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革新的核融合炉実現に向けた分割型高温超伝導マグネットの研究開発 ～ 高温超伝導導体の着脱可能な接合法の開発状況 ～

R&D on a segmented high-temperature superconducting magnet toward realization of an innovative fusion reactor: Progress in development of a demountable joint of high-temperature superconducting conductors

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1. Introduction

Fabrication of huge and complex superconducting coils and magnets is one of the important technical issues for fusion DEMO and commercial reactors. The segmented fabrication of superconducting coils using high-temperature superconducting (HTS) conductors [1]–[4] is now being considered as a solution for the above technical issue. The use of 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. The joint of HTS conductors is the key technology for the concept, and R&D for the joints has been conducted since the year of 2000 in Tohoku University. Since 2012, Tohoku University and National Institute for Fusion Science (NIFS) have collaborated to develop the Stacked Tape Assembled in Rigid Structure (STARS) conductor using *RE*BCO (*RE*$Ba_2Cu_3O_{7-\delta}$) HTS tapes and its joint to be applied to the helical fusion reactor, FFHR-d1 [4]–[6]. During these 15 years, we have increased 10^4 times in achieved current and decreased 10^{-5} times in joint resistance with developed joints [2], [7].

In this presentation, we firstly introduce the design concept of the segmented fabrication of the HTS magnets especially for the helical reactor, and then, address recent progress in R&D on joints of HTS conductors.

2. Design concepts

Fig. 1 shows schematic illustrations of segmented fabrication of HTS coils proposed for the helical reactor. The initial proposal was the remountable (demountable) HTS helical coil, whose half-pitch coil segments are assembled with demountable joints [1], [2]. The design gives attractive features: easy fabrication of huge and complex helical coils at a construction phase and high accessibility to inner reactor components such as a blanket and a divertor at a maintenance phase. As an extension of the concept of the remountable coil, joint-winding of the helical coils was also proposed: the helical coil is wound by connecting half-pitch or one-pitch of conductor segments with permanent joints [3], [4]. Although the conductor segments cannot be demounted after the construction, the concept still has an advantage of easy fabrication of huge and complex helical coils, which is the most important technical issue in the helical reactor.

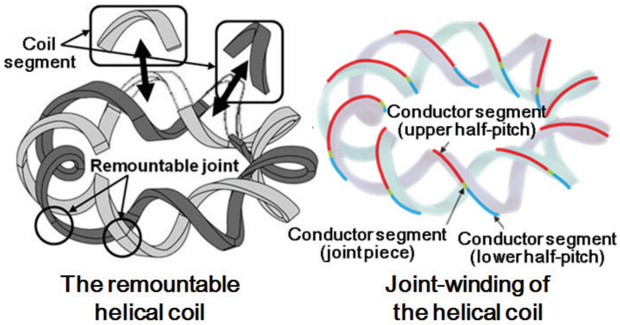

Fig. 1. Schematic illustration of segmented fabrication of HTS helical coils.

3. R&D on joints of HTS conductors

3-1. Proposed joints and achieved resistance

Mechanical joints have been investigated as demountable or permanent joint, in which joint surfaces of the STARS conductors are just pressed together with joint force. Some mechanical joints have been developed [2]: butt joint (scarf joint), edge joint and lap joint (normal-type and bridge-type). Among the above joints, the bridge-type mechanical lap joint was actually applied to 100 kA class prototype STARS conductor as shown in Fig. 2 and we achieved a joint resistance of 1.8 nΩ at 100 kA, 4.2 K [4], [5]. The achieved joint resistance is sufficiently small from the viewpoint of refrigeration energy.

3-2. Resistance dependency on operating conditions

In order to design and optimize the joint with sufficiently low resistance, it is necessary to predict joint resistance dependency on operating conditions and conductor joint structure. For that purpose, we firstly evaluated joint resistance as functions of temperature, magnetic field orientation and conductor structure, using samples of the mechanical lap joint of *RE*BCO tapes [7]–[9]. Then we proposed a model to predict contact resistance, which is one of the factors of the joint resistance. The model so far can predict joint resistance as functions of temperature and magnetic field except in the case at temperatures of <10 K and magnetic field parallel to the joint surface [9].

3-3. Mechanical strength

To discuss mechanical strength of the joint, structural analysis for the FFHR magnet system with joint-winding of the helical coil has been conducted using the multi-scale analysis [7], [10], [11]. The analysis showed that the maximum shear stress of 32 MPa is induced in a plane of joint surface. We also conducted tensile shear tests of mechanical lap joints with inserted indium foils and soldered lap joint of *RE*BCO tapes [7], [10], [12]. The mechanical joint has shear strength of > 32 MPa with joint pressure of > 50 MPa as shown in Fig. 3. On the other hand, soldered lap joint fractured due to stress concentration at the edge of solder before reaching the required load. From the results, the mechanical joint is preferable even in the joint-winding of the helical coil with permanent joints.

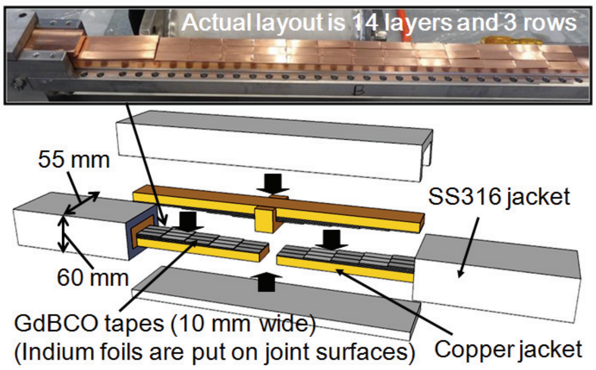

Fig. 2. Bridge-type mechanical lap joint applied to the 100 kA-class prototype STARS conductor.

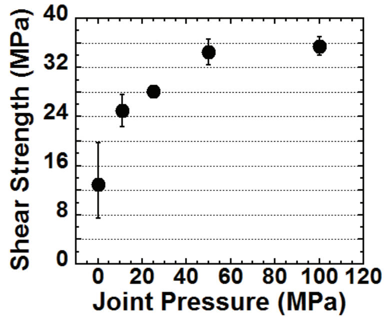

Fig. 3. Shear strength of the mechanical lap joint as a function of joint pressure.

3-4. Quality assurance

In order to reduce joint resistance and its variation, we proposed to apply heat treatment of joint during the fabrication [13]. The joint with the heat treatment showed the joint resistance, reduced to 60% of the value obtained without heat treatment, when we controlled the heating temperature to be 75–90 °C. We have also tried to develop nondestructive testing to inspect the joints: radiation, electromagnetic and ultrasonic inspections. So far, we confirmed X-ray CT can detect macroscopically non-contact region [7], and the other candidates are now under development.

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