Development of a Novel Method to Efficiently Measure Critical Bending Diameter of 2G HTS Tapes

Jiamin Zhu, Shuiliang Zhen, and Zhijian Jin

***Abstract*—High critical current density is desired for cables adopted in fusion or accelerator applications. The bending diameter of REBCO tapes is very important for the preparation of such cables. The bending diameter of REBCO tape is related to many factors. It is necessary to identify the most important factors determining the bending diameter by experiments. In this article, a new measurement method for bending diameter is developed. Short samples are taken from individual tapes in a large batch and connected in series into one long piece for bending diameter measurement. This way, a large batch of tapes can be efficiently assessed in one go. The samples prepared by Shanghai Superconducting Technology Co., Ltd. (SST) have been tested. It is concluded that the critical bending diameter of the tapes, which we define that the critical current attenuation is less than 10%, is closely related to its thickness, stiffness, superconducting layer thickness, and copper plating thickness. The composition of the superconducting layer has little effect on it. By testing the tapes prepared by SST in large quantity, it is found that when the REBCO faces inward during bending, tapes plated with 5 and 10 μm copper on one side only have smaller critical bending diameter than tapes plated with copper on both sides. The current has no attenuation when the bending diameter is 2.6 mm. When REBCO faces outward, copper plating has little effect on the critical bending diameter, which varies between 6 and 14 mm.**

***Index Terms*—High-temperature superconductor (HTS) tape, inward and outward, minimum bending diameter.**

I. Introduction

The second-generation high-temperature superconductor (2G HTS) tape is associated with higher current density, better performance under external magnetic field, and lower raw material cost, in comparison to BSCCO tapes. At present, many 2G HTS tape manufacturers around the world have entered the mass production stage, which can supply tapes consistently in a large quantity [1]–[8]. Commercialized tapes have been widely adopted in power and magnet applications. In particular, it has promoted the development of high field magnets, particle accelerators, and nuclear fusion.

In some large magnets, the inductance needs to be low enough to ensure that the voltage of the coil is maintained at a reasonable value during charging or discharging. The reduction of inductance is achieved by reducing the number of turns, which must correspondingly increase the working current. Therefore, large magnets are usually prepared using cables rather than a single tape [9]–[11]. As a result, many institutions began to research and develop 2G HTS cables, for example for fusion.

2G HTS tapes can be manufactured into three types of cables: the twisted stacked tape cable (TSTC) [12], [13], the conductor on round core (CORC) [14], [15], the Roebel assembled coated conductor cable [16], [17].

Based on the three fundamental types, cables with more complicated structures have been developed to target different application requirements: based upon TSTC, European Nuclear Energy Agency developed five twisted-stack conductors [18], Swiss Plasma Center developed 12T prototype twisted-stack conductor [19], Karlsruher Institut für Technologie (KIT) developed 2G HTS cross conductor [20], National Institute for Fusion Science developed FAIR conductor and STARS conductor [21], [22], North China Electric Power University (NCEPU) developed quasi-isotropic strand stacked [23], Massachusetts Institute of Technology developed a vacuum pressure, impregnated, insulated, partially transposed, extruded, and roll-formed cable [24]. European Organization for Nuclear Research, based upon CORC structure, developed cable-in-conduit conductor [25]. KIT, based upon Roebel structure, developed coated conductor rutherford cables [26].

Given the design and structure of the cables, thinner and narrower 2G HTS tapes can significantly improve their performance. Shanghai Jiao Tong University used 1 mm wide 2G HTS tape and developed a novel soldered-stacked-square 2G HTS wire [27], which significantly reduced ac loss and shielding current under high magnetic field [28]. Houston University used 2G HTS tapes made from thin substrates and asymmetrical copper coating and developed symmetric tape round wire (STAR), with engineering current density (J_e) exceeding 450 A/mm^{-2} at 4.2K 15 T with 15 mm bending radius.

Cables for compact fusion application desire high current density. This often requires the 2G HTS tapes to have a higher critical current density, which is often achieved by using thick superconducting film or pinning technology with a thin substrate.

