Joining condition dependency of joint resistance in ultrasonic welding of high-temperature superconducting tapes with indium

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Abstract. Ultrasonic welding (UW) is a candidate for easy and simple fabrication of lap joints of high-temperature superconducting (HTS) tapes. Our previous study applied UW to both silver-sheathed BSCCO tapes and copper-stabilized REBCO tapes with indium foil inserted in-between. However, the fabrication was performed with limited joining conditions and critical current, $I_c$, degradation was confirmed in some of the BSCCO tape joints. In this study, we evaluated the joining-condition dependence of joint resistance and $I_c$ to improve UW-jointed HTS tape performance. Various UW samples using BSCCO and REBCO tapes were prepared with different thicknesses of indium foil, ultrasonic vibration amplitude, joining pressure, joining time, and metal plate arrangement. The results showed that HTS tapes layered between metal plates on the top and bottom can avoid $I_c$ degradation even with higher joining energy, however thinner indium foil induced degradation in the BSCCO samples. Through this study, we found the value of joint resistivity only depended on the joining energy per unit joint area. The achieved joint resistivities were 14.0 nΩcm$^2$ for the silver-sheathed BSCCO tapes and 36.1 nΩcm$^2$ for the copper-stabilized REBCO tapes though it was strongly influenced by interface resistivity of the REBCO tape itself.

1. Introduction

Nowadays, high-temperature superconducting (HTS) tapes, e.g., silver-sheathed BSCCO ($\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$) tape and copper-stabilized REBCO ($\text{REBa}_2\text{Cu}_3\text{O}_y$, RE: rare-earth) tape are applied to developments of various superconducting applications, such as power cables for an electrical grid and railway systems [1, 2], nuclear magnetic resonance (NMR) magnets [3, 4], fusion magnets [5, 6] and so on. It is still yet a challenge to make a single long HTS tape with uniform critical current, especially for REBCO tapes. In such a situation, a single long HTS tape is provided by joining multiple HTS tapes. Furthermore, the aforementioned applications require HTS tape joints to connect HTS cables, pancake coils and conductors. Resistance requirements for HTS tape joints are different depending on the applications. NMR magnets needs superconducting joints [7–9] for its persistent current operation whereas the other applications need simply- and quickly-fabricated low-resistance joints.
The most popular and widely-used joining technique is soldering with tin-lead solder. Tin-lead solder joints of silver-sheathed BSCCO tapes or copper-stabilized REBCO tapes have achieved a joint resistivity \( R_{\Sigma} \) (product of joint resistance \( R_j \) and joint area \( S_j \)) of 30–50 nΩcm\(^2\) [10, 11] or 20–60 nΩcm\(^2\) [10, 12] at 77 K, self-field, respectively. However, tin-lead soldering also has a risk to decrease critical current \( I_c \) due to the temperature limit of HTS materials without oxygen annealing. There have already been several examples of joining techniques for silver-sheathed BSCCO and copper-stabilized REBCO tapes without oxygen annealing. Mechanical joints (pressure welding) with indium foil inserted between the joint surfaces with a low-temperature heat treatment at \( \sim 370 \) K for over ten minutes [13–16] have achieved 18–25 nΩcm\(^2\) for silver sheathed BSCCO tapes and 25–35 nΩcm\(^2\) for copper-stabilized REBCO tapes at 77 K, self-field. Ultrasonic welding (UW) has been also applied to HTS tape joints as a quick process. Hybrid welding (HW) combining UW (joining time: \( \sim 1 \) s) and post-solder (indium-tin solder) infiltration [17, 18] applied to copper-stabilized REBCO tapes have achieved 39–57 nΩcm\(^2\) at 77 K, self-field.

