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Effect of transverse compressive monotonic and cyclic loading on the performance of superconducting CORC® cables and wires

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Abstract

Superconducting CORC® cables and wires have become practical conductors for use in high-field magnets for fusion machines and particle accelerators by demonstrating their ability to carry very high currents in background magnetic fields of up to 20 T. The high mechanical stresses that develop on the CORC® conductor during such operation could result in permanent degradation of the conductor critical current. Transverse compressive stress is one of the predominant mechanical stresses when CORC® cables or wires are bundled into CICCs that allow fusion and detector magnets to operate at currents as high as 100 kA. The effect of transverse compressive load on the critical current of CORC® cables and wires has been investigated at 76 K to determine their irreversible load limit under monotonic loading and load cycling up to 100 000 cycles. The results show a clear effect of the CORC® conductor layout with respect to gap spacing between tapes, thickness of the copper plating surrounding the tapes and thickness of the former onto which the tapes are wound. CORC® cables and wires have demonstrated a remarkable resilience to transverse compressive load cycling where their critical current decreased by no more than a few percent after 100 000 load cycles at peak loads that resulted in an initial decrease in critical current of less than 5%. The results indicate that no significant degradation of CORC® cable and wire performance due to transverse compressive load is expected in large magnets after 100 000 load cycles, as long as the peak load on the conductor does not exceed the irreversible load limit defined at 95% retention in critical current. The irreversible load limit of CORC® conductors could be increased further by increasing the size or hardness of the former that makes up the conductor's core.

Keywords: CORC® cables, CORC® wires, transverse compression

(Some figures may appear in colour only in the online journal)

1. Introduction

RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) coated conductors are one of the most practical high-temperature superconducting (HTS) materials to enable the next generation of high-field magnets to operate at fields exceeding 20 T or at elevated temperatures far above the boiling point of liquid helium. The deposition of the almost single-crystalline superconducting film on strong metal substrates results in a highly elastic conductor that can withstand much larger axial [1–4] and transverse compressive stresses [5–8], compared to other HTS materials that are being developed for high-field magnets. The brittle nature of the ceramic filament structure in for instance $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes and $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) wires, in combination with the soft silver-based matrix that surrounds the filaments, make them highly susceptible to degradation under axial and transverse tensile [9] and compressive stress [5, 10]. Bi-based superconductors thus require extensive conductor reinforcement to limit the conductor stresses when applied to high-field magnets. Such external reinforcement is not necessarily required for REBCO coated conductors that contain strong metal substrates, such as Hastelloy C-276 used in

REBCO tapes from, for instance, SuperPower Inc. [2, 11]. As a result, several high-field magnets wound from single REBCO tapes have been successfully demonstrated in recent years [12–14].

Large superconducting magnets for particle accelerators and detectors, and for fusion machines, require operating currents that cannot be achieved by single-tape conductors. Several cables in which many REBCO tapes are bundled to achieve much higher currents have been developed over the years, including Roebel cables [15, 16], the twisted stacked tape cable (TSTC) [17, 18] and Conductor on Round Core (CORC®) cables and wires [4, 19, 20]. CORC® cables and wires have demonstrated their ability to carry currents between 5 and 10 kA in background fields as high as 20 T [21, 22], and have recently demonstrated a record engineering current density (J_e) extrapolated to 20 T of 423 A mm^{-2} [23].

The high currents that have been achieved in HTS cables still are not sufficient for many large magnets for fusion and particle detectors that require operation at currents as high as 50–100 kA. Multiple HTS cables need to be bundled into a cable-in-conduit-conductor (CICC), similar to what has been done with low-temperature superconductor (LTS) for use in fusion reactors such as ITER [24, 25]. Irreversible degradation in critical current (I_c) and a reduction of the current sharing temperature due to compressive stress acting on the bundle of cables or strands has been a major issue in the development of LTS-based CICC for ITER due to insufficient support of the strands. Several conductor optimization steps followed that resulted in an acceptable conductor performance with reduced degradation due to transverse compressive cycling [24, 25].

Development of HTS-based CICC have started in recent years, based either on the TSTC [26, 27], or on CORC® cables [28, 29] and initial tests of HTS CICC at high currents in background fields as high as 12 T have been performed [26, 28, 29]. Significant degradation in I_c was measured in two CICC samples based on the TSTC cable [26] due to the effect of transverse compressive stress on the tape stacks in the CICC, where stress is aligned along the narrow side of the tapes due to twisting of the stack [30]. A major benefit of CORC® conductors over the TSTC is that transverse compressive loads applied to CORC® conductors are always applied to the wide side of the tapes, as long as the deformation of the CORC® conductor remains mainly elastic. The tapes are much more resilient to transverse stress in this direction, potentially eliminating the need to provide external support to the CORC® conductor that may be an inevitable requirement for the TSTC, but also for Roebel cables [31, 32].

Even with a potential higher resilience of CORC® cables to transverse compressive stress compared to TSTC, significant degradation occurred in one of the two CORC®-CICC samples that was tested at up to 50 kA in a 10.9 T background field in the SULTAN test facility at the Paul Scherrer Institute in Switzerland. The degradation was likely caused by the deformation of the CORC® cables in one of the 6-around-1 conductors due to incorrect cable design parameters in combination with the bundle and jacket tolerances [23, 33]. The degradation was not intrinsic to the CORC® conductor, because the CORC®-CICC that formed the sister sample during the test, but had different CORC® cable design parameters and jacket layout, did not show such degradation. Optimization of the HTS cable and the CICC layout is essential to avoid degradation due to transverse compression and their successful application in large-scale magnets.

This paper outlines measurements of the effect of transverse compressive load applied in liquid nitrogen to CORC® cables and wires. Besides measurements under monotonic transverse load, loads were cycled up to 100 000 cycles in liquid nitrogen at different peak loads. The results reveal to a first degree how the CORC® conductor parameters affect their response to transverse compression and how the conductor layout could be optimized to further increase the irreversible load limit.

Table 1. Specifications of CORC® samples containing solid stainless steel formers.

