Bridge-Type Mechanical Lap Joint of a 100 kA-Class HTS Conductor having Stacks of GdBCO Tapes*)

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In this paper, we reported design, fabrication and test of a prototype 100-kA-class high-temperature superconducting (HTS) conductor, especially for joint section, to be used for segmented HTS helical coils in the FFHR-d1 heliotron-type fusion reactor. The conductor has a geometry of three rows and fourteen layers of Gadolinium Barium Copper Oxide HTS (GdBCO) tapes embedded in copper and stainless steel jackets and has a joint section with bridge-type mechanical lap joint. We introduced improved method to fabricate the joint based on pilot experiments and we were able to apply a current of ~ 120 kA at 4.2 K, 0.45 T to the sample without quench at joint. The obtained joint resistance was ~ 2 nΩ, which was lower than our previous data. Though joint resistance increased with a rise in current and magnetic field, predicted joint resistance in the environment of actual helical coil in the FFHR-d1 was small enough to properly run the cryoplant of the reactor.

Keywords: high-temperature superconductor (HTS), REBCO, fusion reactor, helical reactor, FFHR-d1, mechanical joint, joint resistance, remountable HTS magnet, segmented HTS magnet

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1. Introduction

The FFHR-d1 heliotron-type fusion reactor requires 100-kA-class superconducting conductors for a pair of helical coils experiencing a maximum magnetic filed of 12 T [1]. The use of high-temperature superconducting (HTS) conductors can allow the coils to be operated at elevated temperatures (> 20 K), where the coils can have higher heat capacity and lower refrigeration energy than low-temperature superconducting (LTS) coils. These features could make it possible to fabricate the coils by assembling short conductors or segments with resistive joints [2, 3]. Figure 1 shows schematic of the present design of the FFHR-d1 using the above idea, which can give heliotron-type fusion reactors a solution for an engineering issue to fabricate large and complex helical coils. Among HTS wires and tapes, we are now choosing a Rare-Earth Barium Copper Oxide HTS (REBCO) tape as the first candidate to be used for the conductor because it can maintain high critical current at high temperature and high magnetic field. The HTS conductor for the helical coil is fabricated by stacking untwisted REBCO tapes and embedding them inside a rectangular or a concentric copper and stainless steel jackets [4]. The joint sections in the basic option shown in Fig. 1 have a stepwise geometry and tape layers are joined by soldering [5] or by bridge-type mechanical lap joint [6]. The straight joint sections for ~ 1 m are located every half-pitch of the helical coil, which has little influence on the magnetic field for plasma confinement. Here we note that the heliotron-type reactor as a direct current (DC) machine can use the simple stacked conductor with high mechanical strength and thermal stability. Adjustment of REBCO tapes to be parallel to the magnetic

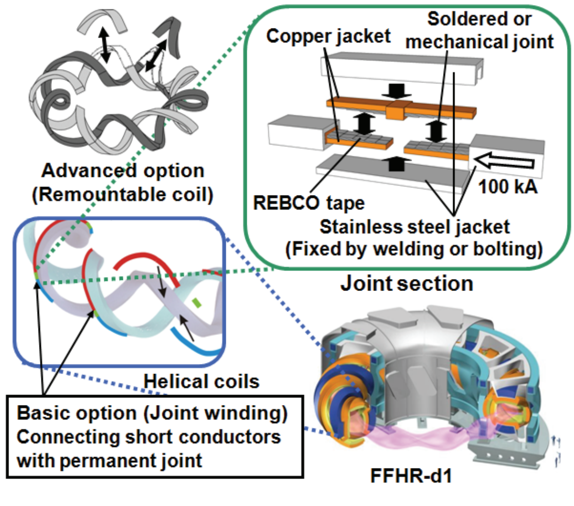

Fig. 1 Schematic of the present design of the FFHR-d1 using segmented HTS helical coils.