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Fujikura Ltd. and THEVA Dunnschichttechnik GmbH adopted thick superconducting film process. In addition, all suppliers adopt the pinning technique to achieve higher current under low temperature and high field. In addition, Superpower [30], SuperOx [5], and SST [31] have all plated the superconducting film on thin substrates, which reduces the thickness of the tapes and improves the engineering critical current density, i.e., J_e of the tapes.

When deployed in a cable, the 2G HTS tape ought to maintain its current carrying capacity when it is bent, which puts forward a requirement on the bending diameter. If the tape has a smaller critical bending diameter, the cable can be manufactured with a smaller cross-sectional area under the same current carrying capacity, which can also yield a higher critical current density. As a key parameter in cable application, the bending characteristics of REBCO tape need to be studied in depth.

National Institute of Standards and Technology studied in-plane bending and large intrinsic effect of the axial strain of 2G HTS [32], [33]. American Superconductor Corporation, Inc. proposed that placing the superconducting layer at the center of the tape by lamination can significantly improve the bending characteristics of the 2G HTS tape [34]. Houston University changed the thickness of the copper plating layer of the tapes and found tapes with the smallest bending diameter for STAR cables [35].

The critical bending diameter of REBCO tape is related to many factors, including the thickness and type of the substrate, the material and thickness of superconducting layer, the thickness of stabilizer layers, etc. The actual effect of these factors on the critical bending diameter needs to be derived through a large number of experiments. The traditional method is to wind the tape onto a stick and carry out the measurement. This method is very inefficient and is unsuitable when a large number of tapes need to be measured. It is urgently needed to develop a more efficient and effective test method for 2G HTS tape bending diameter measurement.

A number of methods to measure the bending diameter have recently been developed. Fujikura Ltd. used the bending machine to measure the bending characteristics of BMO doped 2G HTS tape prepared by PLD [36]. KIT used the bending machine for single tapes [37]. NCEPU measured the bending diameter with a specifically designed wheel [38]. Lai Lingfeng of the Beijing Eastforce Superconducting Technology Co., Ltd. wound the tape on a thin rod, removed it, and calibrated the bending diameter of the tape with MCorder [39].

In this article, a new rapid method for measuring the critical bending diameter of 2G HTS tapes is developed. Using this method, samples taken from tens or even hundreds of tapes can be measured in a single experiment, significantly improving the efficiency of measuring critical bending diameter of 2G HTS tapes. Tapes of various specifications, prepared by SST, have been tested, and data are collected and analyzed. These data and conclusions can provide useful references for users when considering the application of 2G HTS tapes.

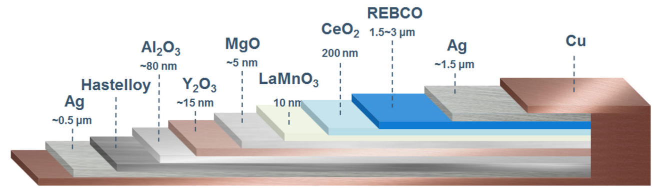


Fig. 1. Geometrical structure of 2G HTS tape made from SST.

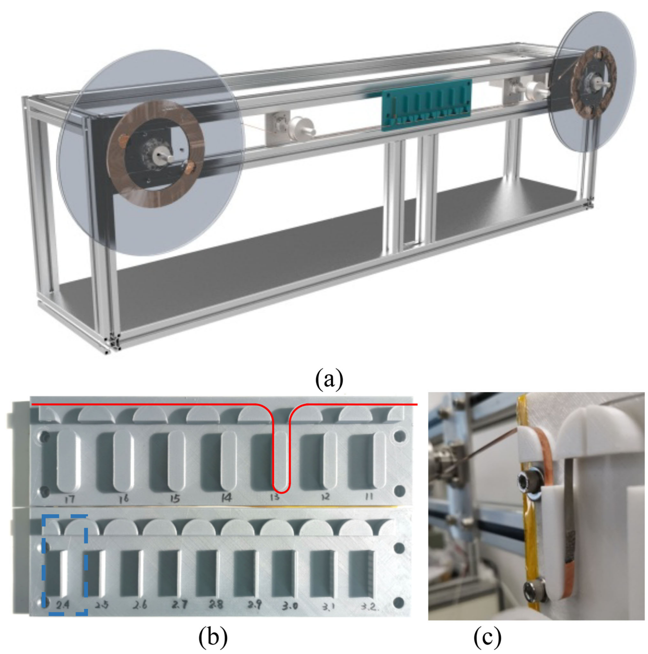


Fig. 2. Test device for bending of 2G HTS tapes. (a) Installation structure. (b) Test board. (c) Test details.

