Development of ReBCO-CORC Wires With Current Densities of 400–600 A/mm^2 at 10 T and 4.2 K

Tim Mulder, Jeremy Weiss, Danko van der Laan, Marc Dhallé, and Herman Ten Kate

***Abstract*—Thin ReBCO tapes of 2 mm in width and only 30-μm substrate thickness allow production of thin CORC wires of 3–4 mm in diameter. These CORC wires feature high bending flexibility and high current densities as required for high field magnets. Two CORC wires, the first with 50 tapes and the second with 29 tapes, were developed and tested in a common effort of CERN, ACT, and the University of Twente. The two CORC wires were tested as small solenoids in transverse magnetic fields of up to 10.5 T and at 4.2 K. Afterwards, single tapes were extracted from the samples and tested individually in self field at 76 K. The first CORC wire had a critical current of 4255 A and an engineering current density of 322 A/mm^2, while the second wire showed 3970 A and 412 A/mm^2, both at 10 T and 4.2 K. The extracted tape analyses showed points of improvement for both wires, and therefore, provide valuable feedback for improving the wire production process and wire handling. CORC wire optimization resulted in no performance degradation of the 29-tape wire during electromagnetic load cycling at high magnetic fields. In this paper, details are presented on the CORC wires and measurement results are summarized.**

***Index Terms*—CORC, high magnetic field, HTS, REBCO wires.**

I. Introduction

THINNER substrate ReBCO (Re=Rare Earth) tapes nowadays produced by SuperPower makes it possible to produce high current thin ReBCO CORC wires of 3 to 4 mm diameter. The reduction of the tape's substrate thickness from 50 to 30 μm leads to a significantly reduced minimum bending radius of ReBCO tapes [1], [2]. The 30 μm thick substrate tapes can now also be slit to 2 mm width. Thinner substrates and narrower tapes make it possible to produce CORC wires with more bending flexibility and high engineering current density. The technique of thin and round CORC wires is widening their application in high field magnets and insert coils operating at 4 K as well as magnets operating at elevated temperatures in the 20 to 50 K range, a range uniquely served by ReBCO. CORC wires with various tape layouts are being developed in a common effort of CERN, Advanced Conductor Technologies (ACT) and the University of Twente in support of this potentially break-through technology [2]. The 3.0 to 4.5 mm CORC wire samples were tested in transverse magnetic field of up to 10.5 T as small solenoids operating at 4.2 K at the University of Twente and in self field at 76 K at ACT. The tests aim to demonstrate the ease of use and high performance of the new CORC wires. In addition, the tests provide feedback needed to optimize wire manufacturing and joint terminal production.

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T. Mulder is with the University of Twente, 7522 NB, Enschede, The Netherlands, and also with CERN, 1211 Geneva, Switzerland (e-mail: tim.mulder@cern.ch).

J. Weiss and D. van der Laan are with Advanced Conductor Technologies (ACT), Boulder, CO 80301 USA, and also with the University of Colorado, Boulder, CO 80203 USA.

M. Dhallé is with the University of Twente, 7522 NB Enschede, The Netherlands.

H. Ten Kate is with CERN, 1211 Geneva, Switzerland.

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TABLE I
PROPERTIES OF THE TWO CORC WIRES

Property	Wire 1	Wire 2	Unit
Manufacturer	ACT	ACT	–
Tape manufacturer	Superpower	Superpower	–
Tape type	SCS-2030	SCS-2030	–
Number of ReBCO tapes	50	29	–
Number of layers	20	11	–
Outer diameter	4.1	3.5	mm
Core material	Cu	Cu	–
Core diameter	1.9	2.5	mm
Wire length	1560	1780	mm

II. ReBCO CORC Wire Samples

Two CORC wires and their measurement results are described in this paper. Both CORC wires use the SuperPower Inc. SCS-2030 ReBCO tapes, which are 2 mm wide and comprise 30 μm of Hastelloy substrate. The tapes are plated with 5 μm of copper stabilizer on each side for a total thickness of 44 μm. The first CORC wire had 50 tapes wound in 20 layers. The initial layer of the 50-tape wire was wound on a copper former with an outer diameter of 1.9 mm. This diameter is lower than the minimum bending radius of the tapes and therefore some degradation of the first few layers was expected. The second sample was more conservative with 29 tapes in 11 layers on a copper former of 2.5 mm. This wire was thinner and comprised fewer layers compared to the other sample and therefore was more flexible and more practical to handle and bend. More details on the two CORC wires are presented in Table I.

