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Design prospect of remountable high-temperature superconducting magnet

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ABSTRACT

The remountable (mountable and demountable repeatedly) high-temperature superconducting (HTS) magnet has been proposed for huge and complex superconducting magnets in future fusion reactors to fabricate and repair easily the magnet and access inner structural components. This paper summarizes progress in R&D activities of mechanical joints of HTS conductors in terms of the electrical resistance and heat transfer performance at the joint region. The latest experimental results show the low joint resistance, 4 nΩ under 70 kA current condition using REBCO HTS conductor with mechanical lap joint system, and for the cooling system the maximum heat flux of 0.4 MW/m^2 is removed by using bronze sintered porous media with sub-cooled liquid nitrogen. These values indicate that there is large possibility to design the remountable HTS magnet for fusion reactors.

1. Introduction

The concept of remountable (mountable and demountable repeatedly) superconducting magnet had been proposed using low-temperature superconducting (LTS) materials in 1980s for both tokamak and heliotron reactors [1,2] due to its attractiveness for improving reactor maintenance and/or construction of the large and complex superconducting magnets. The LTS materials, however, could not be available for the design due to both joule heating at joint to lead to quench easily, and large electric power for refrigerating all joints and therefore this concept has no reality at that time.

On the other hand, the high-temperature superconducting (HTS) material can be operated under relatively high temperature (>20 K), which can allow a number of resistive joint because of its high heat capacity and reduced electric power for refrigerating the materials. Utilizing these attractive characteristics, the remountable superconducting magnet with the HTS materials shown in Fig. 1 has been proposed for future fusion reactors, segments of which are mounted and demounted repeatedly with mechanical (or electrical) joints [3–5]. This attractive concept could be very helpful for DEMO or commercial fusion reactors beyond ITER. For example, the concept has been proposed to apply to a component-testing machine (small tokamak), Vulcan [4], and a heliotron-type fusion DEMO reactor, FFHR-d1 [3,5,6]. Among the HTS wires and tapes, a REBCO tape (second generation HTS tape, coated conductor) shown in Fig. 2 is primary candidate to fabricate conductors for the design, which can keep high critical current at relatively high magnetic field and have high tensile strength with the substrate. Although fabricating long REBCO tape keeping high critical current in entire length is one of the most important technical issues, the idea of remountable magnet also makes it possible to use relatively short HTS tapes or wires having high performance.

In this paper, therefore, recent R&D activities are summarized on mechanical joints of HTS conductors in terms of the electrical resistance improvement and heat transfer enhancement for showing prospect of the design. Effect of electromagnetic force on the joint performance will be discussed in a future research to optimize the joint structure with the mechanical support against the large hoop stress.

2. Mechanical joints of HTS conductors

2.1. General description of progress in R&D of mechanical joints

The R&D activities on mechanical joints of HTS conductors in Tohoku University have been performed since 2000 year [3,5,7–15]. Fig. 3 shows three types of proposed and tested joint configuration; mechanical lap [5,7–11], butt [5,7,12–14] and edge [14,15] joints. The first decade in the R&D, BSCCO 2223 tapes (DI-BSCCO Type H, Sumitomo Electric Industries Ltd.) and its stacked conductor were used for test conductors in joint tests as fundamental studies. In

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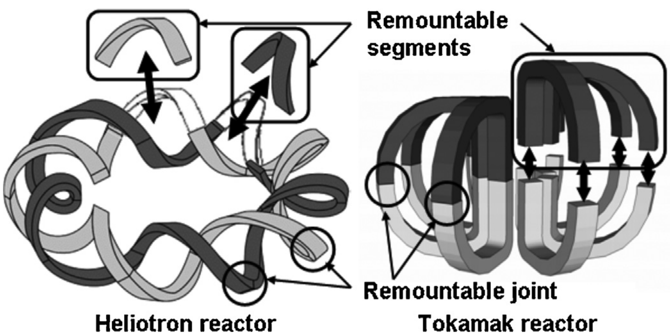

Fig. 1. Schematic illustration of remountable HTS magnets.

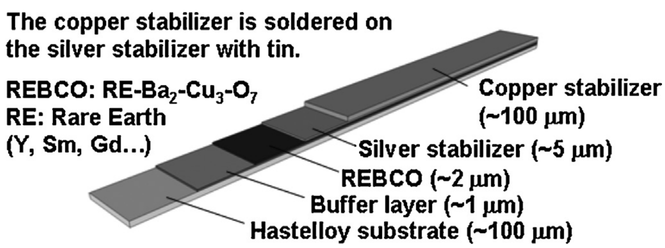

Fig. 2. Schematic illustration of a REBCO tape produced by Fujikura Ltd., Japan.

