A Study on Joint Resistance between Nb-Ti Superconducting Wires for MRI Magnet

Sang-Soo Oh, Yingming Dai, Dong-Woo Ha, Hyun-Man Jang, and Kang-Sik Ryu

Abstract

The joints between the superconducting wires are inevitably needed from the requirement of a high magnetic stability with respect to time in the superconducting MRI magnet. In this study, a new superconducting joint using Cu/Nb-Ti sleeve has been tried on the MRI type Nb-Ti superconducting wires. The transformer induction type apparatus was made and applied to measure the joint resistance. A very low joint resistance of 10^{-15} Ω could be successfully obtained from this joint method. It was confirmed that the initial rapid current decay occurs before the very stable current decay due to only superconducting joint. Some unstable part in the joint like exposed filaments causes the initial induced current to lower and influence on the increase of the joint resistance.

I. Introduction

A MRI-CT is recognized to be a promising technology for medical diagnosis because of its high quality image. As a rule, superconducting coils are used in persistent mode for generating static magnetic field in the MRI-CT owing to the requirement for high stability of magnetic field with respect to time. Fully stabilized Nb-Ti superconducting wires are wound on the bobbin and connected in series during the fabrication process of persistent mode superconducting MRI coil. Therefore, the joint resistance of connection part of superconducting wires has to be minimized.

Iwasa and Leupold[1, 2] researched to evaluate the joint resistance using field decay method. They could estimate the joint resistance of $10^{-13}\sim10^{-14}$ Ω for the joint with copper block between the multi filamentary Nb-Ti superconducting wires. On the other hand, Tominaka[3] tried SQUID measurement technique and could evaluate joint resistance of 10^{-14} Ω for the spot-welded joint. They observed initial rapid decay of the induced magnetic field.

In the experiment, a new superconducting joint using Cu/Nb-Ti composite sleeve was tried. Nb-Ti superconductor was located at center with a hole in the composite sleeve. Therefore, superconducting Nb-Ti filaments inserted into a hole can be contacted with same Nb-Ti superconductor and the current flows almost through the superconducting part. According to this, joint resistance can be predicted to be lower than them reported before by other groups. In this study, the feasibility of this joint method using Cu/Nb-Ti composite sleeve on the joint resistance was investigated. The transformer induction type apparatus adopting the field decay method was applied to measure the joint resistance between the superconducting wires in liquid helium temperature. Addition to this, the fabrication factors of joint influencing on the joint resistance were investigated.

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II. Experimental

1. Specimen Preparation for the Joint

The 1 mm-diameter round Nb-Ti superconducting wires were used for the lap joint(LJ) and superconducting joint(SJ), respectively and the wire's cross section is shown in Fig. 1. This superconducting wire is composed of stabilizer Cu and twenty four Nb-Ti superconducting filaments of about 50 μm in diameter. The geometries of specimens are shown in Fig. 2. The straight parts in the specimen SJ1 and SJ2 were soldered with Pb-Sn for mechanical support. The filaments were exposed at the upper part of joint in the specimen SJ2 for a comparison of the decay property. The Nb-Ti filaments were inserted in the Cu/Nb-Ti sleeve and pressed to insure the sufficient contact areas of filaments each other for the superconducting joint. All specimens were finally prepared with the shape of a 21 mm - diameter single turn loop and 14 cm long straight part with the joint at the end. The specimen LJ has only lap joint soldered with Pb-Sn in the straight part.

