Development of a REBa$_2$Cu$_3$O$_{7-}$ multi-core superconductor with ‘inner split’ technology
Development of a REBa$_2$Cu$_3$O$_{7-\delta}$ multi-core superconductor with ‘inner split’ technology

Xinzhe Jin$^1$, Hidetoshi Oguro$^2$, Yugo Oshima$^3$, Tetsuro Matsuda$^4$ and Hideaki Maeda$^1$

$^1$Center for Life Science Technologies, RIKEN, Yokohama-shi, Kanagawa 230-0045, Japan
$^2$High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University, Sendai-shi, Miyagi 980-8577, Japan
$^3$Condensed Molecular Materials Lab., RIKEN, Wako-shi, Saitama 351-0198, Japan
$^4$Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama-shi, Kanagawa 226-8503, Japan

E-mail: xinzhe.jin@riken.jp

Received 29 October 2015, revised 14 January 2016
Accepted for publication 20 January 2016
Published 3 March 2016

Abstract

Recently, advanced research into fine filament technology for tape-shaped superconducting-coated conductors composed of REBa$_2$Cu$_3$O$_{7-\delta}$ (RE123, RE: rare earth such as Gd or Y, 0 $< \delta < 1$) has been carried out to improve performance in high magnetic fields by reducing the large diamagnetism of the RE123 superconducting layer. The major challenge for high-field NMR/MRI applications is to obtain high tensile stress tolerance above 500 MPa with a high critical current. In this study, a RE123 multi-core superconductor was fabricated via an ‘inner split’ method using a commercially available RE123 single-core coated conductor, where only the ceramics (RE123 and buffer layers) in wire are electrically separated to multi-filaments without superconducting current flow between the filaments. Experimental results show that wires having 2, 3, 4, or 5 cores have a high critical current (above 95% of the original) and maintain tensile stress tolerance above 650 MPa. The diamagnetism of the five-core wire is reduced $\sim$85% of the original at 7 T. Thus, the wire was optimized via inner split method for high-field use.

Keywords: RE123, multi-core, superconducting wire, inner split

(Some figures may appear in colour only in the online journal)

1. Introduction

The development of commercially available high-temperature superconducting (HTS) wires has been a long and winding road since the discovery of the first high-temperature superconductor in 1986 by Bednorz and Müller [1]. Nevertheless, the substantial effort of a multitude of researchers has led to success in the incredibly challenging fabrication of wires composed of brittle HTS ceramics. The first-generation HTS wire was a silver-sheathed Bi$_2$223 tape wire [2–5], which was applied to power transmission cables and high-field magnets. Recently, further research and development of the tensile strength in coils is carried out for further application in ultra-high magnetic fields [6]. The second-generation (2G) HTS wire was a thin tape-shaped REBa$_2$Cu$_3$O$_{7-\delta}$ (RE123, RE: rare earth such as Gd or Y, 0 $< \delta < 1$) single-core coated conductor (single-filament of RE123 layer) having a high critical current and a high tensile stress tolerance, which was applied in a variety of situations including electric transformers and high-field research magnets [7–11]. Recently, there have been good advances in Bi2212 round wire technology for application in future high-field (>30 T) magnets [12], since first developments of the wire and Rutherford cable [13, 14]. Focusing on application field, a third-generation (3G) HTS wire having a high critical current and a high tensile stress tolerance and a low diamagnetism is required, to use in even...
more instruments (in superconducting wire application fields) including NMR and MRI as 3G HTS coil [15]. However, it is not easy to fabricate a 3G HTS wire based on current techniques, such as RE123 round wire (multi-filament) that has low critical current in current study. Therefore, we consider the fabrication of a RE123 multi-core superconductor (multi-filament of RE123 layer) by addition of a performance (low diamagnetism) into the single-core 2G HTS wire with keeping the original performances (high critical current and high tensile stress) in this study.

