Measurement of the Joint Resistance of Large-Current YBCO Conductors*)

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Feasibility studies on applying high-temperature superconductors (HTS) to the LHD-type heliotron fusion energy reactor FFHR are being carried out. Because the HTS conductor has high cryogenic stability at elevated temperature operations (e.g. 20 K) and the refrigeration power has enough margins, it is considered that Joule heating dissipation generated at joints of conductors is acceptable to facilitate the segmented fabrication of the helical coils of FFHR. In this study, the joint resistance with 10-kA class YBCO conductors has been measured to evaluate the joule heating dissipation in the FFHR magnet. The experiment has been carried out by fabricating a soldered lap joint and a mechanical lap joint. The feasibility of segmented fabrication is examined by the measured results.

Keywords: high-temperature superconductor, YBCO, joint resistance, soldered lap joint, mechanical lap joint

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1. Introduction

Feasibility studies of the LHD-type heliotron fusion energy reactor FFHR are being carried out at NIFS. For FFHR, the ~40-m diameter helical coils are required [1, 2]. There are three options for the superconductor selection: the cable-in-conduit (CIC) conductor using low-temperature superconducting (LTS) strands such as Nb_3Al or Nb_3Sn [3], the indirectly-cooled solid-type conductor using LTS [4] and the indirectly-cooled solid-type conductor using high-temperature superconductors (HTS) represented by YBCO [5–8]. Presently, the well-established LTS conductors are being used in fusion devices like the Large Helical Device (LHD), and this could be the primary option for the FFHR magnet. They, however, are prone to quench due to the low specific heat of the material at 4 K unless the strands are well cooled by helium in CIC conductors. In addition, degradation of the conductor critical current due to the strain is a large issue; the strain is exerted on LTS strands by the winding process, by the cooling from ~1000 K (for heat treatment) to 4 K (for coil operation) and by cyclic operations in case of CIC conductors. In contrast, the HTS provides high cryogenic stability due to the elevated temperature operation associated with a reduced refrigeration power. Because of these advantages, the use of HTS conductors in future fusion reactors is being studied [9, 10], and the segmented-fabrication method using the HTS conductors has been proposed for FFHR [6–8]. Figure 1 shows a schematic illustration of the segment-fabricated HTS helical coils. In this fabrication method, 100-kA class HTS conductors are used with joints in every half-pitch. Figure 2 shows schematic illustrations of a 100-kA class conductor design for FFHR: (a) the joint section and (b) the cross-sectional image. The conductor has a stainless-steel jacket outside the stabilizing copper to secure the mechanical rigidity and the jacket is welded at the joint. The strain is a problem also for HTS tapes [11–13], however, during the fabrication of the half-pitch segment of HTS conductors, YBCO tapes are imbedded into the jacket which is already bent and twisted in a helical shape, and thus, the YBCO tapes experience almost no strain during the conductor fabrication. Since the conductor assembly (by soldering) is done at ~473 K, the difference of thermal contractions among composites of the conductor may give rise to some limited strains to YBCO tapes during the cooldown. The Joule heating dissipation is produced at joints of conductors, however it is considered to be acceptable by the refrigeration power of FFHR [14].

In this study, 10-kA class YBCO conductors have been fabricated and joined to make samples. Then, the measurements of joint resistances have been carried out to verify the feasibility of the segmented fabrication of the helical coils of FFHR with the HTS option.

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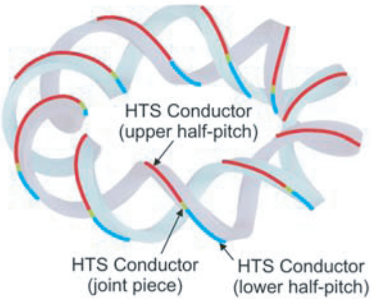

Fig. 1 Schematic illustration of the winding method of segment-fabricated helical coils using HTS conductors.

