Current Sharing and Mechanical Properties of Slot-n-Fill REBCO Tapes

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***Abstract*—Rare earth barium copper oxide (REBCO) coated conductor tapes and cables are promising material candidates for high- power-density and highly efficient electric machines and high magnetic field applications. Enhancing the current sharing in between different strands/layers is one of the practical methods to improve the overall quench stability of a multi-strand cable or a no-insulation coil. In this work, we introduce the slot-and-fill (Slot-n-Fill) method to increase current sharing in REBCO tapes. Compared to the original tape, the Slot-n-Fill tape has slightly different bending retention performance, ∼7% lower irreversible tensile strength, and ∼5% lower I_c. However, the current sharing metric (CSM) in a 2-ply stack is improved from 1.025 in the control sample to 1.2 in the Slot-n-Fill tape stack.**

***Index Terms*—Cables and current leads, Hts cables, mechanical properties, strain dependence, superconducting tapes, stress, strain measurement.**

I. Introduction

REBCO coated conductors (CCs) are of interest for high-power-density and highly efficient electric machines and high magnetic field applications due to their exceptional high J_e at high field (>20 T) [1]. Unlike low-temperature superconductors like Nb_3Sn, which have a normal zone propagation velocity of 1–100 m/s [2], [3], REBCO CCs exhibit a much slower normal zone propagation velocity of only 0.01–0.1 m/s [4], [5], [6]. Such a slow normal zone propagation velocity will lead to a slow increase in fault-induced voltage and localized hot spot, which make it hard to detect quench in a magnet before catastrophic failure takes place.

Long tapes with uniform critical current (I_c) will be most favored for magnet and cable fabrication. Currently, commercial tapes can achieve uniform I_c over hundreds of meters. However, this I_c uniformity is mostly characterized by scanning hall probe microscope systems [7] or TAPESTAR at 77 K and under low field (<1 T). At lower temperatures and higher magnetic fields, tapes that exhibit good I_c uniformity when measured at 77 K and low field can show inconsistent I_c [8], [9]. Therefore, quench detection and protection become the major challenges to the large-scale applications of REBCO CCs. Considerable efforts have been devoted to developing more sophisticated quench detection techniques for REBCO CCs. These techniques include, but are not limited to, acoustic emission [10], time-frequency domain reflectometry [11], [12], [13], and fiber optics [14], [15], [16]. Alternatively, improving the stability of REBCO coils and multi-strand cables can be achieved by preventing quenching through the self-protection mechanism of current sharing [17], [18], [19], [20].

Current sharing in REBCO CCs can be improved by modifying the inter-tape contact resistance (ICR) between different tapes. One of the major contributors of the ICR is the surface oxide on the tape surface. Previous researches have introduced various techniques, including cold pressing [21], [22], [23], [24], hot pressing [25], ultrasonic welding [26], [27], and metal plating [21], [25], to reduce the surface contact resistance of REBCO CCs. Due to the presence of the insulating buffer layer, the only current sharing path in these aforementioned works is through the edge silver and copper. Therefore, we proposed increasing current sharing by introducing additional current-sharing paths.

The method we applied to realize this concept involves using a laser to create small slots on the wide surface of the tape, extending through its entire thickness, which are then refilled with silver and copper. By doing so, parts of the insulating buffer layer is replaced with silver and copper, creating additional current sharing paths via the refilled slots. Our previous study has already demonstrated that this Slot-n-Fill method can enhance current sharing in double-sided REBCO tapes [28]. In this work, we will demonstrate the enhanced current sharing in commercial tape (single-sided tape) stack through this method, the tensile property, and the bending limit of the Slot-n-Fill tapes.

II. Experiments

In this work, the starting tape we used was 12-mm-wide silvered REBCO tape from Shanghai Superconductor Technology Co., Ltd. Then starting tape was laser slit into 4-mm-wide tapes. After laser slitting, a 2 μm silver overlayer was deposited on

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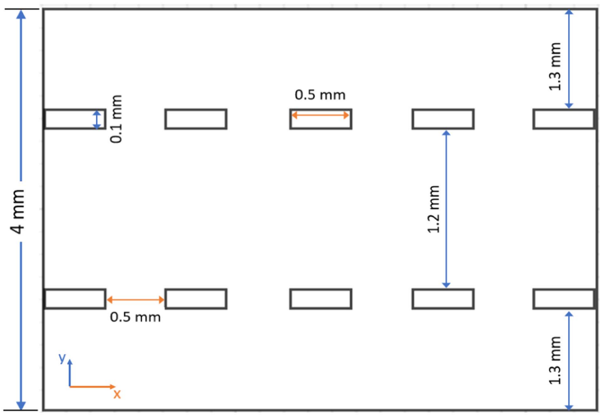