III. Sample Holder

The sample holder is a cylindrical stainless steel mandrel with an outer diameter of 60 mm, which is similar to the

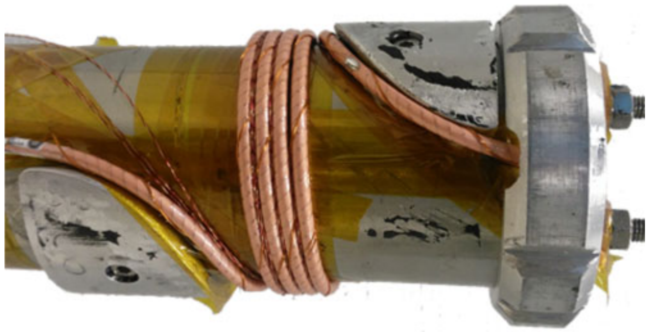

Fig. 1. CORC wire wound into a 5 turn solenoid on the stainless steel sample holder prior to applying mechanical reinforcement.

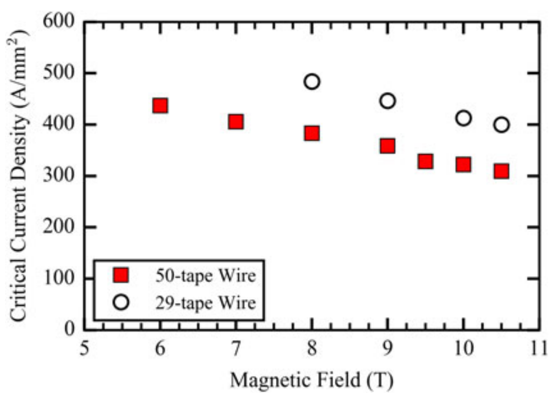

Fig. 2. Measured critical current densities for both the 50-tape and 29-tape CORC wire as function of magnetic field at 4.2 K.

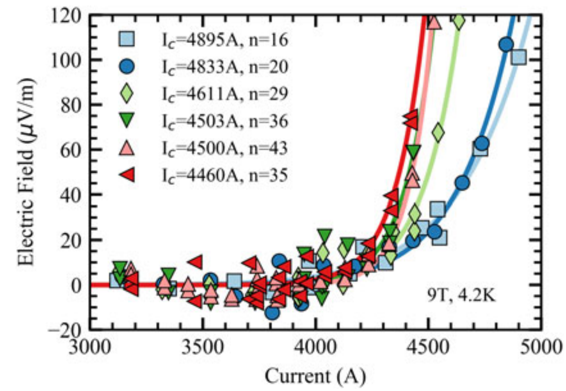

Fig. 3. Critical current I_c(9 T, 4.2 K) measurements of the 50-tape CORC wire show a clear sign of degradation in critical current due to electro-magnetic load cycling with the Lorentz forces pointing inwards.

bending diameter of conductors used in research magnets and other applications where space is restricted. The wires were wound in several turns around the mandrel in the shape of a small solenoid. A picture of the 29-tape wire on the sample holder is presented in Fig. 1. The sample holder was inserted in a Nb_3Sn solenoid providing up to 11 T background field. All tests were performed in liquid helium. The self-field contribution in this setup is very low compared to the background field as the self-field mainly points in the direction parallel to the tapes. The CORC wires included a 30 μm thick layer of polyethylene insulation. Earlier measurements at the University of Twente have shown less buckling of the tapes occurs while bending the CORC wire if the insulation is still present while the wire is bent. The entire sample was then wrapped in Teflon tape and coated with glass cloth and epoxy resin to provide mechanical support to the windings during the tests.

