Degradation Free Vacuum Epoxy Impregnated short REBCO Undulator Magnets

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Abstract. The source of high-brilliance, hard x-ray radiation in light sources and free electron lasers are undulator insertion devices. Recently, REBCO-based superconductors have been demonstrated to be a potential candidate to enhance the performance of the undulator insertion devices. Epoxy impregnation remained as one of the steps which is crucial to fully realize this technology. Epoxy impregnation of magnets is required because it prevents the motion of the wire and provides conduction cooling to the winding layers. Up until now, most of the impregnated REBCO coils/magnets showed some degree of degradation after cold cycles. We developed a vacuum impregnation technique that does not degrade the performance of the short REBCO prototype undulator magnets after cold cycles. The results showed that in order to prevent degradation, a bumper layer between the magnet winding stacks and the epoxy/powder mixture is required. Microstructure images of vacuum impregnated coil packs showed homogenously-spaced REBCO winding layers and very thin epoxy fillings between the layers, which is important for the overall performance of the device.

1. Introduction

REBCO (RE = rare earth, barium copper oxide) coated conductors (CCs) are becoming a promising candidate to enhance the performance of an undulator’s magnetic structure [1-3]. The main advantage of using REBCO CCs in undulator structures, compared to its counterparts, is that it does not require a high temperature reaction process (Nb\textsubscript{3}Sn \textasciitilde650 \degree C for \textasciitilde48 hrs). Typically, the wire is reacted after winding the magnet due to its brittle nature in superconducting phase. This high temperature reaction process poses additional magnet design challenges. In contrast, REBCO CCs are used as received without any post-processing. Avoiding this extreme reaction temperature is a significant convenience considering the possible deformation of the stringent tolerances required by the field quality. Most of the technical questions regarding the winding, insulating, and measuring of the undulator magnet have been addressed in our previous works [1-3]. However, the epoxy impregnation of the REBCO magnet systems remains a challenge. Epoxy impregnation is especially necessary for conduction-cooled magnet systems such as undulators. It serves as a mechanical support structure, secures the tape conductor and impedes the conductor motion that could, otherwise, result in a catastrophic failure. While the epoxy impregnated magnets are mechanically more robust and uniformly-cooled compared to non-epoxy...
impregnated magnets, it has been reported that most of the epoxied coils or magnets demonstrated some degree of degradation [4-6]. This behaviour is mainly attributed to the weak c-axis or transverse direction delamination strength, which is possibly a result of in-plane (ab plane oriented) defect structures [7]. Thermal stresses potentially originating from the different thermal expansion coefficients among different components in a magnet system could trigger this type of delamination. We also recently found that cracks in the epoxy is a major contributor to the performance degradation [6] in REBCO coils. Dry-wound or soft impregnated coils, due to the weak bounding between soft impregnation material and REBCO tape, did not show any degradation, suggesting that the epoxy component has to be compatible with the REBCO tape as the epoxy is strongly bound to the REBCO tape. Typically, epoxy resins have a much larger thermal expansion coefficient than REBCO tapes, and have to be altered to reduce that difference. In the past, we have added different types of powders to make the epoxy component more compatible with the REBCO tape. Regardless of the powder type and size, all the impregnated coils have been degraded [6]. Figure 1 presents the percentage of the critical current, Ic, degradation with respect to different powder types and sizes along with respective weight percentage of the powder content. Epoxy with diamond and alumina fillers offer the least performance degradation although alumina degradation is slightly higher. n-value degradations were also provided in the same figure. We also found that reducing the epoxy/powder mixture thickness can also eliminate performance degradation since the impact of the thin epoxy to the REBCO tape is not as severe as the thick epoxy. Keeping the epoxy thickness under control is very difficult in an intricate undulator magnet geometry (Figure 3 and 7). A different procedure is therefore required to prevent the degradation. We developed a vacuum impregnation technique that does not degrade the performance of the REBCO undulator prototype magnets after cold cycles. We investigated wet-wound and vacuum impregnated short prototype undulator magnets. The results showed that the most effective way of preventing the degradation is that of using a bumper layer between the magnet winding stacks and the epoxy. Microstructure images of vacuum impregnated coil packs showed uniformly spaced REBCO winding layers and very thin epoxy fillings between the layers, which is important for the overall performance of the device.