RE123 coated conductors are expected to provide high superconducting performance, including high critical current and high critical field, since the aligned crystalline orientation in RE123 thin-films was developed via the ion beam assisted deposition method [16]. For example, RE123 conductors are in practical use in high current electric power cables. Moreover, it is expected to be superior in order to achieve higher performance of many machines, such as high-field research magnets (above 30 T), high-resolution NMR/MRI (above 1.2 GHz) instruments, and high-precision accelerators. Of note, for a RE123 coated conductor, a thin-filament-type structure is required of the RE123 layer for use in NMR and MRI due to the large screening current induced magnetic field from diamagnetism of the RE123 superconducting layer [17]. However, there are still a few problems to be solved in the current studies of RE123 coated conductors, such as coil degradation by epoxy impregnation [18], magnetic field instability in the coil center, difficulties with the persistent current mode (due to the large, resistive joint between the soldered, coated conductors), and deterioration of the magnetic homogeneity due to the large diamagnetism of the tape surface [19]. With respect to coil degradation, some effective solutions utilizing its mechanism [20] have been obtained, such as wax impregnation [18, 21]. To improve the magnetic field instability, one solution employs current sweep reversal [22]. Our lab has approached the persistent current mode issue by developing a superconducting joint via a crystalline joint by melting bulk method [23]. However, the last issue remains without any effective solution for single-core coated conductors. In particular, a high homogeneity in the magnetic field (<0.1 ppm) is required for NMR/MRI. Therefore, the large diamagnetism of the coated conductor is an issue which needs to be solved because it inhibits the adjustment of the magnetic field homogeneity using an external shim coil. Thus, the development of a coated conductor that has high critical current, high mechanical strength, and low diamagnetism is an important research issue in the current development of the high-field NMR [17].

One way to reduce the diamagnetism of a coated conductor is to generate a multi-filament structure for the RE123 layer that the magnetic field lines will pass through the gap between the RE123 filaments. For this purpose, scribed wires have been produced via many methods including mechanical grinding, chemical etching, and laser slotting. Recently, high critical current scribed wires for application in power transmission cables were developed using a laser scribing and etching method with a reduction rate in the critical current of about 50% for a five filament-long wire, which is a great improvement in AC loss [24, 25]. For the next generation of ultra-high-field magnets, further improvement in the critical current is essential; one goal is maintaining 90% of the original critical current for a five filament-long wire. The tensile stress tolerance of wires must also be estimated when using them in magnets. Furthermore, the development of a faster fabrication speed (and cost reduction) for production of long wires is necessary, while for mass production, it is better to raise the speed above few hundred m/h.

In this study, a novel ‘inner split’ technology is utilized to quickly and conveniently fabricate a high performance RE123 multi-core superconductor, the remarkable performance of which is also reported.

2. Fabrication principle of multi-core

The word ‘multi-core’ signifies the various number of RE123 filaments in a coated conductor, which typically consists of a Cu stabilizer, an Ag layer, a RE123 layer, a buffer layer, and the Hastelloy® substrate, as shown in figure 1. In this study, fabrication of a RE123 multi-core superconductor was attempted using a commercially-available, single-core, coated conductor (the ‘original sample’) via electrical separation by phase stress (ESPS). The phase stress in this paper indicates the RE123 phase stress, which the RE123 filaments were electrically separated without superconducting current flow by increase of the phase stress. Capitalizing on the difference in toughness between the ceramics (including the RE123 and buffer layers) and the metal phases (including the Cu stabilizer, Ag layer, and Hastelloy® substrate) in the coated conductor is a useful way to split the RE123 layer without disconnection of the metal layers. We denote the split formed at the ceramics layers in the coated conductor the ‘inner split,’ where a single inner split results in 2 cores, 2 inner splits results in 3 cores, etc. The wire is called a ‘split wire’.

Two fabrication methods with different types of stresses were considered for ESPS, these are electrical separation by bending of tape along longitudinal direction of wire (electrical separation by bending stress, ESBS) and electrical separation by crushing pressure between filaments without bending treatment of wire (electrical separation by pressure concentration, ESCP), as shown in figures 1(a) and (b), respectively. The two methods are distinguished by the dominant stress component, using a softer or a harder material under the coated conductor, where the bending and stress concentration occur. In practice, the choice of method can be made based on the flexibility of the coated conductor; e.g., the ESBS method is applicable for the 0.1 mm thin coated conductor fabricated by SuperPower Inc., and the ESPC method is useful for the 0.2 mm thick conductor made by Fujikura Ltd. To facilitate production with a small load value on the tape surface, the increased bending angle of the ESBS method is preferable. Furthermore, using the ESBS method, it is best to perform a partial or entirely V-shaped bend in the coated conductor for perfect electrical separation (non-superconducting connection) of the RE123 filaments. In this study, experimental assessment (critical current, tensile stress tolerance, and
diamagnetism) of multi-core superconductors, fabricated via a partial V-bend ESBS method using a desktop single splitter as shown in figure 1(c), has been carried out.