Based on these ideas, the authors recently proposed UW applied not only to copper-stabilized REBCO tapes but also to silver-sheathed BSCCO tapes [16]. The proposed UW was with indium foil inserted between the joint surfaces and metal plates between an anvil and HTS tape to protect them. The technique with a joining time of within 0.1 s achieved 22.7–46.5 nΩcm\(^2\) for silver sheathed BSCCO tapes and 31.6–33.7 nΩcm\(^2\) for copper-stabilized REBCO tapes at 77 K, self-field. However, the fabrication was performed with limited joining conditions and significant \( I_c \) degradation was confirmed in some of the BSCCO tape joints. Therefore, in this study, we evaluated the joining-condition dependence of \( R_{\Sigma} \) and \( I_c \) to improve UW-joined HTS tape performance. First, various UW samples using BSCCO tapes were prepared with different thicknesses of indium foil, ultrasonic vibration amplitude, joining pressure, joining time and metal-plate arrangement to investigate what parameter influences joining performance. Furthermore, the effects of metal-plate arrangement and HTS tapes from different manufacturers on the joint performance were examined for REBCO tape joints. \( R_j \) and \( I_c \) of the samples were estimated using current-voltage curves (\( I-V \) curves) evaluated at 77 K, self-field for the above purposes. Details of sample preparation and the experimental procedure are shown in Section 2, followed by the results and discussion in Section 3, and the conclusion appears in Section 4.

2. Material and method

2.1. Sample preparation

Three different HTS tapes listed in Table 1 were prepared for joint samples, Sumitomo's BSCCO tape, Bi(SEI), SuperPower's REBCO tape, RE(SP), and SuperOx's REBCO tape, RE(SO). First, the surfaces of the HTS tapes were polished with #240 sand paper then cleaned with ethanol. After that they were pressed together with indium foil inserted in-between by a UW machine (SNOPET ΣGM-1200, Seidensha Electronics Co., Ltd., Tokyo, Japan) with an ultrasonic frequency of 19.15 kHz, in which the ultrasonic vibration is in the HTS tape width direction. In principle, the UW process can join metals covered with oxides, however, all HTS tapes were polished to use the same surface conditions for all joining conditions.

Figure 1 shows the UW process of the HTS tapes used in this study. Metal plates (1-mm-thick 1050 aluminum alloy (A1050) or 0.5-mm-thick 316 stainless-steel (SS316)) were set beside the HTS tapes to avoid their degradation from the triangle-shaped teeth tips on the horn (0.2 mm pitch) and anvil (1.5 mm pitch). Two arrangements of metal plates were examined: (a) A bottom-plate (BP) arrangement, and (b) A layered-between-top-and-bottom-plate (TBP) arrangement as shown in Figure 1. The BP arrangement was the same as in the previous development [16]. The TBP arrangement was newly introduced in this study to avoid HTS tape degradation because our preliminary experiment confirmed the top side of Bi(SEI) was broken with >0.11 s joining times for the BP arrangement.

Only the TBP arrangement was used for the BSCCO sample fabrication. The parameters for the BSCCO samples were metal plate material (A1050 or SS316), joining time (0.08–0.12 s), ultrasonic vibration amplitude (26, 38, or 51 μm), joining pressure to a cylinder inside the UW machine (0.1, 0.2, or 0.3 MPa), and initial indium foil thickness (20, 50 or 100 μm). For the comparison, only one
parameter was changed keeping the standard condition: using A1050 plates, 0.10 s joining time, 51 μm amplitude, 0.3 MPa pressure, and 100-μm-thick initial indium foil thickness. Noting that the UW machine has a cylinder with a diameter of 50 mm and the cylinder generates the normal load to the joint region via the horn, which means 0.3 MPa joining pressure to the cylinder generates 589 N normal load and 22.8 MPa joining pressure to 4.3 mm × 6 mm joint area.

The parameters for the REBCO samples were the metal-plate arrangement (the BP or TBP arrangements), REBCO tapes from different manufacturers (RE(SP) or RE(SO)), joining time (0.10–0.16 s) and initial indium foil thickness (20, 50 or 100 μm). The standard condition is using A1050 plates, 51 μm amplitude, 0.3 MPa pressure, and 100-μm-thick initial indium foil thickness. For the parameter of initial indium foil thickness, the joining time was fixed to 0.1 s. During the UW process for both the BSCCO and REBCO tapes, ultrasonic vibration energy $E$ (J) applied to the sample was also recorded, and used for discussion.

