Experimental and numerical study of influence of ferromagnetic cover on critical current of BiSCCO-2223/Ag tape superconductor

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Abstract. Samples of commercially available BiSCCO-2223/Ag tape have been partially covered by the ferromagnetic material. Improvement of the self-field critical current up to 15% has been achieved by this procedure. A critical current of such tape strongly depends on geometric and magnetic properties of both, the superconducting tape as well as the ferromagnetic cover. Numerical simulations, based on the critical state model using commercial finite element method (FEM) code, have been performed. Properties of superconductor are characterized by anisotropic dependence of the critical current density on magnetic field as well as detail geometry of filaments. The ferromagnetic material is characterized by nonlinear magnetization curve. Nonlinear dependences of the critical current on selected parameters are shown in this work. Optimization of the cover parameters using these curves has been made. Samples with various parameters have been manufactured for the confirmation of numerical simulations results. Experimental results are in good qualitative agreement with results obtained by numerical simulations.

1. Introduction

The critical current density of superconductor strongly depends on local magnetic field. Moreover this dependence is nonlinear and anisotropic with respect to the ab-plane of superconductor crystal structure. Magnetic field can be created by both external source (magnet) or superconducting current itself. As was experimentally found [1] and confirmed by numerical simulations [2] it is possible to improve critical current of BiSCCO-2223 tape using ferromagnetic material deposited on the edges of the tape. In a work [2] cross-section of superconductor was simplified to ellipse what was in good agreement with cross-section of investigated tape. In our work we found procedure to calculate critical current of superconductor with arbitrary cross-section also if it is close to ferromagnetic material. Moreover this procedure allows us to analyze the distribution of the magnetic field in detail.

2. Numerical simulation basics

Similar to papers [2,3] we use commercial finite element (FEM) code to find the distribution of current density in superconductor cross-section. We assume tape invariant in longitudinal direction and therefore problem is solved in 2D. Superconductor reaches the critical current when it is filled completely by critical current density (in same direction). Local critical current density is generally
different because of different local magnetic field. To assume this phenomenon we described local critical current density by formula:

\[ J_c(B_x, B_\perp) = \frac{J_{c0}}{1 + \left( k \cdot \frac{B_x^2 + B_\perp^2}{B_0} \right)^\beta} \]  \hspace{1cm} (1)

Using proper parameters of this formula FEM code is able to find distribution of current density equivalent to real one. The critical current of such superconductor can be calculated by integration of current density over the whole superconductor cross-section:

\[ I_{c, \text{tape}} = \int_{S_{\text{tape}}} J_c(x, y) dS \] \hspace{1cm} (2)

Magnetic field in superconductor is influenced by ferromagnetic material placed close enough to it. In our case the distance between the ferromagnetic nickel and superconductor is less than 50 µm and therefore influence of this material on magnetic field and distribution of current density is evident. For magnetic properties characterization of this material we use formula:

\[ \mu_r = \mu_{r, \text{min}} + \frac{\mu_{r, \text{max}}}{1 + \left( \frac{B_x^2 + B_\perp^2}{B_C} \right)^{2\alpha}} \] \hspace{1cm} (3)

which takes into account saturation of magnetic moment, but doesn’t assume hysteresis of this material. However, in a case of DC current in superconductor and DC applied magnetic field this simplification is feasible.

3. Particular sample analysis
To estimate proper constants in formulas (1) and (3) it is necessary to measure real properties of both superconductor and ferromagnetic material. In measurement setup material properties itself are affected by finite dimensions of the sample. In a case of superconductor critical current measurement it is affected by magnetic field produced by flowing current itself and in case of magnetic moment measurement it is influenced by demagnetizing field of the sample. To find the parameters in formula (1) the critical current \( I_c \) of the bare superconducting tape sample exposed to the external magnetic field with various orientations was investigated. The constants \( J_{c0}, k, B_0, \beta \) were estimated by comparing the calculated critical current with experimental data.

In this work we use multifilamentary BiSCCO-2223/Ag tape with dimensions 4.2x0.22 mm and self field critical \( I_{c0} = 100.8 \) A. Parameters which represent the best fit of measured data are: \( J_{c0}=2.46 \cdot 10^8 \) A, \( k=0.14, B_0=0.015 \) T, \( \beta=0.65 \). Average difference of measured and calculated \( I_c \) is 1.3 A. Both, measured and calculated dependences of critical current on magnetic field are shown in figure 1.
Parameters in formula (2) were estimated using data of magnetic moment measurement in SQUID magnetometer. In this measurement we used Ni layer 10 µm thick deposited on silver substrate with dimensions 4x4 mm. Magnetic moment of this sample was measured in parallel magnetic field to minimize shape effect. We found following parameters as a good approximation of electroplated nickel properties: $\mu_{r_{\text{min}}}=1.5$, $\mu_{r_{\text{max}}}=250$, $B_C=0.38$ T, $\alpha=2.2$. Real magnetization loop and approximate curve are compared in figure 2.

