Heating and loading process improvement for indium inserted mechanical lap joint of REBCO tapes

Tatsuki Nishio, Satoshi Ito, and Hidetoshi Hashizume

***Abstract*— A mechanical lap joint of REBCO high-temperature superconducting (HTS) tapes with an indium foil inserted between joint surfaces has been proposed for segment-fabrication of HTS magnet of an advanced fusion reactor and various HTS applications. In a previous study, we successfully achieved a joint resistivity of about 3.5 pΩm² by heat treatment during fabrication of the joint. In this study, improved heat treatment method is developed by controlling contact pressure and combining bake-out process. During the development, we evaluated joint resistance and critical current of the joint depending on the heating condition and bake-out condition. For example, the joint resistivity after heat treatment was 2.5 pΩm² without decreasing critical current for a joint sample with conditions of heating temperatures of 90-140 °C, heating time for 30 minutes, contact pressure of 100 MPa and bake-out time for 30 minutes. The method proposed in this study, applying contact pressure during the heating, can increase true area of the contact surface and decrease the thickness of the indium greater than the previous method owing to applying contact pressure when the indium becomes softer. The contact resistance also decreased progressively according to increase of the bake-out time due to an increase of releasing gases.**

***Index Terms*— Fusion reactors, high-temperature superconductors, power cable connecting, superconducting magnets**

I. Introduction

Various lap joining techniques have been proposed and developed for connecting Rare-Earth Barium Copper Oxide (REBCO) tapes used for high-temperature superconducting (HTS) applications: pressure controlled solder joint with a joint resistivity (the product of joint resistance and joint area) of 3 pΩm² [1], ultrasonic weld-solder hybrid joint with 3 pΩm² [2], nano-particle metal paste joint of silver stabilized REBCO tapes with 4.8 pΩm² [3], silver diffusion joint with 0.67 pΩm² [4], superconducting joint of with 10^{-4} pΩm² [5] where the joint resistivity was evaluated at 77 K and self field. Especially, mechanical lap joint which is able to mount and demount easily is expected for "Remountable" (demountable) HTS magnet or segment-fabrication of HTS magnet proposed for future fusion reactors [6]–[9].

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In the previous studies of mechanical lap joint, a soft metal (e.g. indium) inserted between mechanical lap joint can reduce contact resistance [10], [11]. We also fabricated a 100-kA-class HTS conductor having a bridge-type mechanical lap joint with indium foils inserted between joint surfaces, which was a prototype conductor and its joint for segment-fabrication of HTS magnet in the Large Helical Device type fusion reactor, FFHR-d1 [12]. The conductor had three-row and fourteen-layer of 10-mm-wide Gadolinium Barium Copper Oxide (GdBCO) tapes embedded in copper and stainless steel jackets. We successfully achieved a joint resistance of 1.8 nΩ (a joint resistivity of about 10 pΩm²) at 100 kA, 4.2 K, 0.45 T, which is acceptable from a view-point of refrigeration energy [13][14]. According to temperature dependence of joint resistance, the joint resistivity corresponds to be about 30 pΩm² at 77 K and that was higher than expected value due to non-uniform contact pressure distribution [15]. For solving the problem, our previous study [15] also proposed heat treatment during fabrication of a mechanical lap joint with an indium foil for reducing joint resistance. The joint resistivity was reduced to be 3.5 pΩm² at 77 K with the heat treatment at 90 °C, which was reduced to be 60 % of the joint resistivity obtained without the heat treatment. This method can simply fabricate a joint at low temperature without oxygen annealing, which is an advantage compared to other joint techniques for HTS applications. However, joint resistivity was slightly higher than other joint methods. And therefore, one target is achieving joint resistivity equivalent to pressure controlled solder joint. In the previous study [16], we applied contact pressure using a jig having 4 bolts adjusted with a certain torque. Fig. 1 shows relationship of contact pressure after the heat treatment. Contact pressure after the heat treatment decreased by thermal deformation and thinning of indium layer inserted between joint surfaces. Holm [17] and Tabor [18] showed that resistance at contact of two materials is proportional to the hardness and inversely proportional to the pressure, therefore joint resistance will decrease by applying constant pressure during the heat treatment. In addition, metals having low melting point like indium can creep at room temperature [19]. Hence we should evaluate relationship between the joint resistance and the creep deformation by changing heating time. The previous study [15] also proposed bake-out process in order to remove voids in the indium at the joint, which might be caused by gas desorption from the GdBCO tape and the indium foil though what the released gas was and which temperature the gas was released were not identified.

