Transport current distribution in soldered joint of BSCCO and REBCO tapes

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Abstract. Transport current density distribution at the solder joints of BSCCO tapes and GdBCO tapes are examined by means of scanning 3-dimensional (3D) Hall sensor. After measuring the three components, $B_x$, $B_y$ and $B_z$, of self field distribution near the tape induced by the transport current, the current density distribution was calculated by solving the inverse problem through matrix method implemented in the code in MATLAB environment. By using this technique, we successfully obtained the profiles for perpendicular component $J_z$ of transport current that is passing through the joint area.

1. Introduction

Despite the recent rapid progress in the manufacturing technique of high temperature superconducting (HTS) tapes, the tape length is still limited to several hundreds meters. Therefore, joining technology is indispensable in the construction of large-scale power application equipment such as transmission lines. The crucial point is the necessity to reduce the joint resistance as much as possible. Although various joining technologies have been studied so far, the solder joint technique is being used in practice. Nevertheless the reported values of joint resistivity widely vary \cite{1-2} and a deep and comprehensive investigation of joint properties is still required.

One of the important questions is the transport current flow and current density distribution in tapes before and after passing the joint area. Another important point is the distribution of the current in joint itself. The information about current density distribution in joints will help to improve joints performance. In this paper, we present the non-destructive technique to examine the current distribution at the solder joint of BSCCO tapes and GdBCO tapes. By means of 3-dimensional (3D) Hall probe we scan the magnetic field above joint area of tapes to obtain 2D mapping of three components of magnetic field $B_x$, $B_y$ and $B_z$. Then these datasets are used to solve the inverse problem and to reconstruct the real current density distribution in joints.

Various methods have been proposed for solving inverse problem to obtain the current distribution from measurement of magnetic field distribution at the sample surface. In most cases, the suggested algorithms include the two-dimensional Fourier transforms of magnetic field, current densities and weight functions. \cite{3-5}. These method are suitable to calculate localized limited in size current loops, but cannot be used for a long HTS tape. So we developed new methods that are suitable for
examination of current density distribution in long HTS tapes. In our methods, current density profile is obtained by solving an inverse problem through matrix method implemented in the code that we developed in MATLAB environment. We developed several codes, in which two mathematical methods are combined: one is based on solution of set of linear equations (SLE), and other is based on the method of least squares (MLS). Detailed description of our calculation method can be found in Refs. [6-7]. In the present study, we apply this technique to calculate the current density distribution in joint of HTS tapes.

2. Experiment

2.1 Samples

We use two kinds of spliced HTS tapes in the present study. Specifications of each tape including size, architecture, critical current, type of solder, joint resistance etc. are described in Table 1. Note that the joint resistance of BSCCO spliced tape is very large compared to their standard value (50-100 nΩ). We used this sample in order to understand the reason for this large resistance. On the other hand, the GdBCO spliced tape, kindly provided from Super Ox, is joined by the standard technique used in their manufacturing process. Joint resistance was measured by a standard 4-probe technique in LN$_2$ with varying current from 0 to 150 A.

Table 1. Specification of spliced HTS tapes used in the present study.

|                     | BSCCO                   | GdBCO                  |
|---------------------|-------------------------|------------------------|
| **Tape Width**      | 4.5 mm                  | 4 mm                   |
| **Tape thickness**  | 0.35 mm                 | 0.11 mm                |
| **Architecture**    | DI-BSCCO$\text{^°}$ Type HT-CA (Reinforced with 50 µm Cu alloy) | Cu stabilizer layer (20µm), Ag layer (2µm), HTS layer (~0.7 µm), Hastelloy substrate (60µm) |
| **$I_c$(77K, s.f.) (A)** | 163 A                  | ~135 A                |
| **Joint length**    | 10 mm                   | 30 mm                  |
| **Solder**          | Cu/Bi/Ag                | Pb$_3$Sn$_6$           |
| **Joint resistance**| $1.3 \times 10^4 \Omega$ | $73.2 \times 10^9 \Omega$ |

2.2 Experimental Setup

A schematic view of experimental configuration is shown in Figure 1. HTS tape is fixed on an FRP sample holder, connected to the current feeding wires and immersed in an open cryostat filled with LN$_2$. The 3D Hall probe system consists of three Hall probe sensors with 0.05 x 0.05 mm$^2$ active areas (Axis3, AREPOC).

![Figure 1. Experimental setup for 3D Hall probe measurement.](image)

After applying a constant electric current, $I_a$, to the tape, the magnetic field profiles at the tape surface were measured by scanning Hall probe across the tape in y direction (tape’s width) and in x
direction (tape’s length) at a fixed altitude, \( z_h \) (mm). During the measurement, scan lengths of Hall probe are controlled by stepping motor using the data acquisition system in Labview environment and three components of the magnetic field, \( B_x \), \( B_y \) and \( B_z \) are measured, synchronously.

3. Results and Discussion

3.1. Transport current distribution in the soldered joint of BSCCO tapes

Figure 2 shows schematic illustration of measured area for BSCCO sample. The origin of coordinates is located in the center of soldered joint area and the magnetic field was measured for \(-6 \text{ mm} < x < 6 \text{ mm}, \) and \(-6 \text{ mm} < y < 6 \text{ mm} \) at a fixed altitude, \( z_h = 0.1 \text{ mm} \). During the measurement, the transport current runs in \( x \) direction in the upper HTS tape passes the joint area with solder length of 10 mm and transits to the second tape.