II. Experiments Details

A. Sample Preparation

Prior to film deposition, SST prepares its substrates by electro-polishing, in order to achieve a roughness of 1nm per 1 μm $\times$ 1μm. The buffer layers have a structure of CeO_2($\sim$300 nm)/ $LaMnO_3$($\sim$10 nm)/ MgO($\sim$5 nm) / Y_2O_3($\sim$15 nm)/Al_2O_3($\sim$80 nm), as depicted in Fig. 1, with each layer obtained by deposition. The superconducting layer is achieved by PLD, typically a double-layer structure with a total thickness of 1.8 μm. The silver stabilizer is deposited by magnetron sputtering, the layer next to REBCO layer is 1.5 μm, and the layer next to Hastelloy substrate is 0.5 μm. Copper is electro-plated to surround the final product, with thickness customized to application requirement.

B. Bending Test Set-Up

The testing unit for the critical bending diameter of each superconducting tape is composed of two 90° arc modules of large radii and a 180° arc module of fixed diameter, as shown in the blue dotted line box in Fig. 2(b). The tape wound on the module can rotate 180° along the circumferential diameter.

The whole testing board includes several test units, made by 3D printing. Each arc surface is finely polished and very smooth.

As shown in Fig. 2(a), the test board is fixed at the center of the tape winding machine, and lead tapes are connected on both ends of the tested 2G HTS tape. During the test, the 2G HTS tape coming off the release reel of the winding machine sequentially passes through each gap of the test module and arrives at the pick-up reel of the winding machine. The tension applied to the tape is set at 5 N. The tape tightly leans onto the 90° and 180° arcs with fixed diameter in the bending test unit. The red line in Fig. 2(b) illustrates how a tape is set up and moves along the arcs on the 3D-printed test board during a typical measurement. There are several 3D-printed test boards, with 90° and 180° arcs of different diameters.

The bending characteristics of the inside and outside surfaces of 2G HTS tapes are different. Fig. 2(b) only shows two of them: the board on top is used to measure larger bending diameters typically associated with REBCO facing outward condition; the board at the bottom is used to measure smaller bending diameters typically associated with REBCO facing inward condition. Therefore, for the inward bending test of the tape, the bending diameter of test, controlled by the 180 ° arc, is increased from 2.4 to 6.0 mm at an interval of 0.1 mm. For the outward bending testing, the bending diameter is increased from 6 to 18 mm at an interval of 1 mm.

C. Methodology

MCorder is used to measure the critical current of superconducting tape [40]. If the same piece of tape is not damaged by bending, testing it several times with MCorder should yield the same critical current curves. If the tape is locally damaged by bending, the data of the two tests will be slightly different.

Before bending test of a 2G HTS tape, its critical current is first measured with MCorder as a benchmark. Then its bending test is carried out. The bending diameter, controlled in the bending test, is gradually decreased. The tape sample to be tested is connected to lead tapes at both ends and wound into a spool. For every bending diameter tested, the tape passes through the bending measurement setup [see Fig. 2(b) blue box] and is driven by the electric motor of the winding machine into another spool. It then enters MCorder for corresponding *Ic* measurement, in order to check whether the critical current has degraded. If the currents are consistent, the bending diameter is further reduced in the next bending measurement. Repeat the previous step for the next bending diameter test. If it is inconsistent, check whether the extent of reduction in the critical current exceeds 10%. If it exceeds 10%, the tape is regarded to have been damaged by bending.

As shown in Fig. 3, a typical SST 2G HTS tape shows no apparent deterioration in critical current after bending diameter tests from 7 to 3.6 mm. After the tape was bent at a diameter of 3.5 mm, its critical current degraded. When benchmarked against original critical currents, which are represented by the peaks at both ends of the graph, the degradation of the critical current is more than 10%. It is concluded that the critical bending diameter of this tape is 3.5 mm.