Fig. 1. 2–2 laser slot pattern in a REBCO tape. (X-direction is the tape length direction, y-direction is the tape width direction).

each side of the control samples, followed by plating 20 µm of copper on each side. For the Slot-n-Fill samples, a 2–2 slot pattern, as shown in Fig. 1, was created on the tape using a reel-to-reel laser slitting system. In order to retain >90% of the tape's original I_c, the dimension each slot was set to 0.5 mm long and 0.1 mm wide. The distances between two slots are 0.5 mm in the tape length direction and 1.2 mm in the tape width direction [28]. The slots were cut through the full thickness of the tape. Hence, laser parameters similar to the laser slitting process can be used to create the slot patterns via a reel-to-reel process. Optimized laser parameters, such as laser power and frequency, should limit the damage to the REBCO tape near the slot edges to only a few micrometers. The slotted tapes were then subjected to silver sputter deposition and copper plating, which refilled the slots with silver and copper. In this work, we applied a thicker silver layer (approximately 5 times normal thickness) to ensure that REBCO is completely covered with silver and avoid the exposure of the REBCO layer to the acid Cu plating solution.

To compare the current sharing behaviors between tapes with and without slots, we made 2-ply stacks of two different types. The first type of the 2-ply stack consisted of two control tapes. as presented in Fig. 2(a). The second type of the 2-ply stack was made of two Slot-n-Fill tapes, shown in Fig 2(b). In both cases, a 2-mm-diameter artificial defect was created in the bottom tape that reduced the I_c of the tape to 50% of its original value. The 2-mm-diameter artificial defect created by laser can be considered as one of the worst cases. In reality, the defects are usually micrometer-scale. The current was injected into the defective tape. In both cases, the 2 tapes in a stack were soldered together with the In52/Sn48 solder in the face-to-back configuration. The voltages were measured in both the bottom (defective) and top (parallel) tapes in the region across the defect.

Uniaxial tensile test along the tape length direction were performed on both the control tape and the Slot-n-Fill tape. Each tested sample was 13 cm in length. The ends of the samples were secured by copper terminals mounted on the testing frame, while the voltage across the central 8 cm section was monitored. Cyclic loadings (loading and unloading) were applied on the samples to determine the 95% I_c irreversible tensile limit of these two types of tape.

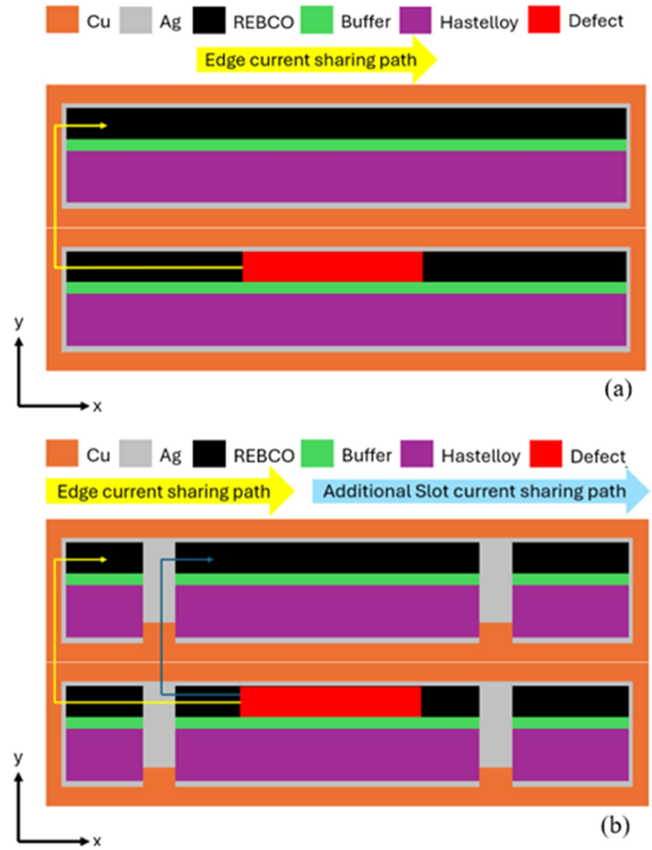

Fig. 2. Schematics of current sharing paths in 2-ply stacks (a) 2-pyl stack of control tapes, (b) 2-pyle stack of Slot-n-Fill tapes (X-direction is the tape width direction, y-direction is the tape thickness direction).