	Former	Tapes	Layers	Copper thickness (μm)	Gap spacing (mm)
CORC®-1	Solid SS	9	3	20	0
CORC®-2	Solid SS	9	3	20	0.5
CORC®-3	Solid SS	9	3	20	0.5
CORC®-4	Solid SS	6	3	20	1
CORC®-5	Solid SS	9	3	5	0
CORC®-6	Solid SS	9	3	5	0
CORC®-7	Solid SS	9	3	5	0
CORC®-8	Solid SS	9	3	5	0.5
CORC®-9	Solid SS	9	3	5	0.5
CORC®-10	Solid SS	6	3	5	1
CORC®-11	Solid SS	6	3	5	1.1
CORC®-12	Solid SS	6	3	5	1
CORC®-13	Solid SS	6	3	5	1

2. Experimental

2.1. Preparation of CORC® cables and wires

Two sets of samples were prepared to investigated the effect of transverse compressive load on the CORC® conductor performance. All samples were prepared from REBCO tapes from SuperPower Inc. that contained a Hastelloy C-276 substrate of either 30 or 50 μm thickness and a surround-plated copper layer with thickness of either 5 or 20 μm.

The first set of samples was prepared to investigate the effect of gap spacing between tapes in CORC® cables and of the effect of the copper layer thickness that was surround plated onto the tapes (table 1). The 0.3 m long CORC® samples were prepared by hand and contained a solid stainless steel former of 4.9 mm thickness onto which six or nine tapes with 50 μm thick substrates were wound into three layers. The stainless steel former was selected to minimize its deformation under transverse compressive load and the potential effect on I_c that such deformation may have. Samples were prepared with gaps spacing of 0, 0.5 and 1.0 mm between

Figure 1. (a) Sample CORC®-1 wound without gaps between the tapes, (b) sample CORC®-2 containing 0.5 mm wide gaps, and (c) sample CORC®-4 containing 1 mm wide gaps.

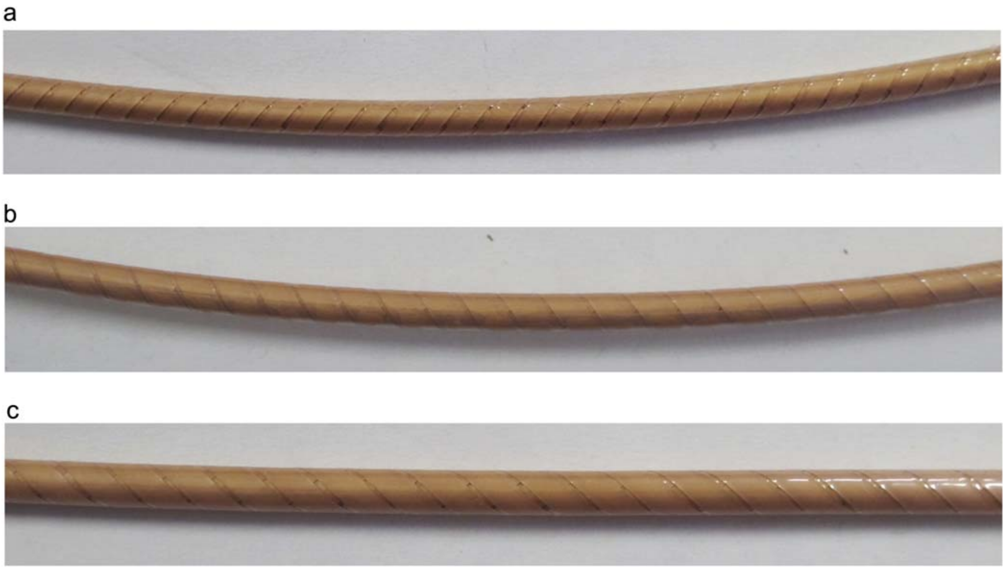

Figure 2. (a) CORC® wire CORC®-W1 containing 27 tapes of 2 mm width, (b) CORC® wire CORC®-W2 containing 12 tapes of 3 mm width, and (c) CORC® cable CORC®-C1 containing nine tapes of 4 mm width.

Table 2. Specifications of production CORC® cables and wires containing a solid copper former.

		CORC®-W1	CORC®-W2	CORC®-C1	CORC®-C2
Type		wire	wire	cable	cable
Former size	(mm)	2.55	3.2	4.92	4.92
Tape number		27	12	9	9
Tape width	(mm)	2	3	4	4
Gap spacing	(mm)	0.3–0.4	0.3–0.4	0.1	0.3–0.4
Substrate thickness	(μm)	30	30	50	50
Copper plating thickness	(μm)	5	5	5	5
Maximum strain	(%)	−1.16	−0.93	−1.00	−1.00

tapes (figure 1) containing tapes with 5 or 20 μm thick copper plating.

The second set of samples consisted of production CORC® cables and wires wound at longer length with a custom cable machine using solid copper formers (table 2). The CORC® wires contained tapes with 30 μm thick substrates, while the CORC® cables contained tapes with 50 μm thick substrates. The tapes were wound with average gap spacing of either 0.1 mm, or ranging from 0.3–0.4 mm, depending on the sample (figure 2). Only tapes containing a 5 μm thick layer of surround-plated copper were used. The main difference between the CORC® wires, besides the number and width of the tapes, was the thickness of their formers that determines the amount of compressive in-plane strain the REBCO layer experiences due to bending around the former. CORC® wire CORC®-W1 contained a 2.55 mm

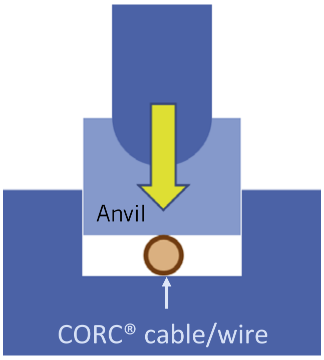

Figure 3. Overview of a CORC® cable or wire located between two flat anvils.

thick former, which resulted in maximum compressive in-plane strain in the REBCO film of the tapes in the innermost layer of about −1.16%, which is very close to the value of −1.25% at which irreversible degradation occurs [4]. CORC® wire CORC®-W2 contained a former of 3.2 mm thickness, resulting in only −0.93% maximum compressive in-plane strain in the REBCO layers of the inner tapes.