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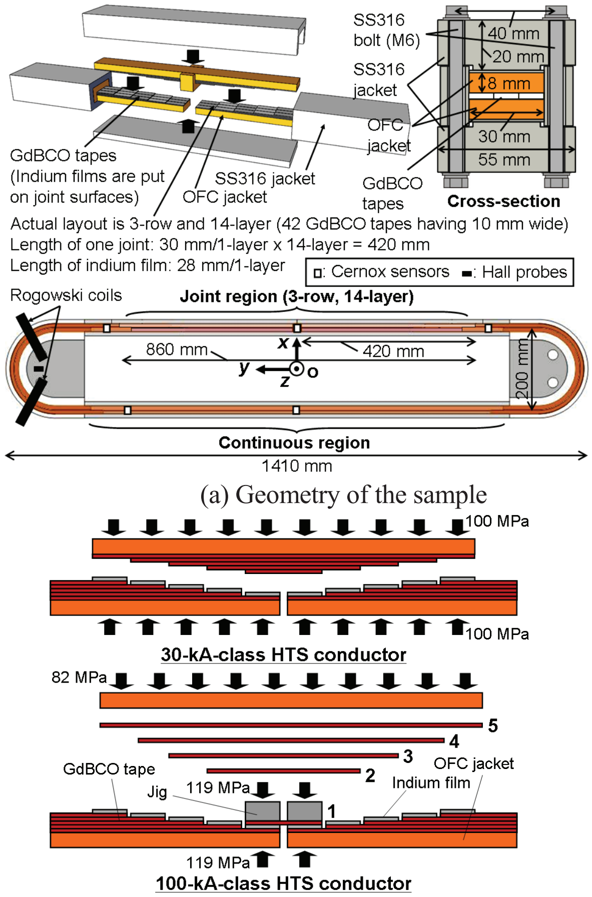
field can avoid critical current degradation and reduce alternating current (AC) losses and shielding current [7]. The acceptable excitation time is predicted to be ~ 6 hours considering AC losses, even without the above adjustment, in the present design where a temperature rise of 10 K is allowed with a maximum nuclear heating of 600 W/m^3. The interlayer resistance between respective REBCO tapes in continuous region of the conductor is predicted to be ~ 20 nΩ for 1 m overlap length [8], which is enough small for current to transit from one tape to other tapes when hot spot occurs in joint section for example. High thermal conductance with the copper jacket having large cross-section also could make minimum propagating distance longer and make it possible to detect quench though detail technique for quench detection is under consideration.

We have already fabricated and tested a 30-kA-class HTS conductor sample having a bridge-type mechanical lap joint [4, 9, 10]. The conductor sample consisted of two rows and ten layers stacked Gadolinium Barium Copper Oxide HTS (GdBCO) tapes embedded in copper, stainless steel and glass fiber-reinforced plastic (GFRP) jackets. We successfully achieved a critical current of ~ 70 kA at 4.2 K, 1.2 T [9]. The joint resistance was ~ 4 nΩ [10], which was acceptable for delivering power for cryogenic refrigeration in the FFHR-d1. As a next step, we fabricated and tested a 100-kA-class HTS conductor having bridge-type mechanical lap joint. In this paper, design, fabrication and experimental results are reported especially for the joint. At first, we performed a pilot experiment using three rows and four layers stacked GdBCO conductor to show the validity of a method to fabricate joint. After that we fabricated and tested the 100-kA-class GdBCO conductor sample having three rows and fourteen layers at the test facility at the National Institute for Fusion Science (NIFS).

2. Design of Joint Section for 100-kA-class HTS Conductor Sample

Figures 2 (a) and (b) show a geometry of the 100-kA-class HTS conductor for this experiment and the method to fabricate the joint section, respectively. The sample consists of three rows and fourteen layers of GdBCO tape embedded in oxygen-free copper (OFC), type-316 stainless steel (SS316) and GFRP jackets. The GdBCO tape (FYSC-SC10, Fujikura Ltd.) was 10 mm wide and had a layered structure of Hastelloy substrate (100 µm)/buffer layers (0.5 µm)/GdBCO (2.3 µm)/silver (8 µm)/tin (2-4 µm)/copper (100 µm). The total length of the GdBCO tape used for the sample was about 130 m, a half of which has a critical current of 660 A and another has that of 644 A at 77 K, self-field. We predicted critical current of the conductor sample is over 100 kA at 4.2 K, self-field based on numerical analysis, the method was reported in [9]. The conductor was connected by bridge-type mechanical lap joint to be one turn race-track coil having no current leads: current is supplied by induction



