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Xinzhe Jin, Yasuteru Mawatari, Toshihiro Kuzuya, Yusuke Amakai, Yoshinori Tayu, Naoki Momono, Shinji Hirai, Yoshinori Yanagisawa, Hideaki Maeda

***Abstract*— For application to ultrahigh-field nuclear magnetic resonance spectroscopy (e.g., 30 T), we have started to develop a $REBa_2Cu_3O_{7-\delta}$ (RE123, RE: rare earth) multi-core coated conductor in which the ceramic layers (RE123 and buffer layers) are electrically separated to create multiple filaments. This method is called electrical separation by inner splitting, and the wire is called a split wire. The multi-core structure is fabricated using electrical separation by a phase stress, which utilizes the difference in toughness between ceramics and metal, such as partial V-bending by stress along the longitudinal direction of the coated conductor using a commercially available single-core RE123 coated conductor. In addition, about 10 narrow cores (width: 5–15 µm) can be formed by one bending. These cores are called subcores. The wire is composed of main cores and subcores. In this study, a 4 mm wide multifilamentary RE123 split wire with 16 main cores and 150 subcores was fabricated and evaluated. The manufacturing method, microstructure, and critical current properties under an external magnetic field and tension are presented.**

***Index Terms*— inner split, multi-core, RE123, split wire**

I. Introduction

RECENT developments in fine filament technology for tape-shaped $REBa_2Cu_3O_{7-\delta}$ (RE123, RE: rare earth) coated conductors have improved the performance of high-field magnets by reducing the large diamagnetism of the RE123 superconducting layer [1-6]. For an example, laser scribing method has been used to fabricate the multiple filaments that many slits are formed in RE123 layer [1, 2]. In this method, RE123 and partial metal substrate (e.g., hastelloy) are usually removed at the slit portion. The effectiveness and practicality of multifilamentation on shielding current and AC loss have been demonstrated for wires and coils [1-4].

We previously proposed a multi-core RE123 coated conductor called a split wire that utilizes inner splitting technology [5, 6]. The fabrication method is called electrical separation by inner splitting (ESIS), where electrical separation means that the cores are separated electrically without superconducting current flow. ESIS with mechanical modification is called electrical separation by phase stress. Depending on the type of applied stress, electrical separation by bending stress (ESBS) or electrical separation by pressure concentration (ESPC) can be adopted. In this study, ESBS was used to fabricate RE123 split wires.

In the split wire, the ceramics, namely the RE123 and buffer layers, are separated without removing any material. Due to the use of bending in the fabrication process, the wire extends slightly (e.g., a few micrometers) in the width direction, and narrow splits form due to elongation.

With the mechanical bending process, fast fabrication can be achieved (e.g., 800 m/h per inner split). Recently, we demonstrated the fabrication of split wires with 2, 3, 4, and 5 cores for 4-mm-wide wire that exhibited high performance, such as a high critical current, above 95% of that for the original non-split wire, and a high tensile stress tolerance of above 650 MPa [5].

In the present study, a 16-main-core and 150-subcore split wire was prepared and evaluated.

II. Experiments

A. Sample Preparation

A (Y,Gd)123 coated conductor with a width of 4 mm and a length of 1 m manufactured by SuperPower Inc. (type SCS4050) was used to make the split wire. The thicknesses of silver layers on both (Y,Gd)123 and hastealloy sides are 2 µm and 1.8 µm, respectively. These for copper layers on both sides are the same 20 µm. A compact roller splitter, reported previously, was used for bending the wire for ESBS [5]. Fig. 1 shows an image of ESBS process. To form 16 main cores, the bending process was carried out 15 times from one edge of the wire to the other edge at intervals of about 200 µm in the width direction of the wire. The bending direction was towards the hastelloy side [6] to reduce damage to the (Y,Gd)123 layer. For comparison, a 2-core split wire was also