3. Experiment

3.1. Equipment development

To prepare the multi-core superconductor via ESPS method, a compact, desktop single splitter was fabricated first, as shown in figure 1(c). The single splitter consists of a cemented carbide pressure roller (width of blade edge: 20 μm), a polyoxymethylene (POM) guide roller (concave shaped cross section), a stainless steel spring (<90 N), and an Al alloy frame. By initially pressurizing the load onto the tape surface of the coated conductor using the spring, the coated conductor is easily transformed into a partial V-bend at the machining point of the sharp-edged pressure roller and the soft guide roller. By increasing the load of the pressure roller, the inner split is formed by disconnection of the ceramic (RE123 and buffer) layers without disconnection of the metals in the coated conductor, and an appropriate load value needs to be chosen for perfect electrical separation. Then, via a rotary forming process, a longer-length inner split (along the long-itudinal axis of the coated conductor) can be produced. In order to obtain a straight inner split along either the longitudinal or the lateral axis of the coated conductor, the latter is denoted a ‘cross split’ in this study. The results show that a load of 80 N for an inner bend using the single splitter is sufficient for complete electrical separation (no superconducting current flow), as discussed in section 4.2.

3.2. Sample preparation

To prepare the multi-core samples, a tape-shaped (4 mm wide, 0.1 mm thick) RE123 single-core coated conductor fabricated by SuperPower Inc. was chosen as the original sample. Since the RE123 layer is structurally situated away from the center of the wire (in the thickness direction), two bending directions (from opposite sides) can be chosen with the ESBS method. The bending direction is defined as either an inner bend (figure 1(a)) or an outer bend. In this study, multi-core samples with 2, 3, 4, and 5 cores (length: each the same 1 m) were prepared by the inner bend method with a manufacturing speed of 720 m h⁻¹ per inner split in a load of 80 N.

To estimate the extent of electrical separation due to the pressure roller load, two types of samples were prepared with a single inner split along either the longitudinal or the lateral axis of the coated conductor. The latter is denoted a ‘cross split’ in this study. The results show that a load of 80 N for an inner bend using the single splitter is sufficient for complete electrical separation (no superconducting current flow), as discussed in section 4.2.

3.3. Observations and measurements of samples

A 3D-digital microscope (VHX-500F) from Keyence Corporation was used to observe the samples. Measurement of the critical current with and without tensile stress was performed for a 4 cm long sample at 77 K. The critical current was estimated based on a criterion of 1 μV cm⁻¹. The magnetic moment along the vertical axis of the tape surface was measured for two pieces of wire using a superconducting quantum interference device made by Quantum Design, Inc.
4. Results and discussions

4.1. Microstructures of the samples

In the fabrication process of the multi-core superconductors (multi-core samples) using ESBS method, a recessed line is formed on the surface of the Cu stabilizer by bending the original tape sample using a sharp-edge pressure roller, as shown in figure 2(a). The depth and width of the recessed line are 9 and 8–16 $\mu$m, respectively. The Cu stabilizer, which is about 20 $\mu$m thick in the original sample, remains about half of the thickness at the recessed line following the inner split treatment.

To observe the RE123 layer after the inner split treatment, the layers on the Hastelloy® side (Cu stabilizer, Ag layer, Hastelloy® substrate, and buffer layer) were removed by delamination of the sample [23]. An inner split line with a narrow distribution width of $\sim 30\,\mu$m was observed on the surface of the RE123 layer, as shown in figure 2(b). This value is less than 1% of the 4 mm width of the wire, which indicates that >99% of the width of the original sample remains for effective current flow after a single inner split treatment. That is, this method results in only a few percent decrease of the effective width per inner split, which is considered ideal.