(a) Geometry of the sample

(b) Method to fabricate the joint section

Fig. 2 Schematic of the 100-kA-class HTS conductor sample.

method using bias magnetic field. The joint surface of the GdBCO tape (surface of copper layer) was polished by a sandpaper with a grade of #400, which was decided based on a pilot experiment described in Section 3, then cleaned with ethanol to decrease film resistance caused by an oxide layer and a smear. 100-µm-thick indium films were inserted between the joint surfaces to prevent misalignment and achieve nearly uniform contact pressure distribution. Additionally 50-µm-thick and 200-µm-thick indium films were inserted between the GdBCO tape and the OFC jacket and between the OFC and SS316 jackets, respectively. Because the jackets experienced bending deflection when contact pressure was applied by bolting the jacket, the jacket needed sufficient thickness to avoid its plastic deformation and a compliant layer was also needed for achieving uniform contact pressure distribution. We plan to weld the stainless steel jacket while a pressing machine gives the contact pressure in fabrication of the actual coil. Cross-sectional size of the jacket can also become small enough to be accepted in limited space for the helical coil. The 100-kA-class conductor sample was mechanically reinforced by stainless steel support structure to withstand electromagnetic forces as well as the 30-kA-class conductor sample described in [4]. Numerically evaluated tensile stress in GdBCO tapes in the joint region is less than 5 MPa with the support structure, which means joint pressure is less affected by electromagnetic forces. The detail investigation on the influence of tensile, bending and torsion electromagnetic forces on the joint in the actual reactor environment is our future work.

In the fabrication of 30-kA-class HTS conductors [9], all GdBCO tapes joined at one time by applying a joint pressure of 100 MPa from outside of the jackets. One time, we failed the fabrication at that time; there existed overlapping of the steps and it caused quench at joint with a large joint resistance of ~ 30 nΩ. We improved the fabrication method where a joint pressure of 119 MPa was applied to each step individually by bolting a jig as shown in Fig. 2 (b). After joint pressure was applied, the jig was removed (the pressure was released) to put next layer. Joint resistance is less influenced significantly by this unloading process, which was confirmed in a pilot experiment described in Section 3. Before putting the next layer, we were able to check if overlapping of the steps or rows occurred and if relatively uniform pressure distribution was achieved using pressure monitor sheets. After setting all GdBCO tapes, a joint pressure of 82 MPa was applied from outside of the jackets.

3. Pilot Experiments

Before fabrication and test of the 100-kA-class HTS conductor sample, we performed some pilot experiments. At first, we confirmed influences of polishing process for joint surface and history of joint pressure (loading history) on joint resistance. We prepared sample of mechanical lap joint of single GdBCO tape with an inserted indium film of 100 μm thick. Joint surface (copper surface of the GdBCO tape) was polished with a sandpaper of #400 or #3000 (alumina particles having 40 μm or 5 μm in particle diameter, respectively). Joint resistance was evaluated by current and voltage drop in the joint region at 77 K, self-field with a joint pressure of 100 MPa. To investigate the influence of loading history, the joint resistance was evaluated with a joint pressure of 120 MPa for some samples. The pressure released and applied again to be 80 MPa at room temperature, then joint resistance was evaluated again at 77 K. The loading history was almost the same as fabrication process in the joint of the 100-kA-class HTS conductor sample. Figure 3 shows joint resistivity (product of joint resistance and joint surface) as a function of joint pressure. The results obtained with single and double layer bridge-type lap joint, where the joint surface was polished with alumina particles having a particle diameter of 5 μm [6], are also shown in this figure. The results showed that rougher joint surface tended to achieve lower joint resistance. Holm's contact theory [11] explained contact resistance in mechanical contact region is summation of constriction resistance and film resistance. In the mechanical joint with an inserted indium film, film resistance