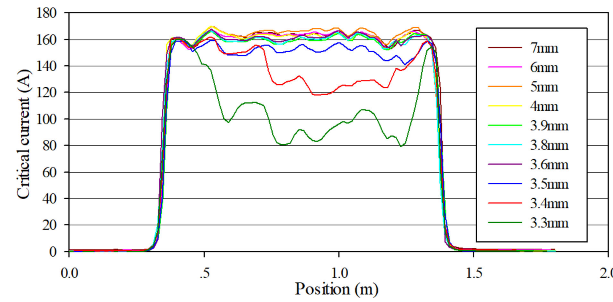


Fig. 3. Critical current distribution of 2G HTS tapes before and after bending test.

The critical current at the two ends of the 1-m tape does not deteriorate because the 2G HTS tape has been connected to the lead tapes by spot soldering, and the spot soldering part is hard. The spot solders cannot pass through a 180° arc with a small bending diameter. Therefore, each time the spot solders are located to bypass the 180° arc before bend-testing the tape, as shown in Fig. 2(c).

This rapid measurement method differs from the traditional bending diameter measurement in the way that the traditional measurement puts a tape sample under bending condition and simultaneously passes current to test if the 2G HTS film has been damaged by bending. The rapid measurement method studied in this article bends the tape first and relaxes the tape to normal condition, then measures the critical current to see if irreversible damage has been caused by bending.

The conventional method of critical bending diameter measurement can only test one sample per experiment. With this method, *n* samples can be connected for testing at the same time, which can greatly improve the efficiency of bending measurement. In comparison to the conventional method, this novel method can also, in a single experiment, measure the critical bending diameters at all points along the entire length of a tape. This is the advantage of this method.

III. Results and Discussion

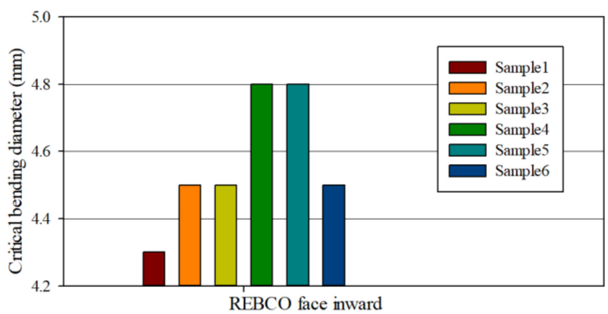
A. Measurements of 2G HTS Tapes With Silver Plating

The test method, described in this article, can be used to measure the critical bending diameters of 2G HTS tapes of various specifications. The experiments can be divided into two groups. The first group primarily studies the variations of some intrinsic parameters of 2G HTS tapes. The second group focuses on 2G HTS tapes mass-produced for 2G HTS cables in fusion application.

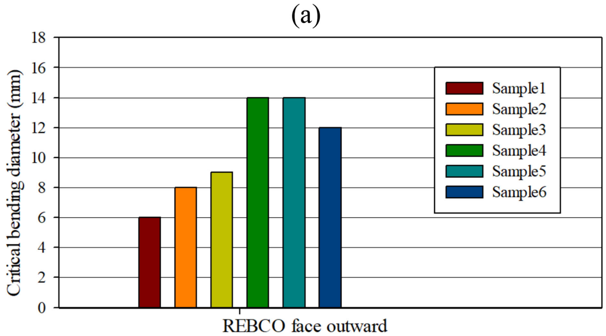
The first group of experiment focuses on 4 mm wide silver-plated 2G HTS tapes. The thickness of superconducting layer is 1.8 μm. The thickness of silver stabilizer layer next to REBCO is 1.5 μm. The thickness of silver stabilizer layer on the other side next to the substrate is 0.5 μm. Six samples have been prepared, by varying the substrate thickness, the type of substrate, and the pinning characteristics of the superconducting layer, as shown in Table I. Samples 1–5 have used Hastelloy substrates manufactured from cold-rolling, which are associated

