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Enhancement of the transverse stress tolerance of *RE*BCO Roebel cables by epoxy impregnation

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Abstract. *RE*BCO Roebel cables are considered for application in high-temperature superconducting (HTS) inserts for accelerator magnets, because of their fully transposed geometry, high engineering current density and adequate bending tolerance. In these magnets the cables experience Lorentz forces, leading to transverse stresses up to 100-150 MPa. Previous reports have shown bare Roebel cables to degrade under such high stresses, so that additional reinforcement is required. In this work, two identical Roebel cables are vacuum impregnated with a mixture of epoxy and fused silica, in order to improve their tolerance to transverse stress. After impregnation, the critical current of the cables is measured under transverse mechanical loading at $T = 4.2$ K, $B_{\perp} = 10.5$ T. A reference cable without impregnation is tested as well. Pressures up to 350 MPa are applied to a short (30 mm) section of each cable. No degradation was observed for pressures up to 250 MPa and 170 MPa in the two impregnated cables. The critical current of the non-impregnated cable, in contrast, started to decrease at stresses as low as 40 MPa.

Keywords: *RE*BCO Roebel cable, epoxy impregnation, transverse stress

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1. Introduction

The development of future accelerator magnets aims for magnetic fields up to 20 T [1]. At these fields, the current density of Nb_3Sn cables is prohibitively low, and HTS insert magnets are needed. CERN has designed [2, 3] and will build a HTS demonstration magnet, as part of the collaborative project EuCARD-2 [4]. The aim is to generate a 5 T field standalone and 17 T in 13 T background field. The design focuses on a so-called "aligned block" magnet wound with *RE*BCO Roebel cables. In an aligned block coil, the wide surface of the *RE*BCO tape is aligned parallel to the magnetic field to take advantage of the I_c anisotropy. The Lorentz force is thus largely perpendicular to the wide face of the cable. Calculations predict the stress in the demonstrator coil to be up to 110 MPa when operated in a 13 T background field [2]. Therefore, a careful analysis of the effect of such stress levels on Roebel cables must be made.

Transverse pressure tests on *RE*BCO *tapes* show that they typically tolerate transverse stresses of at least 300 MPa [5, 6, 7, 8]. In a cable configuration, however, the force is not always homogeneously distributed, leading to local stress concentrations. J. Fleiter et al. showed that the effective stress bearing section of a Roebel cable made at Karlsruhe Institute of Technology (KIT) on a flat anvil is only 23% [9]. This means that local peak stresses are at least four times higher than the average pressure. D. Uglietti et al. pressed Roebel cables with insulated strands to transverse stresses up to 70 MPa [7]. Degradation was observed at pressure levels as low as 10 MPa and the I_c value of most strands degraded by more than 20% at 40 MPa. Recently, G. Kirby et al. subjected a stainless steel Roebel dummy cable to 150 MPa transverse pressure, resulting in severe plastic deformation [2]. These results indicate large stress concentrations and confirm the need to reinforce the cable.

A common reinforcement method used with resistive as well as superconducting coils is impregnation with epoxy resin. For *RE*BCO coated conductors (CC), however, epoxy impregnation leads to complications. An impregnated *RE*BCO pancake coil from T. Takematsu et al. showed degradation of the critical current [10]. After visual inspection, a separation of the layers within the individual conductor (delamination) was observed. This type of damage results from a mismatch in thermal expansion between the conductor and the epoxy: When epoxy is cooled down from room temperature to liquid helium temperature (T = 4.2 K), it seeks to contract by 1.33%, while the *RE*BCO tape contracts by only 0.25% [11]. This mismatch leads to thermal stresses which can delaminate the conductor.