The formation mechanism of the narrow distribution width of the inner split line via the ESBS method is worthy of consideration. Split lines caused by bending stress in ceramic materials on a macro scale are generally formed with a broad distribution width, e.g. cracking a glass window. However, the distribution width of the split line is strongly related to the thickness of the ceramic. In other words, a thin film can be separated with a narrow distribution width by use of a small bending diameter. The RE123 layer in the original sample has an ultra-large aspect ratio (width:thickness) for a tape-shaped, coated conductor (4000:1), which is considered to be the reason for the formation of the narrow distribution width. The inner split is formed at the bent area, as shown with a red border at the center of figure 1(a). Clearly, the outer diameter of the RE123 layer is decreased by decreasing the RE123 layer thickness, resulting in a reduction of the distribution width of the inner split line. That is, the ESBS method effectively utilizes the characteristic tape shape.

4.2. $I$–$V$ characteristics

To estimate the appropriate load value for the pressure roller in the inner split fabrication process, the $I$–$V$ properties of two types of samples (inner split and cross split), each fabricated with various load values, were measured between two adjacent filaments, where the current flows across the inner split or cross split of the sample, as shown schematically in figure 3(a). The cross current for the inner split sample was evaluated by making a cutout in each filament, as shown in the figure. For the cross split sample, the critical current $I_c$ begins to decrease with increasing load value above ∼30 N, and then shows behavior similar to a sigmoid curve approaching 80 N. For the inner split sample, almost the same behavior was obtained in a load range of 50–80 N. At a load of 80 N, the linear behavior indicative of normal conductivity appears, as shown in the inset. This indicates that 80 N, the load value chosen for all of the multi-core samples used in this study, is sufficient for the complete electrical separation of (no superconducting current flow between) RE123 filaments.

The critical currents of the multi-core samples ($I_c$) and the original sample ($I_{co}$) were measured at 77 K without external magnetic field. The ratio of $I_c/I_{co}$ versus the number of inner splits in the wire is plotted in figure 3(b). The inset figure shows the determination of the critical current for a four-core sample (3 splits) and the original sample, at 1 $\mu$V cm$^{-1}$.) As can be seen in the figure, the $I_c/I_{co}$ ratio slowly decreases with increasing number of inner splits up to five cores, maintaining at least 95% of the original value. The
The $I_c/I_{co}$ ratio decreases only 1.2% per inner split. This value is similar to the 1% reduction rate in the effective width obtained above, indicating a good manufacturing result. Thus, high manufacturing accuracy was achieved with the ESBS method, substantially maintaining a high critical current.

4.3. Tensile stress tolerance and magnetic field dependence of the critical current

The tensile stress tolerance of the critical current for the multi-core superconductor should be tested with respect to the large hoop stress ($\sim 500$ MPa) which are generated in high-field magnet operations. The tensile stress of the original sample necessary to retain 95% of the critical current $\sigma_{95}$ is about 700 MPa; a high retention ability (above 80% of the original value) is necessary for practical application. Experimental assessment for the tensile stress tolerance of the samples was carried out by applying a linear tension along the longitudinal axis of the wire without external magnetic field. Figure 4(a) shows the results, where the criterion to determine the tensile stress tolerance is 95% of $I_c/I_{co}$. The two patterns fundamentally overlap.

Figure 3. Estimation of critical currents in the samples. (a) The pressure roller load dependence on the critical current $I_c$ passing through either the inner split or cross split. The inset shows the $I-V$ behavior at an 80 N load. (b) The $I_c/I_{co}$ ratio versus the number of inner splits. The criterion to determine the $I_c$ is 1 $\mu$V cm$^{-1}$. The plots were fitted with a linear function, and the inset figure shows an example of the determination of $I_c$.

Figure 4. Assessments of retention capability of critical current under tensile stress or in external magnetic field. (a) The tensile stress $\sigma_{95}$ to retain 95% of $I_c/I_{co}$. The plots were fitted with a linear function. The inset figure shows an example of the determination of $\sigma_{95}$ with a criterion of 95% of $I_c/I_{co}$. (b) Magnetic dependence of the $I_c/I_{co}$ ratio under a tensile stress of 50 MPa. The two patterns fundamentally overlap.
It is known that high magnetic homogeneity is of great importance when evaluating the magnetic behavior and superconducting properties of a superconductor. The achievement of high tensile stress tolerance is an outstanding characteristic of this new splitting wire, and is a great advancement toward the realization of ultra-high field magnets for use in high-resolution NMR/MRI. That is, the conventional challenge with the tensile strength of a RE123 multi-core superconductor can be resolved by the ESBS method with inner split technology.