2. Experimental

2.1. Conductor and impregnation details

The REBCO coated conductors used in this work were fabricated by SuperPower Inc (SP). The conductor architecture consists of buffer layers of alumina, yttria, MgO, and LaMnO3 (LMO), deposited on a non-magnetic electro-polished Hastelloy substrate followed by deposition of ~1 µm thick REBCO by metal organic chemical vapour deposition (MOCVD). The superconducting film was capped by a ~2 µm annealed Ag stabilizer and a 20 µm electroplated copper on both sides. We used Araldite epoxy and Aradur hardener with a mixing ratio of 10:1 in the epoxy impregnation of the prototype undulator magnets. The advantage of using araldite epoxy systems has been discussed in [6]. In order to reduce the CTE, we mixed the epoxy with diamond and Al2O3 powders. The bare epoxy has extremely low
fracture toughness and it is susceptible to crack formation during thermal cycles. After mixing the epoxy and powders, the mixture was degassed in a vacuum and the air were removed as much as possible. The magnets were then impregnated after adding the Aradur hardener into the mixture.

Table 1. Details of the short prototype undulator magnets prepared for epoxy evaluations.

| Magnet   | Number of racetrack coils | Wet-wound (WW) or vacuum impregnated (VI) | Number of layers in a coil | Powder, weight ratio [%], size [µm] |
|----------|---------------------------|-------------------------------------------|---------------------------|-------------------------------------|
| Magnet 1 | 1                         | WW                                        | 25                        | Diamond, 40, 0.1                    |
| Magnet 2 | 3                         | VI                                        | 30                        | Diamond, 20, 0.1                    |
| Magnet 3 | 3                         | VI                                        | 50                        | Al₂O₃, 15, 0.08                     |

2.2. Prototype undulator windings and epoxying

We fabricated three prototype undulator magnets – two for the vacuum impregnation and one for the wet-winding (see Table 1 for details). Prototype undulator magnet cores for the vacuum impregnation were 3D printed and the wet-wound magnet core was fabricated from a low carbon steel (LCS) (Figure 2b). The width and depth of the winding grooves are 4 and 6 mm, respectively. We use a special scheme to continuously wind the magnets, and details of this are provided in [2]. The magnet structures have racetrack coils with alternating current directions (Figure 7b), thus creating a periodic on-axis magnetic field pattern that is necessary for producing x-ray beam. For winding the magnets, a home-made winder was used. The tape motion and tension were provided by a stepper and a torque motor, respectively. Intermediate spools, as shown in Figure 2a, are inserted into the winding system during the wet winding to immerse the tape into the epoxy/powder mixture. Excess epoxy is removed by spring loaded metal plates. Higher filler ratios can be afforded by this method and the Araldite epoxy mixed with 40 wt. % diamond powders to wet wind the magnets. A picture of the wet-wound coil pack has been provided in Figure 2b.

![Figure 2. Wet winding schematic (a) and the wet-wound magnet (b). The excess epoxy is removed by the metal plates. The load on the plates are adjusted via springs.](image)

Vacuum impregnation steps are presented in Figure 3. First, the prototype undulator magnet is dry-wound (Figure 3a) and characterized at 77 K. Since the epoxy thickness is not easily controllable in the vacuum impregnation due to the complex shape of the undulator magnet, the magnet winding stacks were decoupled by locating a bumper layer between the epoxy mixture and the REBCO layers (Figure 3b) from the winding stack before the vacuum impregnation. The bumper layer used was a dummy sacrificial REBCO tape in the first prototype and sticky silver tapes in the second prototype. The sticky Ag tape was chosen in the second one because it was easier to apply. This bumper layer (sacrificial REBCO tape or sticky Ag tape) is used to prevent the damage on the REBCO tape by decoupling them from the epoxy. Any kind of crack propagation is absorbed by this outermost bumper layer as illustrated in Figure 3b and the magnet windings are protected. The winding layers also supported by fiberglass sleeves which acts as an extra reinforcement material. An epoxy tight 3D-printed mold was used during
the vacuum impregnation (Figure 3c). The pictures of the prototype undulator after disassembling the mold have been presented in Figure 3d. The current leads are visible in the figure. The electron beam side of the undulator magnet has been shown in Figure 3e, revealing the winding stacks that are at the same level with the plastic poles on this side.

2.3. Measurements
A conventional four-probe method was used for the electrical characterization of the magnets. The magnet voltage was recorded at a 24-bit Dynamic Signal Analyser (DSA) module in a PXI chassis. A calibrated current transducer was used to measure the current. All magnets were slowly cooled (~4 hours) and tested at liquid nitrogen temperature (~77K). In addition, repetitive fast cooling cycles were performed. In these fast cooling tests, the magnets were essentially dunked into LN₂ very quickly, followed by a performance measurement.

![Figure 3](image)

Figure 3. Prototype undulator magnet with a bumper layer (a), a 3D sketch of the bumper layer located between winding stacks and the epoxy/diamond mixture (b) the 3D printed vacuum impregnation mold (c). Magnet after vacuum impregnation and disassembling it from the mold (d) and electron beam side showing the magnet stacks (e).

