Investigation of trade-off solution in mechanical edge joint of STARS conductors

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Abstract. Mechanical edge joints of stacked tapes assembled in rigid structure (STARS) conductors have been proposed to be applied to remountable high-temperature superconducting fusion magnets. Our previous study showed the joint resistance decreases with an increase in stabilizer thickness and joint pressure. However, this induces a trade-off between joint resistance and critical current due to increasing strain in the REBCO tape during bending (winding) for the conductors. Furthermore, an appropriate joint surface structure has not been discussed about taking into account a remountable joint. Based on the above background, this study first numerically evaluated the joint resistance depending on the structure of REBCO conductors with copper jackets. The results showed the copper jacket does not efficiently decrease the joint resistance compared to a copper stabilizer. Furthermore, to make strains lower than irreversible strain limit, the joint length should be longer than 500 mm. In addition, the joint surface structure was investigated based on joint testing and observing the surface, from which it was proposed that protective layer on the joint surface is needed to remove the remaining indium and keep the flatness of the joint surface. Therefore, a new structure for the issue was proposed for a remountable joint and the reattaching performance was evaluated experimentally.

1. Introduction

The “remountable” (demountable, reattachable) high-temperature superconducting (HTS) magnet (here “remountable” means being able to mount and demount, or attach and detach repeatedly) has been proposed to enable segmented assembling of superconducting magnets for a fusion reactor having large and complex magnets and to allow easy access to inner reactor components such as the blanket and divertor [1, 2]. These magnets consist of some HTS coil or conductor segments with mechanical joints (demountable joints). There are some examples of reactor designs with this concept, for example small tokamak such as Vulcan [3] and ARC [4] designed by the Massachusetts Institute of Technology (MIT), and the FFHR-d1 heliotron-type fusion reactor [5] with large twin helical coils designed by the National Institute for Fusion Science (NIFS). NIFS has designed the HTS conductors consisting of simply-stacked Rare-Earth Barium Copper Oxide (REBCO) tapes within a metal jacket called a stacked tapes assembled in rigid structure (STARS) conductor [6, 7]. Some mechanical joints of STARS conductors have been investigated in previous studies from which bridge-type mechanical lap joints [6–9] and mechanical edge joints [10, 11] have achieved low joint resistance with indium foil inserted between the joint surfaces. Figure 1 shows a schematic of the bridge-type mechanical lap and mechanical edge joints. For example, the bridge-type mechanical lap joint achieved 1.8 nΩ joint resistance at 100 kA,
4.2 K and 0.45 T using a 100-kA-class prototype STARS conductor with 860 mm joint length [8]. However, REBCO tapes are easily detached by peeling them in the direction perpendicular to the tape’s surface, which is induced when the joints are detached due to bonding with the indium-insertion. Therefore, the bridge-type mechanical lap joint is useful only for assembling magnets with the joint-winding concept [5–9], but not preferable for reattaching the coil or conductor segments. On the other hand, the edge joint does not suffer from the same peeling issue, and the joint part is easily detached, which is appropriate for remountable HTS magnet design.

In the previous study [11] of the edge joint, the effect of the stabilizer thickness of a REBCO tape on the joint resistance was evaluated numerically and experimentally. The result showed that the joint resistance decreased with an increase in the stabilizer thickness. Furthermore, a joint resistance of 80 nΩ was achieved at 77 K, self-field with a 50-mm-long joint by attaching 100-μm-thick copper tape on the stabilizer. However, increasing stabilizer thickness can influence the critical current of the REBCO tapes when the STARS conductor is wound in a coil shape. The easiest procedure to fabricate the coil is first stacking REBCO tapes in a straight metal jacket with solder to be STARS conductors and then winding the STARS conductors. In the procedure, the bending and twisting process induces strain on the REBCO tape. For example, bending strain increases with an increase in the stabilizer thickness and it causes critical current degradation. Therefore, increasing stabilizer thickness induces a trade-off between the joint resistance reduction and the critical current degradation. Another issue is treating the joint surface during the reattaching process, indium remains on the joint surface after detaching the conductors, therefore flatness of the joint surface changes, which requires re-polishing the joint surface.