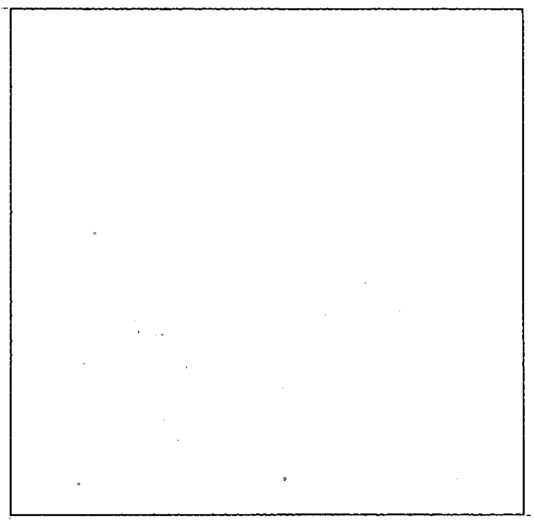

Fig. 1. Cross secondstional view of Nb-Ti superconducting wire.

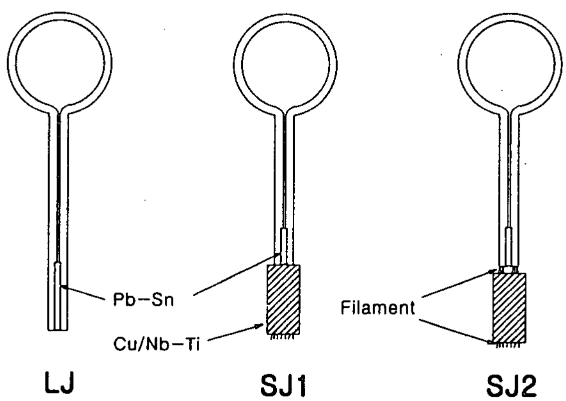

Fig. 2. Three kinds of specimens with different joint.

2. The Measurement Apparatus

Superconducting transformer type induction device was designed and fabricated to evaluate the joint resistance. As schematically shown in Fig. 3, this device consists of a superconducting primary coil and the specimen, which acts as the secondary current loop of the transformer. A cryogenic hall sensor(Lake Shore Model HGCT-3020) and a precise current source(Lake Shore Model 120CS) was used to measure the hall voltage from the specimen. Suppling the current to the specimen, the hall sensor output voltage was measured before the main experiment. The sensitivity of the specimen current and the hall voltage was 0.42 μ *V/A*. Using this sensitivity value, the current induced along the sample was calculated. The cryogenic hall sensor was installed inside the FRP bobbin of primary coil to detect the magnetic induction. Around the straight part of the specimen, a heater wire was wound to control the current loop whether it is in superconductive or normal state. The superconducting primary coil was made with 0.33 mm - diameter multi-filamentary Nb-Ti wires. The main parameters of the primary coil are described in table 1.

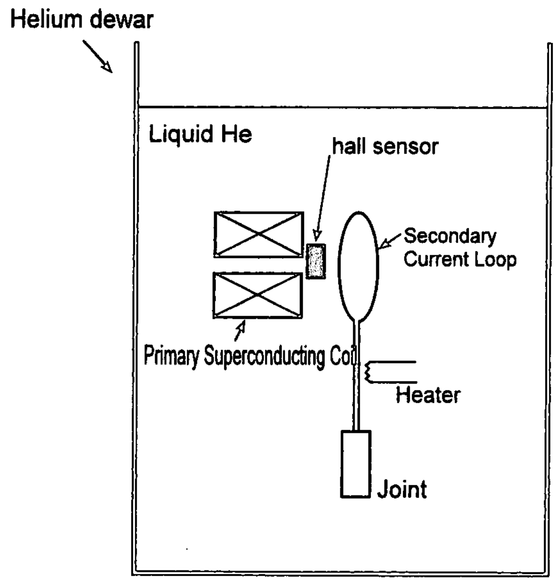

Fig. 3. Layout of the apparatus for joint resistance measurement.

Table 1. Main parameters of primary superconducting coil.

Parameters		Values
Diameter	Outer	19 mm
	Inner	20.5 mm
Length		13 mm
No. of turns		77
Inductance		99.975 μH

According to the designed parameters of the superconducting transformer device, the mutual inductance *M* between the primary coil and the secondary current loop was calculated[4] as 0.55 μH. The self inductance(L_S) of the secondary circuit(specimen) consisting of single turn loop and straight part was calculated[4] as 0.094 μH.