To further investigate the effect of the inner split on the critical current, the magnetic field dependence of the \( I_c/I_{co} \) ratio was measured for the two-core and the original samples under a constant tensile stress of 50 MPa. The results show effectively the same behavior as shown in figure 4(b), thus confirming that the inner split is not correlated to the magnetic field dependence of the critical current. The number of cores is of great importance when evaluating the magnetic behavior of the samples.

### 4.4. Magnetic moments

It is known that high magnetic homogeneity (<0.1 ppm) is required for NMR/MRI operation. The magnetic homogeneity at the center of the magnet is usually controlled by an outer shim coil through the stacked superconducting wires in the main coil. Therefore, reducing the diamagnetism from the tape surface of the coated conductor by introducing many magnetic penetration routes through gaps (slots or splits) is a good approach for success in the development of a high-field NMR/MRI using a RE123 coated conductor. To estimate the diamagnetism of a sample in a straightforward way, measurement of the magnetic moment of a short length of sample is a useful and efficient method. In this study, all samples were the same size (4 mm long, 4 mm wide, and 0.1 mm thick). A Bi2223 multi-core wire (Cu–Ag laminate, 0.3 mm thick) fabricated by Sumitomo Electric Industries, Ltd which was used in a 1.03 GHz (24.2 T) NMR instrument at the National Institute for Materials Science (NIMS) [28] was measured for comparison. The Bi2223 wire was also measured over a tape area which would be applicable in an NMR/MRI in terms of magnetism. To obtain the magnetic moment of the wire per unit area of tape, the magnetization \( M \) (a magnetic moment per unit volume) was converted to a magnetic moment per unit area: \( P = Mh \), where \( P \) is the magnetic moment per unit area for a piece of the wire, and the \( h \) is the wire thickness.

The magnetic field dependence of \( P \) is shown in figure 5(a). With an increase in the core number of the RE123 coated conductors, the plot is shifted significantly to increased \( P \). For the five-core sample, the diamagnetism is smaller than that of the Bi2223 wire at above 5 T. A reduction of about 85% from the original (i.e. single-core) sample is observed in a magnetic field of 7 T. This indicates that low diamagnetism was achieved in the five-core wire. The diamagnetism of the original sample was effectively reduced by the multi-core treatment of the ESBS method.

The total magnetic moment of the wire material can be approximated to that of only the superconducting layer since the magnetic moment of the high-temperature superconductor is much larger than that of any other materials in the wire. Figures 5(b)–(d) show the schematic illustrations of magnetic field patterns in the samples. With an increase in the external magnetic field, magnetic penetration occurs at the inner splits, and after the lower critical magnetic field of the RE123 layer is reached, magnetic penetration occurs at the inside of superconductor (RE123 cores) known as mixed state. As seen in the figures, the internal field of the superconductor...
5. Conclusions

A RE123 multi-core superconductor, having potential application in high-field NMR/MRI, has been fabricated via an inner split method and experimentally evaluated with high-performances as required in the 3G HTS coil. The fabrication method utilized an ESPS method, specifically ESBS (as opposed to ESPC), allowing the preparation of multi-core samples as a fast manufacturing speed.

The critical current, tensile stress tolerance, and diamagnetism of the RE123 split wires were evaluated, and found to be superior to materials currently in use in high-field applications. The diamagnetism is greatly enhanced and the critical current and tensile stress tolerance are each maintained above 95% when subjected to practical use conditions. Thus, the inner split method is a valuable new approach to producing RE123 multi-core superconductor for use in high magnetic field applications.

Acknowledgments

The experiments for tensile stress tolerance in magnetic field were carried out at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

References

from transposed striated CC tapes Supercond. Sci. Technol. 26 075020


[27] Osamura K et al 2009 Reversible strain limit of critical currents and universality of intrinsic strain effect for REBCO-coated conductors Supercond. Sci. Technol. 22 025015