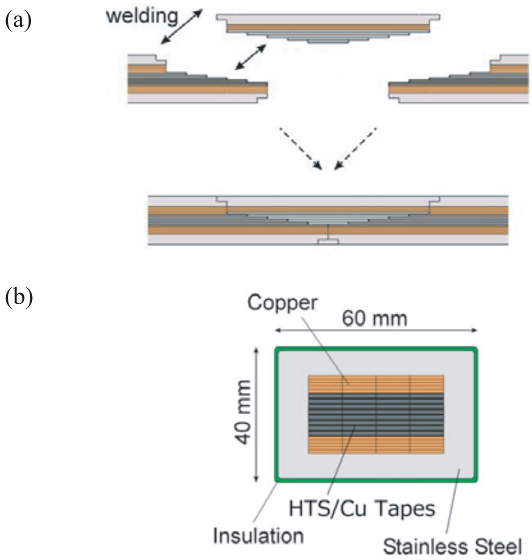

Fig. 2 Schematic illustrations of a 100-kA conductor design for the helical coils of FFHR: (a) the joining method and (b) cross-sectional image.

2. 10-kA Class Conductors

As stated in the former section, 10-kA class YBCO conductors have been fabricated and tested in this study. Here, the "10-kA class" means that the rated current of the conductor is about 10 kA at the operation conditions of temperature 20 K and magnetic field 12 T. The fabricated conductors used 14 YBCO tapes (seven layers and two rows) simply imbedded in copper jackets. A cover of the jacket is fixed by 60%Pb-40%Sn solder. The joint part has a stepwise pattern of YBCO tapes to overlap them. In the present experiment, YBCO tapes having a copper lamination is used ("344 Superconductor" manufactured by American Superconductor with a 4.3 mm width and 0.2 mm thickness). The tape consists of a Ni-W alloy substrate (50-75 μm), buffer layer (~200 nm), YBCO (~1 μm), Ag (~1 μm) and copper lamination (123-147 μm). The critical current is ~90 A at 77 K in self-magnetic field. Figure 3 shows schematic illustrations and a photograph of a 10-kA class joint sample. Figure 4 shows schematic illustrations of the fabricating method for (a) a soldered lap joint and (b) a mechanical lap joint.

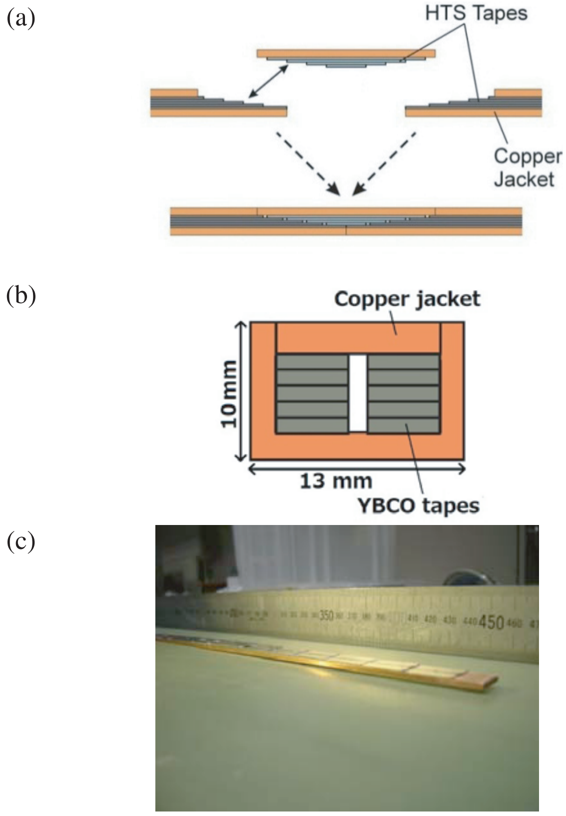

Fig. 3 Schematic illustrations and a photograph of the 10-kA class joint sample: (a) the joining method, (b) cross-sectional image and (c) a joining piece with stepwise lamination of YBCO tapes on a copper plate.