3. The Measurement Principle and Procedure

Appropriate operations of the primary coil and the heater are necessary to induce a desired current inside the specimen. This induced current, I_S begins to decay in the secondary R-L circuit as soon as the primary current reduces to zero. This current decay can be expressed as a below exponential decay formula.

$$I_s(t) = I_s(0)\, e^{-t/\tau} \quad (1)$$

where $\tau = L_s/R$ is the characteristic time constant and $I_s(0)$, the initial current of the R-L secondary circuit of the current loop. According to the report by Leupold et al.[1], slow residual decay occurs due to the characteristics of the experiment after an initial relatively rapid decay and this induced current can be expressed

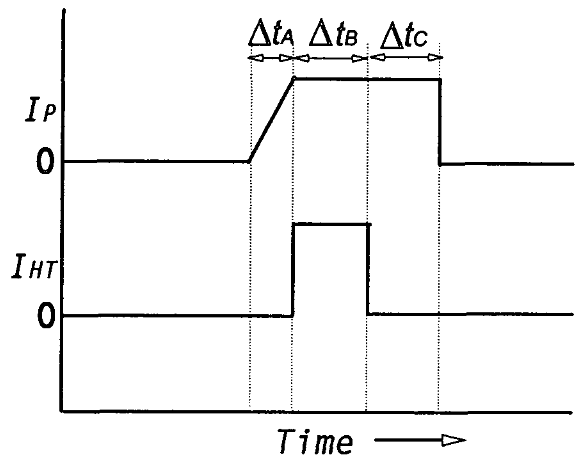

Fig. 4. Schematic current patterns of the primary coil and the heater during the measurement, where I_P and I_{HT} are current of primary coil and heater current, respectively.

accurately by a linear relationship[1].

$$I_s(t) = I_s(t_o)\,[1 - \frac{R}{L_s}\,t] \tag{2}$$

where, $I_s(t_o)$ is the induced current value where a linear relationship begins. From equation (2), joint resistance R is given by

$$R = \frac{\Delta I_s}{I_s(t_o)}\,\frac{L_s}{\Delta t} \tag{3}$$

The current patterns of the primary coil and the heater during the measurement are schematically shown in Fig. 4 and the measurement procedures are as follows :

1) providing a necessary magnetic flux inside the current loop by charging the primary coil during Δt_A with a designed current and keeping it constant for Δt_B. During this process, the current is induced in the loop depending on its superconductivity, which is controlled by the heater. When the heater is turned on just after Δt_A, the hall sensor output voltage increases sharply due to the disappearance of counter magnetic field from the current loop against that from the primary coil. For our purpose to null this loop current before discharging the primary current, there is no difference between the pre-turn on and after-turn on of the heater. But the later case has the advantage of saving a little helium and providing a chance for live monitoring the induced current in the loop. 2) Turning off the heater after Δt_B to change the specimen superconductive and later, shutting off the primary coil after Δt_C. According to this, the current is induced in the current loop and the hall sensor voltage is only contributed by this induced current. 3) Joint resistance evaluation from the decay of the hall sensor output voltage which is recorded as a time base with a precise analog pen recorder. Finally, the hall sensor voltage was calculated as current value due to it's calibration mentioned above.