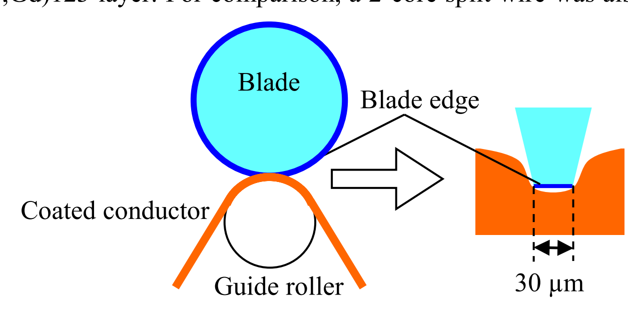

Fig. 1 Schematic illustration for manufacturing split wire with ESBS.

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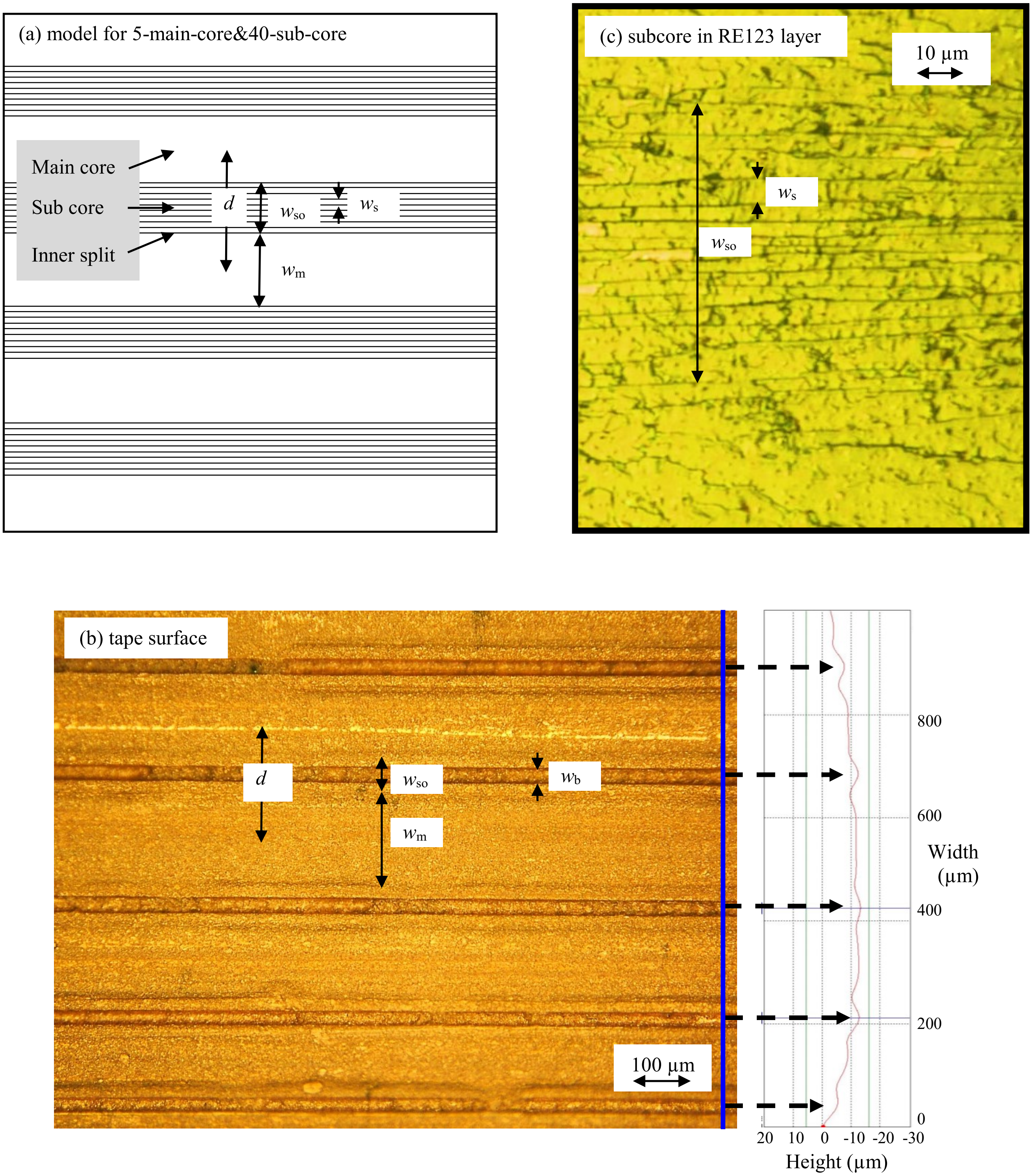