As a result of the above-mentioned background, we evaluate joint resistance characteristics with a change in temperature, contact pressure and heating time during heating process. In addition, we select bake-out conditions based on analysis of desorbed gas. Finally, we propose the improved process combining bake-out and heating processes for the mechanical lap joint of REBCO tapes with an indium foil inserted between joint surfaces.

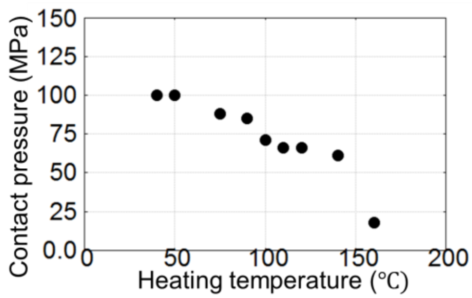

Fig. 1 Relationship of contact pressure after heat treatment

II. Sample preparation and Experimental procedure

The sample is a mechanical lap joint of 5-mm-wide GdBCO tapes (FYSC-SC05, critical current is 275 A at 77 K, self field, Fujikura Ltd.). The GdBCO tape has layer structure of Hastelloy substrate (75 µm)/buffer layers (2 µm)/GdBCO (2 µm)/silver (2 µm)/tin (2–4 µm)/copper (75 µm). The copper surfaces at joint section of GdBCO tapes were grinded by sandpapers (the abrasive particle diameters were 81 µm) and then cleaned with ethyl alcohol. After that, GdBCO tapes were baked out at a certain temperature for a certain time in a vacuum condition (10^{-2} kPa). Table 1 shows conditions of the bake-out process. Then, we analyzed outgases from the GdBCO tape by means of Thermal Desorption Spectroscopy (TDS: WA1200, ESCO co. Ltd., Fig. 2) which can observe gas molecule from a surface when the surface temperature increased. We set GdBCO tape samples on a stage made of quartz in the TDS, and samples were heated by infrared,in which the temperature increased from 40 °C to 200 °C with a rising rate of 1 °C/sec.

After bake-out process, the mechanical lap joint samples were fabricated using the set-up shown in Fig. 3, which can continuously apply contact pressure during the heating process. The samples had joint length of 10 mm (a joint area of 50 mm^2) and indium foil having a thickness of 100 µm was inserted between GdBCO tapes. The contact pressure in fabricating mechanical joint was 5 MPa, 25 MPa, 50 MPa and 100 MPa. After fabricating the joint, once we released the contact pressure to measure thickness of the joint for evaluating resistance of the indium layer. Then we applied the contact pressure again, and measured initial joint resistance and critical current at 77 K (in liquid nitrogen). After the joint resistance measurement, we applied heating process to the samples. Each of contact pressure was the same pressure as when fabricating joint (5 MPa, 25 MPa, 50 MPa and 100 MPa). Heating temperature was 50 °C, 90 °C, 120 °C, 140 °C, 160 °C and heating time was 10 min, 20 min, 30 min, 60 min for each. Heating temperature over the melting points of indium (156.6 °C) was considered as indium solder joint. After the heating, we measured joint resistance, critical current and thickness of joint again.

