Fundamental Evaluation of Joint Resistance in Mechanical Butt Joint of a Stacked GdBCO Conductor*)

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In this study, joint resistance in mechanical butt joint of a single GdBCO tape was evaluated by experiments and current distribution analyses to apply a remountable HTS magnet for a future fusion reactor. The results showed that thickness of the metal layers of GdBCO tape, cutting angle of the conductor and existence of soldered interface affect the joint resistance. According to discussion based on the results, an optimized joint structure could achieve joint resistance of 0.4 μΩ for single GdBCO tape, which corresponds to 5 nΩ for 100 kA class HTS conductor. The resistance has to be reduced almost a half value of the present result to be accepted from the view point of electric power for cooling.

Keywords: superconducting magnet, high-temperature superconductor, mechanical joint, remountable high-temperature superconducting magnet, current distribution analysis

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1. Introduction

A remountable or demountable high-temperature superconducting (HTS) magnet where segments of the magnet can be mounted and demounted repeatedly has been proposed for a component-testing machine (small tokamak) [1] and a helical DEMO reactor having complex configuration [2]. The superconducting magnet is made of HTS tapes having high critical current at relatively high operating temperature, which could tolerate joule heat at the joint section because of its relatively large heat capacity. There are three typical advantages for the design: to simplify the fabrication of a complex and huge magnet like helical coils, to repair or replace damaged segments due to neutron irradiation or quench and to access reactor components easily. The concept for a helical reactor is also included in the HTS coil option for the LHD-type DEMO reactor, FFHR [3].

Mechanical lap joint [4, 5], butt joint [2, 6] and edge joint [7] were investigated as the remountable joint methods. Our latest study on the mechanical butt joint [6] shown in Fig. 1 achieved about 140 nΩ of joint resistance for a stacked BSCCO 2223 conductor with copper jacket having a critical current of 1 kA at 77 K. However, the BSCCO 2223 cannot be used under a strong magnetic field such as a fusion reactor environment because its critical current drops significantly. Therefore, ReBCO superconductors such as YBCO or GdBCO should be used for the concept, which can comparatively keep the critical current under the strong magnetic field.

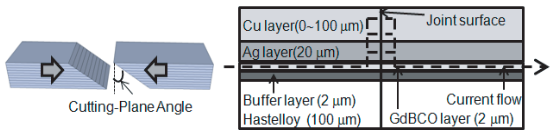

Fig. 1 Schematic views of the mechanical butt joint.

In the butt joint of ReBCO tapes and stacked ReBCO conductors, current flows not directly from HTS layer of one side to that of another side but through the conductive metal (silver and copper) layers of the tape in the joint section as shown in Fig. 1. Hence, the joint resistance depends on contact area of the metal layers. The contact area could be determined by the thickness of the metal layers and the cutting-plane angle θ of the conductor as shown in Fig. 1. In addition, interface resistance between component materials of the HTS tape also influences the joint resistance. In this study, therefore, the effect of the HTS tape structure such as thickness of the metal layer and the interface resistance on the joint resistance was evaluated by current distribution analysis and experiment at first. In this experiment, we used GdBCO tape to make test conductors, which is one of the ReBCO tapes. Then the optimum cutting-plane angle was evaluated by current distribution analysis. Based on the results, we discussed the optimum structure of ReBCO conductor and joint section for the butt joint.

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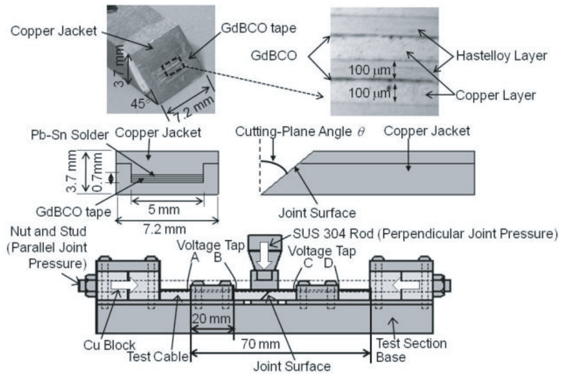

Fig. 2 Test conductors and test section.