Several different methods to reduce such thermal stresses on the conductor have been proposed and were tested successfully. Epoxy resin bonds firmly to metals. Impregnation materials with a lower bonding strength cannot build up as much tensile stress on the surface. T. Takematsu et al. impregnated a *RE*BCO pancake coil with paraffin, which has a negligibly small bonding strength [10]. The critical current of this coil was not affected by the impregnation. M. Matsumoto et al. achieved a field of 24 T with *RE*BCO pancake coils impregnated using this method. However, impregnation with paraffin might not be suitable for Roebel cables because it may lack the mechanical strength needed to reduce stress concentrations. K. Mizuno et al. proposed impregnation of *RE*BCO pancake coils with cyanoacrylate resin [12]. They showed that this resin has a bonding strength significantly lower than epoxy, and demonstrated that a coil can be impregnated with this material without degradation of the critical current. Tensile stresses can also be reduced by introducing a weak mechanical barrier between the conductor and the epoxy resin. T. Trociewitz et al. did this by inserting the *RE*BCO coated conductor in a polyester heat-shrink tube before coil winding and impregnation [13]. A layer-wound coil produced with this method generated a record magnetic field of 35.4 T. A similar concept was used by Y. Yanagisawa et al., who added a layer of polyimide to the *RE*BCO conductor by electrodeposition [14]. Also this method was successful in preventing degradation due to impregnation. A different approach is to add filler particles with low thermal expansion to the epoxy resin. C. Barth et al. impregnated a Roebel cable with a 1:1 mixture of epoxy and fused silica without critical current degradation at $T = 77$ K and in self-field [11].

In this paper, we report on the transverse strength of short Roebel cables impregnated with such an epoxy-silica mixture. This impregnation method was chosen because of the proven mechanical properties of epoxy and because of its easy application to the cable structure using vacuum impregnation. Adding polyester or polyimide barriers to the strands or using resins other than epoxy may remain interesting options for future investigation. For comparison, a cable without impregnation was tested as well. The cables are subjected to transverse pressures up to 357 MPa, at a temperature of 4.2 K and in an applied perpendicular magnetic field of 10.5 T.

2. Experimental details

This section describes the preparation of Roebel cables for the transverse cable press at Twente University. In this facility, forces up to 250 kN can be applied using an electromechanical press. The sample current is generated by a 50 kA superconducting transformer. Both transformer and press were built earlier and used in transverse stress tests of LTS Rutherford cables. More details about this system can be found in [15].

Three identical 75 cm long 10-strand cables were prepared from *RE*BCO tape from SuperPower (SCS12050-AP). A 12 mm wide tape with a 50 μm Hastelloy substrate, 2 μm of silver and 40 μm of copper stabilization was used. The tape was punched into the meandering Roebel pattern with a transposition length of 126 mm [16]. In this process, the current carrying width of the tape is reduced from 12 to 5.5 mm. Before cable assembly, the critical current of the separate strands was measured in liquid nitrogen ($T = 77$ K) and magnetic self-field. The strands had an average I_c value of 172 ± 2 A. This corresponds to a critical surface current density of 31 A/mm-width compared to 33 A/mm-width before punching. The average *n*-value was 29 ± 1.

After assembly, the cable was mounted on a U-shaped sample holder, suitable for measurements inside a solenoid magnet (figure 1). The corners of the sample holder have a radius of 20 mm; the horizontal section in between the bends is 26 mm long. The *RE*BCO coated side of all strands are facing the sample holder, since this side will be soldered to the current leads. The cable is electrically insulated from the stainless steel sample holder with a layer of polyimide tape. A block of Teflon is pushed against the flat "bottom" of the U-shape to create a flat epoxy surface and to prevent epoxy from flowing out during the curing process. Three pairs of voltage taps are soldered to the cable over a length of one transposition length including the bottom sample section.

Two of three cables (cable 1 and 2) were then vacuum impregnated with a mixture of epoxy and fused silica powder. The epoxy resin Araldite CY5538 with hardener HY5571 was supplied by Huntsman corporation, and it is mixed with Silbond FW600 EST fused silica powder with a median particle size of 4 μm. The mixing ratio of resin, hardener and silica powder is 1:1:2 by weight. To remove trapped gas bubbles, the mixture is evacuated to 1-2 mbar for 30 minutes. Impregnation is done by slowly lowering the sample holder into an epoxy bath at low pressure (3 mbar), and then releasing the vacuum. During impregnation, the epoxy bath as well as the sample holder are heated to 80 °C to reduce viscosity. The sample is retracted from the bath and the resin is cured at 100 °C for 24 hours.

