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Performance study of a new epoxy resin IR-3 in HTS-based high-field magnet application

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Abstract

REBCO (Rare-earth-based barium copper oxide) conductors are appropriate materials for high-field magnet applications. Vacuum impregnation using epoxy resin is a technique widely used for stable operation of superconducting coils. However, epoxy-impregnated REBCO coils often experience critical current degradation problems. Finding a suitable impregnating material for REBCO coils is important for their application in high-field superconducting magnets. A new toughness epoxy, IR-3, was developed recently. An in-depth understanding of IR-3 on the performance of REBCO coils is critically necessary for its application. Thus, this paper explores the effects of IR-3 impregnation on the performance of REBCO coils at 77 K and 4.2 K. The test results are compared to similar coils impregnated with CTD-101 K and MY750. Meanwhile, the radial stresses at 77 K in self-field and 4.2 K under 10 T were simulated. All epoxy impregnated REBCO coils showed no decay in critical current after thermal cycles at 77 K. When charged at 4.2 K in external fields of 5 T and 10 T, the IR-3 impregnated REBCO coils avoided performance degradation problems and had superior electrical stabilities. Combing the excellent performance at low temperatures, IR-3 is a promising candidate material for impregnating high-field REBCO coils.

1. Introduction

Strong magnetic fields are required in many applications, such as high-resolution NMR systems [1–6], ultra-high-field MRI systems [7–9], high energy particle accelerators [10–12], large nuclear fusion devices [13–15], high power electric machines [16], and so on. Considering technical feasibility and cost-effectiveness, hybrid magnet designs utilizing high temperature superconducting (HTS) coils as insert field boosters are favored choices for very high field (>20 T) magnets [17–20]. Amongst the HTS materials available commercially, REBCO coated conductors are strong candidates because of their good mechanical properties and large in-field current-carrying capability [21–23].

For superconducting high-field magnet applications, the HTS coils are subjected to very large thermal stresses and electromagnetic stresses. Impregnation is applied to the coils for mechanical stability and to reduce stress concentrations. Wax or paraffin has been used to impregate REBCO coils [5, 24]. However, their mechanical properties are weak and may not contribute too much to the overall mechanical stability of the large high-field magnets [25]. Recent experiments showed that the mechanical stability of no-insulation (NI) HTS coils can be greatly enhanced using the solder impregnation method [26, 27]. But the time constant of the solder impregnated coil is large. In case of a quench, the HTS insert coils must discharge as quickly as possible to avoid
high currents due to the coupling effect [28]. Also, the high soldering temperature in the impregnation process may damage the coil [29].

Due to their excellent mechanical strength, good adhesion, superior dielectric properties, and easy applicability [30], epoxy resins are preferred materials for the impregnation of superconducting magnets. Nevertheless, for REBCO coated conductors, epoxy impregnation often leads to performance degradation [31–33]. It has been reported that mismatch of thermal expansion between epoxy and conductors and cracks in epoxy are major contributors to performance degradation [34, 35]. Accordingly, solutions to the conductor degradation problem in epoxy impregnated HTS coils are actively being investigated. For example, Trociwitz et al achieved a field of 35.4 T without critical current degradation in the epoxy impregnated REBCO insert coils by sticking the conductor in a polyester thermal shrink tube [21]. The fabrication procedure of this method is complex which may limit its practical application. Barth et al reported that a REBCO Roebel cable vacuum impregnated with a mixture of epoxy and silica powder did not show critical current degradation [36]. However, one of the disadvantages of this method is the poor dispersion of the fillers in the epoxy matrix. An appropriate epoxy is therefore urgently required to prevent degradation.

Recently, a high toughness epoxy IR-3 was successfully developed for high field magnets impregnation. A primary investigation in reference [37] showed that the stainless steel (SS) co-wound REBCO coils impregnated with IR-3 could avoid critical current degradation after cold cycles at 77 K. For high magnetic field HTS insert coils, good field linearity, and low time constants are needed [38, 39], then the Kapton insulation (KI) HTS coils are recommended. Hence, in this paper, the suitability of IR-3 for application in KI REBCO coils is validated. Firstly, cool-down, over-current, and repetitive-cooling tests were performed at 77 K to evaluate the effect of the epoxy on the thermal and electrical stabilities of HTS coils. Then, the effects of epoxy impregnation on the current-carrying capability of REBCO coils at 4.2 K under 5 T and 10 T background fields were conducted. Meanwhile, the corresponding results at 77 K and 4.2 K were also discussed. Our experimental results will provide useful data for the application of epoxy impregnated REBCO HTS coils in high-field magnets.

