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Estimation of Physical and Electrical Properties of Various REBCO Tapes for Construction of Very-High-Field REBCO Magnet

Jung-Bin Song, Xavier Chaud, François Debray, Kévin Paillot, Philippe Fazilleau, Thibault Lécresse, Thomas Herrmannsdörfer, Carmine Senatore, Marc Dhallé, and Anis Smara

Abstract— The physical and electrical properties of four recent REBCO CC were assessed: 1) THEVA; 2) Shanghai Supercond. Technology; 3) Faraday Factory Japan; and 4) Fujikura. For estimating their physical properties, the delamination strength of each tape was checked by removing a polyimide ribbon stuck on the tape and by cutting the tape after pre-tinning. Their windability and the uniformity of their thickness were also investigated through our metal-as-insulation winding process. For evaluating their electrical properties, their critical current was measured at 4.2 K under various external magnetic fields perpendicular to their ab-plane. Joint samples of each tape were fabricated and tested in a bath of liquid nitrogen at 77 K in self-field. The results are described in this paper for the four tapes.

Index Terms—Electrical and physical properties, HTS magnet, Metal-as-insulation, REBCO, Very-high-field, Windability.

I. INTRODUCTION

IN 2019, the ‘NOUGAT’ project, which aimed to develop an HTS insert of 10 T for generating a combined field of 30 T with a resistive outsert of 20 T, has been successfully completed [1]–[3]. Especially, the main achievement of this project was that despite two quench events (a quench due to an outsert fault at 28 T and a quench of the HTS insert at 32.5 T) there was no damage of the HTS windings except at the inner/outer electrical junctions thanks to our protection scheme consisting of the metal-as-insulation (MI) winding

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technique and magnetic shielding method [4], [5]. Based on the results of this project, the ‘SuperEMFL’ and ‘FASUM’ projects are being conducted to develop very-high-field superconducting magnets for end-users. For the first step of magnet design, the electrical properties of commercialized conductors are needed under very high magnetic field at low temperature. Furthermore, practical qualities of the conductors, such as the delamination strength and the thickness uniformity, should be guaranteed to use such a conductor for fabricating very high field magnets.

REBCO tape manufacturers have been making efforts to reduce the production cost and improve the current density of their products. Apart from these efforts, there are insufficient reports on electrical, thermal and mechanical properties of these REBCO tapes under extreme conditions recently published by companies. In particular, in the case of high magnetic field coils that require a large number of turns wound with high tension on a small diameter, it is very important to estimate the windability of the tapes, but we were not able to find public reports on these matters. Therefore, we undertake an evaluation of the physical and electrical properties of various tapes. In this paper, four REBCO products bought in 2022 were tested: 1) THEVA (TV); 2) Shanghai Superconductor Technology (SST); 3) Faraday Factory Japan (FFJ), previously named SuperOx Japan; and 4) Fujikura (FJK). We focus on this study on: 1) delamination strength; 2) windability; 3) tape thickness uniformity; 4) joint characteristics; and 5) in-field performance of each tape.

II. PHYSICAL PROPERTIES OF REBCO TAPES

Table I shows the specifications of the tapes. The width of all tapes was about 6 mm. The measured total thickness values of three tapes except FFJ tape were approximately 74 ~ 76 μm . In the case of FFJ, the measured total thickness values were about 60 ~ 64 μm due to the thinner substrate.

A. Delamination strength

For the construction of REBCO magnets, cutting, pre-tinning and soldering of the tapes are some tasks frequently performed. In addition, during these processes, polyimide tape is mainly used to protect and fix the REBCO tape, and removed after work. If the adhesion between the REBCO tape’s layers is not sufficient during this process, delamination problems occur. Therefore, we checked the delamination strength as follows. The first step is to attach a polyimide tape on the REBCO tape and to remove it. The second is to cut the

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tape with scissors after pre-tinning the REBCO tape. Although this evaluation method is a rough one, it is a very practical approach for the construction of actual HTS magnets. In addition, to ensure reproducibility in evaluating tape delamination strength, we tested a minimum of eight samples from each company's product, selecting them from at least four conductor spools per company. Fig. 1 shows pictures of delaminated REBCO tapes. In the case of the first check (see Fig. 1a), REBCO tapes of three companies (TV, FFJ and FJK) were easily delaminated. In the case of the second check (see Fig. 1b), the tapes of two companies (TV and FFJ) were delaminated at the cut edge. In addition, even if the tapes did not delaminate immediately after cutting, it occurred several hours later, which means that the tapes with weak adhesion between layers are physically very unstable at the cutting area. Consequently, REBCO tapes of three companies, except SST tape, require an increase of their delamination strength. Recently, TV reported to us that they succeeded in developing a new tape with an improved delamination strength. The preliminary evaluation on samples of this new tape using Kapeton showed no delamination; next, we are planning to evaluate the new TV tapes in the coil under high field.