3. Results and Discussions
Each prototype magnet was tested before and after application of the epoxy through wet-winding or vacuum impregnation, and had its performance evaluated. In Figures 4, 5 and 6, the markers are the measurements and the solid lines are fits to a power–law, \( V = V_c (I/I_c)^n \), where \( V_c \) is the critical voltage. The power–law fits describe our measurements well. In the interest of simplicity, because the inductive voltage is not the interest here, it was subtracted from the total voltage. This subtraction is evident from Figure 6, as the voltage starts from a negative value (~0.25 mV). Each magnet was wound with a single long tape; however, we used different tapes from different batches to wind different prototypes and, therefore, there are no \( I_c \) correlations among the prototype magnets. For example, the \( I_c \) of the wet-wound magnet is low even though it has the lowest number of winding layers compared to other magnets because the received \( I_c \) of the tape is also low.

3.1. Wet-winding
The thickness of the epoxy can be kept relatively small in the wet-winding with the fixture described (Figure 2a). Two coil packs were first dry-wound with 25 and 5 layers with a transition piece used to continuously wind the magnet. Current and voltage (IV) curves of the dry-wound coil were first measured at 77 K, and the magnet was unwound onto a spool. Then the same unwound tape was used to wet-wind the magnet. After a slow cool down, the \( I_c \) was measured. Exactly the same \( I_c \), 37.6 A at 1µV/cm criteria value was obtained before and after the wet-winding indicating that there is no
performance degradation (Figure 4). In Figure 4, ‘BWW’ stands for ‘before wet-winding’ and ‘AWW’ stands for ‘after wet-winding.’ Also in the figure, ‘SC’ and ‘FC’ stand for slow-cooled and fast-cooled, respectively. Slow cooling denotes that each coil was first exposed to cold nitrogen gas and then slowly immersed into the LN$_2$ bath. The cool down time for each coil was ~4 hours. Fast cooling denotes that the coil was suddenly immersed into the LN$_2$. The degradation due to the epoxy impregnation is unpredictable and even a low level of or no $I_c$ degradation does not guarantee that repeated cooling cycles do not result in further degradation. It is therefore important to cool the magnet repetitively and to measure the $I_c$ performance. In this wet-wound magnet, we repeatedly cooled the magnet down to 77 K – the same as the first cool down for the following four consecutive days, and each time exactly the same $I_c$ value was obtained. Furthermore, shock tests were performed to determine if the fast cooling would result in any performance degradation. Even essentially dunking the magnet into the LN$_2$ did not result in any $I_c$ degradation. $n$-values were not also affected by the first and repetitive cool downs and the same value was obtained after each cool down. These results indicate that wet-winding and a diamond powder addition eliminate the performance degradation in the short REBCO prototype undulator magnet.

![Figure 4. $IV$ curves of the wet-wound prototype magnet obtained at 77 K. ‘BWW’ stands for ‘before wet-windings’ and ‘AWW’ stands for ‘after wet-winding’.](image)

3.2. Vacuum impregnation

Two short prototype magnets were prepared for the vacuum impregnations. The magnets were dry-wound and tested at ~77 K. These magnets were then vacuum impregnated using Araldite and Aradur epoxy systems mixed with 20 wt. % diamond powder in the first short prototype and 15 wt. % Al$_2$O$_3$ powder in the second short prototype. The reason these two powders were chosen is because these powders showed the least performance degradation in our previous study [6]. In Figures 5 and 6, ‘BI’ stands for ‘before impregnation’ and ‘AI’ stands for ‘after impregnation.’ Again, the markers in the figures are the measurements and the solid lines are fits to the power–law.

The $IV$ curves for the first vacuum impregnated magnet epoxy filled with diamond powders are provided in Figure 5. The $I_c$ values and $n$-values are almost the same before and after the vacuum impregnation. Even after two-day shock tests, the $I_c$ values are unchanged. The small fluctuations in the $n$-values are within the tolerance of the measurement system. These results prove that the bumper layer effectively absorbs the energy produced by the cracks and does not transfer it to the REBCO tapes. In addition, the bumper layer also prevents any possible delamination as it physically detaches the REBCO conductors from the surrounding epoxy compound. The second prototype coil was impregnated using Al$_2$O$_3$ fillers. The results showed some fluctuations – slightly more than the first one (diamond loaded epoxy used) – in the $I_c$ and $n$-values (Figure 6). The $n$-value increased from 16 to 17.4 after one slow and two fast cool downs, which is still slightly lower than the value before the vacuum impregnation. $I_c$ values of the magnet after the epoxy impregnation increased about 1.5 A. These fluctuations could be
due to the noise or very small degradation resulted using the alumina fillers. The insets in Figures 5 and 6 are the log-log scale of the transition regions.