2. Experimental setup

2.1. Conductors and epoxy resins used

The REBCO tapes used in this study were manufactured by Shanghai Superconducting Technologies Co., Ltd (SSTC), which are in the same batch as the tapes used in our previous paper to be published [37]. They are 4.8 mm in width and 220 μm in thickness. The thickness of the Hastelloy substrate, silver surface layer, and superconducting layer are 50, 1.5, and 2 μm, respectively. The conductor is laminated with 75 μm-thick copper
plates per side. The $I_c$ values of the REBCO conductor at 77 K in self-field with a criterion of 1 $\mu$V cm$^{-1}$ range from 160 to 218 A. Detailed parameters of the tapes are listed in Table 1.

Table 2 summarizes the specifications of the tested epoxies. The IR-3 includes three components, of which component A is a diglycidyl ether bisphenol-A (DGEBA) epoxy, component B is an anhydride hardener, and component C is a mixture of a self-made toughening agent and an amine accelerator. The mass ratio of component A, component B, and component C is 100:102:20. The epoxy system has high toughness. The relevant low-temperature properties of IR-3 were discussed in [37].

CTD-101K from the company Composite Technology Development Inc. is also a three-component epoxy resin including DGEBA epoxy, anhydride hardener, and accelerator with a mixing ratio of 100:90:1.5. It has commonly been used for the encapsulation of superconducting coils.

The two-component epoxy system MY750 is a product of the Huntsman Advanced Material. It is composed of a high viscosity liquid, solvent-free Bisphenol A resin (Araldite MY750), and an aliphatic diamine hardener (HY5922). The stoichiometric weight ratio between the resin and the hardener is 100:55. The epoxy system has outstanding thermal shock resistance but a relatively short ‘useable life’ and exhibits a low glass transition temperature ($T_g$) at 45 °C when fully cured.

2.2. Coil fabrication and impregnation

2.2.1. Coil fabrication

Six double pancake (DP) coils with two different diameters were fabricated and tested in this paper. Before coil winding, the HTS tape was wrapped with 20 $\mu$m thick Kapton insulation. Then the Kapton-wrapped HTS tape was wound around the copper bobbin. Key parameters of the DP coils are listed in Table 3. Coils 1, 2, and 3 were 60 mm in inner diameter, and coils 4, 5, and 6 with the same inner diameter of 50 mm. During coil winding, a series of silver voltage taps at certain distances were positioned within the coil to help identify performance degradation in the conductor. To measure the temperature changes in the coil during the cooling test, a Pt100 resistance thermometer was placed between the outermost layer of the coil and the end-shoe made of G10 material. After the coil was impregnated, the thermometer was fully covered with epoxy and did not contact any other parts of the coil. Figure 1 shows the schematic distribution of Pt100 and voltage taps for a 50 mm inner diameter coil.

2.2.2. Coil impregnation

After preliminary testing at 77 K before epoxy impregnation, the six coils were fully dried and then impregnated using the vacuum pressure impregnation (VPI) standard process [37]. Briefly, for IR-3 and CTD-101K, after
mixing the weighted components, the mixture was stirred and degassed in a vacuum until bubbles evolved infrequently. The resin was then injected into the pre-heated coil vertically placed within a vacuum chamber. When resin filled the coil, the chamber was pressurized with atmospheres up to 4 bars for 10 min to facilitate the resin entering the coil void. The above steps were repeated 3 times. Finally, the impregnated coil was cured according to the curing procedures given in table 2. In the case of MY750, due to its short pot life, the resin and hardener were pre-degassed separately and then pumped proportioned to the coils. Figure 2 displays photographs of the six epoxy-impregnated coils.

2.3. Performance tests

2.3.1. The coil performance test at 77 K in self-field

2.3.1.1. Cool-down tests

The cool-down tests from room temperature (RT) to 77 K were performed in a bath of liquid nitrogen. The Model 218 temperature monitor (Lake Shore) was used to record the temperature changes in the coils with the same geometric size during testing. The horseshoe made of aluminum will be removed during the cool-down test.

2.3.1.2. Critical current tests

The critical current ($I_c$) for the coils before and after impregnation with epoxy was measured by using the standard four-probe method. The $I_c$ of each coil was tested three times to reduce the experimental errors.

2.3.1.3. Thermal cycle tests

Thermal cycle tests were conducted as follows: cooled the impregnated coils in a liquid nitrogen bath to 77 K; measured the $I_c$ values at 77 K, and warmed up the coils back to RT. The thermal cycling was done 21 times in the study.