2. Effect of HTS Tape Structure on the Resistance

2.1 Experiment

2.1.1 experimental set-up

Figure 2 shows a test conductor and section. Stacked GdBCO conductors with copper jacket were used for the test conductors. The conductors were made by laminating 4 GdBCO tapes of 5 mm width inside the copper jacket and fixing them with Ag-Sn solder. We prepared two types of GdBCO conductors to investigate the effect of HTS tape structure: Conductor A using GdBCO tapes having layer structure of Ag (20 μm)/GdBCO/buffer layer/Hastelloy substrate (FYSC-S05, Fujikura Ltd.) and Conductor B using the tapes having the structure of Cu (100 μm)/solder/Ag (20 μm)/GdBCO/buffer layer/Hastelloy substrate (FYSC-SC05, Fujikura Ltd.). The critical current of Conductor A and B were about 570 A and 730 A, respectively. A pair of test conductors for the joint test was fabricated by cutting one stacked conductor to have cutting-plane angel θ of 45-degree and the joint surfaces were polished with #1500 abrasive. Indium film with thickness of 50 μm was inserted between joint surfaces to avoid an increase in the joint resistance due to misalignment of the joint surfaces.

The experimental set-up shown in Fig. 2 can apply the perpendicular and parallel joint pressures to the joint section. The perpendicular one is given by the rod and monitored by a load cell, which can be controlled before and after the cooling the test section with liquid nitrogen. The parallel one is given by clenching the nut and the stud with a certain torque. In this experiment, the parallel pressure was given by applying a torque of 1.6 Nm before cooling. Then the perpendicular pressure was given 60 MPa after cooling. The joint resistance was evaluated with voltage drop between Voltage Taps A and D. Current-voltage characteristics was also evaluated between Voltage Taps A and B before and after cutting the conductor.

2.1.2 results and discussions

Figure 3 shows the joint resistances obtained at 250 A. The averaged joint resistance of Conductor A is 1.21 μΩ and that of Conductor B is 0.83 μΩ, which is about 69% of that of Conductor A. The difference cannot be explained only by difference of contact area of the conductive metal layers. The reason is thought to be existence of the solder layer in Conductor B and that of the copper jacket in both conductors. The former reason will be discussed in next subsection. Later one can be explained by current-voltage characteristics shown in Fig. 4, which shows the characteristics of Conductor A before and after cutting it. Critical current (Electric field criterion of 1 μV/cm) before cutting was about 570 A which is about four times of the critical current of the GdBCO tape, whereas that after the cutting is about 300 A. The GdBCO tape has the layer structure where one surface is conductive metal layer having small resistance and opposite one is Hastelloy substrate having large resistance. Only the conductive layer of GdBCO tape laminated on the top of the test conductor can contact to copper jacket directly in the test conductor structure. Therefore, most of current flows through the top rather than other tapes because the current can flow through the copper jacket easily in the joint section. That is why the critical current decreased after the cutting. Therefore, the joint resistance shown in Fig. 3 is underestimated because there is a parallel circuit, which consists of a current pathway through the jacket and that from a GdBCO tape to another side of GdBCO tape directly in the joint section

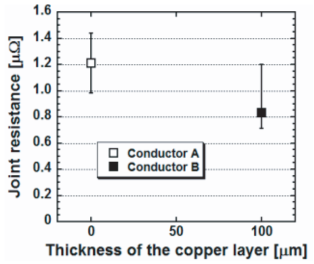

Fig. 3 Relationship between thickness of the conductive metal layer and joint resistance.

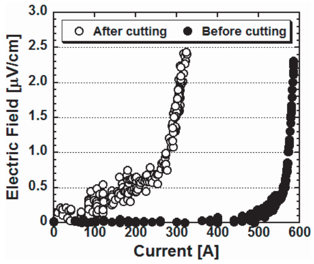

Fig. 4 Current-Voltage characteristic of Conductor A.

2.2 Current distribution analysis

2.2.1 numerical models

The effect of the tape structure on the joint resistance was analyzed by a two dimensional current distribution analysis for the butt joint of two GdBCO tapes. We made models for the two types of GdBCO tape: Models A and B were for GdBCO tapes with and without solder layer

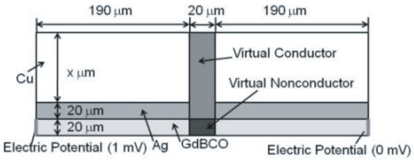

Fig. 5 Numerical model (Model A).