2.2. Application of transverse compressive load

Transverse compressive load was applied to CORC® cables and wires in liquid nitrogen by placing the CORC® samples between two flat stainless steel anvils (figure 3). The bottom anvil was part of the load reaction frame attached to a servo-hydraulic actuator, while the top anvil was attached to the piston. The top anvil was about 50 mm in length, while the bottom anvil was about 115 mm in length. The sample is held in pace by fixating the copper adapters that hold the sample terminations. Figure 4 shows a CORC® wire placed onto the bottom anvil, while the bottom part of the load frame is located in an insulating foam cryostat that would be filled with liquid nitrogen. The CORC® terminations were attached to two copper adapters that allowed currents in excess of 2000 A to be injected into the samples.

The procedure to measure the effect of monotonic transverse compressive load on the critical current of CORC® samples was to measure the voltage versus current (*V–I*) characteristic of the sample at a fixed applied load. The voltage was measured over the low-resistance terminals, and included their contact resistance. The load was increased stepwise and *V–I* measurements were taken after each load step and before the load was increased further. The results are presented as a function of applied load in kN m^{-1} contact area length (0.05 m) and not as a function of stress, because the width of the contact area between the flat anvils and the round samples is unknown and is expected to increase with load.

Transverse compressive load cycles were performed in liquid nitrogen at a fixed maximum load that would result in a predetermined irreversible reduction in sample critical current. The load was cycled using a sinusoidal function between 10% (P_{min}) and 100% of the peak load (P_{max}). The load cycling was paused after a number of cycles, followed by a *V–I* measurement to determine I_c.

Figure 4. A CORC® wire being installed into the load frame, before the top anvil is placed on top of the sample.

3. Results

3.1. Effect of transverse compressive load on CORC® conductors containing solid stainless steel formers

The first part of this paper focuses on the effect of transverse compressive load on CORC® samples that contain a solid stainless steel former (table 1). The measurements allow the determination of the effect of the gap spacing between tapes and the thickness of the copper plating surrounding the tapes on the irreversible load limit at which the critical current starts to decrease.

Figure 5 shows the change in normalized critical current of two CORC® samples containing tapes with 20 μm copper surround plating, wound with 0.5 mm gap spacing between them. The critical current of both samples decreased when the load exceeded about 200 kN m^{-1}. The critical current decreased irreversibly by about 70% for sample CORC®-2 at a load of 500 kN m^{-1}, while I_c of sample CORC®-3 decreased by about 50% at that load.

Figure 6 compares the decrease in I_c with transverse compressive load of three samples wound from tapes with 20 μm thick copper plating, but each having different gap spacing. The results show that the onset of degradation in the samples under application of transverse compressive load depends on the gap spacing. The sample with the largest gap spacing of 1.0 mm between the tapes (CORC®-4) showed

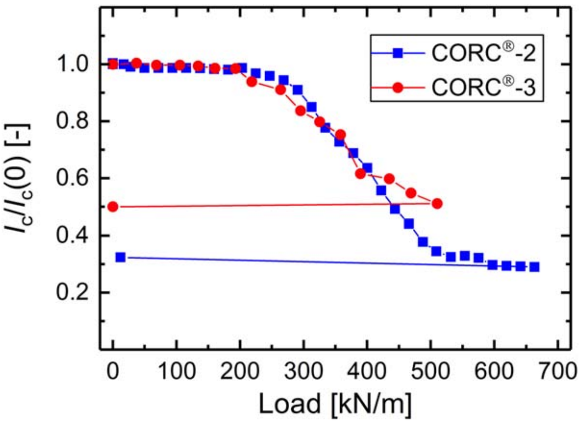

Figure 5. Dependence of the critical current normalized to its value before load was applied on transverse compressive load at 76 K of samples CORC®-2 and 3 containing tapes with 20 μm thick copper plating and 0.5 mm gap spacing.

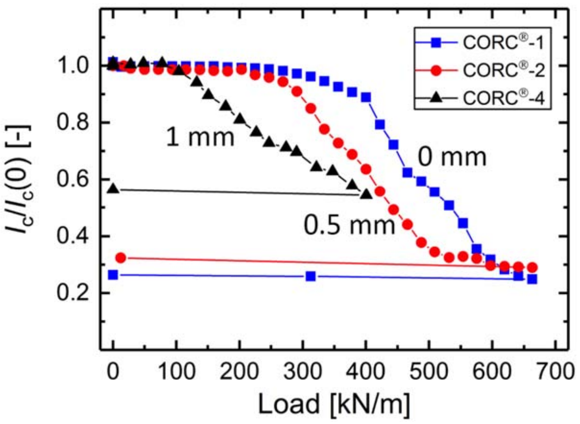

Figure 6. Dependence of the normalized critical current on transverse compressive load at 76 K of samples CORC®-1, 2 and 4 containing tapes with 20 μm thick copper plating and different size gap spacing.

initial degradation at a load of about 100 kN m^{-1}, while I_c of the sample with 0.5 mm gap spacing started degrading at a load of about 200 kN m^{-1}. The sample that was wound without gaps between the tapes showed an initial decrease in I_c at about 250–300 kN m^{-1}. Table 3 lists the average transverse compressive load at which I_c degrades by 1%, 3% and 5%, respectively, for samples wound from tapes with 20 μm thick copper plating.

Several CORC® samples containing tapes with 5 μm thick copper plating were measured as a function of transverse compressive load to investigate the effect of the copper plating thickness on the onset of I_c degradation. Figure 7 shows the results obtained on samples CORC®-5 to CORC®-7 in which the tapes were wound without a gap between them. The critical current in the samples remains almost constant up to a load of between 360 and 450 kN m^{-1} (table 3), which is a significantly higher load than was the case for similar samples containing tapes with 20 μm thick copper plating. Figure 8 shows the results of four samples (CORC®-10 to CORC®-13) containing tapes wound with a gap spacing of 1 mm between them. Initial decrease in I_c was measured when the transverse load exceeded between 200 and 240 kN m^{-1}, which was also significantly higher than their counterparts with 20 μm thick copper layers.

