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Ultra-small Diameter Round REBCO Wire with Robust Mechanical Properties

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***Abstract*— The compressive bend diameter (REBCO layer facing inward in all cases) dependence of critical current (I_c) of commercial (stabilizer free- SF, 50 µm substrate) and thin (22 µm substrate) REBCO tapes have been compared after copper electroplating only on REBCO side and on both sides of the tape. We have experimented with different substrate and stabilizer thickness of the REBCO tape to maximize high I_c retention while the tape is bent into smaller diameter forms. Single-layer round wires made by winding the most robust REBCO tapes on 0.81 mm copper former have been tested for its critical current at different twist pitches under combined torsion and compressive strains. Using the best tape, the critical current of a multilayer round wire of 1.6 mm overall diameter (0.81 mm core) has been tested under bending over a range of diameters from 12 cm to 3 cm. These studies confirm the superior retention of critical current under combined effect of high torsion and compressive bend strain of our ultra-small diameter REBCO wires.**

***Index Terms*— Compressive bend diameter, critical current, REBCO, stabilizer, HTS, ultra-small, round wire, flexible.**

I. Introduction

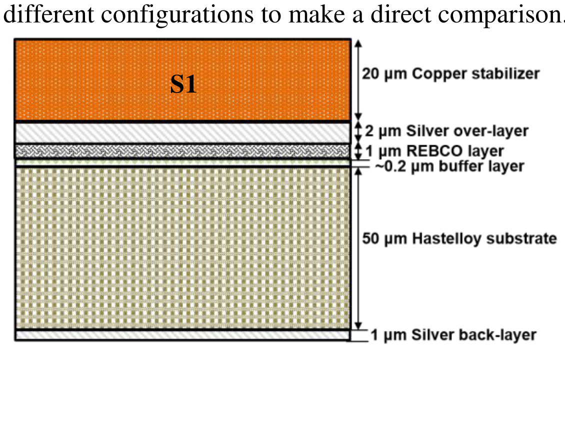
THE ultra-high critical magnetic fields of $REBa_2Cu_3O_x$ (REBCO, RE=rare earth) High Temperature Superconductors (HTS) provide the opportunity for superconducting magnets that can operate well above 20 T [1]. In spite of the superior high-field properties of REBCO tapes, two factors limiting their use in ultra-high-field magnet applications. The first factor is their flat tape with wide aspect ratio geometries and the second factor is high axial compressive strain in the range of the irreversible strain (ε_{irr}) limit in the presence of huge Lorentz forces [2]. Measurements of critical current density (J_c) as a function of tensile strain (ε) on flat REBCO conductors before ε_{irr} showed that strain levels above 0.4% degraded the J_c irreversibly [2-5]. REBCO tapes can withstand much larger compressive strain (REBCO layer facing inward) than tensile strain (REBCO layer facing outward).

Conductor-on-round-core (CORC) geometry using REBCO coated conductors (CCs) addresses the inherent deficiency of converting a flat tape into a round cable by spiral winding on a solid cylindrical former [6]. Because of the use of the large diameter former, the engineering critical current density (J_e) of the cable is significantly reduced and the critical current (I_c) degrades irreversibly by 95% over -2% compressive strain [6]. An approach that is being undertaken to address this lower J_e issue is to use a coated conductor manufactured starting with a nonstandard 30~38 µm thick substrate. Preliminary results reported with CORC cables made using commercial 4 mm wide coated conductor produced using short lengths of nonstandard 38 µm thick substrate are promising [7]. Short lengths of REBCO cable on round 2-3 mm metallic core formats with final diameters of 3-7 mm have been demonstrated [8], but, they are far from the flexible round wire geometries with diameters in the 1-1.5 mm range that are preferred for high field magnets. The use of smaller core/former diameter enhances the flexibility of the round wire while bending into smaller diameter while maintaining a high I_c retention. Recently, the University of Houston developed an innovative approach to fabricate ultra-small diameter REBCO round wires of 1.6 mm final diameter on 0.81 mm flexible copper wire former using 2 mm wide REBCO tapes with thickness less than ½ of that of typical commercial REBCO tapes [9]. As the REBCO tapes are composite by nature, it is expected that an architecture with a thin substrate along with stabilizer only on one side will reduce the strain experienced by the REBCO layer due to the shift of neutral axis close to REBCO layer. In the present work, the electromechanical properties of the ultra-small diameter round wire and of the thin tapes have been investigated.