2.3.1.4. Over-current tests

To explore the thermal stability of the epoxy impregnated coil, over-current tests were performed at 77 K. During over-current testing, various overcurrent were applied to each coil by continuous ramping at a rate of 1 A s$^{-1}$, and then the coil was maintained at each target current for some time. When the total voltage increased irreversibly, the current was cut off to protect the coil from quench damage.

2.3.2. The coil performance at 4.2 K in external fields

To provide guidelines on the epoxy impregnated REBCO coils at high fields, the coils were then tested at 4.2 K with external magnetic fields of 5 T and 10 T. After the coil was cooled to 4.2 K in liquid helium, the external magnet was charged to 5 T or 10 T, and then the test coil was charged with a constant current increment rate until the coil voltage reached the critical criterion of 1 $\mu$V cm$^{-1}$. For comparison, critical current tests of short tapes were also performed at 4.2 K in a perpendicular applied magnetic field.

Figure 2. Photographs of the six epoxy-impregnated coils.
To simulate the worst-case scenario, the cool downs to 77 K and 4.2 K were done as quickly as possible by completely immersing the samples in liquid nitrogen and liquid helium, respectively.

3. Results and discussion

3.1. The coil performance at 77 K in self-field

3.1.1. Cool-down tests

Figure 3 shows the temperature curves of the IR-3 impregnated coil 1, the CTD-101 K impregnated coil 2, and the MY750 impregnated coil 3 during cooling from RT to 77 K. According to the temperature traces measured by each of the thermocouples, the time required to reach 77 K for coils 1, 2, and 3 were 138.9 s, 158.1 s, and 146.8 s, respectively. The thermal conductivity of the three epoxies was not significantly different at 77 K, which may be the reason for the small difference in experimental data on cooling time. The cool-down test results implied that the IR-3 impregnated coil enabled as good thermal stability as the coils impregnated with the CTD-101 K and MY750.

Figure 3. Cool-down tests of IR-3 impregnated coil 1, CTD-101 K impregnated coil 2, and MY750 impregnated coil 3 from RT to 77 K.

Figure 4. The self-field critical current at 77 K of six coils before and after epoxy impregnation.

To simulate the worst-case scenario, the cool downs to 77 K and 4.2 K were done as quickly as possible by completely immersing the samples in liquid nitrogen and liquid helium, respectively.
3.1.2. Critical current tests
Figure 4 shows the self-field $I_c$ at 77 K of six coils before and after epoxy impregnation. After fast cooling to 77 K, all the coils carried almost the same current before and after impregnation at a $1 \mu V cm^{-1}$ criteria value. This indicates impregnation with these three epoxies does not cause degradation of the current-carrying capabilities of KI REBCO coils. In addition, coils 1, 2, and 3 were 60 mm in inner diameter, and coils 4, 5, and 6 were 50 mm in inner diameter. No $I_c$ degradation occurs also implied that all the epoxies have no obvious effect on the performance of the two inner diameter coils in this study.

3.1.3. Thermal cycle tests
The normalized current-carrying capabilities $I_c/I_{c0}$ of the impregnated samples after repeated thermal cycling between RT and 77 K are shown in figure 5. The data shown in each thermal cycling experiment was the average of three measurements from the same sample. The normalized $I_c$ values of the six impregnated coils after the 21st test from RT to 77 K were 1.01$I_c$, 1.01$I_c$, 1.00$I_c$, 1.00$I_c$, 1.01$I_c$, 1.01$I_c$, respectively. This indicates that the critical currents of all the epoxies impregnated KI REBCO coils were hardly affected by repeated thermal cycling between RT and 77 K.

Figures 6(a)–(c) provide the $V$-$I$ curves for the 1st and the 21st tests of thermal cycles of the selected (a) IR-3 impregnated coil 4, (b) CTD-101K impregnated coil 5, and (c) the MY750 impregnated coil 6 measured at 77 K.

The previous experiment observed a 3% $I_c$ degradation of the CTD-101K impregnated SS co-wound REBCO coil. By comparing the differences of the samples, the avoidance of $I_c$ degradation in this study may be due to the existence of Kapton. The Kapton may protect the REBCO coated conductor from damage during coil fabrication and avoid significant delamination when impregnated with epoxy [40].