### Table 1. Specifications of HTS tapes used for joint samples.

| HTS tape                  | Name                      | Width | Architecture (Thickness)                                                                 | Minimum $I_c$ (77 K, self-field) |
|---------------------------|---------------------------|-------|-----------------------------------------------------------------------------------------|---------------------------------|
| Silver-sheathed BSCCO tape| Bi(SEI)                   | 4.3 mm| Bi-2223 multi-filaments / Ag sheath / Ag ratio: 1.6                                       | 170 A                           |
| - Model: DI-BSCCO Type H  |                           |       |                                                                                         |                                 |
| - Manufacturer: Sumitomo Electric Industries, Ltd., Osaka, Japan |                           |       |                                                                                         |                                 |
| Copper-stabilized REBCO tape | RE(SP)                   | 4.0 mm| Total thickness: ~95 μm / Cu (~20 μm) / Ag (~2 μm) / Hastelloy (~50 μm) / Buffer (~0.2 μm) / YBCO (~1.6 μm) / Ag (~1.6 μm) / Cu (~20 μm) | 128 A                           |
| - Model: SCS4050-AP       |                           |       |                                                                                         |                                 |
| - Manufacturer: SuperPower Inc., Schenectady, NY, USA |                           |       |                                                                                         |                                 |
| Copper-stabilized REBCO tape | RE(SO)                   | 4.0 mm| Total thickness: ~110 μm / Cu (~20 μm) / Ag (~1-2 μm) / Hastelloy (~60 μm) / Buffer (0.2–0.3 μm) / GdBCO (1–3 μm) / Ag (1–2 μm) / Cu (~20 μm) | 150 A                           |
| - Model: No name          |                           |       |                                                                                         |                                 |
| - Manufacturer: SuperOx Japan LLC, Sagamihara, Japan |                           |       |                                                                                         |                                 |

![Figure 1. Ultrasonic welding process of HTS tapes.](image)
2.2. Evaluation of joint resistivity and critical current

The fabricated samples were cooled by liquid nitrogen (77 K) and the \( I-V \) curve was measured at self-field environment. Voltage taps were attached on each sample with an interval of about 30 mm so that the joint region was located between the taps. The positions of voltage taps were at least 5 mm away from the current terminals, which was sufficiently larger than the current transfer length (CTL) of HTS tapes [19, 20]. \( R_I \) was evaluated by the linear slope below 50 A and \( I_C \) was estimated using \( I-V \) curve obtained by subtracting the original \( I-V \) curve by the linear slope and 1 \( \mu \)V/cm criterion.

Experimentally obtained joint resistance, \( R_I \), is analyzed to discuss the joint performance depending on samples. \( R_I \) for the BSCCO sample is expressed as the following equation,

\[
R_I = 2R_{\text{BSCO/Ag}} + 2R_{\text{Ag}} + 2R_{\text{Ag/In}} + R_{\text{In}} = 2R_{\text{Bi-tape}} + 2R_{\text{Ag/In}} + R_{\text{In}}
\]

where \( R_{\text{Ag}} \) and \( R_{\text{In}} \) are the resistances of silver and indium, \( R_{\text{BSCO/Ag}} \) and \( R_{\text{Ag/In}} \) are interface resistances between BSCCO and silver, and silver and indium, respectively. Resistance of the BSCCO tape itself, \( R_{\text{Bi-tape}} \), is expressed as a summation of \( R_{\text{Ag}} \) and \( R_{\text{BSCO/Ag}} \). \( R_I \) for the REBCO sample is also expressed as the following equation,

\[
R_I = 2R_{\text{REBCO/Ag}} + 2R_{\text{Ag}} + 2R_{\text{Ag/Cu}} + 2R_{\text{Cu}} + 2R_{\text{Cu/In}} + R_{\text{In}} = 2R_{\text{RE-tape}} + 2R_{\text{Cu/In}} + R_{\text{In}}
\]

with \( R_{\text{Cu}} \) representing the resistance of copper, \( R_{\text{REBCO/Ag}} \), \( R_{\text{Ag/Cu}} \), and \( R_{\text{Cu/In}} \) being the interface resistances between REBCO and silver, silver and copper, and copper and indium, respectively. Resistance of the REBCO tape itself \( R_{\text{RE-tape}} \) is expressed as a summation of \( R_{\text{REBCO/Ag}} \), \( R_{\text{Ag}} \), \( R_{\text{Ag/Cu}} \), and \( R_{\text{Cu}} \). The interface resistances can be experimentally evaluated using the CTL method. In this study, those of RE(SP) and RE(SO) were evaluated by the contact-probing CTL method [20]. The joint resistivity, \( R_iS_i \), is derived by multiplying \( R_I \) by joint area, \( S_i \), which has unit of \( \Omega \text{m}^2 \). With the same manner, each resistance is expressed as \( \Omega \text{m}^2 \) by multiplying the resistance by \( S_i \). To analyze the factors of the joint resistance, the thickness of the indium foil after the joining process was also evaluated by measuring the thickness of the joint region with a micrometer.