II. Single turn bending test

A. *REBCO coated conductor specification*

Figure 1 shows the cross-sectional views of REBCO based CCs, used in the present work. To achieve the maximum the I_c retention while bending into smaller diameter, we made these CCs with different configurations to make a direct comparison.



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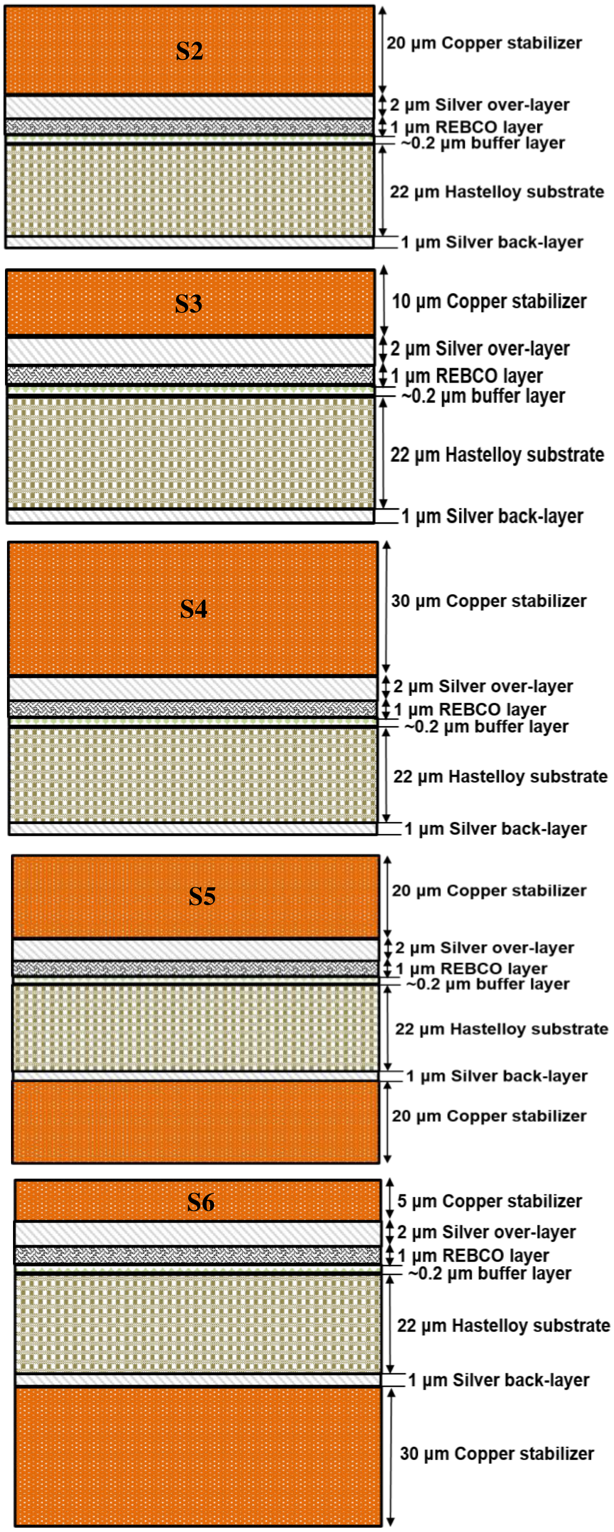

Fig. 1. Cross-sectional schematic views of 2 mm wide REBCO coated conductor samples (S1-S6) for mechanical property test (not to scale).

The stabilizer-free REBCO CCs of 50 μm Hastelloy C-276 substrate were purchased from Superpower Inc. and REBCO CCs of 22 μm Hastelloy C-276 substrate were made in-house at the University of Houston. Both of these CCs consist of a ~0.2 μm ceramic buffer layer and a 1 μm REBCO layer. A silver cap layer, 2 μm thick on the top of REBCO layer and 1 μm thick on the substrate side was deposited using DC magnetron sputtering. The REBCO coated conductors were then slit from a 12 mm wide tape to their final width of 2 mm using laser slitting [9]. They were then electroplated in-house with different copper stabilizer thickness for electrical and thermal stability. The critical current of each 2 mm wide tape was measured to be about 50-60 A at 77K.