![Figure 1. Comparison of dependencies measured (dashed lines) and calculated (solid lines) critical currents on magnetic field with various orientations.](image1)

![Figure 2. Comparison of measured magnetization loop of electroplated nickel and curve characterizing its properties used in calculations](image2)
Using these parameters we are able to predict superconductor-ferromagnetic composite tape properties. As was found in [1] it is possible to improve critical current of BiSCCO-2223/Ag tape by ferromagnetic cover on the edges. However, using this procedure it is also possible to decrease critical current [3]. Therefore it is convenient at first to calculate the influence of this covering for every superconductor parameters and cross-section shape. Main parameters of ferromagnetic cover are width of non-covered area – \( d \) and thickness of the layer (see insert in figure 3). In a figure 3 dependences of self-field critical current on \( d \) are shown, parameter of these curves is thickness \( t \) of Ni layer. From this figure one can see that there is an optimal value of parameter \( d \), although dependent on thickness to achieve the highest self-field critical current. Although starting from lower thickness maxima of these curves increases, it saturates reaching thickness of 40 µm.

**Figure 3.** Dependencies of self-field critical current on width of non-covered area – \( d \). Parameter is thickness of Ni layer – \( t \).

Using these curves we made three samples with various values of both basic parameters. Summary of parameters of these samples and parameters of reference sample are in table 1.

| Sample | \( d \) [mm] | \( t \) [µm] | \( I_C \) measured | \( I_C \) calculated |
|--------|--------------|--------------|-------------------|-------------------|
| A      | 4.1          | 0            | 100.8             | 100.8             |
| B      | 1.2          | 30           | 108.1             | 106.4             |
| C      | 2.4          | 30           | 115.7             | 112.4             |
| D      | 2.4          | 15           | 108.3             | 108.4             |

From this comparison is seen good qualitative tendency, but not perfect quantitative agreement. Possible reason is not perfect characterization of the shape of superconductor cross-section. In previous works [2.3] cross-sections of SC were very similar to ellipse. On the other hand, cross-section of the tape investigated in this contribution differs from this assumption (see figure 4).
4. Calculation using image processing

For detail analysis of the effect of ferromagnetic cover we developed procedure, which enable us to take into account arbitrary cross-section of superconductor also with ferromagnetic material in close ambient.

To investigate superconductor-ferromagnetic material composite we use micrograph photo of cross-section. This picture should be modified in sense to increase color contrast between different materials of composite. Resolution of picture was then decreased. We used resolution 393x28 pixel as a compromise between computing time and possibility of detail analysis. In figure 4 there is micrograph of original tape – picture on a top, simplified picture ready for calculations – picture in the middle and simplified picture with nickel cover – picture at a bottom. Last two pictures were directly used as input information for FEM code. Each point in picture represents element with properties of vacuum – white colour, superconductor – red colour or ferromagnetic material – green color.

![Image of superconductor cross-section](image)

**Figure 4.** Superconductor cross-section. top – micrograph photo of real tape, middle – simplified picture ready for calculations, bottom – simplified photo with Ni cover on the edges

Using this procedure we are able to calculate also the distribution of magnetic field density in superconductor. Superconductor BiSCCO-2223/Ag has strongly anisotropic properties with respect to the magnetic field. Therefore it is reasonable to investigate parallel and perpendicular component of local magnetic field separately. Orientation of this field is with respect to wide face of the tape. Parallel and perpendicular component of magnetic field was separately discreeted and number of elements with the same level of the magnetic field was divided by total number of elements to quantify influence of magnetic field. We got a curve of the density of elements with certain level of magnetic field by this procedure. As it is visible in a figure 5 a most of elements are exposed to low parallel magnetic field and number of them decreases with increase of level of magnetic field.

![Graph of magnetic field density](image)

**Figure 5.** Percentage number of elements with the same level of parallel resp. perpendicular component of magnetic field
Different situation is in a case of perpendicular magnetic field. This curve has a maximum at magnetic field of about 10 mT. By using of the nickel cover the number of elements exposed to the high perpendicular magnetic field strongly decrease.

5. Conclusions
Calculations of critical current in case of modifying the BiSCCO-2223/Ag tape covering edges of the tape by ferromagnetic material were performed. Optimization of covering procedure was possible using results of these calculations. This allowed us to improve the critical current ~15%. The procedure, which takes into account the detail geometrical structure of the tape, has been developed. Using this procedure it is possible assume arbitrary cross-section of superconductor and ferromagnetic material. This procedure enables quantitative analysis of magnetic field density. Such comparison of bare tape and tape partly covered by Ni layer has been done.

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