After curing the Teflon block is removed. An impregnated cable in this state is shown in figure 2a. Next, two layers of glass fibre ribbon wetted with Stycast 2850FT/23LV epoxy are added to the cable. The 30 mm long pressure anvil is positioned on top of the glass ribbons. The surface of the anvil is aligned at a distance of 1.5 mm from the sample holder using two positioning plates (figure 2b), which are removed when the Stycast has hardened. The cables with the block glued in place are shown in figure 2c. The anvil is glued for two reasons: To avoid stress concentrations at the ends of the pressed section and to ensure parallelism of the anvil and the sample surface. The layer of Stycast and glass fibre between the cable and the stainless steel anvil is relatively soft, while the anvil is aligned with the sample holder. Both precautions ensure that the force is transferred homogeneously over the entire surface covered by the anvil.

A drawback of this preparation method is the possibility of a bond between the anvil and the plates that prevent sample motion under influence of the lateral Lorentz forces (figure 2a). The support plates are fixed to the sample holder and may therefore transmit part of the transverse force during the actual experiment. To minimise this complication, the sides of the pressure anvil and inner surface of the support plates were covered with Kapton tape which hardly bonds with the Stycast resin and sticks to the metal plates with a relatively weak silicone adhesive. As a verification that the lateral support plates play a negligible role in the pressure tests, the support plates were made lower for cable 2 (3 mm vs. 14 mm above the sample holder), in order to reduce the contact area with the anvil.

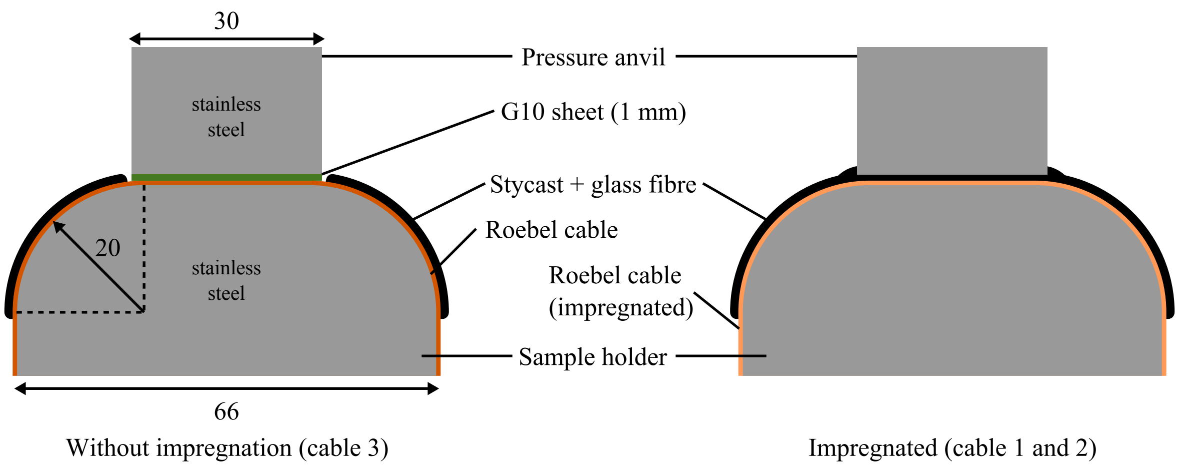
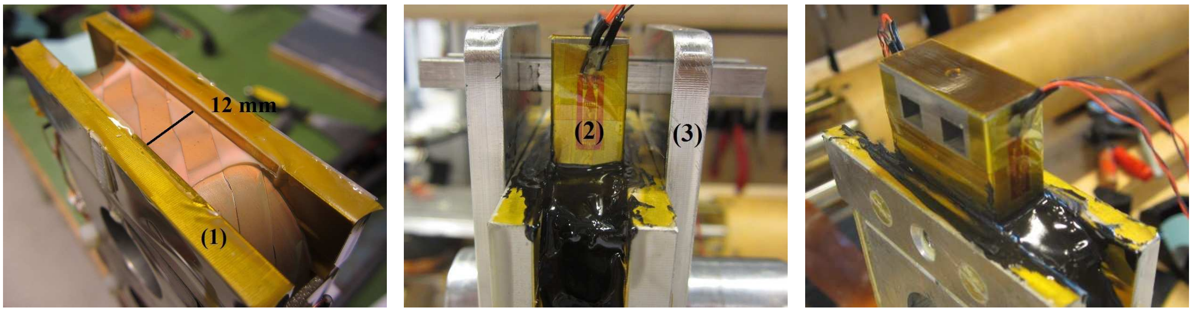


Figure 1: Cross-sectional view of the experiment for both samples with and without impregnation.