B. Windability of REBCO tapes

To construct double pancake (DP) coils for very-high-field magnet, the REBCO tapes were co-wound with a stainless-steel tape (Durnomag® - 6 mm width and 30 μm thick) on a stainless-steel (SS) inner ring with a 50 mm diameter and a 1 mm thickness at a winding tension (WT) of 100 MPa. The reason for co-winding is to apply the advantages of the MI technique to the DP coil [6]-[10]. If a deformation of the coil was noticeable at a WT of 100 MPa, the winding process was repeated by gradually reducing WTs to evaluate the minimum WT applicable with no deformation.

1. THEVA REBCO tape

Fig. 2 shows pictures of TV DP coils. As seen, the DP coils were wound uniformly without any deformation at a WT of 100 MPa, demonstrating that TV tape has good physical properties in terms of windability.

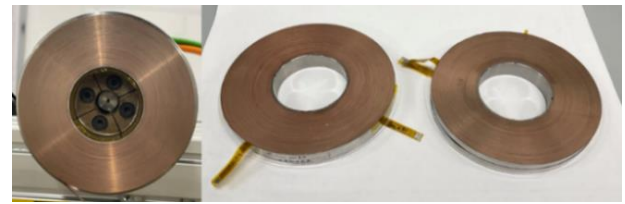


Fig. 2. Pictures of TV REBCO DP coils at a WT of 100 MPa.

2. Shanghai superconductor technology REBCO tape

Fig. 3 shows pictures of SST DP windings at WTs of 100 (a) and 60 (b) MPa. In the case of 100 MPa, the winding was well aligned without any issue up to 249 turns. At 250 turns, the winding was suddenly deformed in a conical shape (see the far right of Fig. 3a). At a WT reduced to 70 MPa, deformation of the winding could not be avoided. At a WT of 60 MPa, the SST DP coil was successfully wound without deformation. However, deformation of this winding occurs in some area during charging-discharging tests in a liquid nitrogen (LN2) bath at 77 K in self-field (see Fig. 3b). Finally, at a WT of 50 MPa, the SST winding was free from deformation after winding process and LN2 test.

SST investigated the causes of deformation of REBCO tapes at high WTs and found that one edge is slightly thicker ($\sim 3 \mu\text{m}$ thickness difference) than the other. The reason for the thickness difference between the edges of SST tape is that 1) the substrate has a slight thickness variation along its width and 2) the bottom end of tape tends to be thicker because the tape is placed vertically during copper-plating. Fig. 4 illustrates the winding deformation using REBCO tapes with a different thickness between edges at high WTs. When the thicker edge of the tape faces the bottom of the coil, the winding is denser than at the top of the coil wound with the thinner edge. If the coil is wound with a large number of turns at a high WT, the coil may suddenly deform into a conical shape at a certain number of turns exceeding the critical point of deformation. In contrast, if the thin edge is placed toward the bottom of the pancake, the deformation of the coil might be mitigated, but may also reduce winding uniformity. Moreover, even in this case, as the number of turns increases, the outer of the upper part of the coil wound with a thick edge

TABLE I

PHYSICAL DESCRIPTION OF REBCO TAPES					
	Unit	TV	SST	FFJ	FJK
Width	[mm]	6 ± 0.1	6 ± 0.1	6 ± 0.1	6 ± 0.1
Stabilizer thick. per side	[μm]	10 ± 2	10	10 ± 3	5
Substrate thickness	[μm]	50	45	37 ± 3	50
Measured total thickness	[μm]	74 - 76	74 - 77	60 - 64	73 - 75

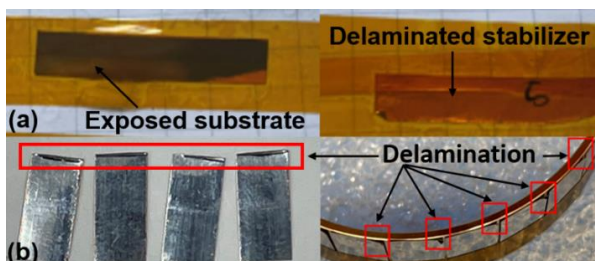


Fig. 1. Pictures of delaminated REBCO tapes: polyimide check (a); and cutting check after pre-tinning (b).