IV. Wire Test Results

A. Electrical Performance

The measured critical current densities of the 50-tape and 29-tape wire are presented in Fig. 2. The criterion to determine the critical current is 1 μV/cm. The 50-tape wire showed a critical current of 4255 A at 10 T and 4.2 K with an n-value of about 30 $\pm$ 15, corresponding to an engineering current density J_e of 322 A/mm^2. The 29-tape wire had a measured critical current of 3970 A at 10 T and 4.2 K with an n-value of around 32 $\pm$ 7, corresponding to a current density of 412 A/mm^2. Several tape batches were tested at Florida State University to determine their critical current at 4.2 K at fields between 6 and 15 T. The lift factor found was 1.8 at 10 T, defined as I_c(10 T, 4.2 K)/I_c(self-field, 77 K), for the batch of tapes that was used for the 29-tape wire. These values, as determined by the ReBCO manufacturing process for these tapes, are relatively low, compared to the typical lift factor of 2.7, which would correspond to a wire current density of about 600 A/mm^2 at 10 T and 4.2 K. Batches of tape have been delivered by Superpower in 2016 with lift factors as high as 3.4, which would have resulted in a wire current density of over 800 A/mm^2 at 10 T and 4.2 K. Both wires had very similar measured critical currents, although one wire comprises many more tapes compared to the other. Therefore, it was expected that the 50-tape wire did show some degradation imposed by the coil winding on the sample holder.

B. Effect of Electro-Magnetic Load Cycles

The Lorentz forces on the wire with 50 tapes pointed inwards during the measurements and the Lorentz forces on the 29-tape wire pointed outwards purposely in order to assess any change in wire performance due to the direction of the Lorentz force. The 50-tape CORC wire showed a reduction in critical current after each load cycle. The measured E(I) curves of the wire at 9 T are presented in Fig. 3 and the critical current as function of magnetic field and run number are shown in Fig. 4. The critical current was reduced by approximately 10% of its original I_c after 12 runs due to electro-magnetic load cycling (at several applied magnetic fields). The current sharing seems to start around the same point in all runs, therefore the n-value increases as the critical current decreases. The 29-tape wire showed no such degradation as the critical current does not change per cycle as shown in Figs. 5 and 6. The much better performance under stress cycling of the 29-tape wire is a direct result of the winding configuration that ensured the strain state of each tape remaining below the critical strain limit during winding and high-field operation. As discussed in the next section, the strain state of many of the tapes in the 50-tape wire already exceeded the critical strain limit during bending [3], [4], while the added Lorenz force during testing, with the force pointing inward, pushed the strain state of the tapes further over their limit.

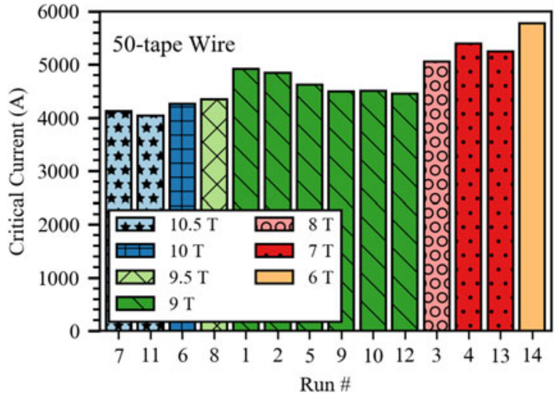

Fig. 4. Critical current as function of magnetic field and run number for the 50-tape CORC-wire. A decrease in critical current is observed with each subsequent run, which indicates degradation due to the electro-magnetic load cycling.

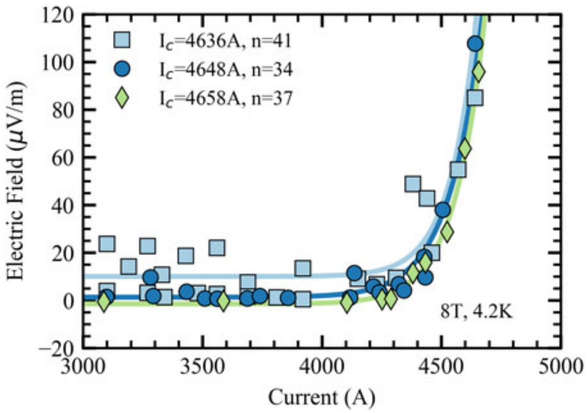

Fig. 5. Critical current I_c(8 T, 4.2 K) measurements of the 29-tape wire show no degradation due to electro-magnetic load cycling with Lorentz forces pointing outwards.