Unlike cables 1 and 2, sample 3 was not impregnated, and the pushing block was not glued to it. Instead, a 1 mm thick sheet of G10 was attached to the side of the anvil in contact with the cable. This sheet compensates for the thinner sample, and reduces stress concentrations at the ends of the pressed section, where otherwise the corners of the anvil would directly cut into the cable. This results in a fairer comparison with impregnated cables, where the anvil and the sample were separated by a 1 mm thick layer of glass fibre with Stycast. Since the cable is not impregnated, it is necessary to reinforce it against Lorentz forces in another way. Outside of the pressed section, along the corners of the U-shape, four



(a) (b) (c)

Figure 2: Cable 2 on the U-shaped sample holder. The cable is supported against the lateral Lorentz forces on both sides by side plates (1). (a) After impregnation and removal of the Teflon block. (b) The pressure anvil (2) being glued in place with Stycast epoxy. The block is aligned to the sample holder using two positioning plates (3). (c) After curing the Stycast and removal of the positioning plates.

layers of glass fibre soaked in Stycast 2850FT epoxy were added. The uncovered section of the cable is supported against Lorentz forces by applying a pressure of 10 MPa before doing any measurements.

Finally, the sample is connected to the NbTi current leads of the transformer by soldering over a length of one transposition length (126 mm) with $Sn_{97}Ag_3$ solder. A fourth pair of voltage taps is connected to the current contacts.

3. Results & discussion

All measurements were done at $T = 4.2$ K in a perpendicular applied magnetic field $B_\perp =$ 10.5 T. The initial IV curves for the three cables are shown in figure 3. In cables 1 and 3, voltage measurements on several strands did not yield useful data and are therefore not shown in the figure.

The critical current of a Roebel cable strongly depends on the orientation of the magnetic field. A voltage will therefore first appear in the cable section where the angle between the wide cable surface and the magnetic field is close to 90°. As the straight section of the cable is relatively short compared to the bends, this length is less well-defined. For determining the critical current, a straight section length of 30 mm a is used, corresponding to the length of the anvil. All possible damage due to transverse pressure will occur in this segment. Using such definition and an electric field criterion of 10^{-4} V/m, the voltage criterion becomes 3 μV.

As discussed in [17], current (re)distribution effects in short-sample measurements such as these lead to the appearance of premature voltages. Determining the critical current by