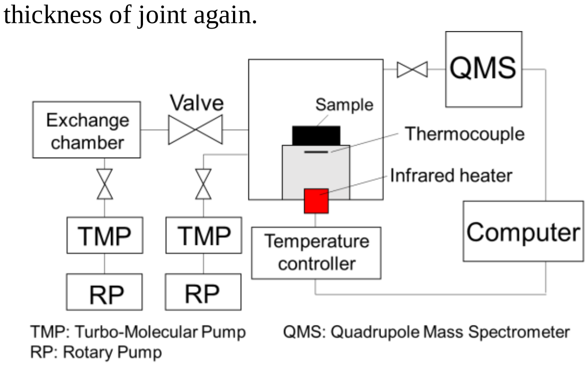

Fig. 2 Thermal Desorption Spectroscopy (TDS) measurements

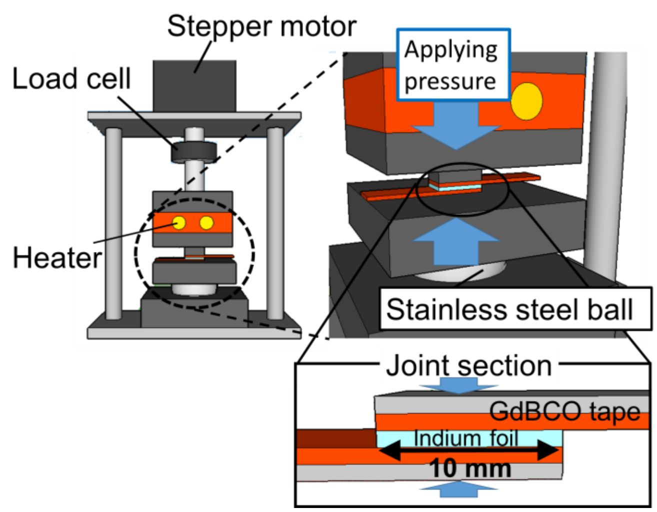

Fig. 3 Heating device

III. Result and Discussion

A. Bake-out process

Fig. 4 shows gases desorbed from GdBCO tapes without bake-out process when temperature changed in TDS. The vertical axis shows the count of molecules of gases per second and horizontal axis shows temperature which increased at a rate of 1 °C/sec. Main gases were H_2, H_2O, CH_4, CO, O_2, CO_2 released over 100 °C. Voids were observed over 120 °C on images of X-ray computed tomography [16], and the fact agrees with the result of TDS. There were two peaks with a change of temperature for H_2O. The lower temperature peak would be caused by evaporation of H_2O detected at about 100 °C-200 °C [20]. The peak at higher temperature would be caused by releasing H_2O dropped by molecular forces whose effect become dominant at 150 °C-300 °C [20]. H_2O would be absorbed by the surface of the GdBCO tape when grinding the joint surface in wet and leaving then exposed to air. Other gases would be also absorbed in the same condition.

Fig. 5 shows relationship between amounts of outgases and temperature with respect to bake-out conditions (Table 1). Fig.

5 (a) was a change of bake-out temperature. The amount of gases from sample No. 1-1, 1-2 and 1-3 was lower than that from No. 0. This fact shows that bake-out process can remove gases from GdBCO tape. In case of No. 1-1, gases were desorbed below 160 °C. On the other hand, almost gases were removed in No. 1-3. It is better to bake out the sample at over 150 °C because the range of heating temperature would be below 160 °C. Fig. 5 (b) shows the bake-out time dependence. The amounts of gases decreased with an increase of bake-out time. Based on the above results, we selected bake-out condition of No. 2-2 because almost gases were removed below 160 °C.

We selected bake-out condition of indium foil based on Temperature Programmed Desorption (TPD) analysis [20]. We selected bake-out temperature 150 °C and bake-out time 30 min considering melting points of indium.

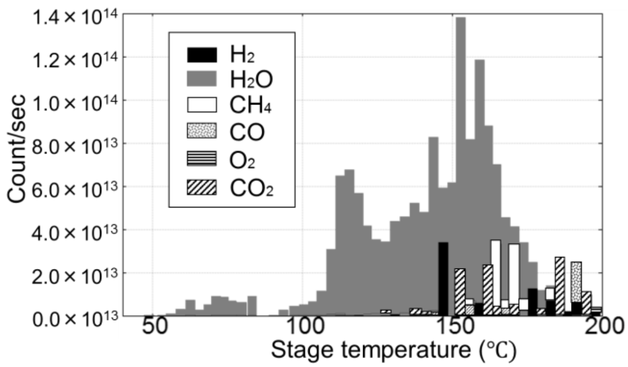

Fig. 4 Gases released from GdBCO tape without bake-out process

Table 1 Bake-out condition

Sample No.	Bake-out condition	
	Temperatrue (℃)	time (min)
No. 0	Without bake-out process	
No. 1-1	50	30
No. 1-2	100	30
No. 1-3 (No. 2-2)	150	30
No. 2-1	150	5
No. 2-2 (No. 1-3)	150	30
No. 2-3	150	180

