Experiment of enhancing critical current in Bi-2223/Ag tape by means of ferromagnetic shielding

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Abstract

Critical current in multifilamentary Ag-sheath Bi-2223 tape is enhanced to some extent by means of thin and narrow coating of pure nickel. The concept of enhancing critical current is based on the magnetic shielding effect resulting in redirection of self-field flux lines. The Ni coating was introduced at the edge regime of the tape in order to redirect the perpendicular component of self-field lines which is severe at the edges. Critical current in a typical Ag-sheath Bi-2223 tape was enhanced up to ~11% by 50 μm thick and 0.4 mm long Ni coating without any change of self-field loss. This fact reveals that additional ferromagnetic loss could be compensated by the shielding effect and increased critical current of the tape. The degree of enhancement in critical current as well as ferromagnetic impact on ac losses depend on the length and thickness of ferromagnetic coating introduced. Therefore, it is very important to control the geometry of ferromagnetic coating in order to balance the critical current and ac loss for optimum superconductor performance. Introduction of ferromagnetic coating and its effect on electromagnetic properties in multifilamentary Bi-2223/Ag tape will be reported in this article.
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1. Introduction

Multifilamentary Bi-2223/Ag tape now becomes a promising candidate for their considerable electromagnetic properties from the point of view of several vital power applications. That is why, to be economically competitive with the conventional
conductor, substantial worldwide efforts have been adopted for upgrading transport properties and/or suppressing ac losses both in first- and second-generation superconductors. Magnetic shielding is one of the techniques that has been utilized extensively for years in superconducting wires and devices to improve superconducting properties. For example, M. Majoros et al. have applied magnetic screening actively to reduce ac losses in multifilamentary superconducting tapes, where individual filaments were coated by ferromagnetic materials [1]. Redistribution of critical current density in superconducting filaments and strips by the influence of magnetic environment was estimated numerically in [2,3]. Several reports have been published on improvement of superconducting properties by using ferromagnetic material like iron sheath in MgBr$_2$ [4–6]. Ferromagnetic effect on critical current and ac losses in HTS coil is also investigated [7,8]. Some experiments on the effect of magnetic shielding with YBCO-coated conductors were accomplished [9,10]. But no substantial works on the experiment of practical multifilamentary Bi-2223/Ag tapes with ferromagnetic influence are published so far from the point of view of practical feasibility. For example, Bi-2223/Ag tape fully covered with bulk iron was measured in order to investigate the effect of magnetic shielding on critical current density and ac losses, where critical current could be improved but with compensation of manifold ac losses [11]. We, in order to improve electromagnetic properties have applied ferromagnetic shielding effect on the multifilamentary Bi-2223/Ag tapes from the point of view of practical feasibility. In this approach, pure nickel was electroplated locally near the edges of elliptical Ag-sheath Bi-2223 tape maintaining almost the constant overall thickness. Since the electro-deposition employs simple aqua solution and no heat treatment is required, microstructure and phase purity of the superconductor was naturally unaffected during the coating. An optimum geometry of ferromagnetic layer, from the point of view of practical feasibility as well as electromagnetic performance, was achieved by controlling coating thickness and area. About 11% enhancement of critical current with almost constant ac loss was obtained by ~40 μm thick and ~0.3 mm long nickel coating.

2. The objectives of ferromagnetic coating

The Bi-2223/Ag tapes, due to its anisotropic behavior, are very sensitive to orientation of the magnetic fields. Particularly, critical current as well as ac losses are greatly affected when magnetic fields held perpendicular to the wide surface of the tape. It has been shown by an approximate estimation that perpendicular component of magnetic self-fields in Bi-2223/Ag tapes (considering two-dimensional thin strip of homogeneous current) rises sharply near the edges indicating a high influence on total critical currents [12]. Therefore, on the basis of redirection of perpendicular component of self-field lines at the edges, ferromagnetic coating in the edge region of the tape is considered to be effective. The partial magnetic shielding of the tape also lowers the quantity of ferromagnetic material, which should reduce the associated ferromagnetic losses.

Magnetic self-field lines of a typical Bi-2223/Ag tape with elliptical cross-section are demonstrated with and without ferromagnetic coating (assuming relative permeability of 100) in Fig. 1a and b, respectively. It can be observed (Fig. 1b) that field lines near tape edges that are mostly perpendicular to the wide surface are redirected along the wide surface by the effect of ferromagnetic shielding.

A schematic of the possible ferromagnetic coating on Bi-2223/Ag tape is also demonstrated in Fig. 2. Two important parameters that define the configuration of ferromagnetic coating are thickness, as denoted by “T” and length (starting from the edge), as denoted by “L” in Fig. 2.

3. Introduction of ferromagnetic coatings

It is very important to determine appropriate candidate of ferromagnetic material from the point of view of magnetic properties (permeability and hysteresis) as well as mechanical properties (hardness and ductility). Nickel is a ferromagnetic material exhibiting moderate relative permeability and a good ductility. In order to realize ferromagnetic coating, however, pure nickel was electroplated on the enamel insulated 61-filament Bi-2223/Ag tape with a cross-section of 4 mm ×
0.25 mm. The plating bath was an aqua solution composed of nickel chloride, nickel sulfate and boric acid. Enamel in the selected area (edge region) of the tape was removed first with a soft silicon paper and rinsed carefully before electroplating. A number of samples were prepared based on the length and thickness of Ni coating. The coating thickness was varied from 20 to 50 μm while the coating length (from edge toward center of the tape) was varied from 0 to 2 mm (half-width). A few of the samples, as listed in Table 1, will be demonstrated in the article as representatives. The cross-sections of various Ni-coated Bi-2223/Ag tapes are observed by optical microscope and displayed in Fig. 3.