The bending limits of the control tape and the Slot-n-Fill tape were also compared by measuring the I_c of different tapes when they were bent around a set of cylinders with diameters ranging from 7 mm to 14 mm. The REBCO film side was placed on the inside (compression) in the bend tests.

III. Result and Discussion

A. I_c of Control Tape and Slot-n-Fill Tape

We first measure the I_c values of the control tapes and the Slot-n-Fill tapes. As shown in Fig. 3, the control tape has an Ic of 154 A, and the Slot-n-Fill tape has an I_c of 147 A. Hence, the I_c retention after this Slot-n-Fill process is 95.5%. To enhance the statistical significance of the results, multiple samples of each type were measured. The control samples exhibit I_c values ranging from 152 A to 160 A, while the Slot-n-Fill tapes demonstrate I_c values between 144 A and 155 A. In conclusion, the I_c retention after the Slot-n-Fill process with the 2–2 slot pattern can exceed 90%.

B. Current Sharing in 2-ply Stacks

The current sharing behaviors in different tape stacks were measured as shown in Fig. 4. Only the bottom defective tape is in contact with the current leads. Hence, the injected current will first fill the ampacity of the bottom tape and then transfer

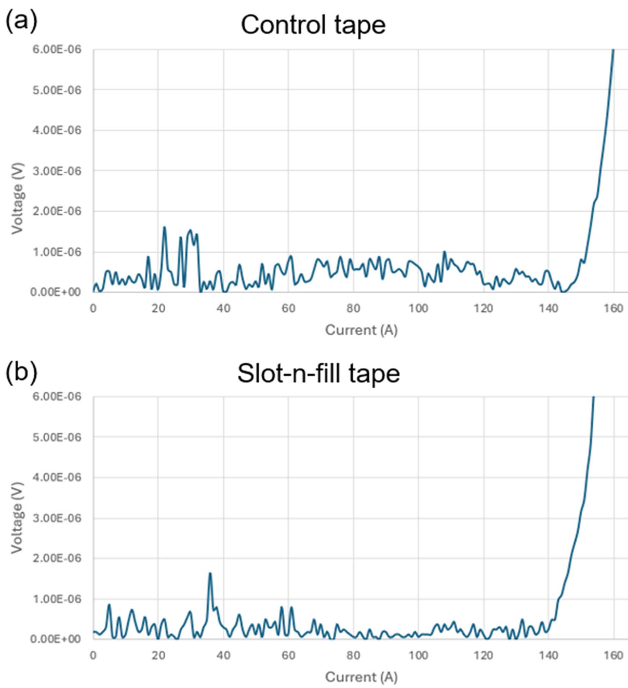

Fig. 3. (a) I_c of control tape, (b) I_c of Slot-n-Fill tape.

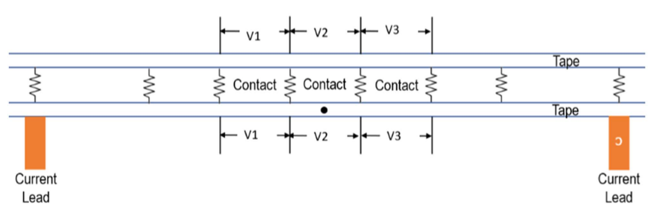

Fig. 4 . Schematic of current sharing measurement. The dark circle on the bottom tape represents the artificial defect.

into the top parallel tape via current sharing. V2 for both of the defective tape and the parallel tape were used to determine the inception of current sharing. V1 and V3 were monitored to ensure the superconducting-to-normal transition does not occur in other parts of the tapes before current sharing happens at the defective region.

To better understand different current sharing behavior in different tape stacks, we introduce the **Current Sharing Metric** (**CSM**), which is defined as the ratio of the maximum measured critical current, $\boldsymbol{I_{defective\ tape}}$, to the nominal I_c, $\boldsymbol{I_{defective\ tape,\ nominal}}$ [28], [29], [30], [31], [32].

$$\boldsymbol{CSM_{defect\ tape}} = \boldsymbol{I_{defective\ tape}} / \boldsymbol{I_{defective\ tape,\ nominal}}$$

The results on current sharing in a 2-ply stack made with the control tapes are presented in our previous work, showing $\boldsymbol{CSM_{defect\ tape}} = 82/80 = 1.025$ for the face-to-back stack configuration [28].