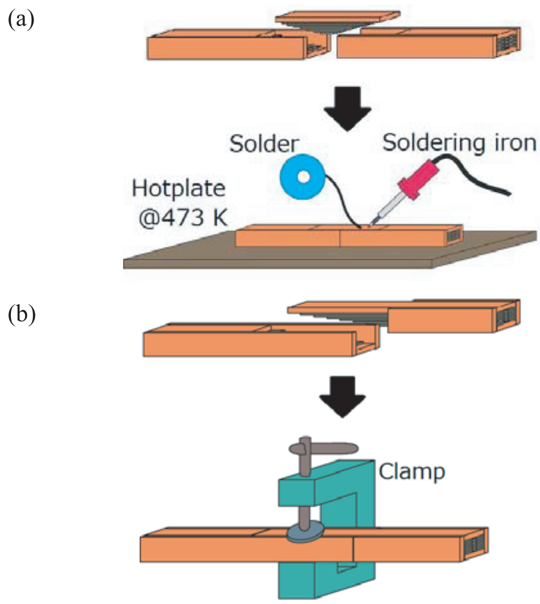

Fig. 4 Schematic illustrations of the fabricating method for (a) a soldered lap joint and (b) a mechanical lap joint.

3. Joint Method and Experiments

To make joint samples in this experiment, two methods were used: a soldered lap joint and a mechanical lap joint. A soldered lap joint method joins conductors by applying a solder and it is considered that a low joint resistance can be obtained. In this fabrication, 60%Pb-40%Sn solder is used at the temperature of ~473 K.

The mechanical lap joint method joins conductors by applying compressive forces on the joint section temporarily and then the welding of the outer stainless-steel jacket is done. In this method, though the joint resistance may become higher, the construction process of the FFHR helical coils will be further eased. In the present experiment, the conductor has no stainless-steel jacket, and thus, the joint section was joined by clamps, not by welding.

In both methods, no specific treatment was done on the surfaces of YBCO tapes. And only one 10-kA class sample was fabricated for each method. The conductor was joined by facing the YBCO sides with each other. Potential taps were attached to the conductor surfaces to measure the voltage rise by the joint resistance as well as by the flux-flow resistance of the conductor (when the transport current exceeds the critical current). All experiments were done in liquid nitrogen at the temperature of 77 K and self-magnetic field.

The joint resistance of two overlapped YBCO single tapes was measured to be used as a reference before carrying out the 10-kA class conductor tests. Then, the measurement of the joint resistance of 10-kA class conductor samples, with a soldered lap joint and a mechanical lap joint, were performed.

4. Results and Discussion

A series of experiments were carried out several times per sample and similar results were obtained in each condition. The following results are the representative data for each sample.

Figure 5 shows schematic illustrations of a single-tape joint with two overlapped YBCO tapes. Potential taps are soldered at a continuous part (Tap A) and at a joint part (Tap B). The joint resistance is evaluated from the voltage signal of Tap A as shown in Fig. 6. The gradient of the voltage as a function of current is the joint resistance when the current is below 90 A. Above this current; there appears a flux-flow resistance for Tap B. In this figure, the joint resistance is found at 98.7 nΩ and the contact resistivity is evaluated to be 42.5 nΩcm^2 taking account of the contacting area We note that the presently obtained contact resistivity is close to the values evaluated by other authors such as presented in [15] that gives 30 nΩcm^2

For the 10-kA class sample with a soldered lap joint, Fig. 7 shows the measured joint voltage as a function of current. In Fig. 7, the joint resistance is evaluated to be 20.2 nΩ and the contact resistivity is 109.5 nΩcm^2. This is about 2.5 times larger than the value obtained by the single-tape sample It is considered that the joining piece was insufficiently pressed when the conductor was joined and the soldering surfaces might not have been uniform Using the