Based on the above background information, in this study, first we numerically evaluated both the joint resistance and conductor resistance depending on the structure of REBCO conductors with copper jackets, which is summarized in Section 2. For that purpose, a STARS conductor design for the edge joint is introduced taking into account the FFHR-d1 design. Then we examined the effect of the copper-jacket thickness on the resistance reduction considering current sharing to the respective REBCO tape layers. After that, we discussed the relation between the resistance and the bending strain depending on the joint and conductor structures. We also investigated the joint surface structure suitable to detach the joint, which is shown in Section 3. In this section, we first conducted joint testing using previously fabricated STARS conductor samples [11] to clarify the issue for the reattaching process. Then we proposed two joint structures and evaluated the joint resistance depending on resistance factors. Three conductor samples including the proposed joint structures were fabricated to evaluate the joint resistance depending on the remounting process. The conclusion appears in Section 4.

![Figure 1. Schematic of bridge-type mechanical lap and mechanical edge joints of STARS conductors.](image)

### 2. Structure dependence of resistance and bending strain for STARS conductor with mechanical edge joint

#### 2.1. Evaluation method of resistance and bending strain depending on structure of STARS conductor
2.1.1. Design of 100-kA-class STARS conductors with mechanical edge joints. The helical coil for the FFHR-d1 has 390 turns of STARS conductors with an operating current of 94 kA at 20 K, 11.8 T [12]. The basic design of the STARS conductor has been proposed under the assumption of using a bridge-type mechanical lap joint with the joint-winding concept [6, 7]. The STARS conductor consists of simply-stacked REBCO tapes embedded in copper and stainless-steel jackets. Forty 15-mm-wide REBCO tapes are arranged twenty layers and two rows. For the edge joint, the REBCO tapes need to be arranged in one row because the side-edge surface of stacked REBCO tapes are joined. In addition, typical REBCO tape provided by manufacturers is 12 mm in width. When considering using 12-mm-wide REBCO tapes, STARS conductors for the edge joint need at least fifty REBCO tapes arranged in one row if the critical current density of a 12-mm-wide REBCO tape is the same as that of a 15-mm-wide one. Figure 2 shows the schematic of a mechanical edge joint for 100 kA-class STARS conductors based on the aforementioned discussion. Structure dependence of resistance and bending strain for STARS conductor with mechanical edge joint was investigated based on the proposed design.

![Mechanical edge joint](image)

**Figure 2.** Schematic of a mechanical edge joint of 100 kA-class STARS conductors.

2.1.2. Resistance evaluation. We evaluated the resistance including both in one joint and one conductor segment as a function of applied current considering current sharing between REBCO tapes in the STARS conductor. Figure 3 shows the circuit model of the 50-layer STARS conductor with the edge joint. The joint resistance \( R_ji \) (\( i = 1–50 \)) and conductor resistance \( R_Ci \) of respective layers constitute the circuit model in parallel. The joint resistance of \( R_ji \) was calculated by numerical analysis of the joint part shown in the next paragraph. First \( R_Ci \) was set to zero and current distribution \( I_{Si} \) for the respective REBCO tapes was decided by \( R_ji \). When \( I_{SN} (N=1–50) \) became higher than critical current \( I_c (2400 \text{ A}) \), \( I_{SN} - I_c \) was shared to other layers where the current did not exceed \( I_c \) based on those \( R_ji \) distribution. Because the voltage in the circuit \( V \) changed due to this procedure, the sum of the conductor resistance \( R_{CN} \) and joint resistance \( R_{JN} \) was determined by the following equation (1) to make voltage to be the same as the other layers’,

\[
R_{JN}+R_{CN} = \frac{R_ji\left[I_{Si}+(I_{SN}-I_c)\left(R_ji/R_{JN,\text{total-N}}\right)\right]}{I_c}
\]  

(1)

where \( R_{JN,\text{total-N}} \) indicates combined joint resistance except for layer \( N \). The numerator of the right side of the equation (1) indicates the voltage of layer \( i \). This value equals the sum of the resistance of layer \( N \)
multiplied by $I_c$. With this procedure, we obtained total resistance $R_{\text{total}}$ (combined resistance in the circuit shown in Figure 3) depending on the applied total current.