The effect of gap spacing between the tapes in CORC® samples containing tapes with 5 μm thick copper layers on applied transverse compressive load is highlighted in figure 9. Table 3 lists the applied compressive loads at which I_c degrades by 1%, 3% and 5%, respectively. A similar dependence of the irreversible load limit on gap spacing was measured in samples containing tapes with 5 μm thick copper plating, compared to those with 20 μm thick copper plating. The critical current in samples with the largest gap spacing degrades at the lowest applied transverse load most likely because the tapes are less well supported against transverse compression when they cross the gaps between tapes in neighboring layers. Figure 10 shows an image of one of the samples with 1 mm gap spacing after high transverse compressive load was applied. The cable shows clear marking in the tapes of the outer layer where they cross the gaps between the tapes in the underlying layer.

The thickness of the copper plating has, besides the gap spacing between tapes, a clear effect on the transverse compressive load at which I_c in the CORC® samples starts to degrade. Thinner copper layers plated around the superconducting tapes result in higher transverse compressive loads that the cable could withstand before I_c degrades. A comparison of the data outlined in table 3 shows that for all CORC® sample configurations, samples with only 5 μm thick copper plating have a irreversible transverse load limit between 10% and 66% higher compared to samples wound from tapes with 20 μm copper plating.

3.2. Effect of transverse compressive load on production CORC® cables and wires containing solid copper formers

The CORC® samples with stainless steel formers outlined in the previous section were specifically designed to investigate the effect of gap spacing and copper plating thickness on their behavior under transverse compressive load. CORC® cables and wires developed for high-field magnet applications typically contain solid copper formers and are wound with a custom cable machine. Certain winding parameters, such as the tape winding angles, vary between layers, which may affect the behavior under transverse compressive load. The dependence of I_c of several production CORC® cables and wires will be outlined in the following sections.

3.2.1. CORC® cables with a 4.92 mm thick copper former. Two CORC® cables of several meters in length were wound using a custom cable machine. Both cables contained a solid copper former of 4.92 mm thickness onto which nine tapes were wound into three layers. One of the cables contained gaps of 0.1 mm width between tapes (CORC®-C1), while the other cable contained gaps of 0.3–0.4 mm width (CORC®-C2), as is typical for most CORC® cables. Figure 11 shows the dependence of the critical current, n-value and electric field versus current (E–I) characteristics on transverse compressive load at 76 K of a 0.5 m long sample (including two 0.15 m long

Table 3. Average irreversible load limit in kN m^{-1} of CORC® samples containing stainless steel formers.

	20 μm copper plating Gap spacing			5 μm copper plating Gap spacing		
I_c decrease	0 mm	0.5 mm	1.0 mm	0 mm	0.5 mm	1.0 mm
1%	250	200	150	360	210	200
3%	260	200	160	420	250	230
5%	270	220	180	450	290	240

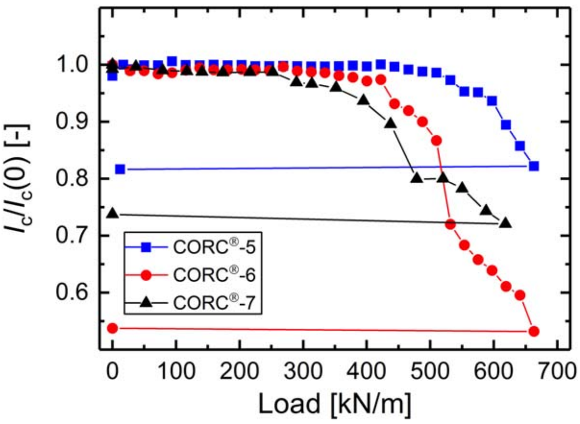

Figure 7. Dependence of the normalized critical current on transverse compressive load at 76 K of samples CORC®-5, 6 and 7 containing tapes with 5 μm thick copper plating and 0 mm gap spacing.

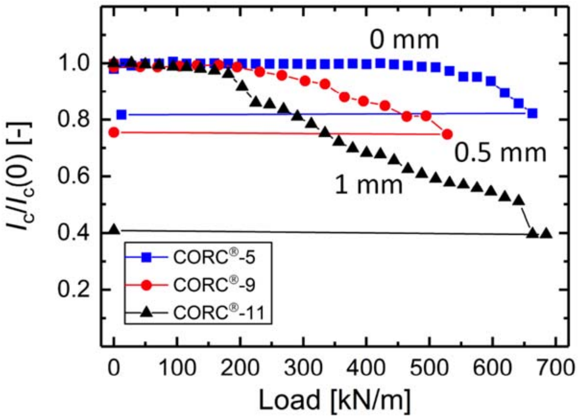

Figure 9. Dependence of the normalized critical current at 76 K on transverse compressive load of samples CORC®-5, 9 and 11 containing tapes with 5 μm thick copper plating and different size gap spacing.

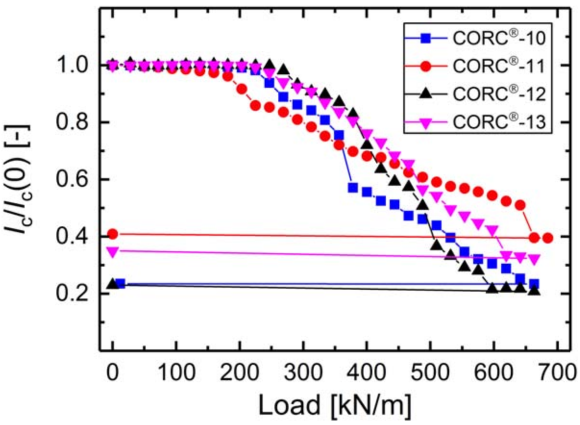

Figure 8. Dependence of the normalized critical current on transverse compressive load at 76 K of samples CORC®-10, 11, 12 and 13 containing tapes with 5 μm thick copper plating and 1 mm gap spacing.