The current sharing behavior in the Slot-n-Fill 2-ply tape stack is presented in Fig. 5. The I_c of the two Slot-n-Fill tapes used in this 2-ply stack is ~155 A. Hence after a 50% defect is created, the defective tape (bottom tape) should have a nominal critical current $\boldsymbol{I_{defective\ tape,\ nominal}}$ of 77.5 A. The measured the critical current of the defective tape as seen in Fig. 5 is $\boldsymbol{I_{defective\ tape}} =$ 93A (determined with 1μΩ.cm criterion). The current sharing metric in this case can be calculated as $\boldsymbol{CSM_{defect\ tape}} = 93/77.5 = 1.2$, which is greater than the current sharing metric of the control sample. Once the injected current exceeds 93 A, the I-V curve of the defective tape exhibits a linear slope until reaching 250 A. Notably, around 230 A, a change in the slope of the I-V curve is observed. This change can be attributed to the maximization of the cooling power of liquid nitrogen at the transition point from nucleate boiling to film boiling [33]. The *I-V* character of the parallel tape also shows a linear slope after the current exceeding 93 A. This is mostly because of heating from the bottom defective tape. The $\boldsymbol{I_{c,\ total}}$ of the Slot-n-Fill 2-ply stack is 250 A, determined by the power-law transition point. Compared to the control sample, the Slot-n-Fill 2-ply stack has a similar $\boldsymbol{I_{c,\ total}}$, 245 A and 250 A respectively. However, the over current margin of the defective tape in the Slot-n-Fill sample is bigger due to enhanced current sharing.

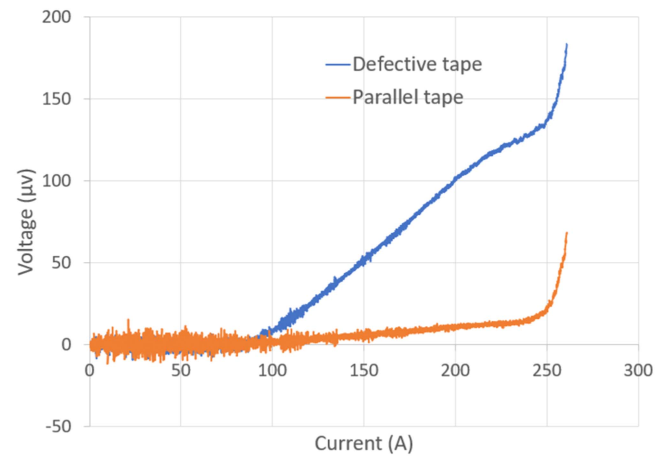

Fig. 5. I-V curves at 77 K, self-field from the central voltage taps of the defective tape and parallel tape. Both tapes are of Slot-n-Fill type.

C. Tensile Property of Slot-n-Fill Tape

Because a part of Hastelloy is removed in the Slot-n-Fill tape, it is necessary to examine its impact on the mechanical property of the tape. One mechanical property measured was the irreversible tensile stress, which is the maximum load that, when removed, still allows the tape to recover 95% of its original I_c. The results are presented in Fig. 6. For the control tape, the irreversible tensile stress is 870 MPa. The 95% irreversible tensile strength of the Slot-n-Fill tape is 810 MPa. The irreversible tensile stress of Slot-n-Fill tape is 93% of that of the control tape. This can be explained by the removal of approximately 5% Hastelloy when the 2–2 slots pattern is created in the Slot-n-Fill tape.

D. Bending Limit Tests

The bending tests results are shown in Fig. 7. For the control tape, the straight-form I_c is 155 A. The I_c remains almost

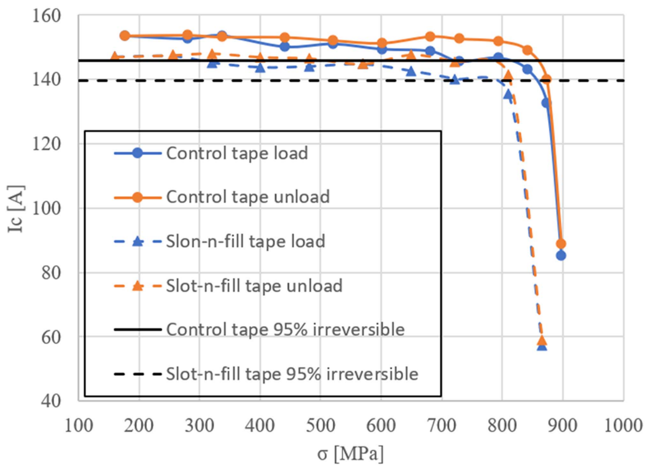

Fig. 6. . Critical current retention at 77 K of the control tape and the Slot-n-Fill tape under an applied tensile load. Measurements were done under loading and unloading condition.