Fig. 2. Model structure of split wire and images of the prepared sample. (a) is model for 5-main-core and 40-subcore wire, (b) is part of the tape surface on the prepared split wire sample with 16 main cores (right plot is a surface height measured along the blue line of width direction), and (c) is subcore in RE123 layer formed along the fold. The distance between two main cores d, width of main core w_m, width of a subcore w_s overall width of subcores w_{so} by a one bending, and width stamped by blade edge of the roller splitter w_b are shown in the figures. The dashed arrow in figure (b) shows the depression formed on the tape surface by bending.

prepared by bending towards the (Y,Gd)123 side [5].

Figure 2(a) shows a model of the structure for a split wire consisting of main cores and subcores. Multiple subcores form along the fold during the ESBS process, and main cores are situated in the non-bending area. The number of split lines N_{split_lines} is $N_{main\_cores}+N_{subcores}+1$, where N_{main_cores} is number of

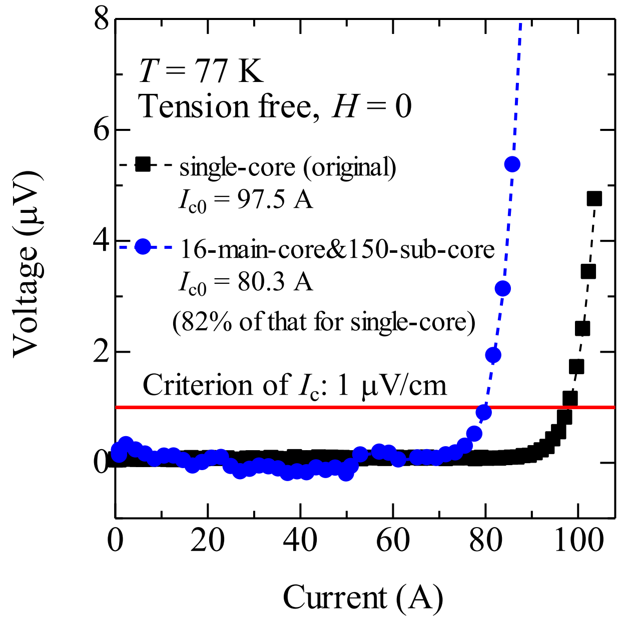

Fig. 3. Current-voltage curves for original coated conductor and 16-main-core split wire in tension-free state without an external magnetic field. The criterion for the criterion for the critical current I_c was 1 μm/cm.