Table 1 Electrical resistivity of constituted material.

Material	Electrical Resistivity (Ω·m)
Cu	0.2×10^{-8}
Ag	0.3×10^{-8}
GdBCO	1.0×10^{-20}
Virtual Conductor	5.28×10^{-8}
Virtual Nonconductor	1.0
Ag-Sn solder	1.5×10^{-7}

between the silver and copper layers, respectively. Fig. 5 shows Model A. For both models, cutting-plane angle is set to be 0-degree and we assumed ideal condition that the GdBCO tapes were jointed without misalignment. In the models, we ignored buffer layer (insulator) and Hastelloy substrate because the current cannot flow to those layers in the ideal condition. In Model B, the solder layer of 20 μm thick was inserted between the silver and copper layers. The electrical resistivity of the solder was decided based on the previous study [8] which reported joint resistivity of soldered lap joint of YBCO tape was $3 \times 10^{-12}\ \Omega\mathrm{m}^2$. In this analysis, we assumed uniform current distribution in the HTS region with extremely small resistivity. Contact resistance was introduced by using a virtual conductor in the contact region of the copper, solder and silver layers. Electric resistivity of the virtual material at the conductive metal layer was decided based on joint resistivity of the stacked BSCCO 2223 conductor of $1.06 \times 10^{-12}\ \Omega\mathrm{m}^2$ [6], which was calculated by only using contact area of silver stabilizer. A virtual nonconductor having extremely large resistivity was placed in the contact region of GdBCO to simulate that no current passes there. Table 1 shows the electrical resistivity of the constituted material. The current distribution analysis was performed using ANSYS ver. 8.1 and the joint resistance was evaluated by total joule loss and total voltage drop of the model. Electric potentials were set in the GdBCO region as boundary conditions as shown in Fig. 5. The total voltage drop was assumed to be 0.1 mV. Element type used in this analysis was 4-nodes isoparametric element and the number of the element was about 1000. The thickness of the copper layer was chosen as a parameter in the analysis.

2.2.2 results and discussions

Figure 6 shows a relationship between the thickness of the copper layer and the joint resistance obtained with Models A and B. The joint resistances decrease with an increase in the thickness of the copper layers. Model B shows larger joint resistance than Model A. Hence, the existence of soldered interface strongly affects the joint resistance. And therefore, using a HTS tape having low in-

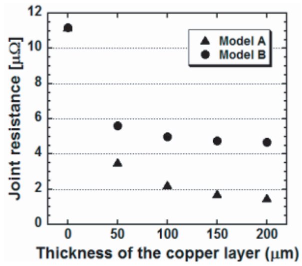

Fig. 6 Relationship between the thickness of copper layer of the GdBCO tape and the joint resistance.

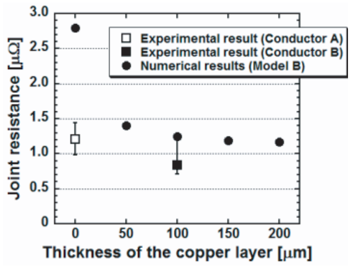

Fig. 7 The numerical results and the experiment results.

terface resistance is effective to achieve smaller joint resistance, for example, Superpower Inc.'s YBCO tape having vapor deposited copper layer on silver layer.

Figure 7 shows the numerical results of Model B and the experimental results. The values of the numerical results are 1/4 of original values to show joint resistance for 4-layer conductors. The joint resistances obtained by the experiment are lower than those by the numerical results. The reason is that there is a parallel circuit in the joint section as described in section 2.1.1. Resistance due to the current pathway through the jacket is calculated to be 2 μΩ by the numerical results of Model B and the experimental results. We plan to perform joint tests with larger conductors having large number of the tapes to evaluate joint resistance for single tapes experimentally.

3. Effect of Cutting Plane Angle on the Resistance

In this section, a relationship between the cutting-plane angle as shown in Fig. 1 and the joint resistance was evaluated by a two dimensional current distribution analysis. And we discussed joint structure of a ReBCO conductor to achieve smaller joint resistance.

