Superconducting joint of REBCO wires for MRI magnet

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Abstract. A high temperature superconducting wire (HTS wire) is promising for various superconducting magnet applications because it operates at a higher temperature than a low temperature superconducting wire (LTS wire) is. Particularly, a MRI magnet using the HTS wires (HTS-MRI magnet) is expected to obtain light-weight, compact and low operating cost compared to a LTS-MRI magnet. The MRI magnets are generally operated by a persistent current mode. A magnet of the persistent current mode consists of multiple superconducting magnets and persistent current switch (PCS) that connects with superconducting joints. However, the superconducting joint of the HTS wires has not been realized stably at this time. We have developed a superconducting joint by using a commercial REBCO wire. The HTS-MRI magnet requires that resistivity of less than 10⁻¹²Ωm and current capacity of more than 100 A is achieved by a direct-joint between superconducting layers of the two REBCO wires. Moreover, measurement equipment for low joint resistivity was prepared as measuring the decay of the magnetic field in the one-turn loop. In our R&D, the joint resistance and the critical current were achieved with 155 A and 5.3×10⁻¹³Ω.

1. Introduction
A MRI magnet using high temperature superconducting (HTS) wires will be operated at higher temperature than a conventional MRI magnet fabricated of low-temperature superconducting (LTS) wires. The HTS-MRI magnet is cooled by a conduction cooling with a cryo-cooler, and is expected to obtain light-weight, compact and low operation cost. The LTS-MRI magnet is operated in a persistent current mode, which doesn’t need an electrical current source to keep a constant magnetic field. NbTi wires used in the LTS-MRI magnet are joined with less than 10⁻¹³Ω-digits resistivity. Recently, several groups have tried and succeeded the superconducting joint for REBa₂Cu₃O₇₋₈(REBCO) coated conductors [1]-[4], but the joint has not been realized stably and good reproducibly yet. The interface in superconducting joint of REBCO wires is required to crystallize into a superconducting structure. Optimization and stabilization of the process condition are important for the reproducibility. In our ongoing project, we aim to contribute the development of a HTS-MRI magnet system, which is operated at 50 K by a cryo-cooler cooling. The joint resistivity will be characterized by temporal magnetic field decay of the magnet. If the static magnetic field fluctuates in time in a MRI system, or if the intensity of the magnetic field is not uniform, the phase of the signal measured in response to the variation changes. This change, distortion and deformation of the image in the image to be re-formed, appear to become uneven tint change. In particular, the speed of recent images, for high performance, susceptible to these fluctuations, the time stability of 0.1 ppm/hour is required.
2. Superconducting joint of HTS wire

2.1. REBCO wire
The REBCO wire has better current loading performance under high magnetic field than other HTS wires do, such as BSCCO and MgB2. Moreover, in the case of the persistent current mode operation, a flux flow resistivity in the wire is needed to be extremely low[5]. Since the REBCO wire has the high n-value as almost same as the LTS wires, the REBCO wire is suitable for MRI magnets. In figure 1, a structure of the commercial REBCO wire that produced by SuperPower Inc. The REBCO wire constructs of a Hastelloy® substrate, intermediate layers such as MgO by the IBAD plating, and a superconducting layer of GdYBCO by the MOCVD process. In addition, the silver layer is deposited on the superconducting layer for a chemical stabilization, and the entire wire is covered with a copper layer by electrical plating for the current loading stabilization.

![Figure 1. Structure of REBCO wire (SuperPower)](image)

2.2. Experiment of superconducting joint
In order to join the superconducting wires with almost zero resistivity, it is necessary to contact the bared surfaces of the superconducting layers and to change the boundary interface into a superconductor. The REBCO wires without a Cu stabilizer were prepared to establish the joint process and the process condition. Table 1 shows the specifications of the REBCO wire used for the joint test.

| Table 1. Specification of REBCO sample tape for superconducting joint |
|-------------------------------------------------|
| Sample                            | SuperPower Inc. (SF6050 AP) |
| Width of tape                       | 6 mm                      |
| Thickness of Substrate              | 50 μm                     |
| Thickness of SC layer               | 1.6 μm                    |
| Thickness of Ag layer               | 2 μm                      |
| Minimum critical current            | 190 A                     |
The process of the superconducting joint consists of 4 steps. In the first step, the silver overlayer of about 1 cm length is dissolved by a chemical etching to expose the superconducting layer. In the second step, the liquid solution containing the superconducting materials of the REBCO is applied on the surface of the superconducting layers. The two tapes are pre-calcined at about 500 degree-C. In the third step, the two tapes are contacted together as shown in figure 2. The two tapes are compressed by the mechanical pressure, and bake it in a furnace at about 800 degrees-C to crystallize the interface. In the fourth step, a process of oxygen annealing is conducted under heating in high oxygen atmosphere.