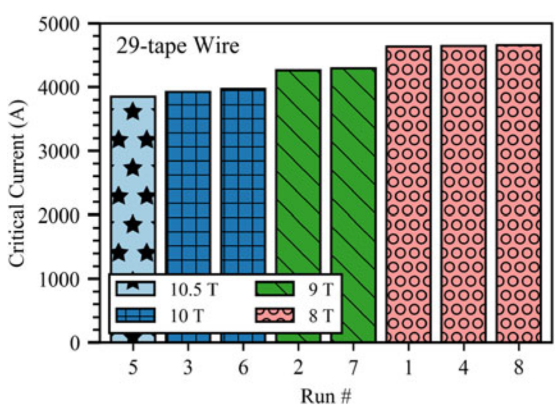

Fig. 6. The critical current as function of magnetic field and run number for the 29-tape CORC-wire. No degradation is observed due to the electro-magnetic load cycles.

C. Analyses of Extracted Tapes

The tapes of the wires that were in the center of the high magnetic field region of the sample holder were extracted at ACT after the test at the University of Twente. Each tape was tested individually to assess any degradation and to pinpoint the layer in which the degradation occurred. The critical current of each tape was measured at 76 K in self field and compared to the

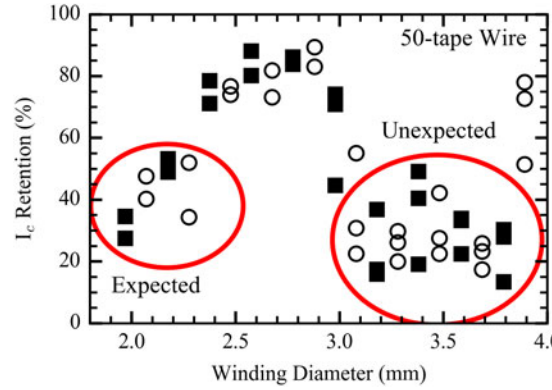

Fig. 7. Critical current measurements of the single tapes extracted from the 50 tape CORC wire after the test at the University of Twente shows degradation, as expected, in the layers with a winding diameter less than 2.4 mm. Unexpected degradation was observed in the outer layers, likely caused by insufficient winding tension during wire production.

performance of an unused piece of tape from the same batch. The 50-tape wire showed large degradation on tapes extracted from the inner most layers, as shown in Fig. 7. This is a clear indication of the winding diameter of the inner layers being too small and the ReBCO layer in the tapes underwent too much compressive strain. This degradation was expected as the strain dependence of ReBCO tapes has been well documented in literature [3], [4].

It also confirms the minimum tape bending diameter of 2.4 mm even after the CORC wires are bent. However, the the partial degraded tapes still provide a significant contribution to the wires critical current. The degradation in outer layers was not expected and rather severe. The outer nine layers show a critical current retention of around 30%, which was likely caused by a too low winding tension during the wire production. If winding tension is too low in wires with a large (>9) number of layers, there is enough accumulated slack for tapes to deform rather than slide when the wire is bent, resulting in macroscopic kinking and poor I_c retention. Tension needs to be adjusted to be sufficiently high for intimate contact between tapes, but still kept low enough to not damage tapes and to allow tapes to slide when the conductor is bent. The total I_c retention of the 50-tape wire was 48%.

The 29-tape wire had a much higher I_c retention of 82%, but still showed some minor tape degradation, as presented in Fig. 8. The observed degradation was different from that of the 50-tape wire. Every other layer shows a higher I_c retention, suggesting either the wire was torqued during wire bending (every other layer either tightened or loosened) or the tape tension was different when winding tapes in clockwise (CW) direction versus counterclockwise (CCW) direction. Accounting for both the lower lift factor and the observed I_c retention in the extracted tapes, the expected current density at 10 T and 4.2 K is reduced to 400 A/mm^2, which is very close to the measured 412 A/mm^2.