B. Compressive bend diameter dependent critical current measurement

The dependence of the critical current on the compressive bend diameter of the coated conductors was measured at 77 K with the REBCO layer facing inward in all cases. The 2 mm wide tapes were wound over a full turn on G-10 rods of 12.5 mm, 11.0 mm, 9.5 mm, 7.5 mm, 6.5 mm diameter, brass rods of 3.19 mm, 2.06 mm, 1.5 mm, 1.1 mm diameter and ETP-grade copper rods of 0.81 mm, 0.51 mm diameter. Metallic formers were used for smaller diameters to mimic the condition of round wires made subsequently in this work. The compactness of the winding was assured by using kapton adhesive tape over the 2 mm wide tape while bending and two ends were firmly connected to the current connectors. The electromechanical properties were tested by critical current measurements of the REBCO tapes wound on different-sized formers with the REBCO film side in compression (i.e. REBCO layer facing inward). The critical current was determined by four probe measurement using a 1μV/cm criterion.

At first, we started with 2 mm wide tapes of S1-S6 architectures with I_c of 50-60 A (at 77 K, self-field). Figure 2 shows the I_c-bend diameter dependence of S1-S6 when REBCO layer is under compression.

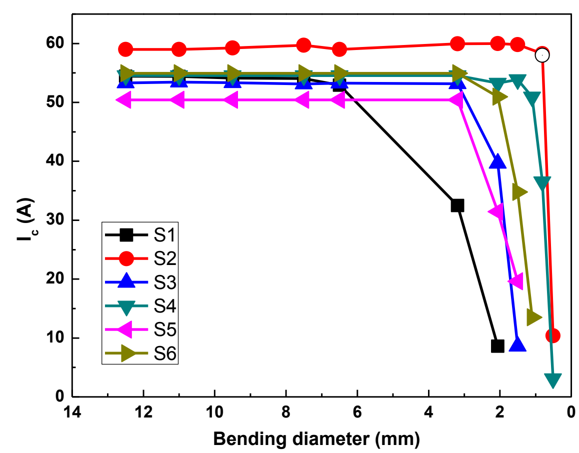

Fig. 2. Critical current (I_c) at 77 K of S1-S6 with different flat tape I_c as a function of bending diameter with the REBCO layer facing inward. The REBCO side is under compression and substrate side is under tension for a full single turn bending over different-sized formers.

It is observed from Fig. 2 that the 22 μm substrate samples of S2 and S4 show no significant I_c degradation at 0.81 mm bending diameter and at 1.1 mm bending diameter respectively. To confirm the I_c reversibility of the sample S2, its critical current was measured after partially unwinding from the 0.81 mm dia. former and releasing the strain (open black circle in fig. 2). It is observed during the test that the samples (S2 and S4) experience plastic deformation after exceeding 3.19 mm bending diameter and can not regain original shape. S2 and S4 also show a reversible I_c up to 3.19 mm bending diameter before plastic deformation, whereas S1, S3, S5 and S6 show drastic reduction in I_c at 2.06 mm, 1.5 mm, 1.5 mm and 1.1 mm bending diameter respectively. Using thin substrate and one-side copper plated tapes, we can certainly enhance the I_c reversibility limit of the REBCO tapes by reducing the imposed strain value. S1 shows 40% I_c reduction when the bending diameter is 3.19 mm but S2 does not show significant I_c reduction at the same bending diameter.

After allowing plastic deformation in the tape, reversible I_c is observed in S2 at 0.81 mm bending diameter indicating that the REBCO layer remains undamaged at that strain level. A possible cause for this high degree of strain tolerance of the REBCO layer under axial compressive strain is the shifting of the REBCO layer towards neutral axis due to reduction in the substrate thickness and copper stabilizer only on REBCO side. It is assumed that the center of the conductor always experiences zero strain within the elastic regime, independent of bending diameter. This strain-free axis is called the neutral axis (*NA*) [10]. The REBCO layer experiences the strain which is imposed on hastelloy, buffer layer, silver and copper during bending. In S1, the neutral axis is far away from the interface of the layers where generally the REBCO layer is located. In S2, the neutral axis is close to the interface of the layers i.e. REBCO layer remains close to the neutral axis and experiences minimum strain and that is the possible reason of improved flexibility and enhanced mechanical properties of thin tape with less I_c degradation at ultra-small bend diameters.