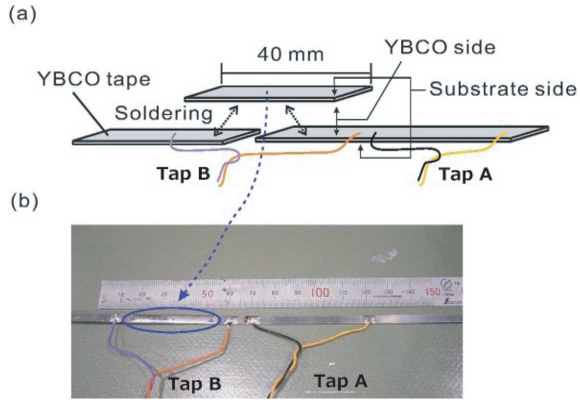

Fig. 5 (a) Schematic illustration of a single-tape joint with two overlapped YBCO tapes and (b) its photograph.

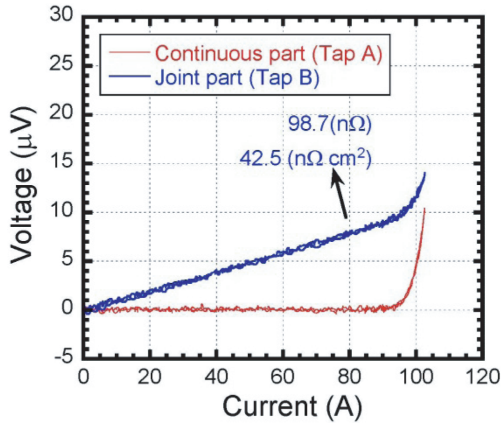

Fig. 6 Joint voltage of a singletape joint as a function of current.

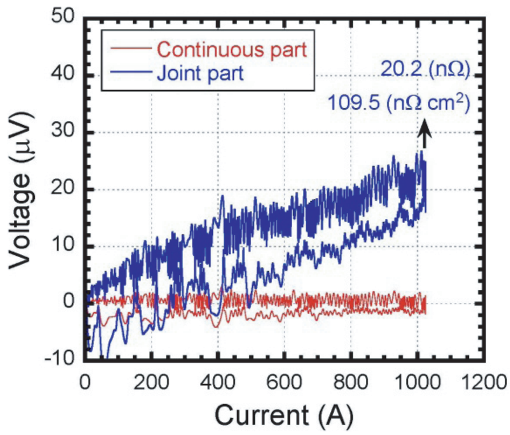

Fig. 7 Joint voltage of the 10-kA class soldered lap joint as a function of current.

value obtained by the 10-kA class joint sample, the overall joint resistance of a 100-kA class conductor is expected to be 1.1 nΩ, consisting of 2 connections at one joint location with 40 HTS tapes, each having a 50 mm joint length and the width of the tape 10 mm. As the entire helical coils will have ~8000 joints (~400 turns of windings in each coil, 10

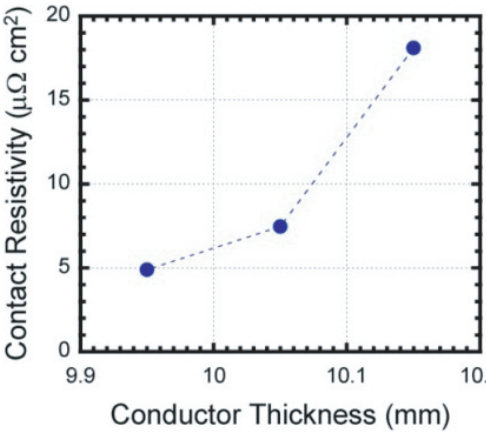

Fig. 8 Contact resistivity obtained by the 10-kA class sample in mechanical lap joint as a function of the conductor thickness.

segmented conductors for a toroidal turn and 2 coils), this requires ∼5.2 MW increase of electrical power for the refrigeration system at room temperature, assuming the coil operation temperature at 20 K. This seems to be acceptable since the required electrical power for the entire FFHR refrigeration system is supposed to be ∼30 MW in case of the LTS options.