![Figure 3. The circuit model of a 50-layer STARS conductor with mechanical edge joints.](image)

Figure 4 shows two-dimensional (2D) analytical models of the edge joint for REBCO tapes embedded in the copper jacket and simple model of 50-layer STARS conductor. We prepared two types of REBCO tape models. The Type 1 REBCO tape consists of Hastelloy substrate (50 μm)/buffer layers (1.0 μm)/REBCO (2.0 μm)/silver (2.0 μm)/copper (20 μm), which is joined via 100 μm-thick indium foil. The Type 2 REBCO tape consists of a copper tape of 100 μm thickness soldered on the copper stabilizer. The joint length was assumed to be 500 mm. Additionally, a model of the REBCO tape stack without the copper jacket (not shown in Figure 4).

The numerical analysis was conducted with a commercial finite element method code, COMSOL Multiphysics® 5.4 AC/DC module to evaluate electric potential distribution and current of each layer. The governing equation was Poisson's equation for electric potential. Electric potential $V = V_0$ was applied on one outer side of the REBCO layer, and electric potential $V = 0$ (ground) was applied on the other outer side as boundary conditions. The joint resistance of each layer $R_{\text{Ji}}$ was estimated from the current of each layer $I_{S_i}$ and $V_0$ using the ohm’s law. Table 1 shows the electrical resistivity of the constituted materials at 20 K. The resistivity of the REBCO layer was assumed to be $1.0 \times 10^{-16} \ \Omega$m. Contact resistance between the joint surface and the indium foil was modeled by using a virtual conductor placed beside the conductive metal (copper, silver, Hastelloy and solder) layers and the copper jacket. The contact resistivity was set to $3.0 \times 10^{-12} \ \Omega \text{m}^2$ based on the joint testing of the mechanical edge joints [11]. Relatively high resistivity was set between the Hastelloy and REBCO layers to simulate the insulating buffer layer. Because the joint resistivity obtained in a Sn$_{62}$Pb$_{38}$ solder lap joint was $2.5$–$4.0 \times 10^{-12} \ \Omega \text{m}^2$ [13], solder layers between REBCO tapes and the impregnated solder region placed between stacked REBCO tapes and the copper jacket were assumed to be $2.5 \times 10^{-12}$ and $4.0 \times 10^{-12} \ \Omega \text{m}^2$, respectively. The analytical model of the mechanical edge joint in Model A is the 50-layer STARS conductor proposed in this study. In Model B insulator is inserted between the S50 REBCO tape (top REBCO tape layer) and the copper jacket to prevent the current from flowing from the S50 REBCO tape to the copper jacket.
Figure 4. 2D analytical model of the mechanical edge joint for the 100-kA-class STARS conductors: (a) Type 1 REBCO tapes, (b) Type 2 REBCO tapes, (c) Model A STARS conductors, and (d) Model B STARS conductors. $t_{\text{jacket}}$ is the thickness of the copper jacket, $t_{\text{stack}}$ is the total thickness of the stacked REBCO tapes.

**Table 1.** Electrical resistivity of the constituted materials at 20 K.

| Material          | Electrical resistivity ($\Omega m$) | Material          | Electrical resistivity ($\Omega m^2$) |
|-------------------|------------------------------------|-------------------|---------------------------------------|
| Copper (RRR $\approx 100$) | $1.7\times10^{-10}$ | Solder layer between REBCO tapes | $2.5\times10^{-12}$ |
| Silver (RRR $= 100$)    | $1.8\times10^{-10}$ | Impregnated solder region | $4.0\times10^{-12}$ |
| Hastelloy          | $1.23\times10^{-6}$ | Contact resistivity       | $3.0\times10^{-12}$ |
| Indium             | $1.6\times10^{-9}$  |                    |                                      |
| REBCO              | $1.0\times10^{-16}$  |                    |                                      |