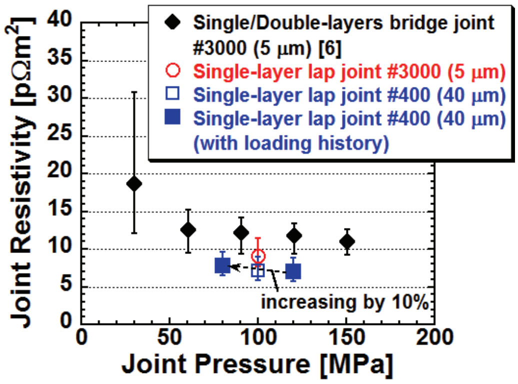


Fig. 3 Joint resistivity as a function of joint pressure obtained in pilot experiments.

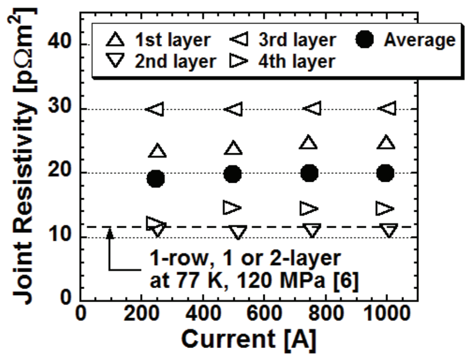


Fig. 4 Joint resistivity as a function of current in a GdBCO conductor having a geometry of three rows and four layers.

can not be ignored because surface of the compliant indium can not be polished easily. Rougher joint surface with relatively large sized notch can break an oxide layer on surface of the indium and it could make joint resistance lower. Based on the result, we chose to use the #400 sandpaper for polishing process for the joint surface in the 100-kA-class HTS conductor. We also noted that the joint resistance increased by just ~ 10% after joint pressure was released and applied again; the loading history in the method to fabricate the sample is not so significant.

We also prepared a sample of bridge-type mechanical lap joint of a GdBCO conductor with a geometry of three rows and four layers embedded in OFC and SS316 jackets, which have the same cross-sectional area as that of the 100-kA-class HTS conductor sample. The method to fabricate the joint was also the same as that for the 100-kA-class HTS conductor sample. Currents up to 1000 A were applied to each layer (each three rows) individually and voltage drop in each layer was also evaluated in liquid nitrogen. Figure 4 shows the obtained experimental result. Joint resistance was almost constant with a change in the value of current. This means there did not exist damaged region to decrease critical current density. Average of obtained joint resistivity was twice larger than predicted value. That could be caused by joint pressure distribution.

The detailed analysis of relationship between the pressure distribution and joint resistance is our future work.

4. Test of 100-kA-class HTS Conductor Sample

The fabricated sample was immerged in liquid helium at a test facility of NIFS and the temperature of joint region was kept to be 4.2 K. A pair of superconducting split coil applied the bias magnetic field up to 8 T to the central region of the sample. Current was induced when the magnetic field changed and attenuated when the field becomes constant. Figure 5 shows typical experimental results over time for the sample, where a maximum applied current of 118 kA was successfully achieved at 4.2 K, 0.45 T. The current was evaluated with Rogowski coils and Hall probes, the bias magnetic field was that at the center of the joint (x = 100 mm and y = 0 mm). Rogowski coils' raw data had offset voltage and the evaluated current increased over time though current should decay. We considered voltage of the raw data obtained after current sufficiently attenuated as the offset voltage. The current evaluated by Rogowski coils after introducing the offset voltage is similar to, but slightly differs from that evaluated by Hall probes. Our previous study [9] indicated that current evaluated by Hall probes count magnetic field generated by shielding current induced in HTS tape whereas Rogowski coils do not count this. In the same manner, we use mainly current evaluated by Rogowski coils to estimate joint resistance in this paper.

