Property of Joint Resistance of Bi2223 Multi-filamentary Tape by Using Sn-Pb Solder

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In this paper, the joint resistance between two Bi2223 multi-filamentary tapes was measured by field decay method. In order to achieve this goal, a closed Bi2223 coil was fabricated. The joint was welded with ordinary Sn-Pb solder. The field decay measurement at the center of the coil was carried out at 77K. Most of results followed the curve predicted by the classical R-L circuit. The result is compared with data from commonly used 4-probe method. An equivalent circuit model was also proposed by which the joint resistance could be quickly approximated.

INTRODUCTION

The availability of high performance Bi-2223/Ag multi-filamentary tape makes it a good candidate to substitute for conventional conductors in electrical power applications. Much contrary to the conventional conductor wire, the Bi2223/Ag multi-filamentary tape was usually fabricated with single tape length less than 1km, therefore, the jointing technique is required for long tape applications.

Though some sophisticated superconducting jointing techniques have been developed to meet the need for persistent current applications such as MRI and NMR device[1,2], for economical considerations, soldering the multi-filamentary tape with ordinary Sn-Pb solder directly was still widely accepted in large magnet applications[3]. The preliminary unit of such joint can be simplified as Figure 1 where the total resistance was mostly contributed from Sn-Pb solder as well as the Ag sheath material. Evaluating the resistance of this joint properly is one of basic issues for HTS electrical devices especially operated under low temperature where the refrigeration capacity and the heat generated by this joint as well as other power dissipation have to be considered systematically.

In this study, a closed Bi2223 coil with one joint was first fabricated and its joint resistance was accurately determined by a field decay method. The results were later compared with the data measured by the commonly used 4-probe method. To improve the understanding, an equivalent circuit model was also proposed where the joint resistance was simply regarded as three Ohmic type resistors connected in serial with each other, through which the joint resistance could be quickly approximated.

Figure 1 The basic unit of the joint area

EXPERIMENT PREPARATION

Sample preparation

For experiment, a HTS coil made of Bi2223/Ag multi-filamentary tape was first fabricated by using single-wound technique. The specifications of the coil are listed in Table 1. The tape was coated with epoxy paint with thickness about 10μm to provide electrical insulation. It should be noted here that a well turn to turn insulation is of critical importance to the accuracy of the measurement, where any current leakage between the turns should be avoided. The end and beginning of tape was later extracted and soldered together with ordinary Sn(60)-Pb(40) solder. A so called "shape hand" structure was applied to the joint area and thus form a closed coil as shown in Figure 2. The overlapped length was about 2.6cm.

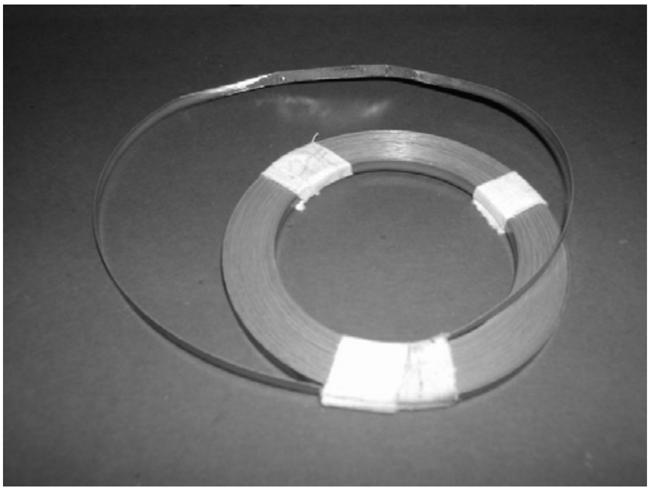

Figure 2 The closed HTS coil

Table 1 Specifications of the HTS coil

Parameters[unit]	Value
Inner diameter [mm]	55.34
Outer diameter [mm]	78.92
Height [mm]	3.99
Turns	56
Critical current [A]	20.03
Magnetic constant [T/A]	0.00105
Inductance [mH]	0.3118

Measuring system

There are three main equipments for the field decay measurement: a copper coil with 480 turns was equipped to provide the background field; a hall probe was utilized to detect the field variation at the center of HTS coil. A Keithley 2400 multi-meter together with a computer was included for data acquisition through the GPIB interface. This system is prove to be capable of distinguish a field variation in a minimum 0.025s.

RESULT AND DISSCUSSING

Field decay measurement

The exciting current of the copper coil was first applied to about 10A, which is able to produce a 400G flux density at the center of the HTS coil. Next, cool the closed HTS coil down to the superconducting state with liquid nitrogen and then shut down the exciting current instantaneously. The field decay curve as a function of time is given in Figure 3. The total measuring time lasts about 10 hours. The measured field was divided by the magnetic constant of the HTS coil and therefore the real current flowing through the coil could be scaled as Y axis.

In a typical R-L circuit whose resistance(R) and inductance(L) are independent to the current, the decay behavior can be described by solving the equation below

$$L\frac{di}{dt}+Ri=0\Rightarrow i(t)=i(0)\exp(-\frac{t}{\tau}) \quad (1)$$

where τ is the time constant defined by L/R. It is clear that if the decay line obeys Eq.(1), the curve in Figure 3 should be a straight line. However, an obvious divergence from the linear rule was observed at the beginning of the curve. Furthermore, a slight divergence was also observed at the end of the curve, the reason for which is not discussed here as it involves the consideration of the HTS behavior. For calculating the joint resistance, only middle part of curve from 5483s to 22691s was considered. Referring to the self inductance 0.3118mH of the HTS coil, the joint resistance was calculated to be $45.8\,n\Omega$.