TABLE I
SILVER PLATED 2G HTS SAMPLES WITH VARYING SUBSTRATE THICKNESS, TYPE OF SUBSTRATE, AND SUPERCONDUCTING LAYER COMPOSITION

	Substrate thickness (μm)	Type of sub-strate	Target type
Sample1	25	Cold-rolled	With Advanced Pinning Center (APC)
Sample2	30	Cold-rolled	With APC
Sample3	35	Cold-rolled	With APC
Sample4	50	Cold-rolled	With APC
Sample5	50	Cold-rolled	Without APC
Sample6	50	Annealed	With APC



(a)



(b)

Fig. 4. Bending diameter of 2G HTS tapes with varying substrate thickness, type of substrate, and superconducting layer composition. (a) REBCO facing inward. (b) REBCO facing outward.

with higher stiffness; while sample 6 has used Hastelloy™ substrates manufactured from annealing, which is associated with lower stiffness.

The critical bending diameter measured from samples 1–6 are presented in Fig. 4(a) REBCO faces inward and 4(b) REBCO faces outward. The six bars, from left to right, illustrate the bending performance of Samples 1–6, respectively. The experimental results show that there is a large difference between the critical bending diameter of REBCO inward and REBCO outward for the same 2G HTS tape sample. This is because when the REBCO layer faces inward, the REBCO layer is subjected to compressive stress. When REBCO faces outward, the REBCO layer is subjected to tensile stress. REBCO is better at bearing compressive stress than bearing tensile stress, hence there is a significant difference in critical bending diameter.

Samples 1–4 are superconducting tapes prepared from substrates of different thicknesses. The type of the substrate is the same, and the superconducting layer is also the same. It can be seen from the results that when the substrate is thinner, the 2G HTS tape has a smaller critical bending diameter whether facing outward or inward.

TABLE II
COPPER-COATED SAMPLES WITH VARYING SUBSTRATE THICKNESS AND SUPERCONDUCTING LAYER THICKNESS

	Substrate thickness (μm)	Superconducting layer thick-ness (μm)
Sample1	50	0.9
Sample2	30	0.9
Sample3	30	1.8
Sample4	50	1.8

Samples 4 and sample 6 are both made from 50 μm substrates and the same superconducting layer. The only difference is that sample 4 uses substrate from cold-rolling technique and sample 6 uses substrate from annealing technique. It can be seen from the test results that the 2G HTS tape using a pliable substrate has a smaller critical bending diameter whether REBCO faces outward or inward.

Sample 4 and sample 5 are made from the same substrate, both of 50 μm thickness and superconducting layer of the same thickness. The only difference is that sample 4 has a superconducting layer with an advanced pinning component and sample 5 has a superconducting layer without pinning component. It can be seen from the test results that there is no significant difference between the two in terms of critical bending diameter, whether REBCO faces outward or inward.

B. *Measurements of 2G HTS Tapes With Copper Plating*

The second group of experiments focuses on 4 mm wide copper-plated 2G HTS tapes. Based upon the first group of experiments, the cold-rolled substrates and advanced pinning composition have been selected. Substrates of two common thicknesses are adopted. One or two superconducting layers are deposited, and the thickness of each layer is 0.9 μm, as shown in Table II.

Before carrying out measurements on the copper-plated tapes, the bending characteristics of silver-plated tapes were first measured. As shown in Fig. 5, from the test results, the smallest critical bending diameter comes from silver-plated tape with thinnest substrate and thinnest superconducting layer. The critical bending diameter when REBCO faces inward is 4.3 mm and the critical bending diameter when REBCO faces outward is 6 mm. The largest critical bending diameter corresponds to the silver-plated tape with the thickest substrate and thickest superconducting layer. The critical bending diameter when REBCO faces inward is 4.8 mm and the critical bending diameter when REBCO faces outward is 14 mm.