For a mechanical lap joint, Fig. 8 shows the contact resistivity as a function of the compressive load which is expressed as the conductor thickness in the present experiment. It is found that the contact resistivity decreases as the load increases, however, the minimum value so far is observed at 4.9 $\mu\Omega cm^2$ (resistance: 406 nΩ). According to the previous study by A.J. Dietz *et al.* [16], the contact resistivity for the YBCO single tape is 200-40 $n\Omega cm^2$ by applying a pressure at 40-200 MPa. In another study by S. Ito *et al.* [17], the contact resistivity of a two-layer joint of BSCCO tapes is twice or three times higher than that of a single layer joint because of the misalignment of HTS tapes. Therefore, the joint resistivity measured in the present experiment may become more than an order of magnitude higher than of [16] because of the misalignment of 14 tapes with insufficient loads. In a mechanical lap joint, a compressive pressure of the order of 1 MPa is required to achieve the low resistance equivalent as that of a soldered lap joint according to [16, 17]. Therefore, the soldered lap joint seems presently more feasible than the mechanical lap joint.

5. Summary

Measurements of the joint resistance of 10-kA class YBCO conductors have been carried out to verify the feasibility of the proposed segmented fabrication of the FFHR helical coils with the HTS option. It has been found that the contact resistivity of a soldered lap joint of the 10-kA class conductors is 109.5 $n\Omega cm^2$, which is about 2.5 times larger than that obtained by the single-tape joint (42.5 $n\Omega cm^2$). The contact resistivity of a 10-kA class sample in the mechanical lap joint measured with a limited condition was about 45 times larger than that of the soldered lap joint. It seems that the soldered lap joint is acceptable for the FFHR helical coils, though further reduction of the contact resistivity is expected. To practically apply the mechanical lap joint, the joint resistance has to be reduced considerably by applying a large pressure. Presently, the soldered lap joint seems more feasible than the mechanical lap joint.

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[1] A. Sagara *et al.*, Fusion Eng. Des. **81**, 2703 (2006).
[2] A. Sagara *et al.*, Fusion Eng. Des. **83**, 1690 (2008).
[3] S. Imagawa *et al.*, Nucl. Fusion **49**, 075017 (2009).
[4] K. Takahata *et al.*, Fusion Eng. Des. **82**, 1487 (2007).
[5] G. Bansal *et al.*, IEEE Trans. Appl. Supercond. **18**, 1151 (2008).
[6] G. Bansal *et al.*, Plasma Fusion Res. **3**, S1049 (2008).
[7] N. Yanagi *et al.*, Plasma Fusion Res. **5**, S1026 (2010).
[8] N. Yanagi *et al.*, Fusion Sci. Technol. **60**, 648 (2011).
[9] W.H. Fietz *et al.*, Fusion Eng. Des. **86**, 1365 (2011).
[10] L. Bromberg *et al.*, Fusion Eng. Des. **54**, 167 (2001).
[11] K. Katagiri *et al.*, Physica C **468**, 1697 (2008).
[12] M. Qiu *et al.*, Supercond. Sci. Technol. **20**, 162 (2007).
[13] S.J. Sun *et al.*, Supercond. Sci. Technol. **16**, 984 (2003).
[14] H. Hashizume *et al.*, Fusion Eng. Des. **63**, 449 (2002).
[15] M. Polak *et al.*, Supercond. Sci. Technol. **19**, 817 (2006).
[16] A.J. Dietz *et al.*, IEEE Trans. Appl. Supercond. **18**, 1171 (2008).
[17] S. Ito *et al.*, to be published in IEEE Trans. Appl. Supercond.