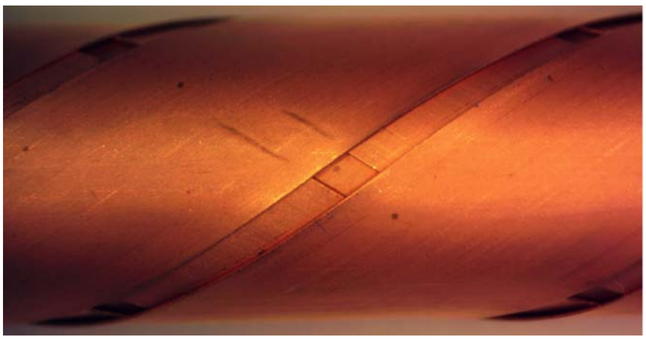

Figure 10. Picture of the outer layer of sample CORC®-11 wound with 1 mm wide gaps between tapes after having degraded due to the application of high transverse compressive load.

terminals) containing 0.1 mm wide gaps between tapes (CORC®-C1). The load at which I_c degraded by at least 3% was about 200 kN m^{-1}, after which I_c declined gradually with load. Figure 12 compares the decrease in I_c under transverse compressive load of CORC® cables containing 0.1 mm wide gaps (CORC®-C1) and those containing 0.3–0.4 mm wide gaps (CORC®-C2). The cables with 0.1 mm gaps could withstand higher transverse loads than those containing wider gaps (table 4), similar to what was measured in CORC® samples containing stainless steel formers.

Several CORC® cables with 0.1 mm and 0.3–0.4 mm gap spacing were subjected to cyclic transverse loading up to 100 000 cycles, while located in liquid nitrogen. Figure 13 shows the dependence of I_c, normalized to its value before load was applied, of several CORC® cables. Both CORC® cables with 0.1 mm and 0.3–0.4 mm gap spacing showed less than 1% additional degradation in I_c after 100 000 cycles to a peak load that caused an initial decrease in I_c of no more than 3%. Only once the peak load caused a much larger initial

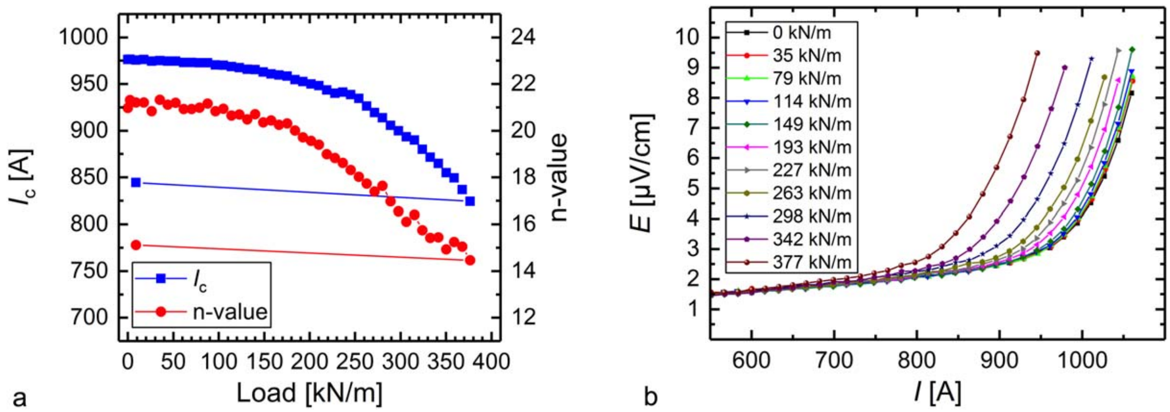

Figure 11. (a) Dependence of I_c and n-value on transverse compressive load at 76 K of sample CORC®-C1. (b) *E–I* curves of sample CORC®-C1 measured at different transverse loads.

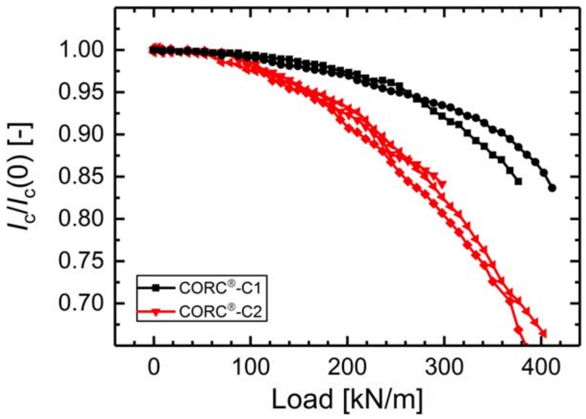

Figure 12. Dependence of the critical current of CORC® cables with 0.1 mm (CORC®-C1) and 0.3–0.4 mm gap spacing (CORC®-C2) on transverse compressive load, measured at 76 K.

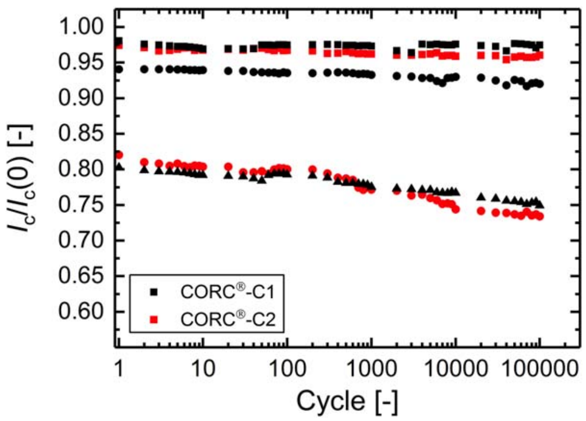

Figure 13. Normalized I_c of cables CORC®-C1 (0.1 mm gap spacing) and CORC®-C2 (0.3–0.4 mm gap spacing) as a function of load cycles, measured at 76 K. The critical current is normalized to the sample I_c before load was applied.

decrease in I_c, did I_c decrease significantly with load cycles. At a peak load at which I_c degraded by about 18%–20% I_c degraded by an additional 5%–8% after 100 000 transverse load cycles. The gap spacing between the tapes in the cables did not influence their behavior during load cycling.

3.2.2. CORC® wires with 2.55 and 3.2 mm thick copper formers. Two CORC® wires that contain solid copper formers were prepared using a custom cable machine. The layouts of the production wires were similar to those being designed for a number of magnet applications, and thus contained gap spacing and tape winding angles that are optimized for best performance in terms of flexibility and current density. The differences between the two wires are their former size, tape width and tape count (see table 2). Figure 14 shows the critical current, n-value and *E–I* characteristics of a CORC® wire containing a 2.55 mm thick former (CORC®-W1) as a function of transverse compressive load. The critical current started to degrade irreversibly at a load of about 115 kN m^{-1}. Figure 15 compares the load dependence of the normalized critical current of several CORC® wires with 2.55 mm thick formers (CORC®-W1) to those with 3.2 mm thick formers (CORC®-W2). The critical transverse compressive load of the CORC® wires with 3.2 mm former was about twice that of the CORC® wires with 2.55 mm thick formers (see table 4).