4. Results and discussion

In order to evaluate the superconducting properties, dc voltage–current characteristics, dc magnetic field dependent critical currents and transport current ac loss were measured for the various Ni-coated tapes. DC voltage–current measurement was performed with 5.5 cm long voltage tap for all the samples with and without Ni coating, and \( I_c \) was determined through 1 μV/cm criterion. The dc \( V-I \) characteristics of samples A and B in Fig. 4a and that of C and D in Fig. 4b are illustrated along with that of Ni-free tape (sample E). It is apparent that critical currents in Ni-coated tapes increase depending on thickness and length of the coating. Sample A with coating thickness, 40 μm and coating length, 0.3 mm exhibits \( I_c \) of 102 A, while sample B with a little thicker coating (45 μm) but same coating length (0.3 mm) exhibits higher \( I_c \) (104 A). Again, sample D with thicker coating (50 μm) but smaller coating length (0.2 mm) shows smaller \( I_c \) (97.4 A). It is remarkable that almost no change in \( I_c \) was found for zero length of coating, that is when coating is just at the edges. Again, in some samples, length of the coating was increased but thickness was decreased from the point of view of maintaining the constant

<table>
<thead>
<tr>
<th>Sample</th>
<th>Coating thickness [μm]</th>
<th>Coating length [mm]</th>
<th>( I_c ) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>40</td>
<td>0.3</td>
<td>102.0</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>0.3</td>
<td>104.0</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>1.0</td>
<td>98.2</td>
</tr>
<tr>
<td>D</td>
<td>50</td>
<td>0.2</td>
<td>97.4</td>
</tr>
<tr>
<td>E (Ni = 0)</td>
<td></td>
<td></td>
<td>92.0</td>
</tr>
</tbody>
</table>
overall thickness of the tape. For example, sample C with coating thickness, 20 µm and coating length, 1 mm is the representative of such samples, which exhibits $I_c$ only 98.2 A. Therefore, it can be concluded that maximum $I_c$ is obtainable for the coating near tape edges with optimizing coating thickness and coating length. But there is restriction of determining coating thickness and coating length from the point of view of the mechanical properties of the tape.

The conventional Ag-sheath Bi-2223 tapes prepared by powder-in tube method exhibit elliptical cross-section, that is, thickness of the tape at center is higher than the edges. For example, Bi-2223/Ag tape employed in the experiment provides thickness of 0.25 µm at center and 0.20 µm at the edges. This allows Ni coating near the edges with thickness of about 20 µm keeping the overall thickness of the tape (0.25 µm) constant. In this case,
the enhancement of $I_c$ should be $\sim 10\%$ as can be predicted from sample C, even with a shorter coating length. On the other hand, $\sim 13\%$ increment of $I_c$ can be obtainable with a thicker coating ($45\,\mu m$) but same coating length ($\sim 0.3\,mm$) as in sample B. But, in this case, the overall thickness of the tape increases by $60\,\mu m$ which may affect the stacking and mechanical properties of the tape. However, in order to determine optimum coating thickness, impact of Ni coating on stacking and mechanical properties of Bi-2223/Ag tape is also required to be investigated. In order to obtain maximum $I_c$, optimization of the configuration of ferromagnetic shielding has been suggested by Genenko [3] but there was no focus on ac losses in the investigation.

Transport current ac loss of Ni-free and Ni-coated Bi-2223/Ag tapes were measured at $30\,Hz$ with the same specimen as used in the dc voltage–current measurement. The measured ac losses along with predicted one by Norris model for elliptical cross-section [13] are illustrated in Fig. 5. It is apparent that no significant reduction of ac loss in Ni-coated sample is observed, rather ac loss increases with increasing coating thickness and coating length (samples B and D). However, sample A with $I_c$ of 102 A shows smallest ac loss among the Ni-coated samples which is almost as same as that of the Ni-free tape. The sample A with moderate coating thickness ($40\,\mu m$) is therefore considered as the best one with about $11\%$ increment of $I_c$ but no extra ac loss.

The sample A is therefore allowed to measure critical current under applied dc perpendicular magnetic field and the result is compared with that of the Ni-free tape as depicted in Fig. 6. It can be observed that difference between critical currents in Ni-free and Ni-coated tape is pronounced enough in the smaller field region up to $70\,mT$, but it tends to gradually decrease toward upper field. However, further dependence of critical current on higher field could not be measured due to lack of source of sufficient high field. Nevertheless, it can be anticipated from this result that Ni-coated tape with increased $I_c$ might be useful for the devices like cables and coils held with some moderate fields. It is also interesting that HTS coil made with Ni-coated tape should provide low $I_c$-degradation as Ni coating minimizes the field effect at the coil edges. Besides, since ferromagnetic coating is introduced on existing HTS tape rather than individual filaments by this approach, no question for heat treatment or mechanical deformation will arise and hence, microstructure and phase purity of the superconductor should be unaffected.

5. Concluding remarks

Experiment of enhancing critical current in existing multifilamentary Bi-2223/Ag tape based
on ferromagnetic influence was performed. About 11% increment of critical current without any extra ac losses was obtained by introducing \( \sim 40 \) \( \mu \)m thick Ni coating near the tape edges. The increased critical current is well sustainable up to 70 mT although it decreases gradually with increasing field. Due to elliptical cross-section of conventional Bi-2223/Ag tape, critical current up to \( \sim 10\% \) could be enhanced, keeping the constant overall tape thickness, by introducing \( \sim 20 \) \( \mu \)m thick Ni coating near the tape edges. The Ni-coated Bi-2223/Ag tapes with enhanced critical current can be used in some power applications with moderate magnetic fields.

References