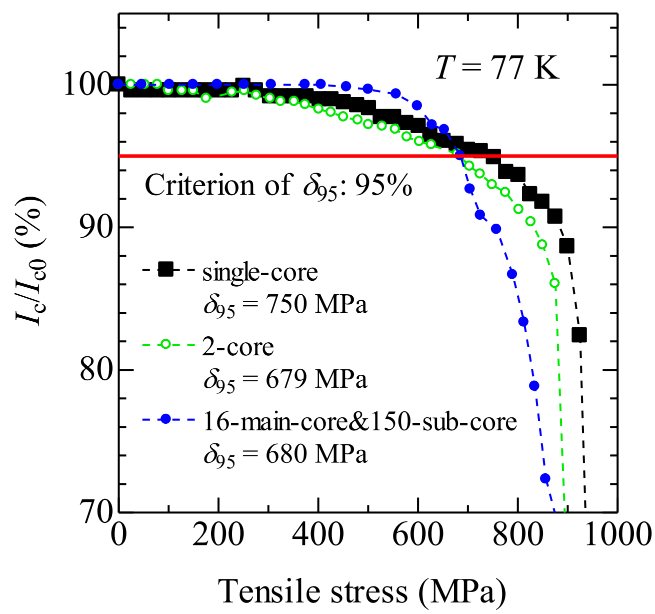

Fig. 4. Critical current ratio I_c/I_{c0} under tensile stress. The criterion for tensile stress tolerance was 95% of I_{c0}.

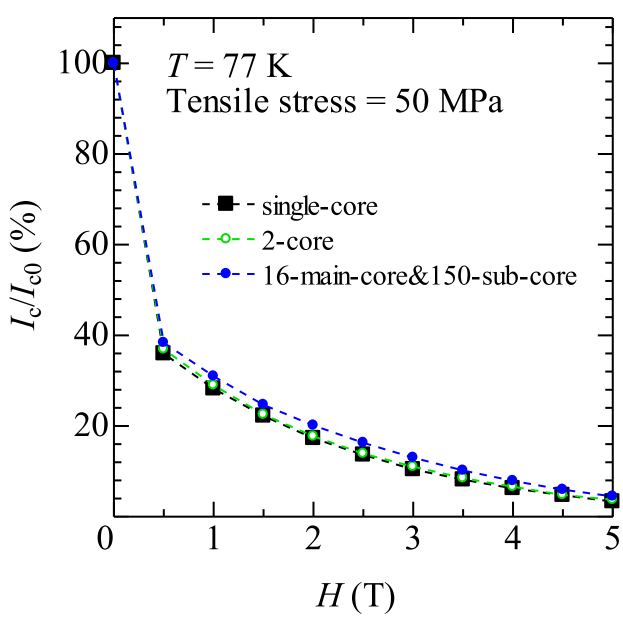

Fig. 5. Magnetic field dependence of critical current ratio I_c/I_{c0}. A small tension of 50 MPa was applied to prevent bending by the electromagnetic force.

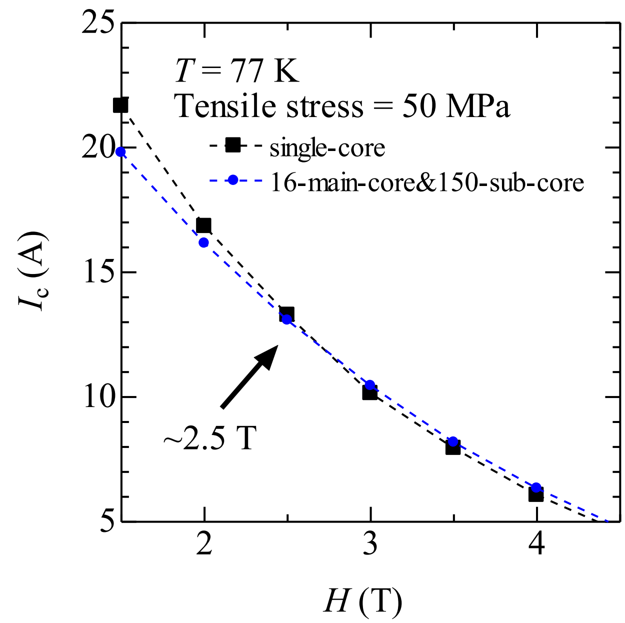

Fig. 6. Critical current changes for 16-main-core and original coated conductors. The arrow shows the crossover point about 2.5 T.

main cores, and $N_{subcores}$ is number of subcores. To observe the microstructure of the (Y,Gd)123 layer, the (Y,Gd)123 surface was exposed via delamination of the Cu and Ag layers.