3. Results and discussion

3.1. Joint samples of BSCCO tapes

Figure 2 shows critical current \( I_C \), energy per unit joint area \( E/S_i \) (J/cm²), and joint resistivity components \( (R_iS_i = R_{\text{In/In}} + (2R_{\text{Bi-tape}} + 2R_{\text{Ag/In}})) \) evaluations for the BSCCO samples depending on various parameters. Two or three samples were fabricated for each parameter condition. Figure 3 also shows \( I-V \) curve for selected samples with different \( I_C \). Samples Bi-1 and Bi-2 were fabricated with the standard condition, and sample Bi-3 was fabricated with 20-µm-thick indium foil. These samples data are also included in Figure 2. The linear slopes seemed to include voltage with lower \( n \)-value and evaluated \( I_C \) depends on the linear slope evaluation. We assumed the linear slope was kept until 50 A and analyzed \( I_C \) with the assumption. In the case of \( I_C \) less than 50 A, we used the linear slope until 10 A. The overall results other than the samples fabricated with 20 or 50-µm-thick indium foil show that \( I_C \) of the BSCCO samples is less influenced by the parameter changes set in this study. \( I_C \) was degraded by 5–25% from Bi(SEI)'s original \( I_C \), but the degradation was suppressed compared to samples fabricated with the BP arrangement [16]. Our previous study [16] also indicated the SS316 plate suppressed \( I_C \) degradation rather than the A1050 plate in the BP arrangement, however, metal plate material less influenced the present samples in the TBP arrangement according to Figure 2 (a) and (b). On the other hand, 20 or 50-µm-thick indium foil adversely affected the joint performance, i.e., \( I_C \) drastically decreased in most samples, which is also shown in Figure 3. After the UW process, the thickness of the foil became almost zero and the BSCCO tapes could contact each other directly. The direct friction to the BSCCO tapes possibly damaged the filaments and caused \( I_C \) degradation.
Also from Figure (a) and (b), joint resistivity decreases with an increase in joining time, but the decreasing rate becomes subtler over 0.1 s joining time. The joint resistivity decreased with increases in ultrasonic vibration amplitude and joining pressure as shown in Figure 2 (c) and (d). The amplitude had a larger impact to decrease the joint resistivity, which is related to ultrasonic vibration energy applied to the samples. Figure 4 shows joint resistivity components as a function of ultrasonic vibration energy per unit joint area for all the samples with initially 100-µm-thick indium foil. This result indicates that the joint resistivity, indium foil thickness after the UW process and contact interface resistance $R_{Ag/In}$ only depended on the energy. This tendency teaches us that we should set over 3 J/cm² when we fabricate longer joints as well as applying adjustments to avoid $I_c$ degradation. The minimum joint resistivity obtained in this study was 14.0 nΩcm².

**Figure 2.** Critical current, energy per unit joint area, and joint resistivity components for BSCCO samples as functions of (a) Joining time, (b) Joining time using SS316 plates, (c) Ultrasonic vibration amplitude (d) Joining pressure to the cylinder of the UW machine and (e) Initial indium foil thickness. (a), (c)–(e) were for samples fabricated using A1050 plates.
3.2. Joint samples of REBCO tapes

Figure 5 shows joint resistivity components \( R_{\text{joint}} = R_{\text{in}}S_{j} + 2R_{\text{Cu/In}}S_{j} + 2R_{\text{RE/paste}}S_{j} \), critical current \( I_{C} \) and energy per unit joint area \( E/S_{j} \) \((J/cm^2)\) evaluations for the REBCCO samples depending on various parameters. Two samples were fabricated for each parameter condition in the present study. Noting that Figure 5 (a) includes data obtained in our previous study [16]. In the previous study, we used REBCO tapes manufactured by SuperPower Inc. with the same structure of RE(SP) in the present study, but with a different minimum \( I_{C} \) (91 A). Interface resistivities, \( R_{\text{Ag/Cu}}S_{j} + R_{\text{Cu/In}}S_{j} \), evaluated using the contact-probing CTL method for the previous RE(SP), the present RE(SP) and RE(SO) were 8.5 n\( \Omega \)cm\(^2\), 12.9 n\( \Omega \)cm\(^2\) and 15.6 n\( \Omega \)cm\(^2\) for a single REBCO tape, respectively. Figure 6 also shows \( I-V \) curve for selected samples with different \( I_{C} \). Samples RE-1, RE-2 and RE-3 represent a RE(SP) sample in the BP arrangement, a RE(SP) sample in the TBP arrangement and a RE(SO) sample in the TBP arrangement with 0.16 joining time, respectively. The slope below \( I_{C} \) was totally linear for the REBCO samples and the judgement of when linearity ended did not affect the \( I_{C} \) evaluation though we used the linear slope until 50 A for the \( I_{C} \) evaluation.

