in series will not affect the entire resistance, so the entire resistance can be easily estimated for an HTS tape with multiple joints.

For wire C, figure 5(c) shows that the resistance is also suitable enough for engineering purposes. Theoretically, the joint resistance for wire C should equal to the parallel resistance of wire A. However, as is shown above, there are some discrepancies between the data shown in figure 5(c) and the parallel resistance of wire A.

Figure 5. Experimental results of the joint resistances in three types of SS wires described in figure 4.
In order to verify the joint resistances, schematic drawings of the equivalent models for three types of SS wires are shown in figure 6. The part circled by the red dotted line is the resistance to be measured.

To make models more reliable, the resistivities of the copper tape and solder used in this study have been measured in our lab. And the values of the resistors are shown in table 2. In figure 6, \( R_{c} \) is the resistance of the copper tape and its value is determined by the length of the copper tape in each segment. \( R_{s} \) is the resistance of solder between different layers and its value is determined by its thickness and cross-sectional area. \( R_{j} \) is joint resistance which is shown in figure 2. \( R_{HTS} \) is the resistance of the HTS tape, which is set to be 0 \( \mu \Omega \). We use software Multisim 12.0 to run the simulation.
The simulation results show good consistence with the experimental results for wire A and wire B, but also discrepancies with the experimental results for wire C. Simulation results for wire C is around 0.2 \( \mu \Omega \), which is the parallel resistance of two SS wires of wire A.

However, when taking contact resistances between current leads and the SS wire into consideration, the simulation results tend to be consistent with the experimental results for all three types of wires. All the samples are soldered to current leads during the experiment, and since the SS wire is surrounded with solder, the upper and bottom layer (copper tapes on both sides) have small contact resistances while HTS tapes in the middle only have their sides in contact with solder, so the contact resistances for HTS tapes are much larger. As a result, in order to reflect the influence of the contact resistance, increase the value of \( R_{HTS} \) to 1 m\( \Omega \) considering the thickness of the tape from table 1, now the simulation results are in good agreement with the experimental results.

This means that the actual resistance for wire C is 0.2 \( \mu \Omega \) instead of 0.55 \( \mu \Omega \), which is in good agreement with the theoretical analysis.

**Figure 6.** Schematic drawings of the equivalent models for three joint structures shown in figure 4, which is applied to calculate the joint resistances.

**Table 2.** Main parameters of soldered-stacked HTS wire

|                | \( R_{c1-1} \) | \( R_{c2-1} \) | \( R_{c1-3} \) | \( R_{c2-2} \) | \( R_{c1-4} \) | \( R_{c2-3} \) | \( R_{c1-5} \) | \( R_{c2-4} \) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Wire A         | 1770           | 1180           | 1770           | -              | 1770           | 1180           | 1770           | -              |
| Wire B         | 1770           | 1180           | 1180           | 1180           | 1770           | 1180           | 1180           | 1180           |
| Wire C         | 1770           | 1180           | 1770           | -              | 1770           | 1180           | 1770           | -              |
| Wire A         | -              | 0.11           | 1.1            | -              | 1.1            | 0.11           | -              | -              |
| Wire B         | 1770           | 0.11           | 0.55           | 0.55           | 1.1            | 0.11           | 1.1            | 0.11           |
| Wire C         | -              | 0.11           | 0.66           | -              | 0.066          | 1.1            | -              | -              |
| Wire A         | -              | -              | 0              | 0              | -              | -              | -              | 0.39           |
| Wire B         | -              | -              | 0              | 0              | -              | -              | -              | 0.39           |
| Wire C         | 0.66           | 0.11           | 0              | 0              | 0              | 0              | 0.39           | -              |

The unit is \( \mu \Omega \).
4. Conclusion
In this study, a novel jointing technique using spot-welding and stacking method is proposed and three type of joints that are often encountered are tested and simulated, and proved feasible for engineering applications. The lowest resistance of the three structures is around 0.2 μΩ, which is achieved by the structure where two joints are arranged in a ladder-like arrangement. The highest resistance is around 0.8 μΩ, which is achieved by the structure where two joints are in series with each other and each single joint has the resistance around 0.4 μΩ. The second result shows that non-uniformly distributed current in the joint will not affect the applicability of series resistance law in engineering applications. Therefore, in the case where an HTS tape has multiple joints, its entire resistance can be estimated reasonably.

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