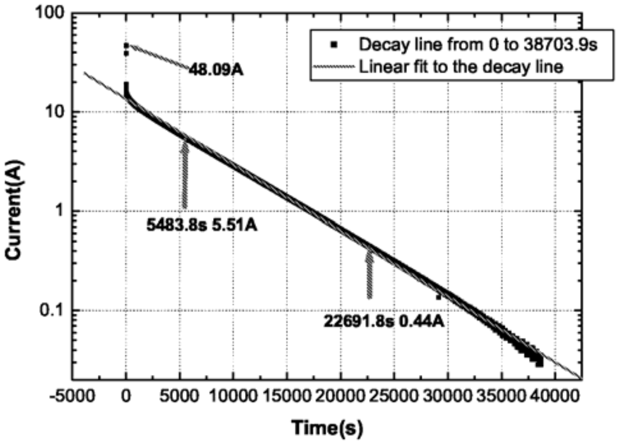

Figure 3 The field decay behavior of HTS coil

Equivalent circuit and 4-probe method

Referring to the joint structure given in Figure.1, in general, the voltage cross over two terminals could be determined as

$$V = R_c I + E_c l_s \left(\frac{I}{I_c}\right)^n \tag{2}$$

where I is the operation current and the R_c is the joint resistance; E_c is the critical current criterion according to 1μV/cm; l_s is the length of the Bi-2223 tape between two terminals. Assume that the current run far below the critical current 40.2A and n index is also large enough, then two parallel superconductor filament as well its outside Ag sheath could be regarded as two equipotent layers. Among this two layers are two inner Ag sheath layers in series with the Sn-Pb layer as depicted in Figure 1. Abased on this assumption, naturally, the applied current flowing through the joint region was uniformly distributed along the contact area. Consequently, the equivalent circuit for joint region was essentially nothing but the application of the Ohm's law. This assumption neglects the real contact resistance between the solder and Ag sheath interface. For a typical Ohmic resistor, the resistance could be determined by $R = \rho l / A$. For this purpose, the resistivity of the Ag alloy was experimentally found to be $1.7093\times10^{-8}\,\Omega\cdot m$ in 77K and the resistivity of the Sn-Pb solder was adopted to be $1.45\times10^{-7}\,\Omega\cdot m$. The length of the joint area was previously mentioned to be 2.6cm. The width of the contact region was assumed to be equal to the tape width 4mm approximately. The thickness of each region was determined by optical micrographs of the joint area as shown in Figure 5, where the averaged thickness of the Ag sheath and Sn-Pb layer are $35.6\mu m$ and $21.7\mu m$ respectively. Combination all of these factors give the total resistance of joint area $41.9n\Omega$, of which Sn-Pb solder layer contributes almost 74.6% of its total resistance. This value is comparable to the measured result $45.8n\Omega$, but a little smaller than the experimental data.

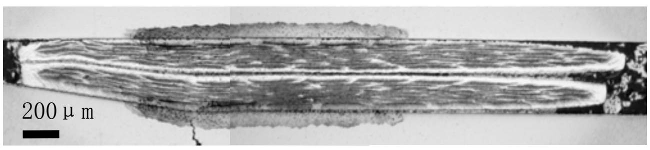

Figure 5 Optical micrographs of cross section of HTS tape

It must be born in mind that the resistivity of the Sn-Pb solder doesn't decrease with the decreasing in temperature as do in conventional pure metal, but it is magnetic field related [4]. Therefore, as long as it was used in high field applications, the joint resistance was suggested to determine experimentally.

In this study, the joint region together with 3cm extension area in each side was cut off from the closed coil and then the commonly used 4-probe method was introduced to measure the *I-V* characteristic of the joint area. Figure 6 show the *I-V* curve of the joint area measured from A-A'. The A-A' corresponding to the l_s=0 in Eq.(2) is exactly contributed from joint region. Therefore, linearizing the curve obtained from A-A' gets the joint resistance $46.6 n\Omega$. This value shows a good agreement with the result obtained from the field decay method.

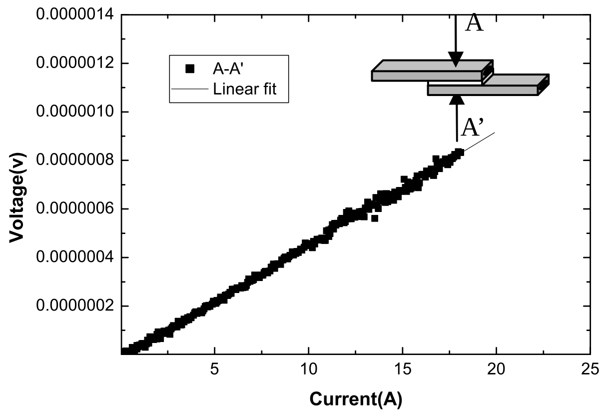

Figure 6 The I-V characteristic of the joint area

CONCLUSION

The joint resistance of the Bi2223/Ag multi-filamentary tape connected with ordinary Sn-Pb solder was studied. The joint resistance with 2.6cm overlapped area was accurately measured to be $45.8 n\Omega$ by a field decay method. This result shows a good agreement with data derived from 4-probe method. An equivalent circuit model was proposed in which the joint resistance was regarded as three Ohmic type resistors connected in serial with each other. This model was prove to be valid for estimating the joint resistance in small current region with error less than 10%. Calculation results based on this model also indicate that the Sn-Pb layer dominates the joint resistance mostly.

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