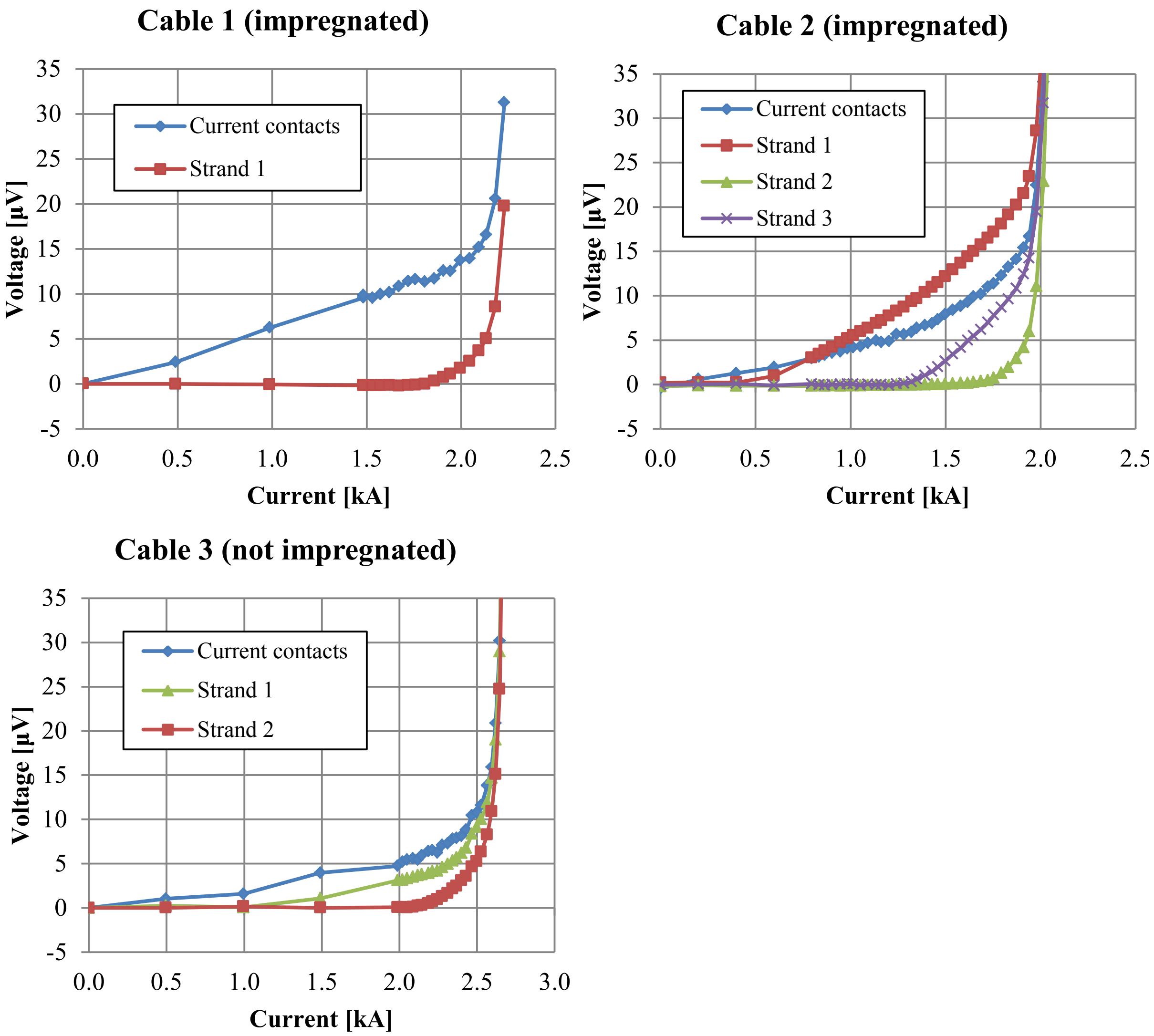


Figure 3: Initial IV curves of both cables at $T = 4.2$ K, $B_{\perp} = 10.5$ T. The voltage was measured over the current contacts and over strands including the pressed section.

interpolation at 3 µV would result in scattered values for the different voltage signals, which would not be representative for the critical current of the entire cable. For this reason, the critical current is computed by fitting a voltage-current power law only through measurements points obtained at higher currents, at which all signals converge. This method yields consistent critical currents (within 60 A) from the different voltage signals.

For the impregnated cables, the initial critical currents were 2.07 kA (cable 1) and 1.87 kA (cable 2). Cable 3, which was not impregnated, had a markedly higher critical current of 2.53 kA. This may indicate that despite the fused silica filler, epoxy impregnation still causes some damage.

However, the impregnated cables clearly are less sensitive to transverse stress. Figure

4 shows the critical currents as a function of the transverse stress. The stress is calculated dividing the measured force by the 12 mm × 30 mm area of the anvil. The critical current of cable 3 started to decrease at stress levels as low as 40 MPa. The impregnated cables on the other hand were not affected for stress levels up to 254 MPa (cable 1) and 169 MPa (cable 2). There is a rather large difference in onset of degradation between the two impregnated samples. Some deviation between different samples is to be expected, since the exact geometry of impregnated cables is hard to control. At increasing stress levels though, there is no clear difference between the strength of the two samples. This demonstrates that a possible bond to the lateral support plates did not play a large role.

To determine whether the I_c degradation is reversible, several measurements were repeated after reducing the stress level. The critical current did not recover, so that the degradation is indeed irreversible. The total critical current degradation observed during the experiment was 27% at 327 MPa for cable 1, 4.5% at 357 MPa for cable 2 and 60% at 198 MPa for cable 3.