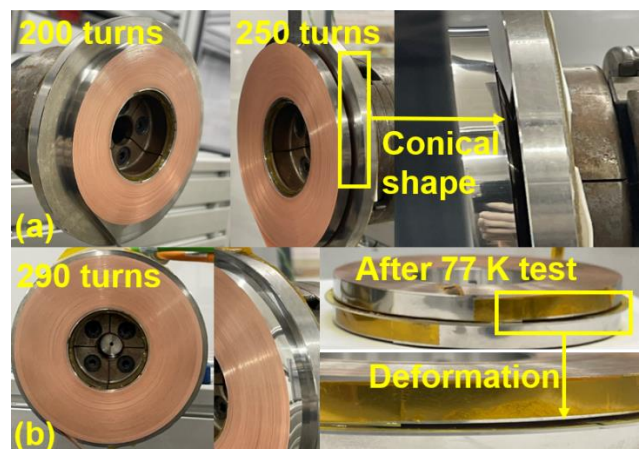


Fig. 3. Pictures of deformed SST MI coils at winding tensions of 100 (a) and 60 (b) MPa.

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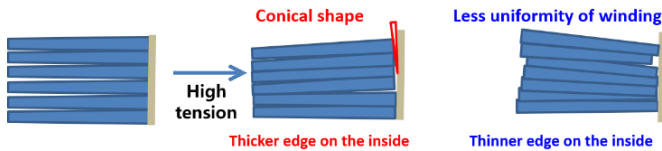


Fig. 4. Illustration of winding deformation under WT using a tape with a difference of thickness between the edges.

may deform downward. Recently, SST notified us that they successfully reduced the difference in thickness between the edges of the tape to less than $1 \mu\text{m}$, and that there was no deformation of DP coils using such tapes under the same winding conditions as ours (REBCO and SS co-winding at a WT of 100 MPa). In the near future, we will evaluate the windability of SST's new products again.

3. Faraday Factory Japan REBCO tape

Fig. 5 shows pictures of FFJ winding as the number of turns increases at a WT of 50 MPa. The FFJ coil not only had an uneven winding arrangement but was also deformed as the number of turns increased, even at a WT as low as 40 MPa. The reason for the winding deformation, as discussed with FFJ is probably due to the thin thickness ($37 - 40 \mu\text{m}$) of the substrate and its geometry after electropolishing. Fig. 6 shows a schematic drawing of FFJ tape's substrate after electropolishing. Since both ends of the tape width are thinner than the middle part, its thickness is inevitably asymmetrical when slitting the initial 12 mm width into 6 mm, which causes conical deformation of the windings. Moreover, in the case of 6 mm width tape cut from the center of 12 mm width tape for these tests (CNRS tape), the difference in thickness between the two ends of the tape is maximized (see Fig. 6a). Official products of FFJ are 4 mm and 12 mm width tapes. FFJ will estimate the windability of their tape using a 6 mm width tape cut at both edges (see Fig. 6b) to use only the central part of the tape. This solution has of course a higher cost.

4. Fujikura REBCO tape

Fig. 7 shows pictures of FJK windings. The coil shows good uniformity without any deformation during winding process. However, after unloading the coil from the winding machine, its outer part suddenly deformed at WTs from 100 MPa down to 50 MPa. In addition, the direction of deformation was opposite to that of SST and FFJ tapes because the thin edge of the tape might face the bottom of the pancake (see the far right of Fig. 4). To investigate the effect of edge direction on the windability, we performed the winding process again at a WT of 50 MPa after changing the edge direction of

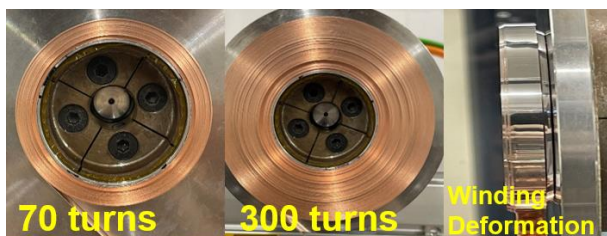


Fig. 5. Pictures of FFJ winding at a winding tension of 50 MPa.