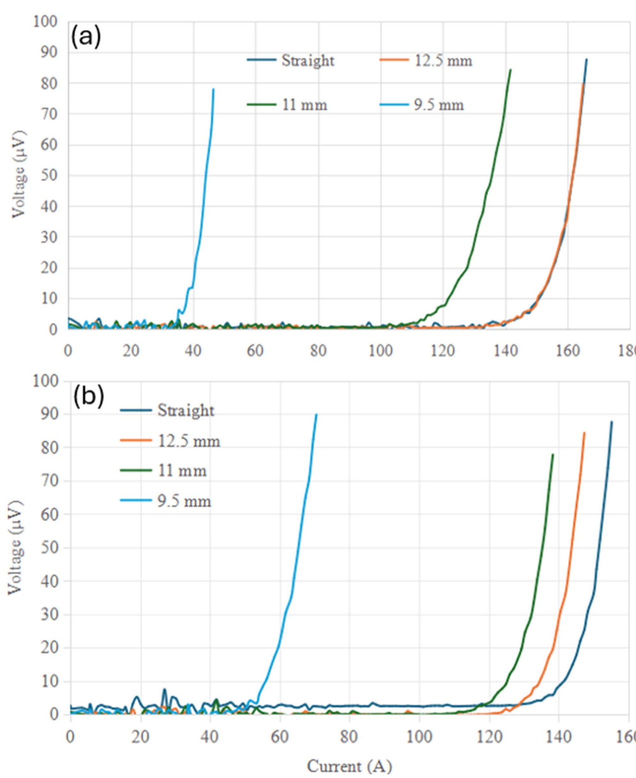

Fig. 7. Bending tests on (a) control tape (b) Slot-n-Fill tape at 77 K when bent on mandrels of different diameters.

unchanged at 154 A when the tape is bent around a core with a diameter of 12.5 mm. However, I_c decreases to 125 A (81%) when the tape is bent around an 11 mm core. A further reduction to just 41 A (26%) is observed when the tape is wound around a 9.5 mm core. For the Slot-n-Fill tape, the straight-form I_c is 144 A. When bent around a core with a diameter of 12.5 mm, the I_c decreases to 135 A (94%). With further reductions in bending diameter to 11 mm and 9.5 mm, the I_c drops to 124 A (86%) and 55 A (38%), respectively.

At the bending diameter of 12.5 mm, the control tape exhibits better I_c retention than the Slot-n-Fill tape. However, when the bending diameter decreases, the Slot-n-Fill performs better than the control tape. For both tapes, the bending limits targeting a 90% I_c retention is in between 12.5 mm to 11 mm. Although our test results indicate that these two tapes exhibit different I_c retention performances at all four tested bending diameters, these differences are unlikely to significantly impact their practical applications.

IV. Conclusion

In this study, we introduce the slot-and-fill (Slot-n-Fill) method with a 2–2 slot pattern to enhance current sharing in REBCO tapes. The current sharing metric (CSM) is employed to quantify and compare the current sharing capabilities of 2-ply stacks made from different tapes. The CSM of the Slot-n-Fill tape stack is 1.2, compared to 1.025 for the control sample. The 50% defective tape in the Slot-n-Fill tape stack showed an I_c of 93 A, while the I_c of the defective tape in the control tape stack is 82 A. Sacrificing ∼5% tape I_c (because of material removed in the slots), the defective tape in a Slot-n-Fill 2-ply stack can have an extra 11 A over current margin. Because ∼5% of Hastelloy is removed when the 2–2 slots are created in the tape, the 95% irreversible tensile stress of the Slot-n-Fill tape reduces to 810 MPa, compared to 870 MPa for the tape without slots. For both the Slot-n-Fill tape and the control tape, the 90% I_c retention bending limit is in between 12.5 mm to 11 mm. Although the mechanical properties of the Slot-n-Fill tape are slightly deviated from the control tape, the differences will not impact much in practical applications. However, the enhanced current sharing in the Slot-n-Fill tapes will lead to better quench stability, particularly in the cases of multi-strand cables and no-insulation coils.

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