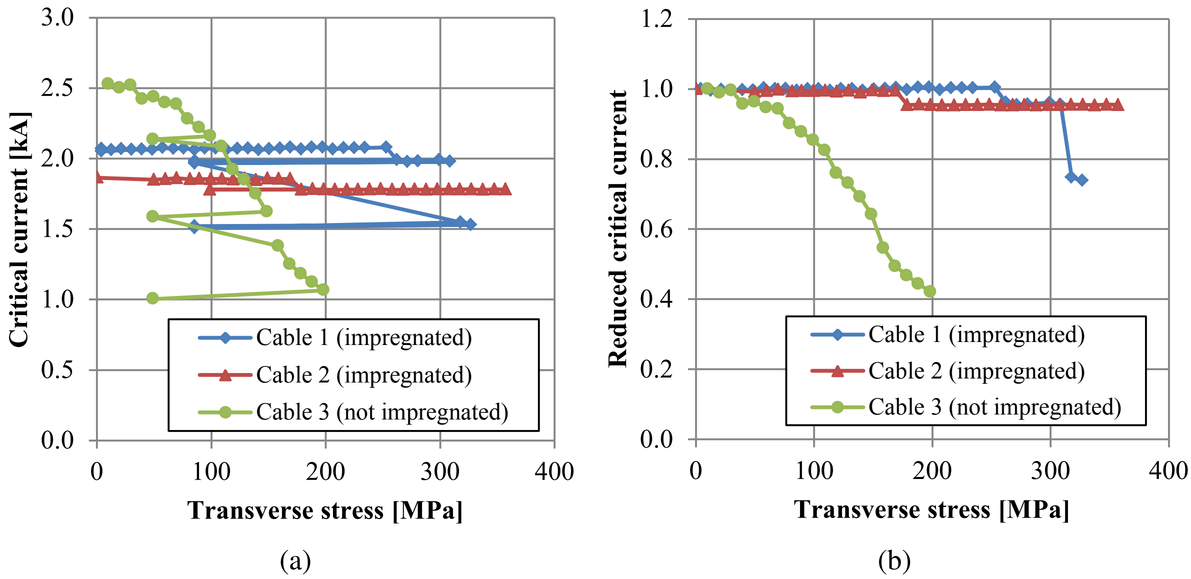


Figure 4: (a) The critical current as a function of transverse stress. The lines connect the data points in chronological order. (b) Critical current normalized to the initial value for each sample.

The measurements show that the impregnated cables withstand transverse pressures up to at least 169 MPa. This is a first confirmation that impregnated Roebel cables can withstand stress levels similar to those expected in accelerator magnets. A remaining point of discussion is that the pressed section (30 mm) is shorter than the transposition length (126 mm). In the pressed section, only four out of the ten strands have a cross-over from one side of the cable to the other, which is the location where stress concentrations are expected to occur [7, 9]. As a result, the measured degradation might be lower than in the case of a longer pressure anvil. Arguably, however, this will not affect the point of onset of the degradation, as it does not influence the magnitude of the stress concentrations at each cross-over.

A cross-section was made of cable 1 to check the impregnation quality and the alignment of the anvil with the sample holder, and to inspect the cable for visible damage. The cable and the anvil to which it was glued were cast in epoxy. Material was then removed by sanding until the pressed section was visible. The surface was polished and examined under an optical microscope. Figure 5 shows an overview of such cross-section. The impregnation was successful: the silica-epoxy mixture filled the structure throughout and there are no bubbles visible. In the Stycast layer there are some empty spaces because no vacuum was used. The thickness of the whole cable-Stycast structure is close to 1.45 mm over the entire width. Including the 50 μm Kapton insulation on the sample holder, the distance between the sample holder and pressure anvil was 1.50 mm, as designed. Note that the impregnated cable by itself is thicker on the left than on the right, presumably because the Teflon block was not exactly straight during impregnation. The difference in height is corrected for by glueing the pressure anvil using the positioning plates. The only visible damage is delamination of the tape closest to the sample holder, clearly visible in figure 6. However, it is unclear whether this delamination is a result of thermal stresses or it occurred when the cable was removed from the sample holder, since for this some tensile force was needed.