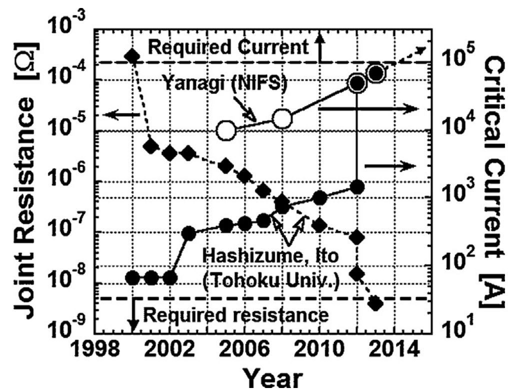

Fig. 4. Progress in performance of simply stacked HTS conductors with mechanical joints.

the second decade (present decade), we have introduced REBCO tapes for test conductors and examined the mechanical joint for a large-scale stacked REBCO conductor. Furthermore, we started corroborative R&D of mechanical joints with NIFS and MIT [10,15]. Fig. 4 shows progress in our R&D of mechanical joints of stacked HTS conductors in terms of the joint resistance and flowing current. In this R&D activity, the required current and resistivity are determined to be 100 kA and 4 nΩ, respectively based on design requirement in FFHR-d1 (100 kA, 13 T) and electric power consumption in the joint region compatible to non-remountable LTS magnet operated at 4.2 K [14]. As seen in the figure, we have almost achieved the allowable joint resistance and can soon fabricate the 100 kA-class HTS conductor sample. The results will be discussed in detail in the next section.

2.2. Mechanical lap joint

In the mechanical lap joint as shown in Fig. 3, broad surfaces of the HTS tapes are jointed mechanically to reduce the joint resistance. The bridge-type mechanical lap joint (mechanical bridge joint) is suitable for the coated conductors having single-sided conductive surface though the number of joint becomes twice larger than that in normal-type one. One of the technical issues in the lap jointing method is how to apply uniform contact pressure distribution avoiding misalignment or overlapping of the layers especially in the case of a multi-layer conductor [8]. To solve this problem, compliant metal films such as an indium film are inserted between the joint surfaces [9,10] and it was quite effective to achieve almost the same joint resistivity (product of joint resistance and contact area) performance in multi-layer joint as that in single-layer joint. Another technical issue by inserting the indium films in the joint region, like delamination in the coated conductors during demounting process, could be solved by using high temperature gas around 400 K to soften or melt the film without degrading the HTS materials. Even in the case without the demounting process, the joint can be applied to a segmented HTS magnet [16], constructed by connecting short conductors with a permanent (non-detachable) joint method; HTS tapes are connected with the lap joint and jackets are welded.

In the latest study [10,17], a HTS conductor sample (30 kA at 6 T and 30 K, 45 kA at 6.1 T and 20 K, 70 kA at 4.2 K and 1.2 T) was fabricated, whose geometry is 10-layer and 2-row GdBCO tapes (FYSC-SC10, Fujikura Ltd.) embedded in copper jackets. The fabricated conductor sample had also joint section of 840 mm long bridge-type mechanical lap joint with inserted indium films. Through the test, we achieved averaged joint resistance of 4 nΩ (4.2 K, below 1 T) and 5.5 nΩ (30 K, 8 T) [10], which enabled transport current to reach critical current without quench at the joint region. The temperature of 30 K was achieved by using liquid helium with heaters to raise the temperature [10]. Fig. 5 shows

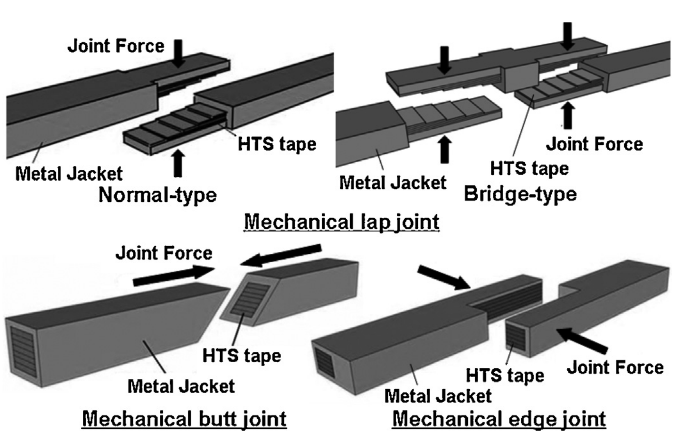

Fig. 3. Schematic illustration of mechanical joints of simply stacked HTS conductors [7–15].

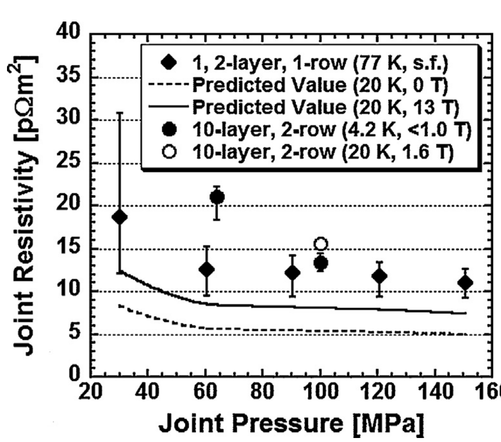

Fig. 5. Joint resistivity as a function of joint pressure in bridge-type mechanical lap joint of stacked GdBCO conductor samples with 100 μm thick indium films [4,10].