V. Outlook

The results of the critical current measurements of wires and extracted tapes are used for feedback and optimizing the various machine setting parameters for the CORC wire production

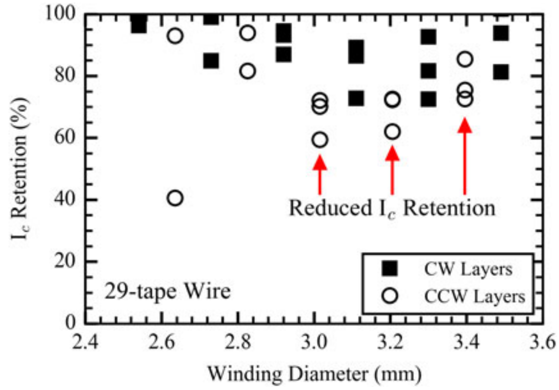

Fig. 8. Critical current retention versus winding diameter of the extracted tapes form the 29-tape wire. In the single tape measurements only some minor I_c reduction was observed in each other layer, suggesting the CORC wire was lightly torqued.

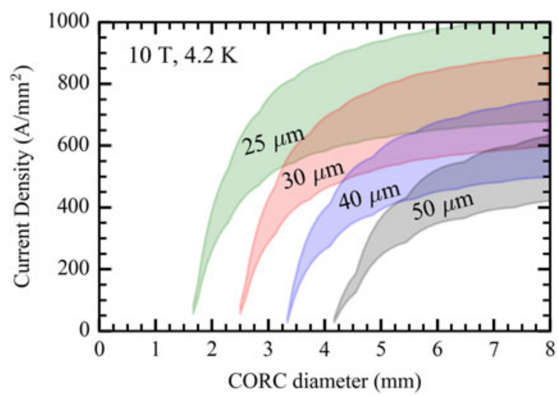

Fig. 9. Wire current density versus CORC wire diameter. The CORC wire current densities that can be achieved by reducing the substrate thickness from 50 μm to 40 μm, 30 μm and 25 μm and lift factors varying from 1.5 to 3.0 at 10 T and 4.2 K.

process in order to reduce degradation effects and improve wire handling.

It is expected that the near future will show CORC wires with nearly 100% I_c retention in bent state thereby allowing small bore high field magnets requiring low winding diameters. In addition, the tape substrate thickness is expected to go down by another 5 to 10 μm from 30 to 25 or 20 μm.

The reduction in tape substrate thickness reduces the minimum diameter of the CORC wires and is expected to increase the wires current density to 700-900 A/mm^2 at 10 T and 4.2 K as seen in Fig. 9.

VI. Conclusions

Two CORC wires, one with 50 ReBCO tapes and the other with 29 tapes, were tested in magnetic fields up to 10.5 T at 4.2 K. The 50-tape wire shows a critical current of 4255 A at 10 T and 4.2 K, which corresponds to an engineering current density of 322 A/mm^2. This wire showed 10% degradation due to electro-magnetic load cycles explained by the strain state of a large number of the tapes exceeding the critical strain limit after sample coil winding and further enhanced by the Lorenz forces during testing. Extracted tape analysis afterwards showed that this additional degradation is likely caused by insufficient tape winding tension during wire production. The resulting I_c retention of the 50-tape wire was 48%. The 29 tape CORC wire performed much better with a critical current of 3970 A at 10 T and 4.2 K, corresponding to an engineering current density of 412 A/mm^2. This wire showed no degradation due to load cycling. The tapes used in the 29-tape CORC wire show a low lift-factor. The performance could have been a factor 2 better when tapes with a higher lift factor were used. The extracted tape analysis shows that the total I_c retention of the 29-tape wire was 82%.

The tests have provided valuable feedback used to further optimize and improve the production and handling of CORC wires to arrive at much higher level of performance.

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