The performance of CORC® wires as a function of transverse compressive load cycling was also measured at 76 K. Figure 16 compares the dependence of I_c of several CORC® wires, normalized to their values before load was applied, on the number of load cycles. CORC® wires with 3.2 mm thick formers showed no significant decrease in I_c after 100 000 cycles at a peak load at which the initial degradation in I_c was 5%. On the other hand, CORC® wires containing 2.55 mm thick formers degraded by almost an additional 5% after 100 000 cycles. The decrease in I_c after 100 000 cycles became larger at peak loads where I_c degraded before cycling by 10%–20%, with the largest additional decrease in I_c measured in the CORC® wires with 2.55 mm formers (CORC®-W1).

4. Discussion

Initial measurements on CORC® cables and wires have resulted in a better understanding of how the sample composition affects their performance under transverse compressive load, including load cycling to 100 000 cycles at 76 K. The measurements were performed using two flat stainless

Table 4. Irreversible load limit in kN m^{-1} of production CORC® cables and wires, defined at different levels of I_c degradation.

I_c decrease	CORC®-C1	CORC®-C2	CORC®-W1	CORC®-W2
3%	207	124	115	217
5%	255	160	133	243
10%	340	226	163	284

steel anvils. Performance estimates of CORC® conductors in magnet applications in which the winding pack is impregnated, or when the conductors are bundled into CICC would benefit from knowing the irreversible stress limit, and not just the irreversible load limit. Such comparison requires the determination of the contact area between the round CORC® conductors and the flat anvils. An initial effort was performed using pressure sensitive film, as was previously reported for Roebel cables [34]. Load was applied at 76 K while the film was located between the bottom anvil and the CORC® conductor. Figure 17 shows the indicated contact profile at a load of 200 kN m^{-1} for the CORC® cables and wires outlined in this paper. The contact area is relatively inhomogeneous for the CORC® cable, while it is much more homogeneous for the CORC® wire containing a 2.55 mm former. The homogeneity of the contact area is likely influenced by the surface roughness of the CORC® cable or wire, caused by the gap spacing between tapes and dog boning of the copper plating on the tapes. The contact area may become more homogeneous when the CORC® cable or wire is deformed to a higher degree under transverse load, such as in the CORC® wires with 2.55 and 3.2 mm thick formers, compared to the CORC® cable with 4.9 mm thick former.

The width of the contact area at 200 kN m^{-1} was estimated by averaging the width of the pattern displayed by the pressure sensitive film at ten different locations. The contact width of sample CORC®-W1 was about 1.16 mm, while that of samples CORC®-W2 and CORC®-C2 was about 0.9 mm. The wider contact area of sample CORC®-W1 is most likely the result of the thinner former being deformed plastically. The contact area width is expected to grow with transverse load. A more detailed investigation of the contact width as a function of applied load would thus be required for all samples to allow conversion of the I_c versus transverse compressive load characteristics shown in for instance figure 15 into transverse compressive stress. The limited information regarding the contact area width that was obtained during the current study only allowed an estimate of the irreversible stress limit of the different samples, as listed in table 5.

One method to determine the irreversible stress limit of CORC® cables or wires when part of a magnet winding pack is impregnated would be to perform tests on samples that are encapsulated by a similar epoxy. Another method that is currently being considered is using anvils that are formed closely to the shape of the round conductor. These methods would allow transverse loads to be transmitted more evenly onto the conductor, similar to what would occur in an actual magnet. One could also consider developing samples that closely reflect the actual application of the CORC® conductor, such as a 6-around-1 CICC with anvils that closely resemble the conductor jacket. Such configuration would likely require much higher loads than currently available in our test setup. Nevertheless, the results using flat anvils have provided us with valuable data that allowed optimization of the conductor layout resulting in higher irreversible load limits under transverse compression.

The tests performed on CORC® samples containing solid stainless steel anvils showed a clear effect of the gap spacing between tapes on the irreversible load limit. Larger gaps of 1 mm resulted in irreversible degradation of I_c at lower loads, compared to samples that contained smaller gaps of 0.5 mm, or no gaps at all. This behavior was expected, because tapes in CORC® conductors are wound into multiple layers with opposite winding direction, and tapes are not mechanically supported at locations where they cross such gaps. The tapes will thus likely be bent into the gaps when transverse compressive load is applied. The gaps between tapes are required for cables that need to be bent, and therefore it is unfortunately not possible to wind the tapes without any gaps between them. Careful optimization to minimize the gap spacing thus needs to be performed, taking the required bending radius of the CORC® conductor into account.

The results also showed that the thickness of the copper plating on the tapes in the CORC® conductor has an effect on the degradation of the tape I_c under transverse load. CORC® conductors containing tapes with thicker layers of copper plating had a lower irreversible load limit. Similar results were obtained by researchers at the University of Twente, who subjected individual tapes that contained copper layers of different thicknesses to transverse compressive load [8]. It was concluded that the in-plane plastic deformation of the soft copper layer under transverse compressive load would be transformed to the REBCO layer, resulting in its strain state to exceed the irreversible strain limit of about 0.6%. This effect was found to be more pronounced with increasing thickness of the copper layer, similar to what was measured with CORC® conductors under transverse compression.