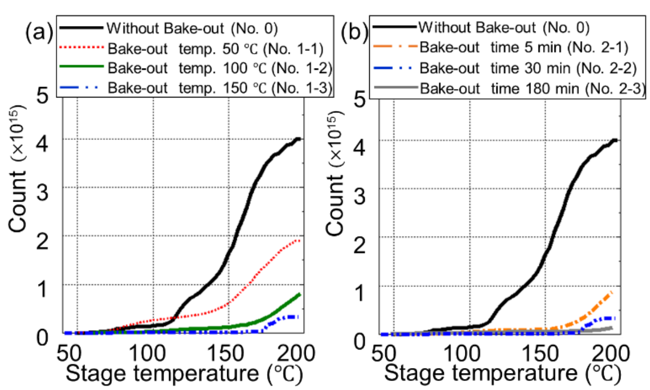

Fig. 5 Relationship between amount of gases and temperature (a) Bake-out temperature dependence, (b) Bake-out time dependence

B. Heating process

In this study, we evaluated R_{joint} (Joint resistivity: Ωm^2) from the model of the mechanical lap joint with an indium (Fig. 6) [21]. We considered resistance of indium layer depending on thickness of indium R_{indium} (Ωm^2) and the contact resistance between copper and indium layer depending on real contact area $R_{contact}$ (Ωm^2). In addition, resistance of copper layer, tin layer and silver layer of the GdBCO tape were R_{Cu}, R_{Sn} and R_{Ag} depending on thickness of each layer. Then, R_{joint} is eventually expressed as

$$R_{joint}=R_{indium}+2R_{contact}+2R_{Cu}+2R_{Sn}+2R_{Ag}. \quad (1)$$

Here we note that the joint section has two contact surfaces. Although there exists interface resistance between the GdBCO and the silver layers, that is assumed to be zero because the interface resistance is negligibly small [22].

Assuming the change in thickness of the joint section is only decided by the thickness of indium layer l_{indium} (m), R_{In}, R_{Cu} and R_{Ag} are calculated as follows.

$$R_i=\rho_i l_i \ (\Omega m^2) \quad (2)$$

where ρ_i and l_i are resistivity ($\rho_{indium}=1.8\times10^{-8}$ Ωm, $\rho_{Cu}=0.2\times10^{-8}$ Ωm and $\rho_{Ag}=0.3\times10^{-8}$ Ωm at 77 K) and thickness of each material, i, respectively. R_{Sn} is evaluated by using experimental obtained vale [21].

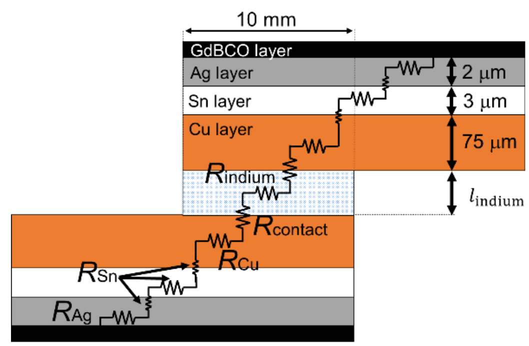

Fig. 6 Model of a mechanical joint resistivity

Fig. 7 (a) shows R_{joint} as a function of heating time and contact pressure when heating temperature was 90 °C. The horizontal axis indicates hold time after reaching at target temperature. It took about 10 min to reaching at 90 °C. R_{joint} decreased with an increase of contact pressure. On the other hand, the decrease of R_{joint} was small with a change of heating time. Indium creep occurs almost immediately with light pressure according to reference [19]. It seems that reduction of R_{joint} by changing heating time was small because indium had almost deformed at heat-up term. Fig. 7 (b) shows R_{joint} as a function of heating temperature and contact pressure when heating time was 30 min. R_{joint} decreased with an increase of contact pressure and heating temperature. The results agree with the theory of contact resistance shown by Holm [17] and Tabor [18]. R_{joint} was reduced to be 2.5 pΩm^2 at 100 MPa, 90 °C -140 °C without reduction of critical current, whose value is compatible with the values by other one.