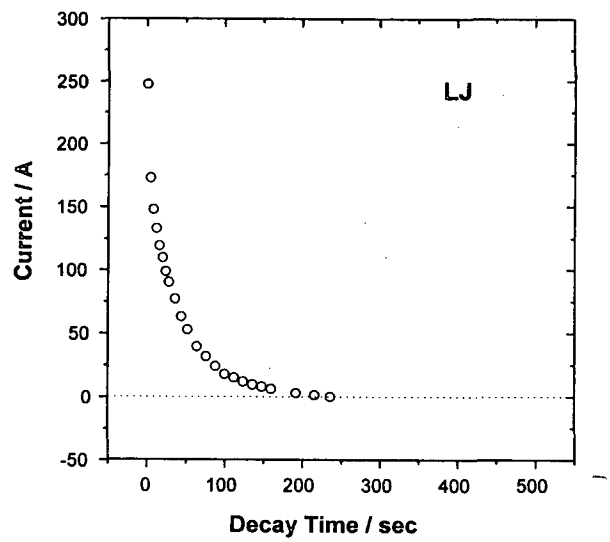

Fig. 5. Induced current as a function of decay time on the lap joint.

III. Results and Discussion

Fig. 5 shows the decay time dependence of induced current for the specimen LJ with lap joint. The current of 250 A was induced when the primary coil's current decreased instantaneously from 40 A to 0 A and decayed exponentially with increasing the time. The induced current reduced to zero at around 200 seconds. In the case of specimen LJ, a linear relationship was not observed. The specimen SJ1 with a superconducting joint, however, exhibited a remarkably slow decay as shown in Fig. 6. The initial current of 251 A was induced on SJ1 joint and this is similar as that of specimen LJ. These measured values were consistent with the predicted value by the formula $I_S = I_P \cdot M/L_S$, when the current of primary coil, I_P is 40 A. The induced current of specimen SJ1 rapidly decayed from 251 A to 193 A at around 4590 seconds and became very stable with increasing the time.

Iwasa and Leupold also confirmed[1, 2] the initial decay of induced magnetic field (current) on the joint. They explained this to current exceeding capability of the superconducting wire and flowing through the copper matrix. On the other hand, Tominaka proposed[3] this initial decay is caused by the change of current distribution behavior inside the multi filamentary superconducting wire. The critical current of the Nb-Ti wire used in this experiment is two times higher than the initial induced current of specimen SJ1. Therefore, it seems to be reasonable that the present initial current decay is attributed to current distribution in superconductor. Fig. 7 shows residual current decay region with a linear relationship for the specimen SJ1. The appreciable current decay could not be detected for around 18,600 seconds under present measurement condition. This indicates that the specimen SJ1 with a superconducting joint entered a nearly perfect persis-

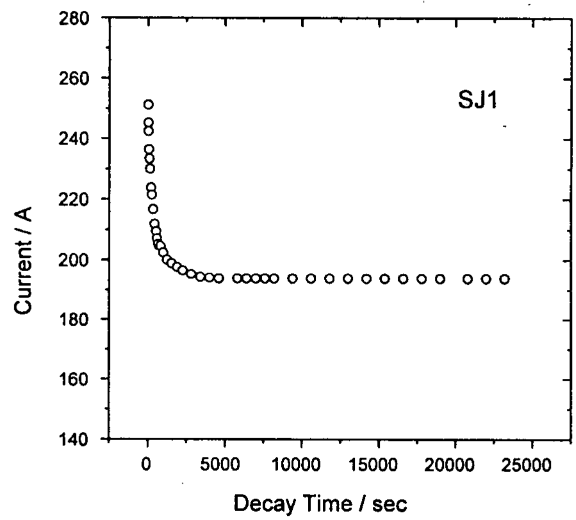

Fig. 6. Induced current as a function of decay time on the superconducting joint of SJ1.