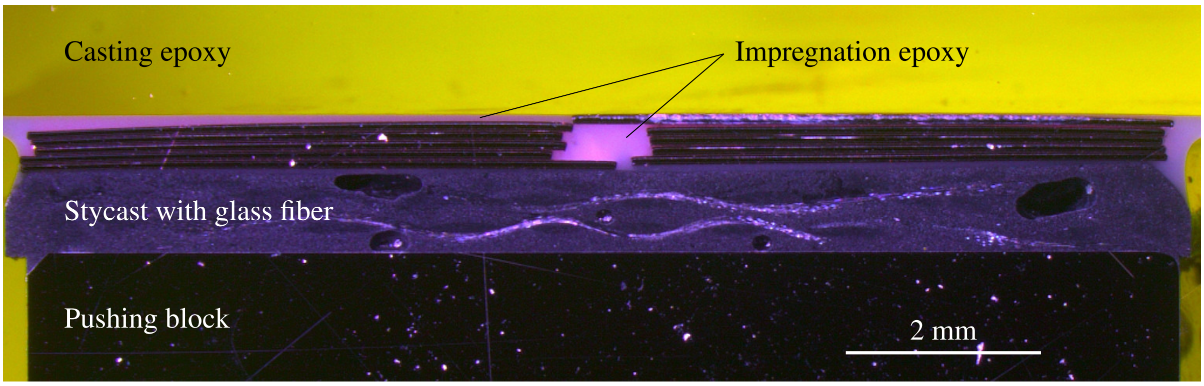


Figure 5: Overview of the cross-section of sample 1. The upper surface was placed on the sample holder. From top to bottom one can distinguish the casting epoxy; the Roebel cable; the glass-reinforced Stycast layer; and the pressure anvil.

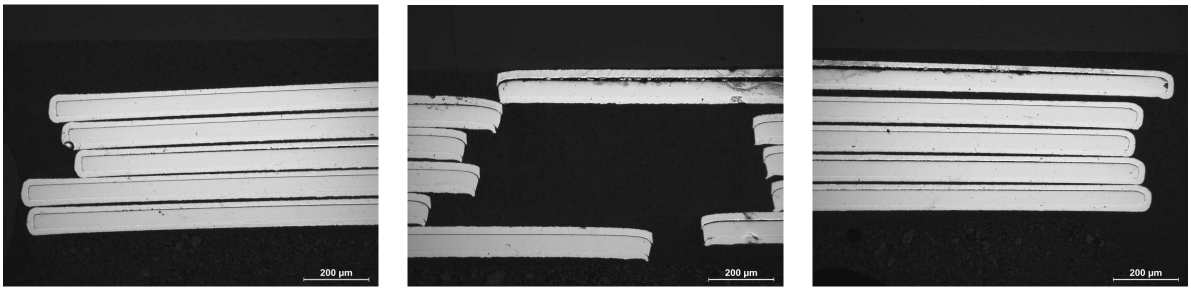


Figure 6: Close-ups of the left end, the central hole and the right end. Delamination is visible in the upper right tape. The *RE*BCO layers are on the top side of each tape.

A marked increase was observed in the transverse stress tolerance of the Roebel cables after impregnation, constituting an important first step in demonstrating their use in accelerator magnets. In these experiments pressure was applied over relatively short lengths of just two impregnated samples, resulting in somewhat different stress-critical current characteristics. Within the EuCARD-2 collaboration, a larger number of samples with different layout, tape material and impregnation method will be tested to determine the factors that influence transverse stress tolerance in more detail. Additionally, experiments with longer sample lengths are planned in a facility such as FRESCA [9, 18] to reduce the effect of local variations in the geometry. Also possible effects of cyclic loading, closely mimicking the mechanical conditions in repeatedly ramped magnet windings, remain to be addressed.

4. Conclusion

Two *RE*BCO Roebel cables (cable 1 and 2) were vacuum impregnated with a mixture of epoxy resin and fused silica powder. The critical current of the impregnated cables as well as a reference cable that was not impregnated (cable 3) was measured as function of transverse pressure at $T = 4.2$ K, $B_{\perp} = 10.5$ T. The initial critical current was 2.07 kA for cable 1, 1.87 kA for cable 2 and 2.54 kA for cable 3. The I_c reduction of the impregnated samples compared to the cable that was not impregnated may indicate damage due to impregnation. Proper impregnation methods and materials for *RE*BCO Roebel cables therefore remain an issues that need further work. Pressure levels up to 357 MPa were applied over a length of 30 mm. No degradation was observed for pressures up to 253 MPa for cable 1 and up to 169 MPa for cable 2. In contrast, the critical current of cable 3 started to decrease already at stress levels as low as 40 MPa. These results are a first confirmation that impregnated Roebel cables can withstand transverse pressures well above the 110 MPa expected in accelerator magnets.

Acknowledgements

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