Fig. 8 shows relationship between R_{joint} and heating temperature with a contact pressure of 100 MPa for the heating time of 30 min. R_{joint} obtained in this study when contact pressure was kept to be applied during heating was lower than that in previous method because contact pressure was applied when the hardness of indium became lower. Fig. 9 (a) shows relationship between R_{indium} and heating temperature. R_{indium} decreased with an increase of heating temperature. Especially, indium thickness became lower at high heating temperature. Fig. 9 (b) shows relationship between $R_{contact}$ and heating temperature. $R_{contact}$ was the minimum at 90 °C-140 °C. It seems that there is almost no change of $R_{contact}$ at those heating temperatures because contact pressure was high and hardness was low enough. On the other hand, $R_{contact}$ increased at 160 °C. We baked indium foil at 150 °C in bake-out process in order not to exceed melting point of indium. However gases were possibly desorbed over the melting points [23] and it can cause voids in the indium at the joint.

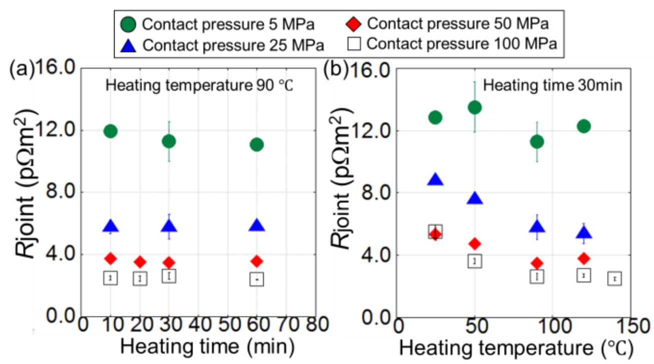

Fig. 7 (a) R_{joint} as a function of heating time and contact pressure (b) R_{joint} as a function of heating temperature and contact pressure

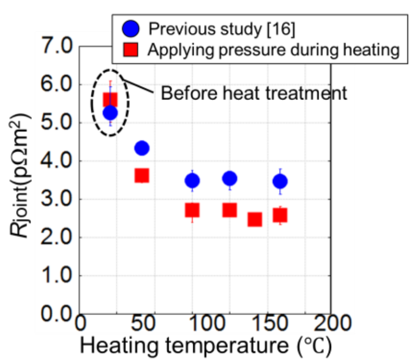

Fig. 8 Relationship between R_{joint} and heating temperature

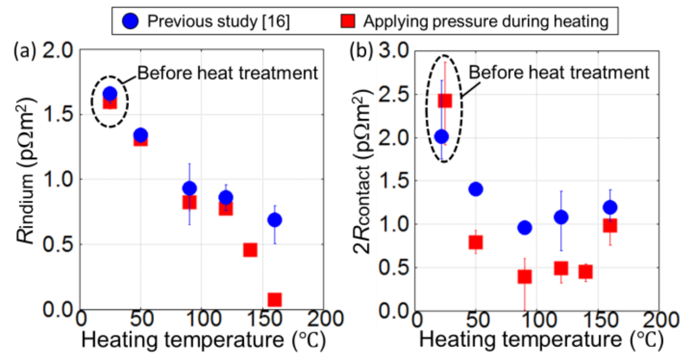

Fig. 9 (a)Relationship between R_{indium} and heating temperature (b)Relationship between $2R_{contact}$ and heating temperature

IV. Conclusion

In this paper, we proposed joining method by means of heat treatment combining bake-out process and heating process.

We improved bake-out condition based on TDS analysis. Main gas which was cause of voids in the indium at the joint was H_2O. Those gases were removed by bake-out process and optimum bake-out conditions for GdBCO tapes were a bake-out temperature of 150 °C and a bake-out time of 30 min.

For improving heating process, we investigated contact pressure, heating temperature, heating time dependencies of joint resistivity, R_{joint}. R_{joint} decreased with an increase of contact pressure and heating temperature. On the other hand, R_{joint} did not change with a change of heating time of 10 min-60 min because deformation of indium would occur almost immediately. Therefore, reduction of R_{joint} owing to creep was small in this jointing method. The minimum value of R_{joint} was 2.5 pΩm^2 at heating temperatures of 90-140 °C with applying contact pressure of 100 MPa, which was reduced to 50% of the value obtained without heat treatment. The joint resistivity is comparable to pressure controlled solder joint applied for HTS cable. This method would be expected for new joining method which is demountable and achieves low resistance easily. As a future task, we plan to apply to multi-row and multi-layer HTS conductor for the fusion application.

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