The effect of transverse compressive load on the performance of production CORC® cables and wires containing solid copper formers did not depend on the thickness of the substrate from which the conductors were wound. On the other hand, the size of the former onto which the tapes were wound, in combination with the substrate thickness of the tapes, did have a pronounced effect on the CORC® conductor performance under transverse compressive load. Figure 15 compares the I_c dependence on transverse compressive load of a number of

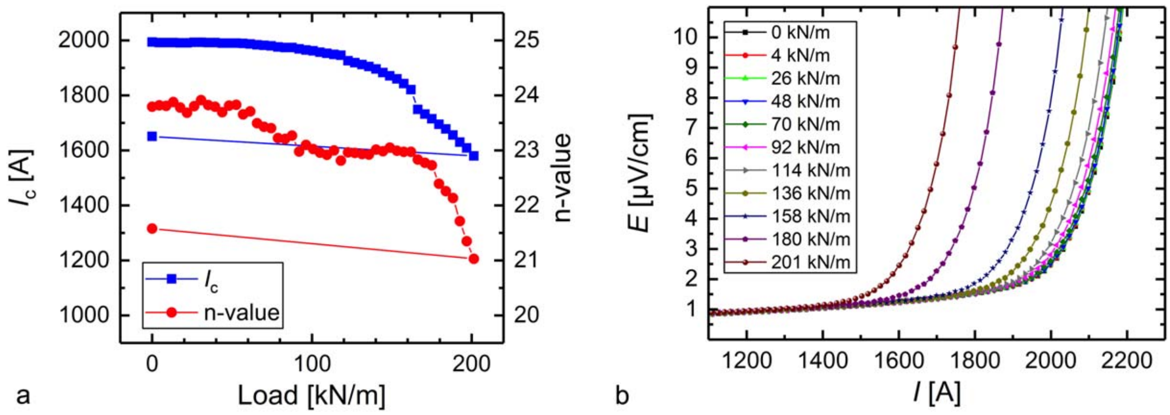

Figure 14. (a) Dependence of I_c and n-value on transverse compressive load of a CORC® wire with 2.55 mm former (CORC®-W1), measured at 76 K. (b) E–I curves of CORC®-W1 at 76 K at different transverse compressive loads.

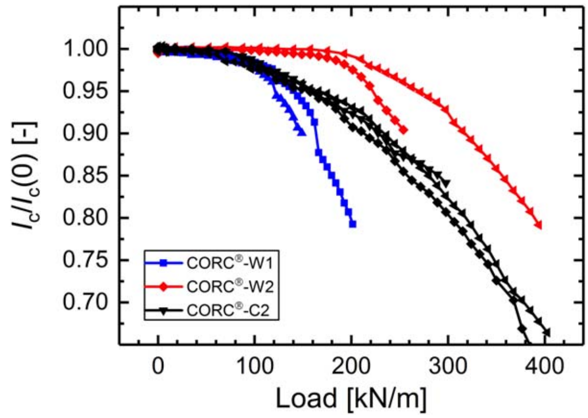

Figure 15. Dependence of the critical current of CORC® wires with 2.55 mm (CORC®-W1) and 3.2 mm formers (CORC®-W2) on transverse compressive load, measured at 76 K. Also included are CORC® cables with 4.92 mm formers (CORC®-C2). All samples shown have gap spacing between tapes of 0.3–0.4 mm.

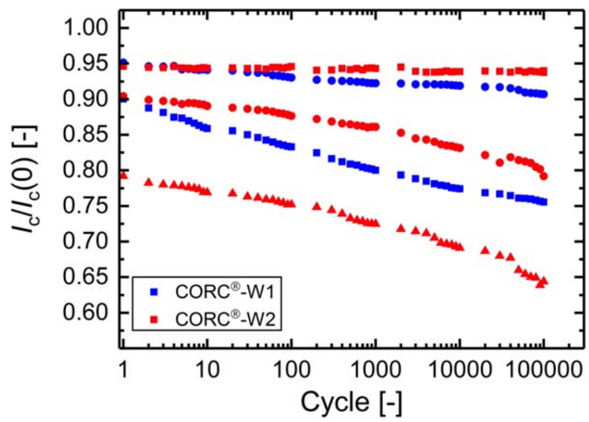

Figure 16. Normalized I_c of samples CORC®-W1 and CORC®-W2 as a function of transverse compressive load cycles, measured at 76 K. The critical current is normalized to the sample I_c before load was applied.

CORC® wires and CORC® cables containing different former sizes, and thus different initial in-plane strain states of the superconducting film in the inner tape layer. The CORC® wire with the smallest former (CORC®-W1) in which the REBCO layer of the inner tapes experience a winding strain of −1.16%, which is very close to the irreversible limit of −1.25%, had the lowest irreversible load limit. The irreversible load limit of the CORC® wires with 3.2 mm former and −0.93% strain in the tapes of the inner layer (CORC®-W2) was almost twice that of the CORC® wires with 2.55 mm formers. The irreversible load limit of CORC® cables with 4.92 mm former and −1% strain (CORC®-C2), was between that of the two types of CORC® wire.

The initial strain state of the REBCO film in the inner layers, which is determined by the former size in combination with the substrate thickness of the tapes, thus has an important impact on the irreversible load limit of CORC® cables and wires under transverse compression. The compression is expected to deform the former, elastically at low loads and plastically at higher loads, thereby reducing the bending radius of the tapes that are wound around the former. The tape I_c will degrade irreversibly as soon as the deformation of the former causes the maximum in-plane strain of the REBCO film in the inner layers to exceed the irreversible limit. The use of larger formers such as done in sample CORC®-W2, and potentially also stronger formers, would increase the irreversible load limit of the CORC® conductor under transverse compression.

The determination of the transverse compressive stress that CORC® cables and wires experience in large magnets requires extensive finite element modeling to take into account the elastic and plastic deformation of the conductor as a function of load. This is especially complex for bundles of CORC® conductors in for instance CICC in which the contact area between cables and the forces transmitted by neighboring cables need to be taken into account. The results outlined in this paper provide us with an initial estimate whether the irreversible stress limit might be exceeded in relatively simple winding configurations in which for instance a single CORC® cable or wire is located within a rectangular channel of a jacket. When the CORC® cable is operated at a current of 13 kA in a background field of 12 T, which corresponds to almost 80 kA in a 6-around-1 CICC, the maximum transverse compressive load experienced by the CORC® conductor would be 156 kN m^{-1}. This load corresponds to about 75% of the critical load of CORC® cable CORC®-C1 and about