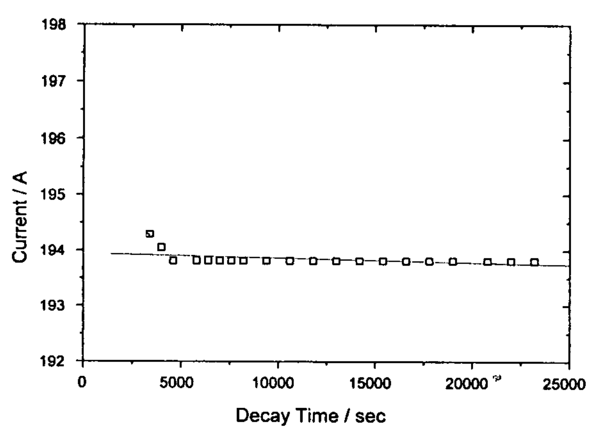

Fig. 7. Linear time dependence of current on the superconducting joint of SJ1.

tent current mode state after the initial current decay for one hour. According to this, the present joint method using the Nb-Ti superconductor as a sleeve is considered to be very effective to the persistent current mode operation of the superconducting magnets. The joint resistance of SJ1 was evaluated by the equation(3). Fitting the data linearly as shown in the Fig. 7, we could obtain the joint resistance of $\sim 4 \times 10^{-15}\,\Omega$ from the specimen SJ1. This low value is thought to be resulted from that the induced current flows almost superconductor even in the joint part. Fig. 8 shows the current decay of specimen SJ2 which has the exposed part of filaments as shown in Fig. 2. The initial induced current of the specimen SJ2 was observed to be 45 A when the current of primary coil reduced to 0 from 40 A. This value was lower than that of specimen LJ and SJ1. The specimen SJ2 seemed to quench when the current flow through exposed filaments because the exposed filaments without supports tended

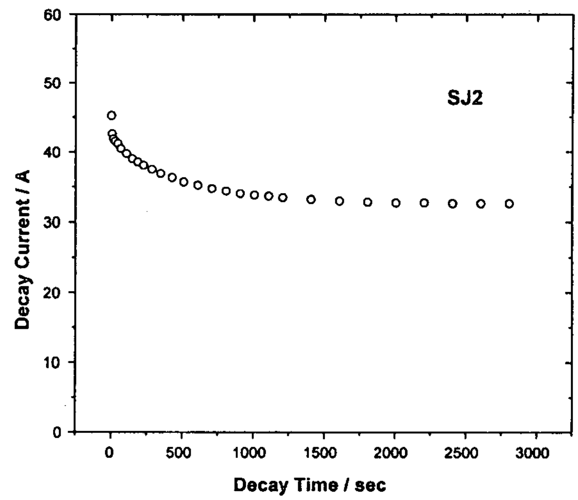

Fig. 8. Induced current as a function of decay time on the superconducting joint of SJ2.

to move due to the electro-magnetic forces acted on the filaments.

Joint resistance of specimen SJ2 was estimated as $\sim 5 \times 10^{-13}\,\Omega$ assuming a linear relationship begins at 1500 seconds. From this result, joint resistance turns out to be sensitively dependent on the appearance of filaments in the joint part.

IV. Conclusions

We have tried to make superconducting joint between Nb-Ti superconducting wires using Cu/Nb-Ti sleeve. The joint resistance was measured with current decay method. The extremely low joint resistance of $\sim 4 \times 10^{-15}\,\Omega$ was successfully estimated on the superconducting joint. The initial exponential rapid current decay and a linear current decay appeared on the superconducting joint, while the only exponential current decay appeared on the lap joint. The instability resulting from the exposed filaments in the joint part caused the decay property of superconducting joint to degradation.

Acknowledgement

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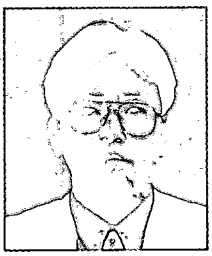

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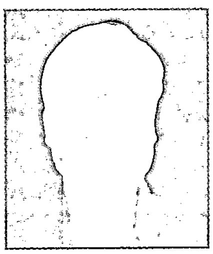

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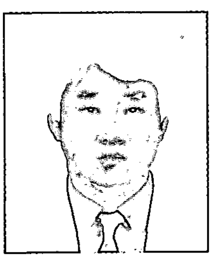

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