2.1.3. *Evaluation of bending strain.* Strain applied to the conductors during operation and fabrication of the helical coil can be attributed to several factors. First, tensile strain is induced by electromagnetic forces. Structural analysis of the helical coil for FFHR-d1A showed electromagnetic forces induced tensile strain along the direction of the coils winding of $\varepsilon_{\text{hoop}} = 0.145\%$ [14]. The bending and twisting process to fabricate the helical coil induces strain by flatwise bending and edgewise bending. The
maximum edgewise bending strain was estimated to be $\varepsilon_{\text{edge}} = 0.1\%$ in the FFHR-d1A [15]. The flatwise bending strain $\varepsilon_{\text{flat}}$ is defined as

$$\varepsilon_{\text{flat}} = \frac{t_{\text{stack}}}{2r}$$

where $t_{\text{stack}}$ and $r$ are the total thickness of the stacked REBCO tapes in the STARS conductor and the radius of the neutral axis, respectively. According to [12], the minimum radius of the inner-most conductors is about 5.45 m. The thickness of each REBCO tape strongly affects the flatwise bending.

The upper limit of the acceptable tensile strain along the winding direction is decided by the irreversible tensile strain $\varepsilon_{\text{irr}} = 0.4–0.6\%$ of the REBCO tapes [16,17]. Therefore, the flatwise bending needs to be roughly less than 0.1% from equation (3).

$$\varepsilon_{\text{flat}} < \varepsilon_{\text{irr}} - (\varepsilon_{\text{hoop}} + \varepsilon_{\text{edge}})$$

2.2. Results and discussion

Figure 5 shows the total resistance $R_{\text{total}}$ in the Type 1 mechanical edge joint for the 100-kA class STARS conductors depending on the total current of different copper jacket thickness $t_{\text{jacket}}$. The total resistance increased with an increase in applied total current for Model A. Figure 6 shows initial current distribution decided by $R_{\text{Ji}}$. Current flow concentrates at S50 and $I_{S50}$ firstly reaches $I_c$. This is the reason for the result shown in Figure 5 for Model A. On the other hand, current flow to all the layers was almost homogeneous and the joint resistance was constant independent from applied total current for the case of Model B and also for the model without the copper jacket ($t_{\text{jacket}}$ equal to 0). Figure 5 also indicates that the thickness of copper jacket influences on the joint resistance less compared to the stabilizer thickness as discussed in [11].

**Figure 5.** Joint resistance in the Type 1 mechanical edge joint for the 100-kA class STARS conductors depending on the total current of different copper jacket thickness $t_{\text{jacket}}$.

**Figure 6.** Current distribution of REBCO tapes embedded in copper jacket in the STARS conductor.
Figure 7 shows the joint resistance and flatwise bending strain $\varepsilon_{\text{flat}}$ calculated by equation (2) in the mechanical edge joint with Type 2 REBCO tapes for the 100-kA class STARS conductors depending on the thickness of the copper tape $t_{\text{tape}}$. The upper limit of copper tape thickness was decided to be 70 $\mu$m by the upper limit of the flatwise bending strain of 0.1%. The yellow-marked region shown in Figure 7 indicates the acceptable region from the viewpoints of both the total resistance and the flatwise bending strain. For the remountable magnet, the half-pitch segment is suitable. Therefore, either a joint longer than 500 mm or further reducing the contact resistance is needed in order for $R_{\text{total}}$ to be acceptable. Furthermore, we can decrease flatwise bending strain if we can develop a fabrication procedure consisting in preparing bent and twisted copper and stainless-steel jackets and then stacking REBCO tapes inside the copper jacket. In such a situation, thicker copper tapes can be used to decrease the total resistance while keeping a short joint length.

3. Structure improvement for remountable joint

3.1. Technical issue clarified by joint testing

We performed joint tests using 10-layer STARS conductors fabricated in our previous study [11]. First the edge joint fabricated in the previous study was detached. Then, indium remaining on the joint surface was removed. After that the joint surface was polished with alumina particles with a diameter of 3 $\mu$m and then cleaned with ethanol. Furthermore, the joint surface was pressed together with 100-µm-thick indium foil at 100 MPa joint pressure and joint resistance was evaluated at 77 K, self-field. The aforementioned procedure was repeated several times. Figure 8 shows joint resistance as a function of the number of reattachment. The joint resistance increased with an increase in the number of reattachment. To clarify why these results were obtained, we observed the joint surface geometry with a laser-scanning microscope, which is shown in Figure 9. The joint surface was relatively flat before the conductor was used for the joint. On the other hand, the indium could not be removed perfectly, and the shape of the surface was not flat anymore. This is due to a difference in hardness between the constituting materials of the conductor. The polishing process grinds the softer copper much more than the harder Hastelloy. This possibly caused joint resistance degradation, and therefore, improved joint surface structure is necessary to be able to reattach the joint.
3.2. Numerical evaluation of joint resistance for new joint surface structure