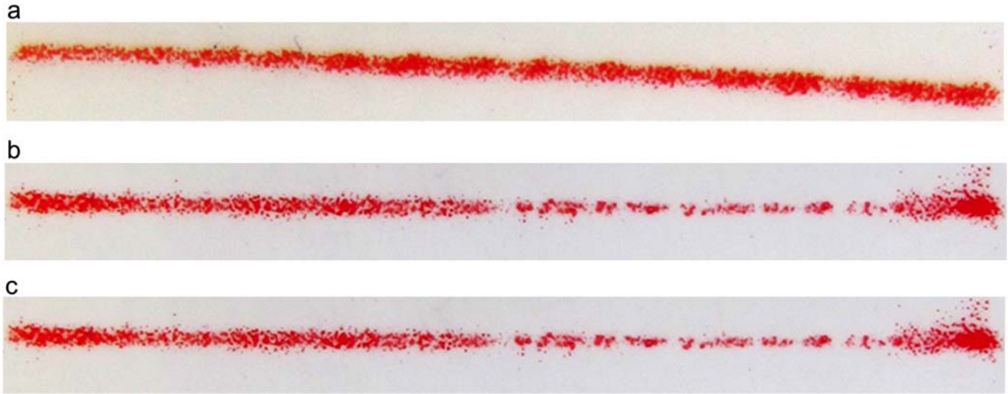

Figure 17. Contact area between the bottom anvil and the CORC® cable and wires at a load of 200 kN mm^{-1} applied at 76 K. (a) CORC® wire with 2.55 mm former (CORC®-W1), (b) CORC® wire with 3.2 mm former (CORC®-W2) and (c) CORC® cable with 4.92 mm former (CORC®-C1).

Table 5. Estimated irreversible stress limit in MPa of production CORC® cables and wires, calculated from the contact area as determined with pressure sensitive film at a load of 200 kN m^{-1}.

I_c decrease	CORC®-C1	CORC®-C2	CORC®-W1	CORC®-W2
3%	230	138	99	241
5%	283	178	115	270
10%	378	251	141	316

72% of the critical load of CORC® wire CORC®-W2 (table 4), while the transverse load exceeds the critical loads of samples CORC®-C2 and CORC®-W1. Optimization of CORC® cables with respect to gap spacing and former size is thus an important design parameter for CORC®-CICC. It is important to point out that optimized CORC® wires, such as CORC®-W2, could withstand the high transverse compressive loads, but will not be able to reach an operating current of 13 kA at 12 T, because their I_c is currently limited to less than 7.5 kA at that field.

A very important result of the measurements of CORC® cables and wires under compressive load cycling was that the additional degradation of I_c after 100 000 cycles performed in liquid nitrogen never exceeded the initial I_c degradation caused by the peak transverse load. Transverse compressive load cycling had no significant effect on I_c of CORC® cables and on CORC® wires containing 3.2 mm formers at peak loads that resulted in an initial I_c degradation of no more than 5%. Only once the peak load was increased and the I_c degraded by 10% for CORC® wires with 3.2 mm thick formers, or 20% for CORC® cables, did significant additional I_c degradation occur after 100 000 load cycles. CORC® wires containing 2.55 mm thick formers showed a much more pronounced decrease in I_c with transverse compressive load cycling, although I_c only degraded by an additional 3% after 100 000 load cycles at a peak load that resulted in an initial I_c degradation of 5%. Most applications would be designed with the applied compressive loads during operation being below the conductor irreversible load limit. These applications would not experience significant performance degradation after a high number of load cycles.

The initial strain state of the REBCO layer of the tapes in the inner layers of the CORC® cables or wires is the main mechanism driving the reduction in I_c under transverse compressive load cycling. Cracks that form in the REBCO layer when the irreversible strain limit under axial compression is exceeded only grow at a relatively low rate with load cycles. The degradation is much less severe with compressive load cycles compared to single REBCO tapes [35, 36] and CORC® wires [37] under axial tensile load cycling, suggesting that the crack growth rates are very different between the two modes of stress cycling.

5. Conclusions

The effect of transverse compressive load on the critical current of CORC® cables and wires has been measured during monotonic loading and load cycling to 100 000 cycles in liquid nitrogen by applying transverse compressive loads with two flat stainless steel anvils onto the round conductors. The irreversible load limit at which the critical current decreased irreversibly was determined and its dependence on cabling parameters was investigated, allowing for conductor optimization that would further increase the irreversible load limit.

The gap spacing between tapes in CORC® conductors showed a significant effect on the irreversible load limit of the critical current. Larger gap spacing resulted in a reduction of the load at which the critical current started to degrade, compared to samples with narrower gap spacing, which is likely due to the lack of support against transverse compression of the tapes crossing these gaps. The thickness of the copper plating on the tapes in the CORC® conductor also showed a significant effect, with a higher copper thickness causing a decrease in irreversible load limit. In-plane deformation of the copper layer is likely transferred to the underlying REBCO layer, causing it to degrade at lower loads, similar to what has been observed in single tapes under transverse compression.

The thickness of the former in CORC® cables and wires has a large effect on the irreversible load limit under transverse compression. Deformation of the former due to loading causes the maximum in-plane strain of the REBCO film of the tapes in the inner layer to increase to higher compression. Irreversible degradation in the tapes occurs when the maximum in-plane strain of the REBCO films exceeds −1.25%. CORC® cables and wires in which the in-plane strain of the REBCO layer in the tapes of the inner layer is close to this critical value after winding had a much lower irreversible load limit under transverse compression compared to samples in which the in-plane strain in the REBCO layers was significantly less than the critical value.

CORC® cables and wires were subjected to transverse compressive load cycling while in liquid nitrogen. Samples were cycled up to 100 000 cycles to various maximum loads that corresponded to a predetermined initial decrease in critical current. Transverse load cycling did not cause significant additional degradation in critical current when the peak load caused the critical current to decrease by no more than 5%, and the former size in the sample resulted in a maximum in-plane strain of the REBCO film in the inner tape layers to be less than about −1%. Load cycling to 100 000 cycles did cause significant additional degradation in critical current of between 5% and 15% when the peak load caused initial degradation in the order of 10%–20%, independent of former size.

The results outlined in this paper are very promising for application of CORC® cables and wires in high-field magnets in which the conductors experience significant transverse compressive loads. The critical current of the conductor is expected to not degrade significantly, even after 100 000 load cycles, as long as the transverse load on the conductor does not exceed the irreversible load limit by a large amount, which is an important design parameter for high-field magnets. CORC® cable and wire optimization, such as limiting the initial strain states of the tapes by selecting larger formers, by using harder formers and by further reducing the gap spacing between tapes, likely allows for even higher transverse compressive loads to be applied.

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