Figure 8 shows the numerical model. Structure of the tape, boundary conditions and method of evaluating the joint resistance are the same as is used in the former numerical analysis of the Model A. The thickness of the copper layer was 100 μm and cutting-plane angle, θ is chosen as a parameter in these analysis.

Figure 9 shows a relationship between the cutting-plane angle and the joint resistance. In the figure, the symbols indicate the joint resistance obtained by the numerical analysis and the solid line indicates simply esti-

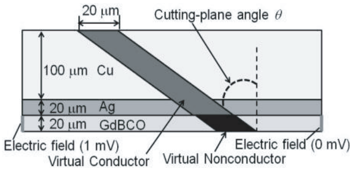

Fig. 8 A model for the tape having a cutting-plane angle.

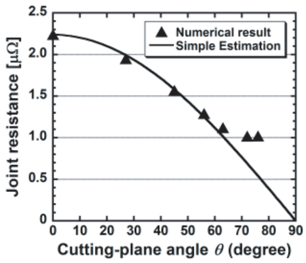

Fig. 9 A relationship between the cutting-plane angle and the joint resistance.

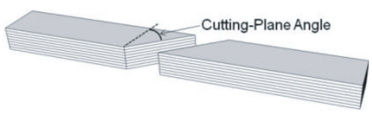

Fig. 10 Schematic view of the alternative joint structure.

mated joint resistance by assuming that the joint resistance is inversely proportional to the contact area of the conductive metal layers. The joint resistance obtained by the analysis gives close agreement with the simply estimated resistance below the point of the cutting-plane angle of 63-degree. The obtained joint resistance becomes, however, constant value of 1 μΩ above the cutting-plane angle of 72-degree whereas the simply estimated one monotonically decreases. In the case of 72-degree, current flowing path through the conductive layers becomes longer, which causes an increase in joint resistance. Therefore, the joint resistance in the mechanical butt joint of a single GdBCO tape cannot be reduced below 1 μΩ by increasing the angle. Based on the joint resistance, electric power to remove the joule heat at the joint sections of remountable HTS magnet for FFHR is calculated about 60 MW. This value is calculated under the following conditions [8]. The conductor is made by laminating 80 GdBCO tapes of thickness of 5 mm and has critical current of 100 kA at 20 K under several magnetic fields. The joint resistance for the conductor is 1/80 of that for the single tape. The number of the joint sections is 8000. And we assumed that cooling power is 53 times of the joule energy loss based on estimation of the cryogenic refrigeration power in ITER design [9].

Figure 10 shows the alternative joint structure of the butt joint. The above problem could be solved by this joint method because the current can flow uniformly at the contact surface through the conductive metal layers even though the cutting-plane angle increases. In this case, the joint resistance could agree with the simply estimated one shown in Fig. 9. With this assumption, the joint resistance in the mechanical butt joint with single GdBCO tapes is about 0.4 μΩ in the case that cutting-plane angle is 80-degree and the electric power can be reduced to be about 21 MW in the above conditions. The cutting-pane angle of 80-degree could be reasonable and compact design because the length for the joint section is 340 mm on a half pitch of helical coil of about 12.6 m [10] when we use the conductors having cross-sectional area of 60 mm wide and 40 mm high designed by NIFS [8]. However, in the resistance, the fusion reactor could not be operated without restrictions on cost of electric power availability. At least, the resistance should be reduced to about 50%. In this case, the refrigeration power for the joule loss in the joint section is about 10.5 MW and that for HTS magnet without the joint section is about 3.9 MW. The total power is the same as that of the conventional design with LTS coils operated at 4.5 K of about 19 MW [9]. Assumed joint methods for smaller joint resistance are inserting other materials between joint surfaces and applying joint pressure more uniformly to the joint surface.

4. Conclusions

As a first step for R&D of mechanical butt joint of a stacked ReBCO conductor, joint resistance for single GdBCO tape was evaluated by experiments and current distribution analyses. The joint resistance could be reduced by increasing thickness of the conductive metal layer of the tapes and cutting-plane angle of the conductor. In addition, joint structure having angle with respect to the width direction could achieve the joint resistance of 0.4 μΩ, which corresponds to 5 nΩ for 100 kA class conductor. The resistance only has to be decreased more, at least almost a half of the present value, to be accepted from the view point of electric power for cooling.

Acknowledgments

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