B. Measurements

A microscope manufactured by Keyence Corporation (VHX-500F) was used for observation and distance determination. All the measurements of critical currents were carried out with a sample length of 4 cm at 77 K. The criterion for the critical current was 1 μV/cm. The criterion for tensile stress tolerance was 95% of the critical current in the tension-free state without an external magnetic field. For comparison, the original single-core coated conductor and a 2-core split wire without subcores were also measured.

III. Results and Discussions

A. Observation of microstructure

Figure 2(b) shows an image of part of the Cu surface (hastelloy side) on the 16-main-core split wire. The distance d between two adjacent main-core centers is in the range of 160–260 μm. As shown in the right plot for surface height, a depression was formed at each fold. The depth and width of the depression are about 10 μm (one half the original Cu thickness) and 60 μm, respectively.

An image of part of the subcore in the RE123 layer is shown in Fig. 2(c). There are many straight split lines (about 10), which are almost parallel to the longitudinal direction of the wire. This is beneficial for maintaining a high critical current without crossing the current flow direction. In particular, for the development of an ultrafine filament with a large number of cores, the retention of original critical current is very important. The width of a split in this study is only about 0.1 μm, which value cannot be obtained using advanced laser scribing technology that is limited to about 10 μm. The width of a subcore w_s is in the range of 5-15 μm, and the overall width of the subcores w_{so} is 60 μm, corresponding to that of a depression, as shown in Fig. 2(b). The width of the main core is 100-200 μm, as calculated using

$$w_m = d - w_{so},$$

where d is the distance between adjacent main cores, as measured above.

B. Critical currents of the samples

The critical currents I_{c0} in the tension-free state and in a self-magnetic field are shown in Fig. 3. The I_{c0} values for the original coated conductor and the 16-main-core split wire sample were 97.5 A and 80.3 A, respectively. After 15 iterations of the bending process, the critical current was maintained at above 80% of the original value. It indicates that part of the current flows still along the subcores, but the majority of the current flows along the main core. The two samples had the same n value of 25.

The tensile strengths in a self-magnetic field were evaluated. Figure 4 shows the tensile stress dependence of the critical current ratio I_c/I_{c0}. With a criterion of 95% [7, 8], the tensile stresses δ_{95} for the original, 2-core, and 16-main-core samples were 750, 679, and 680 MPa, respectively. The latter is 91% of that for the original coated conductor, indicating that high tensile strength can be maintained after 15 iterations of the bending process for ESBS.

Figure 5 shows the measurement results for the critical ratio I_c/I_{c0} in an external magnetic field. The curves for single-core and 2-core wires are similar, whereas that for the 16-main-core sample is slightly higher. The lack of degradation compared to the original coated conductor indicates high performance in a magnetic field. For further investigation, the critical current changes of the 16-main-core and original wires in magnetic field are shown in Fig. 6. The decreasing rate of critical current for the former is smaller than that for latter. The crossover point as shown with arrow in the Fig. 6 indicates that the critical current of the 16-main-core wire has the same value with original wire at about 2.5 T. This increase may be related to a large increase in the split number as a function of the path of magnetic field lines. The magnetic field lines in direction passing through the tape surface without detouring in split wire is largely increased than that in original coated conductor.

IV. Conclusion

We prepared a multifilamentary RE123 split wire with 16 main cores and 150 subcores using the ESBS method. The widths of the main core and subcore were below 200 μm and 15 μm, respectively. The critical current was maintained at above 80% of that of the original coated conductor with the same n value. In the tensile test, the wire showed high mechanical strength, which remained at above 90% of that of the original wire. The magnetic dependence of the critical current showed no degradation at magnetic fields up to 5 T, and a small increase compared to that of the original wire was found.

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