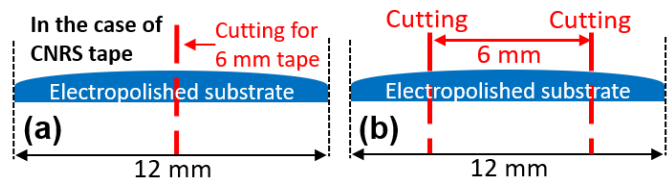


Fig. 6. Schematic drawing of FFJ tape's substrate after electropolishing: center cutting (a); and both-edge cutting (b) for 6 mm width tape.

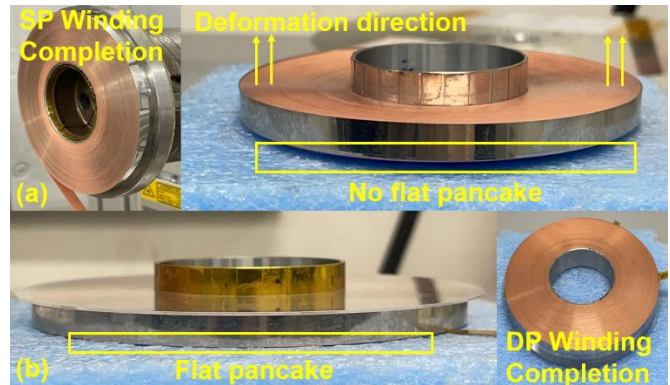


Fig. 7. Pictures of FJK coils before (a) and after (b) changing edge direction.

the tape. Based on SST winding experience, we determined that there would be no deformation of the winding at a WT of 50 MPa. Deformation of the winding didn't occur after unloading the coil (see Fig. 7b). However, after a 77 K test, the sapphire DP spacer maintained by the single-pancake (SP) coils slightly moved, which implies that it is difficult to completely prevent winding deformation.

C. Tape thickness uniformity estimated by winding diameter

Fig. 8 shows the conductor thickness estimated from the diameter of each winding. As seen in Fig. 8, the estimated thickness of TV tapes was within the measured thickness range of tapes (see Table I), indicating that the tape has a consistent thickness in both the width and length directions of tape. In the case of SST, the evaluated tape thickness was slightly higher than the measured thickness because one edge of the tape is thicker than the other. In the case of FJK, the estimated thickness values of tapes were within the measured values for three spools. However, the estimated thickness of tape in one spool after winding was $70 \mu\text{m}$, which is up to $5 \mu\text{m}$ thinner than the measured thickness. We discussed with FJK about this difference in thickness before and after winding, but the cause is not known yet. In the case of FFJ, it was difficult to evaluate the tape thickness by winding diameter because unevenness and deformation of the windings could not be prevented in these tests.

III. ELECTRICAL PROPERTIES OF REBCO TAPES

A. Joint characteristics of REBCO tapes

To evaluate the joint properties of each tape, joining samples were fabricated and tested at 77 K in a LN₂ bath. Table II lists test results of joining samples. As seen in Table II,

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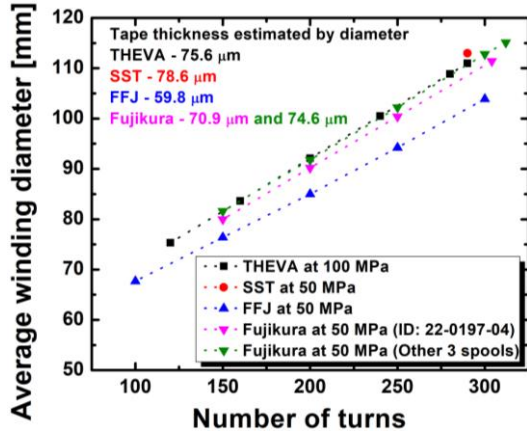


Fig. 8. Number of turns vs. winding diameter of DP coils wound with 4 tapes.