The time constant of current attenuation shown in Fig. 5 was used to obtain the joint resistance for the entire joint at each current. For instance, joint resistance at 50 kA and 100 kA were obtained by using time constant of current attenuation from 55 kA to 45 kA and from 105 kA to 95 kA, respectively. Time constant is expressed as L/R, where R and L are the joint resistance and self-inductance of sample, respectively. The calculated self-inductance was 2.21 μH. Figure 6 shows obtained joint resistance as a function of applied current. Joint resistance increased with a rise in the value of current; that at 100 kA (~ 1.8 nΩ) was 1.2 times larger than that at 30 kA (~1.5 nΩ). There is possibility that the sample had damaged regions but that was not severe or there existed variability of joint resistance among GdBCO tapes.

Figure 7 shows joint resistance and joint resistivity as a function of bias magnetic field obtained at an applied current of 30 kA. The joint resistivity was improved compared to our previous data. Joint resistance at 7.5 T increased by ~20% compared to that at self-field because of magnetoresistance of constituted material of the GdBCO tape and mechanical contact points in joint region. According to our previous report [12], the joint resistance in mechanical lap joint of GdBCO tape with an inserted indium film is almost proportional to bias magnetic field. In this test, bias magnetic field has distribution [10] and average magnetic field is 4.5 T when the bias magnetic filed is 7.5 T at center of the joint. Therefore, joint resistance at a uniform magnetic filed of 4.5 T is predicted to be ~ 1.2 times larger than that at self-field based on this test. Actual helical coil has also magnetic field distribution and its averaged value is ~ 6 T though the maximum value is 12 T. If the orientation of REBCO tapes is adjusted to be parallel to the magnetic field as described in Section 1, the influence of magnetoresistance on joint resistance in the actual helical coil is almost the same as that in this experiment. The averaged joint resistance of the helical coil can be predicted

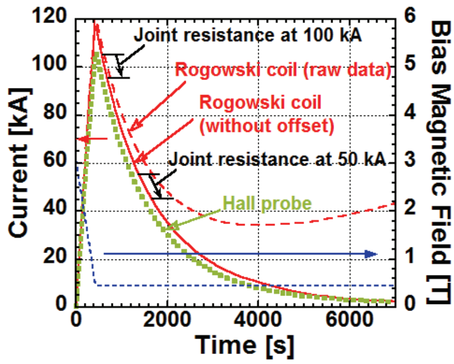


Fig. 5 A typical excitation test result for the 100-kA-class HTS conductor sample.

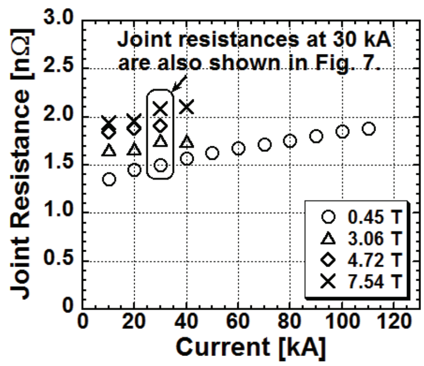


Fig. 6 Joint resistance as a function of current in the the 100-kA-class HTS conductor sample.

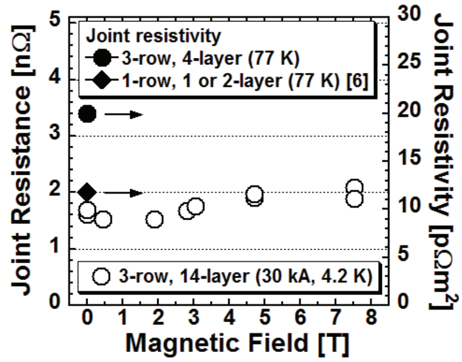


Fig. 7 Joint resistance as a function of bias magnetic field.

to ~ 1.3 times larger than that at self-field. Based on the obtained data and the above discussion, the joint resistivity in the actual helical coil is predicted to be ~ 14 pΩm^2. The value is still small enough to properly run the cryoplant of a helical fusion reactor as discussed in [10].

5. Conclusions

In this study, we fabricate and tested 100-kA-class HTS conductor sample having three rows and fourteen layers of GdBCO tape. We successfully applied a current of ~ 120 kA to the sample and the obtained joint resistance was lower than our previous data with improved method to fabricate the joint. Though joint resistance increased with a rise in current and magnetic field, the resistance is still acceptable for design of helical coil in the FFHR-d1.

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