![Figure 2. The scheme of the soldered joint measurement for BSCCO.](image)

In figures 3 and 4, one can see 3D plots of the components \( B_x \), \( B_y \) and \( B_z \) of the scanned magnetic field for the current value 100 and 125 A, respectively. One can see the shapes of the profiles for each component are equivalent for all three cases. The difference is in amplitude that is defined by the transport current value in the tapes.

In general, \( B_z \) as a function of \( x \) and \( y \) coordinates is used to calculate 1D current distribution in the tape. That means all the current runs in one direction along the tape \( J_z \) and is a function of \( x \) and \( y \) coordinates as well. It gives the robust solution for the inverse problem and is used in many experimental analyses. So at first, we would like to pay attention to the shape of \( B_z \) profile. As can be see from the figures, 3c) and 4c), \( B_z \) is larger for \(-6 \text{ mm} < x < 0 \text{ mm} \) and decreases in the area, \( 0 \text{ mm} < x < 6 \text{ mm} \). That is the clear evidence that current transits from the upper tape to the second tape and the distance between the current and Hall probe enlarges. The same picture is observed for \( B_y \) component.

Hence these experimental data are in consistent with the physical picture of the experiment.

Very important information is represented by \( B_x \) component of the magnetic field, because it is directly related to the transport current running in \( z \) direction \((J_z)\). Figure 5 shows the distribution of \( J_z \) calculated from the \( B_x \) component. Note that \( J_z \) exists not in the whole joint area, but is located in central part of the soldered joint \((-2 \text{ mm} < x < 2 \text{ mm})\). The value of \( B_x \) beyond this area is small enough to stand out from the level of noise and hence \( J_z \) is assumed to be zero for \( x < -2 \text{ mm} \) and \( x > 2 \text{ mm} \). This result suggests that the resistance of the joint is non-uniform: the center area is well bonded with low resistance, whereas the peripheral is poorly bonded and has high resistance. With this information of \( J_z \) distribution, one can also estimate the amount of current that passes from one tape to the other depending on \( x \) coordinate. Basing on that we can calculate 2D current flows in both tapes including joint area, as shown in figure 6 for the case of \( I_a = 100 \text{ A} \). It is observed that after passing the joint the shape of current density becomes more flatten. The flattening may be occurred by the heat generation at joint area due to relatively large joint resistance.
**Figure 3.** $B_x$ a), $B_y$ b) and $B_z$ c) map for BSCCO tape at $I_a = 100$ A.

**Figure 4.** $B_x$ a), $B_y$ b) and $B_z$ c) map for BSCCO tape at $I_a = 125$ A.
Figure 5. 3D plots of $J_z$ component of current density for 100 A a) and 125 A b) in BSCCO tape.

Figure 6. 2D current flow in upper tape (left) and in the second tape (right) for the case of $I_a = 100$ A in BSCCO tape.

3.2. Transport current distribution in the soldered joint of GdBCO tapes

Figure 7 shows schematic illustration of measured area for GdBCO sample. The origin of coordinates is also shown in the figure. The measurement was performed at a fixed altitude, $z_h = 2.0$ mm.

Figure 7. The scheme of the soldered joint measurement for GdBCO tape.

Figure 8 displays 3D plots of the components $B_x$, $B_y$, and $B_z$ of the scanned magnetic field for $I_a = 100$ A. Interesting point is that $B_y$ and $B_z$ are depressed at the joint area, which we did not see in the BSCCO sample. We also perform the measurement at $I_a = 50$ A and 75 A, and similar behavior was observed.

As mentioned in the previous section, we used $B_x$ component of the magnetic field to calculate the perpendicular current density profile $J_z$ in transit zone. Note that $B_x$ increases largely at around $x = 30$ mm in figure 8, which is the end point of joint area. This observation suggests that the current transit from the lower tape to the upper tape occurs not in the whole joint area but towards the end of the lower tape. If so, the majority of the current might flow in the lower tape in the joint area. Then the decreases of $B_y$ and $B_z$ above the joint area could be explained by shielding effect by means of upper tape. This large effect of shielding may be due to the thin film structure of GdBCO tape, in which the
shielding current with large loop is easy to be induced. However, further experiment is needed to confirm this idea.

Figure 8. 3D plots of the components $B_x$, $B_y$, and $B_z$ for $I_a = 100$ A in GdBCO tape.

From the magnetic field component profiles ($B_x$ versus $y$ coordinate) for $I_a = 100$ A, we calculated the current density profiles, $J_z$. $J_z$ profiles for $x = 26$, 28, and 30 mm are presented in figure 9. We can see that $J_z$ is enhanced in a narrow region close to the joint edge, which agrees very well with above scenario. For the coordinate $x < 26$ mm as in a previous experiment the value of $B_y$ beyond this area is small enough to stand out from the level of noise and hence $J_z$ is assumed to be zero.

Figure 9. Current density profiles calculated from $B_y$ data for $I_a = 100$ A for GdBCO.

4. Summary

Using 2D mapping of three components of magnetic field data, we successfully obtained transport current profiles at the solder joint area of BSCCO and GdBCO tapes, by solving the inverse problem. In BSCCO joint with bad property, $J_z$ was found to exist not in the whole joint area, but is located in central part of the soldered joint, probably due to the worse bonding at peripheral region. On the other hand, the current is likely to transit from the first tape to the second tape at the joint edge in GdBCO. The present result demonstrates that this method can be a powerful tool to evaluate the joint properties in a destructive way.

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