III. Mechanical Properties of Round Wire

A. *Ultra-small diameter REBCO wire bending test*

The high flexibility under compressive bending of thin substrate REBCO tapes enables us to fabricate REBCO round wire wound around a 0.81 mm copper former. From the previous single-turn bending test, we found S2 and S4 are good candidates for round wire. An additional test was performed to evaluate the performance of S2, S3 and S4 tape as a function of twist pitch.

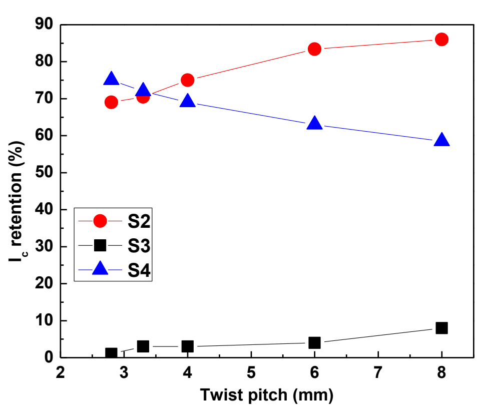

Fig. 3. I_c retention (%) at different twist pitch (0.81 mm dia. copper former).

In the test, we conducted 10 turns of spiral winding (hand-made) of the S2, S3 and S4 tapes on a 0.81 mm diameter copper former at 2.8 mm, 3.3 mm, 4 mm, 6 mm, and 8 mm twist pitch values. In all cases, REBCO layer faced inward compared to the hastelloy substrate. We measured flat tape I_c before spiral winding and compared the I_c data before and after spiral winding to determine the I_c retention (%).

In S4, the neutral axis is shifted to buffer layers due to the copper stabilizer on the REBCO side being thicker than the substrate. Consequently, S2 and S4 experience compressive strain while bending at smaller twist pitch. At longer twist pitch, a large torsional force is imposed which can be the possible reason for the decrease in I_c retention in S3. The Cu layer may also delaminate from REBCO layer in S3 at a longer pitch due to the combined effect of torsion and bending strain.

S4 tape increases the overall diameter of the round wire resulting in a decrease in engineering current density (J_e). To make multilayer round wire, we began with 2.8 mm pitch for the first layer but as the wire diameter increases with additional layers, 2.8 mm pitch cannot be used. After the first layer, we needed to increase the twist pitch and finally, a 4.4 mm twist pitch was used in the sixth layer [9]. Therefore, the best candidate, S2 tape, was used to make multilayer round wire on 0.81 mm diameter soft ETP grade copper former that helps to improve the flexibility as well as thermal stability. The REBCO layer is under compression on the round former (i.e. REBCO layer facing inward compared to the hastelloy). Figure 4a shows a 1.6 mm dia. REBCO round wire made by spiral winding 6 layers on a 0.81 mm diameter copper former using S2 tape. Figure 4b shows the smallest diameter of 3 cm used in the critical current test of the REBCO round wire under bending.

a

b

Fig. 4. (a) Photograph of a 1.6 mm overall diameter round REBCO wire made by spiral winding six layers of 46 µm thick tapes (S2, 22 µm substrate, 20 µm Cu stabilizer) over a 0.81 mm diameter copper former. (b) Photograph of the round wire bent to a diameter of 3 cm during test.

Figure 5 shows the *E-I* characteristics at different wire bending diameter of the REBCO round wire. I_c was determined by measuring voltage (V) as a function of current (I) over the copper terminals at 77 K, self-field using the four-probe method. A fitting of the following equation is used to obtain resistive-part (R_p) of the round wire [7, 8].

$$V = R_p + V_c(I/I_c)^n \tag{1}$$

where, $R_p = IR + V_{off}$, R is the contact resistance, V_{off} is the inductive offset voltage, n is a non-linearity factor, and V_c is the critical electric field (E_c=1 μV/cm) multiplied by the voltage tap distance. Electric field (E) is obtained from the measured voltage divided by the voltage tap distance.