**Figure 5.** IV curves of first vacuum impregnated prototype undulator magnet at 77K. Diamond powders used as a filler. ‘BI’ stands for ‘before impregnation’ and ‘AI’ stands for ‘after impregnation.’ Markers are the measurements and solid lines are the power-law fits. Respective n-values starting from the first legend to last as follows: 22.3, 22, 20.8, 21.7 and 20.6. Ic is about 100.2 A and the same after each additional cold cycle. The inset shows the log-log scale transition region.

**Figure 6.** IV curves of the second vacuum impregnated prototype undulator magnet at 77K. Al2O3 powders used as a filler. Markers are the measurements and solid lines are the power-law fits. Respective n-values starting from the first legend to last as follows: 18.4, 16, 16.1, 17.4. Ic is 74 and 75.5 A before and after impregnation, respectively. The inset shows the log-log scale transition region.

Microstructures of the vacuum impregnated and wet-wound short prototypes are provided in Figure 7. A sketch of the undulator magnet and cross-section are provided in Figure 7a and b respectively. The polarity of the current is displayed inside the winding stacks. Figure 7c is a cross sectional optical microscope image of the vacuum impregnated magnet, showing the REBCO tapes and epoxy between the layers. The layers are almost equally-spaced and there is very little epoxy build-up between the layers. Figure 7d is an SEM image of the cross-section of the vacuum impregnated magnet. Cu stabilizer, epoxy, Ag protective, Hastelloy substrate, and REBCO superconducting layers are visible from the figure. The thickness of the epoxy layer is about 5 µm. Figure 7e is the cross-section of the wet-wound coil. The epoxy thickness between the different layers is highly irregular and changes drastically. The average thickness of the epoxy layer between the REBCO layers in wet wound magnet is about 10 times larger than the vacuum impregnated magnet (Figure 7f). One important difference between the vacuum impregnated and wet-wound magnet is that the vacuum impregnated magnet does not have any diamond powder between the REBCO layers. This can easily be seen from the SEM image (Figure 7d). The epoxied region does not have any contrast variation, which is an indication of the diamond powder in the epoxy. This is because such regions are so tiny and diamond powders accumulate, act as a filter, and do not allow the powders to pass. Only epoxy can squeeze into those places and access to those remote portions of the magnet. However, it is evident from Figure 7f that diamond powders are presented in the wet-wound magnet. The diamond powder is agglomerated inside the epoxy matrix (Figure 7f). Such agglomerations could reduce the effectiveness of the powder fillers and promote formations of the micro-cracks. The source of these agglomerations are not known at this time, but could be due to the poor mixing of the epoxy and powders. Perhaps more sophisticated powder mixing methods need to be employed in order to fully disperse the nano-powder inside the epoxy matrix.
Figure 7. Cross-section SEM images of the vacuum impregnated and wet-wound coils. Sketch of the vacuum impregnated magnet showing dimensions of the prototype magnets with a period of 16 mm (a) and the cross-section (b). Optical microscope image after cross-sectional polishing (c) and an SEM image showing all the layers and the ~5 microns thick epoxy layer. An optical microscope image of the cross-section of the wet-wound magnet (e) and a SEM image providing more details about the thickness of the epoxy layer in the wet-winding technique.

The epoxy thicknesses along the width of the winding stack after the wet-winding at four different positions are provided in Figure 8. It seems that the thickness not only drastically varies between different layers, but also in the each individual layer due to the inclined tape winding. This happens as a result of the non-uniform epoxy build-up in different regions during the wet-winding. Such a thickness variation can be more than 15 µm and accumulated thickness irregularity can be detrimental to the field quality.

Figure 8. Epoxy layer thickness along the width of the tape at four different gaps.
4. Conclusions

We evaluated vacuum impregnation and wet-winding techniques using short prototype undulator magnets and both approaches offered no degradation to the prototype performances. The wet-winding process has been found to be time consuming and difficult to implement, especially for the long undulator magnets. Introduction of a bumper layer has eliminated the performance degradations in the vacuum impregnated magnet when diamond fillers used. Vacuum impregnation is a relatively quick process, although preparation might take a longer amount of time. The actual epoxy drawing time is short: An hour at most for a 1.5 m undulator magnet. In addition, additional attention during the process is not required as wet-winding requires constant surveillance – guiding the tape, and making sure that the thick epoxy build-ups are avoided. Finally, the microstructures that were evaluated showed very thin, homogenously spaced epoxy layer between the REBCO layers, which is crucial for the overall performance. For these given reasons, the vacuum impregnation technique with a bumper layer is suitable for vacuum impregnations of the REBCO undulator coils.

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