1) Measurements of 2G HTS Tapes With Copper Plating on Both Sides: Four types of 2G HTS tape samples 1–4 have each been plated with three different amount of copper on both sides, namely 5,10, and 20 μm per side. From the test results, compared against the silver-plated tapes without copper-plating, the critical bending diameter of some double-sided copper-plated tapes is

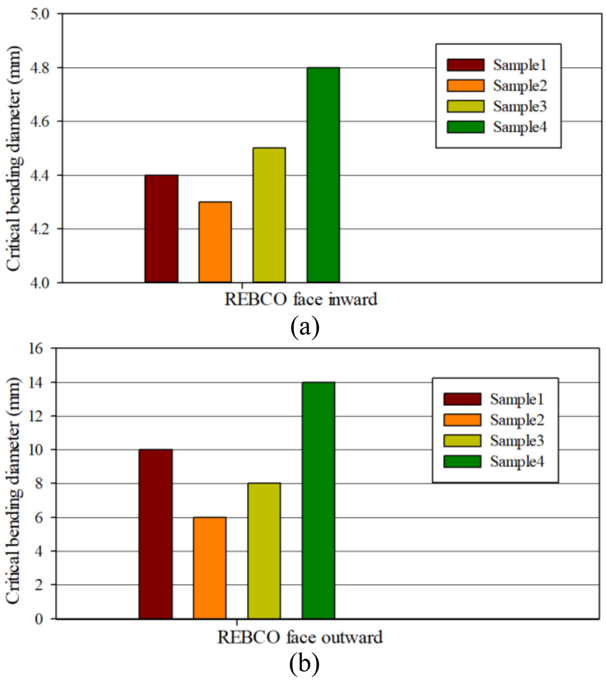


Fig. 5. Bending diameter of silver-plated superconducting tapes with varying substrate thickness and superconducting layer thickness. (a) REBCO face inward. (b) REBCO face outward.

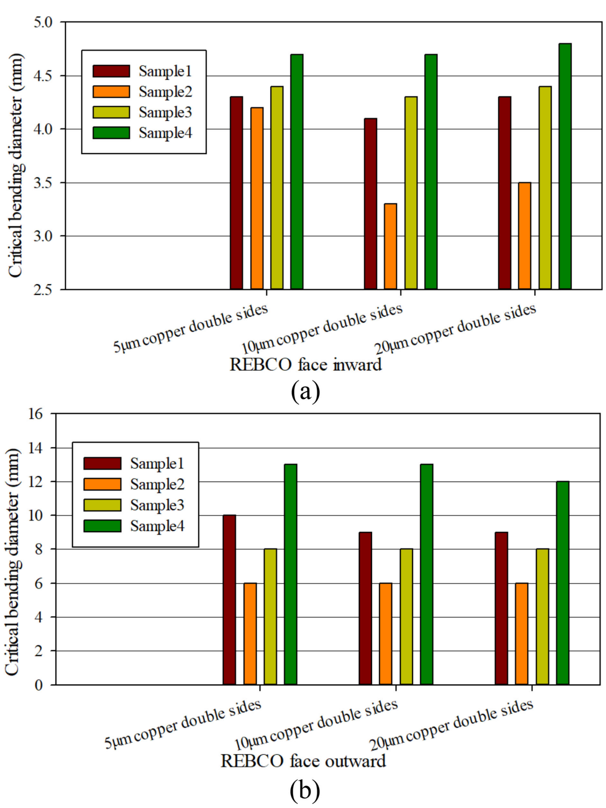


Fig. 6. Bending diameter of silver-plated superconducting tapes with varying substrate thickness and superconducting layer thickness. (a) REBCO faces inward. (b) REBCO faces outward.