The results showed that the BP arrangement with joining times of \( >0.11 \) s induced \( I_{C} \) degradation whereas the TBP arrangement did not until a joining time of 0.16 s. In addition, the samples fabricated with 20 or 50-\( \mu \)m-thick indium foil show no \( I_{C} \) degradation, which was different from the results obtained in the BSCCO samples. Furthermore, samples fabricated with different manufacturers' REBCO tapes showed the same tendency of the joint resistivity. However, the joint resistivity at 0.1 s joining time for the present samples were scattered and higher than the previously fabricated samples. Figure 7 shows joint resistivity components as a function of ultrasonic vibration energy per unit joint area for all the samples with initially 100-\( \mu \)m-thick indium foil and without \( I_{C} \) degradation. At lower energy, the joint resistivity components is scattered, but they tend to be constant at higher energy and became the similar value to the previous data. The minimum joint resistivity obtained in this study was 36.1 n\( \Omega \)cm\(^2\) and still higher than previously obtained one. The resistivity from the REBCO tapes itself, \( R_{\text{RE/paste}}S_{j} \), was dominant factor and strongly affected the value of the joint resistivity. Figure 7 (b) shows energy dependence of interface resistivity between the copper and the indium, \( R_{\text{Cu/In}}S_{j} \), which is not influenced by \( R_{\text{RE/paste}}S_{j} \). This graph shows that \( R_{\text{Cu/In}}S_{j} \) for some present samples was lower than
previous data, because $R_{Ag/Cu}S_j + R_{Cu/In}S_j$ of the REBCO tape used in the previous study was lower than those used in the present study. According to the results, we should apply the energy of $>15$ J/cm$^2$ to obtain stably lower joint resistance.

Figure 5. Critical current, energy per unit joint area, and joint resistivity components for RE(SP) samples as functions of (a) Joining time in the BP arrangement, (b) Joining time in the TBP arrangement, (c) Initial indium foil thickness in the TBP arrangement. (d) shows those for RE(SO) samples as a function of joining time in the TBP arrangement. Noting that (a) include previous data [16] for comparison.
Figure 6. \(I-V\) curves for selected REBCO samples, Samples RE-1 was fabricated with RE(SP) in the BP arrangement, Sample RE-2 was fabricated with RE(SP) in the TBP arrangement and Sample RE-3 was fabricated with RE(SO) in the TBP arrangement. These three samples were fabricated with 0.16 joining time.

Figure 7. Joint resistivity components as a function of energy per unit joint area. Open and closed symbols show present and previous [16] data, respectively. (a) shows all the data for samples fabricated with 100-\(\mu\)m-thick indium foil and without \(I_c\) degradation, and (b) shows enlarged graph of (a) only for interface resistivity between the copper and the indium.

4. Conclusion
In this study, various joint samples of silver-sheathed BSCCO tapes and copper-stabilized REBCO tapes were fabricated by UW with indium insertion. And, joint resistance and critical current for these samples were evaluated as functions of different thicknesses of indium foil, ultrasonic vibration amplitude, joining pressure, joining time, and metal plate arrangement. The layered-between-top-and-bottom-plate (TBP) arrangement can avoid \(I_c\) degradation even with higher joining energy. On the other hand, thinner indium foil induced degradation for the BSCCO samples. Though this study investigated various UW parameters influences, eventually the value of joint resistivity only depended on the joining energy per unit joint area decided by the joining conditions. The achieved minimum joint resistivities were 14.0 n\(\Omega\)cm\(^2\) for the silver-sheathed BSCCO tapes and 36.1 n\(\Omega\)cm\(^2\) for the
copper-stabilized REBCO tapes though it is strongly influenced by interface resistivity of the REBCO tape itself.

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