Based on the discussion in 3.1, we proposed two joint structures shown in Figure 10. Model C shown in Figure 10 (a) has a thin copper jacket residing on the joint surface side. In this structure, the thin copper jackets are joined with indium. Model D shown in Figure 10 (b) has a copper plate attached to the original joint surface with a tin foil. The surfaces of the copper plates are joined with indium. When detaching the joint, we can heat up the joint and detach only the region joined with indium thanks to the difference in melting points. In a previous remountable joint study [18], the HTS conductor fully encased in copper terminals can be attached and detached without change of the joint resistance. According to this result, Model C and D are expected to allow remountability.

For the two models, we evaluated the total resistance using the same 2D numerical analysis shown in Section 2. This time, the analytical model consisted in type 1 REBCO tapes stacked in the copper jacket ($t_{jacket} = 16$ mm). The electrical resistivity of constituted materials is set to the value of Table 1. In the Model D, the contact resistivity of indium and tin foils of all interfaces were set to the same value. Figure 11 (a) and (b) show the total resistance as a function of resistivity of the impregnated solder region and contact resistivity, respectively. In the case of Figure 11 (a), the contact resistivity is set to $3.0 \times 10^{-12} \ \Omega m^2$, and the resistivity of the impregnated solder region is changed $2.0 \times 10^{-12} - 20 \times 10^{-12} \ \Omega m^2$. In the case of Figure 11 (b), the resistivity of the impregnated solder region is set to $4.0 \times 10^{-12} \ \Omega m^2$, and the contact resistivity is changed $1.0 \times 10^{-12} - 10 \times 10^{-12} \ \Omega m^2$. The results showed that the important parameters affecting joint resistance significantly were the resistivity of the impregnated solder region for Model C and the contact resistance for Model D.
Figure 11. Characteristics of the joint resistance. (a) function of resistivity of impregnated solder region. (b) function of contact resistivity.

3.3. Experimental evaluation of reattaching performance

3.3.1. Experimental procedure

Figure 12 shows the structure of the edge joint samples and experimental setup. We fabricated the 10-layer STARS conductors of Model A, C and D to evaluate the reattaching performance by repeatedly attaching and detaching the mechanical edge joint. For the conductor, 4-mm-wide Yttrium Barium Copper Oxide (YBCO) tapes produced by SuperPower Inc. (SCS4050-AP) were used, which have a critical current of 128 A at 77 K, self-field. Ten YBCO tapes and ten 100-µm-thick copper tapes were alternately stacked inside the copper jacket with Sn63Pb37 solder impregnation. The stepwise copper jacket was set as a current terminal to supply current to each YBCO tape. To measure the voltage for each layer, 50-µm-thick copper ribbon voltage taps were attached on each layer. After fixing the copper jacket, the joint region of the conductor was polished to flatten any irregularity of the joint surface by using a surface grinding machine with a particle. At the same time, parallelism tolerance for both side faces were controlled to be less than 0.01 mm, which is less than one tenth of the thickness of the inserted indium film. In addition, Model D conductors had copper plate attached on the conductor at the joint section via 50-µm-thick tin foil with a contact pressure of 100 MPa at 170℃ heat treatment.