TABLE II

TEST RESULTS OF JOINING SAMPLES AT 77 K IN SF

		TV	SST	FFJ	FJK
Min. I_c of HTS pieces for joint	[A]	130	224	272	200
Min. I_c of HTS conductor for joint	[A]	220	224	179	200
Max. joint resistance of the samples	[nΩ]	6.0	16.8	6.5	11.3
Surface resistivity of the samples	[nΩ·cm ²]	24.2	60.6	25.7	44.8
I_c of the samples	[A]	218	263	258	274

the maximum joining resistance values of all samples were less than 17 nΩ, and their critical current (I_c) values were not degraded at least at 77 K. In other words, all tapes show good electrical performance for joint.

B. In-field performance of REBCO tapes

Fig. 9 shows some lift factors of REBCO tapes under various fields perpendicular to the ab-plane (B_{per}). In the particular case of THEVA, the c-axis of the REBCO layer is tilted by approximately 30 degrees with respect to the substrate normal [11]. As shown in Fig. 9, the TV tape shows the highest performance. Fig. 10 shows current carrying capability (CCC) of the tapes per unit width under various B_{per} . The critical current density of all REBCO tapes was over 1000 A/mm² under a B_{per} of 30 T at 4.2 K, which implies that all REBCO tapes are suitable as conductors for fabricating of very-high-field magnet in terms of electrical properties. At this level of current density, the performance of the magnets

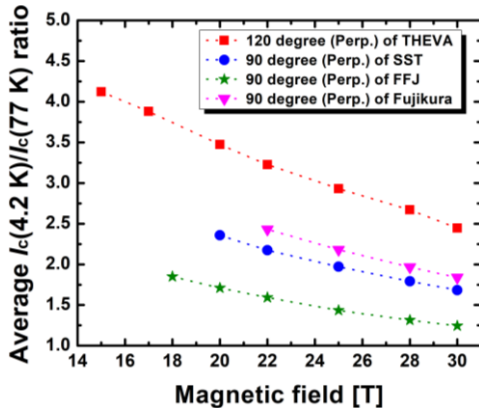


Fig. 9. Lift factor of the tapes under various perpendicular fields from ab plane.

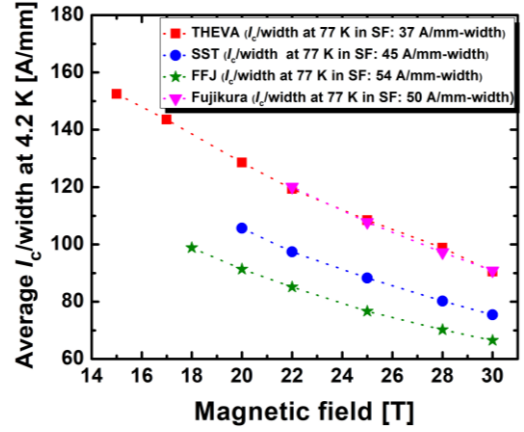


Fig. 10. Current carrying capability of the tapes per unit width under various perpendicular fields from ab-plane.

is limited by the mechanical properties. The CCC of TV REBCO tape was evaluated by reflecting the lift factor to the average I_c (77 K) of purchased 6 mm width tapes. Meanwhile, FFJ informed us that their evaluation results of CCC differ from our test results. Although they measured the CCC of their tape up to a B_{per} of 13 T, the tape shows approximately 14.3 % better performance under a B_{per} of 30 T compared to our result if their result is extrapolated. The reason why our measurement was lower than that of FFJ is probably because the tape may be mechanically damaged under high field due to its thinner substrate.

IV. CONCLUSION

In this study, delamination strength, windability, thickness uniformity, joint characteristics, and in-field performance of THEVA, Shanghai Superconductor Technology, Faraday Factory Japan, and Fujikura REBCO tapes were evaluated. Based on our results, we may conclude that:

- Joining sample of all REBCO tapes show good performance without any critical current degradation at 77 K. Furthermore, the critical current density of all tapes was over 1000 A/mm² under a field of 30 T perpendicular to the ab-plane at 4.2 K. These results indicate that all REBCO tapes are suitable as conductors for fabrication of very-high-field magnet in terms of electrical properties with the present mechanical limits.
- However, in order to construct very-high-field REBCO magnets, it is necessary to improve the physical properties of tapes, such as delamination strength and thickness uniformity. In particular, the difference in thickness between both edges of the tape causes unevenness and deformation of the windings under high winding tension. Therefore, this difference should be mitigated.

In near future, we are supposed to test mock-up magnets wound with new TV and SST products for checking their improved physical qualities.

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