![Figure 2](image1.png)

**Figure 2.** Schematic structure of superconducting joint

By the processes mentioned above, the joint samples were fabricated, and its properties were examined. The joint sample was examined by two kinds of tests. First, a property of current and voltage (I-V) of the joint sample was measured by a four-terminal method in liquid nitrogen. The result of the I-V test is shown in figure 6. Since critical current of HTS wires is generally defined at 1μV/cm criterion, Ic of the joint was evaluated as 155 A in the criterion of the voltage tap length with 5 cm. Also, the straight line of $10^{-8} \Omega$ is shown in the figure, it is understood from this figure that the resistivity value of the joint is less than $10^{-8} \Omega$ at 150 A.

![Figure 3](image2.png)

**Figure 3.** I-V characteristic of superconducting joint at 77K

3. **Persistent Current Decay Measurement**

The extremely lower resistivity than $10^{12} \Omega$ is not measured by the four-terminal method, but by the current decay method [6]. A schematic diagram of the measuring device is shown in figure 4. A one-turn loop is fabricated with the REBCO wire by joining both end of the wire. Persistence current flows
in the loop, and the magnetic field generates by the current in the loop. The magnetic field is measured with a hall sensor. The joint resistivity is derived from equation (1).

\[ R = \frac{L}{t} \times \ln \frac{B}{B_0} \]  

(1)

where \( R \) is resistivity, \( L \) is inductance of the loop, \( t \) is measurement time, and \( B/B_0 \) is decay ratio of the magnetic field. A photograph of test equipment is shown in figure 5. The test equipment consists of the one-turn loop with the joint, the exciting coil made of Cu wire, and the heater that raise temperature at a part of the loop to the normal state temperature. The equipment is set on a cold head of a GM refrigerator to measure a resistivity at various temperates from 77 K to 30 K.

![Figure 4. Structure of low resistivity measurement system using one-turn loop](image)

![Figure 5. Low-resistivity measuring equipment using one-turn loop](image)

One example of the measured results is shown in figure 6. The magnetic field of persistent current in the loop was measured at 30 K. The magnetic field of the loop was decreased immediately after demagnetization of the exciting coil, but the subsequent attenuation became stable and low after 3 hours later. The inductance of the one-turn loop was 0.3 \( \mu \)H by the analysis of a circle current. The resistivity of the joint was calculated by the equation (1), and the resistivity was confirmed to be 9.7 \( \times \)
The current of the loop was calculated by Ampere low, and the magnetic field of 1.7 mT was corresponded to about 70 A.

![Figure 6. Result of magnetic field measurement with one-turn loop at 30 K](image)

4. Conclusion

The superconducting joint of REBCO wires was developed, and 150A of Ic characteristic was achieved in short length of the joint samples. The measuring system of the persistent current with a one-turn loop was prepared, and we measured the one-turn loop sample with a superconducting joint. The joint resistivity was measured from the field decay rate and was achieved to 5.32×10^{-13} \Omega.

In the NEDO project, we are planning to investigate the superconducting joints by using the HTS solenoid magnet systems. The HTS magnet will consist of multiple coils and a persistent current switch (PCS) that connected with the superconducting joints. The HTS magnet will be fabricated by Japan Superconductor Technology Co., Ltd (JASTEC) and the evaluation will be conducted by the National Institute for Materials Science (NIMS). Since it is necessary to make many superconducting joints in high quality without fail in the solenoid magnet system, we will obtain the superconducting joint skill with stability and productivity. Now we have continued the R&D to realize stable superconducting joints until the fabrication of the HTS magnet.

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