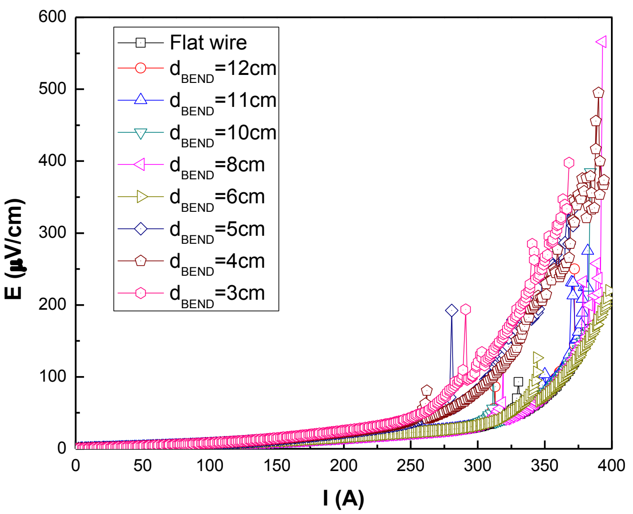

Fig. 5. *E-I* characteristics of the 1.6 mm diameter REBCO round wire at different bending diameters.

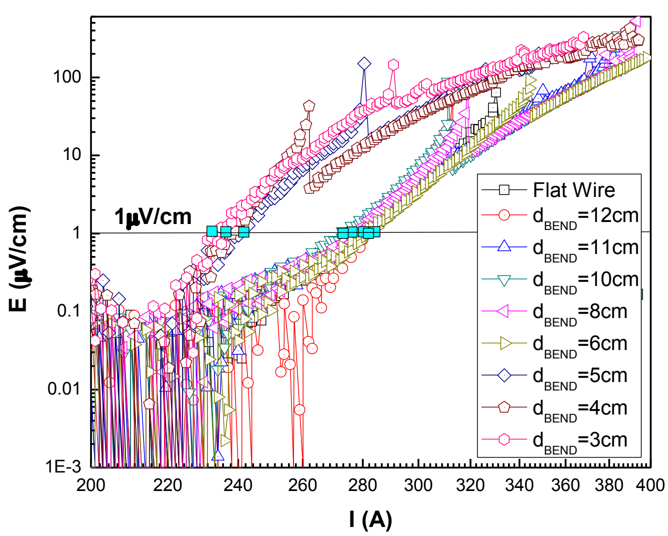

Fig. 6. Zoomed-in *E-I* characteristic in log-log plot of 1.6 mm overall diameter REBCO round wire with 6 layers at different bending diameters. Solid squares show the I_c at different bend diameter.

Figure 6 shows the zoomed-in *E-I* characteristics in log-log plot at different wire bending diameters of the REBCO round wire. The resistive-part (R_p) which comes from copper end connectors was subtracted. It is assumed that the kinks observed in the plot are due to current sharing between each layer. A straight round wire I_c of 283 A (J_e = 141 A/mm^2) was measured at 77 K, self-field and there is no significant I_c degradation when the bend diameter is decreased to 6 cm. The REBCO round wire I_c starts degrading from 5 cm bending diameter down and a maximum I_c degradation of 17% is observed at 3 cm bend diameter.

IV. Conclusions

I_c measurements on 2 mm wide REBCO coated conductors made with 50 μm and 22 μm Hastelloy substrates and different stabilizer thickness have been carried out under compressive bending at different diameters (i.e. REBCO layer facing inward). It is observed that the 22 μm substrate samples of S2 and S4 architectures show no significant I_c degradation at 0.81 mm bending diameter and at 1.1 mm bending diameter respectively. In the plastic deformation regime, reversible I_c is observed for S2 at bending diameter greater than 0.81 mm. Single layer REBCO round wires have been made on a 0.81 mm round copper former using 2 mm wide S2, S3 and S4 tapes at different twist pitch lengths and tested for their I_c under combined effect of torsion and compressive bending strain. It is observed that the tape with a thicker stabilizer layer (S4) shows less I_c retention at longer twist pitch lengths. Therefore, an optimized stabilizer thickness of 20 μm has been used to maximize I_c retention and avoid increase in overall diameter of a six-layer round wire. A J_e of 141 A/mm^2 at 77 K, self-field was obtained in a straight condition. Bend testing of the six-layer round wire shows no degradation in I_c even at 6 cm bend diameter and only 17% (J_e = 117 A/mm^2 at 77 K, self-field) I_c loss at 3 cm diameter. These robust mechanical properties of ultra-small diameter round REBCO wires with higher J_e make them promising for use in high-field magnets.

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