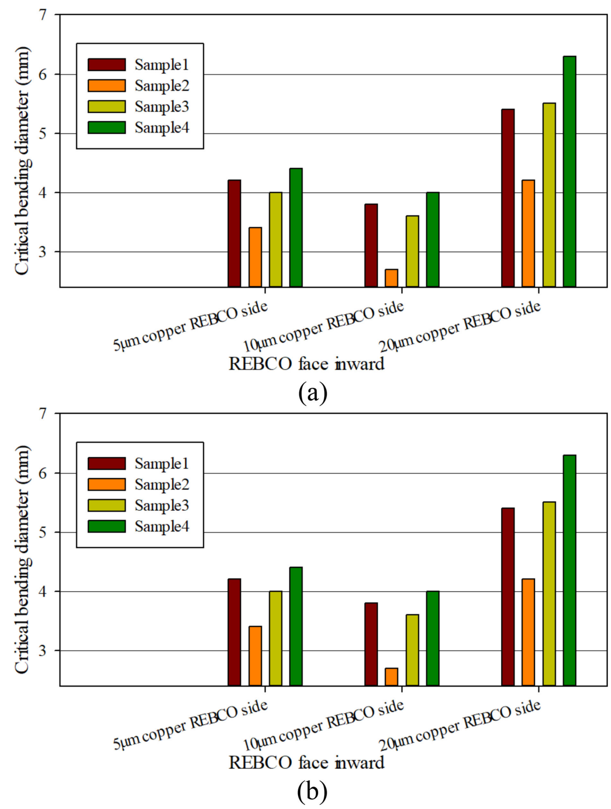


Fig. 7. Bending diameters of superconducting tapes with both sides plated with 5, 10, and 20 μm copper. (a) REBCO faces inward. (b) REBCO faces outward.

larger than its corresponding silver-plated tapes and some are smaller.

As shown in Fig. 6, the most evident comparison is from sample 2: when it is plated with 5 μm of copper on both sides, the critical bending diameter is 4.2 mm, which is less than 4.4 mm of its corresponding silver-plated tape. When it is plated with 10 μm of copper on both sides, the critical bending diameter is 3.3 mm; and when both sides are plated with 20 μm of copper, the bending diameter is 3.5 mm, which are lower than the critical bending diameter of the corresponding silver-plated tapes. This may be due to the thickness of copper plating leading the YBCO surface closer to the center of the tapes. Other samples also demonstrate a similar trend.

When REBCO faces outward, there is no significant difference in the critical bending diameter of double-sided copper plated samples.

2) Measurements of 2G HTS Tapes With Copper Plating on Only One Side: As shown in Fig. 7, when REBCO faces inward, the critical bending diameter of 2G HTS tapes plated with 5 or 10 μm of copper on one side is smaller than that of double-sided copper-plated tapes. This is due to the superconducting layer located at the center of the tape. When the tape is plated with 20 μm of copper on one side, the critical bending diameter of the sample is larger than that of double-sided copper-plated sample. Delamination also occurred in the samples during this particular set of experiments. The delamination of thick copper film may have also attributed to the larger bending diameter.

The critical bending diameter of double-sided copper-plated tapes when REBCO faces outward has little difference.

During the above measurements, some factors affecting the minimum reversible bending diameters of HTS tapes have not been taken into consideration, including cracks at the slit edges and stiffness of the copper layers. These may affect the minimum reversible bending diameter of the HTS tapes measured but are currently difficult to quantify.

IV. Conclusion

Cables for fusion and accelerator applications demand high critical current density. The bending diameter of a REBCO tape is critical for the preparation of cables. The bending diameter of REBCO tape is usually dependent on many factors. It is necessary to identify the key factors determining the bending diameter through experiments. In this article, a novel experimental setup for critical bending diameter measurement has been developed, which can efficiently assess the bending characteristics of 2G HTS tapes in large batches. Compared with the traditional bending diameter measurements, this method first has the sample tape bended and then unfolded to measure for critical current deterioration. Through this, the minimum diameter allowing reversible bending on the sample is identified.

The samples prepared by Shanghai Superconductor Technology Co., Ltd. were analyzed using the method and setup developed in this article. It was found that the bending diameter of the 2G HTS tapes was closely related to the substrate thickness, type of substrate, superconducting layer thickness, and copper-plating thickness and had little correlation to the composition of the superconducting layer. By measuring the critical bending diameter of the tapes prepared by SST, it was noted that, when REBCO faced inward, 2G HTS tapes plated with copper of 5 and 10 μm on one side only had a smaller critical bending diameter than equivalent double-sided copper-plated 2G HTS tapes. The critical bending diameter was as small as 2.6 mm. When REBCO faced outward, copper-plating had barely any effect on the critical bending diameter, and the critical bending diameter of the tapes was 6–14 mm.

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