Figure 12 (a) illustrates the experimental setup for joint resistance measurements. Copper current terminals of convex shape were mechanically fixed to a part of the stepwise copper jackets of the test conductor by tightening bolts and nuts. All samples were joined with 100-µm-thick indium foils, a joint pressure of 100 MPa, and joint length of 50 mm with heat treatment at 100℃. As is shown in Figure 12 (b) the mechanical edge joints have two conductors, which were named L and R. The layers were also named L1, L2, ..., L10 and R1, R2, ..., R10, respectively. The top and bottom copper jackets correspond to TJ1 and BJ1 for conductor L, and TJ2 and BJ2 for conductor R. A current of 1000 A was applied to the sample at 77 K, self-field in liquid nitrogen and voltage drop of each layer (pair of L1–R1 and L10–R1) and top and bottom copper jacket (pair of TJ1–BJ2 and BJ1–TJ2) in the joint region was measured to estimate the joint resistance. The joint resistance is calculated according to the linear slope of the current versus voltage curve below critical current.

After the first attachment and measurements of joint resistance, the detaching procedure began by heating the joint sample above the melting point of indium in an electric furnace. Then, the joint surface was wiped with a swab in silicone oil heated at 160–170℃ to remove the indium remaining on the joint surface. Then, the samples were cleaned using toluene to decompose the silicon oil in an ultrasonic cleaner. Figure 13 shows the photograph of the joint surface of before and after removing the indium.
A silvery looking surface layer including intermetallic compounds like CuIn2 remained on the joint surface after trying to remove them. Therefore, we carried out the joint test of the samples with the remaining surface layer on the joint surface. The attaching procedure is the same as in the previous paragraph. The combination of all the procedures is defined as one “reattaching process”, and reattaching performance was evaluated by repeating this process.

3.3.2. Results and discussion

Figure 14 shows the joint resistance of Model A, C, and D samples. The plotted symbols indicate an averaged value of each layer and the top and bottom copper jacket, and error bars indicate the maximum and the minimum values. The result showed that Model A had the lowest joint resistance among the three types because of attaching the stacked YBCO tapes with each other directly. The joint resistance of Model B is slightly larger than the joint resistance of Model A because the stacked YBCO tapes are covered with Sn63Pb37 solder. Model D showed the highest resistance due to the contact resistance between tin-foil and copper. According to the results of a single lap joint of YBCO tapes with inserted tin-foil, the contact resistivity between tin-foil and copper is predicted to be 3.7 $\Omega \cdot \text{m}^2$. It reaches more than six times as much as the contact resistivity between indium-foil and copper [19]. Further research is needed to reduce the contact resistivity with tin foil, for example, by raising the heating temperature. Therefore, we evaluated the reattaching performance for Model A and C samples.

Figure 15 shows the joint resistance as a function of the number of reattachments. A reattachment value “0” indicates the joint resistance of the first attachment before detaching the joint, which is the same in Figure 14. As mentioned in the previous paragraph, the result of the first attaching shows that the joint resistance of Model A is lower than Model C. However, after reattaching the joints, the joint resistance of both Model A and C increased, however Model C had lower joint resistance than Model A. The cause of increasing the joint resistance is predicted to be from the intermetallic compounds and newly formed contact interface. In the case of Model C, a Cu-In intermetallic compound is generated in
the joint interface. On the other hand, the joint surface of Model A consists of the copper jacket and stacked YBCO tapes including silver, YBCO and Hastelloy. Therefore, a joint surface comprised of complicated constituent materials might affect the increase in the joint resistance. In the previous study [18], a 5-layer YBCO stacked conductor exhibited joint resistance of about 400 nΩ. The joint resistance of a 10-layer STARS conductor with Model C is approximately 60 nΩ, which is sufficiently low compared to the previous study [18]. Based on the above results, Model C is the best joint surface structure of the three models.

Figure 14. Joint resistance of Model A, C and D in mechanical edge joint of 10-layer STARS conductors.

Figure 15. Joint resistance as a function of the number of reattachments.

4. Conclusions
In this study, we evaluated the total resistance and flatwise bending strain depending on the thickness of the copper stabilizer and jacket. The results showed that a thicker copper jacket does not decrease the joint resistance compared to a thicker copper stabilizer. From viewpoints of resistance and strain, the length of the edge joint should be longer than 500 mm. In addition, the change in joint resistance after several reattaching processes was evaluated by considering different joint surface structures. Through joint testing and joint surface observation, we concluded that the joint surface should be protected with an additional layer.

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