When the impregnated coil is cooled from RT to 77 K or lower, radial thermal stress is generated in the winding by the anisotropic thermal contraction of materials constituting the coil. To check the radial tensile stress applied inside of the epoxy-impregnated coil, analysis during the cooling process from RT to 77 K was...
implemented based on the axisymmetric finite element (FE) model. The Lorentz force is small at 77 K in self-field and neglected. Table 4 lists the physical parameters of each material used in the calculation.

Figure 7(a) shows a 2/3 axial symmetry modeling of the thermal contraction for the IR-3 impregnated coil which is composed of REBCO tape, Kapton tape, epoxy, and copper bobbin. The geometry is symmetric about the z plane. Moreover, this modeling is performed such that the epoxy exists as 220 μm thickness coating layers on exposed surfaces of the pancake coil and layers of 5 μm thickness in the gap between the turns [41]. Figure 7(b) is the analysis result for the r-directional normal stress of the coil. The copper bobbin, insulation tape, and epoxy resin domains of the coil are not shown. The radial stress received by the impregnated coil was generally transverse tensile stress within 10 MPa. Considering the delamination strength of the copper laminated REBCO conductor used in the study, this value of tensile stress seems to be small [42]. Thus, the delamination problem did not happen to the conductor layer when the HTS coils were impregnated with IR-3, CTD-101K, and MY750.

3.1.4. Over-current tests
The over-current test results of epoxy impregnated coils 4, 5, and 6 at various applied currents are shown in figure 8. During the over-current test at 1.00 Ic, the terminal voltage of IR-3 impregnated coil 4 (figure 8(a))

![Figure 7](image-url)

**Figure 7.** (a) Modeling of the thermal contraction for the epoxy-impregnated coil and (b) analysis result for the r-directional normal stress.

![Figure 8](image-url)

**Figure 8.** Over-current test results of (a) IR-3 impregnated coil 4, (b) CTD-101K impregnated coil 5, and (c) MY750 impregnated coil 6.

| Material               | Young’s modulus (GPa) | Poisson’s ratio | CTE (× 10^-6/K) |
|------------------------|-----------------------|-----------------|-----------------|
| Copper                 | 110                   | 0.35            | 17.0            |
| REBCO polycrystal      | 140                   | 0.15            | 14.8            |
| Epoxy                  | 5.7                   | 0.30            | 38.9            |
| Kapton                 | 3.6                   | 0.30            | 20.0            |
| G10                    | 30                    | 0.30            | 24.4            |

Table 4. Physical parameters of each material used.
initially started to increase at about 104 s, and then was stable and maintained at its maximum value, indicating thermal equilibrium between cooling by liquid nitrogen and Joule heating induced by the over-current. The test results at 1.02 $I_c$, 1.04 $I_c$, and 1.05 $I_c$ also exhibited the thermal equilibrium state. However, when the operating current increased further up to 1.06 $I_c$, the voltage kept increasing uncontrollably, causing the IR-3 impregnated coil to eventually be quenched. The CTD-101K impregnated coil (figure 8(b)) also showed the thermal equilibrium state at 1.00 $I_c$, 1.02 $I_c$, 1.04 $I_c$, and 1.05 $I_c$, and thermal runaway phenomenon in the subsequent test at 1.06 $I_c$. As for the MY750 impregnated coil (figure 8(c)), the thermal runaway phenomenon was observed at 1.07 $I_c$. By comparison, the over-current results confirmed the IR-3, CTD-101K, and MY750 impregnated KI HTS coils had approximately thermal and electrical stability which allows the quenching heat to be well dissipated without burning out of the coils.

### 3.2. The coil performance at 4.2 K in external fields

In a magnet, the magnetic field at the HTS coil ends is usually not parallel to the tape wide face. Because of the intrinsic anisotropy of REBCO tapes, their critical parameters, in particular $I_c$ and $n$, are extremely sensitive to the orientation of the external magnetic field. At 4.2 K, the angle of the applied field is the main factor affecting the performance of the HTS coil, which has to be taken into consideration for high field applications [43].

Critical current values of the epoxy-impregnated coils were measured at 4.2 K in background fields of 5 T and 10 T. The DP coil was placed in the background magnet as shown in figure 13(a). The angle between the magnetic field and the wide face of the tape is from 0° (parallel field) to 90° (perpendicular field).

As the perpendicular field has the greatest influence on the critical properties, we present here the analysis of critical current data of short tape in the perpendicular field for comparison. Figure 9 shows the $I_c$ test results of the REBCO short tape at 4.2 K in background fields of 5 T and 10 T. Each test experiment was repeated twice. Since the results were the same, only one of them was shown below. As can be seen, under the condition that the
magnetic field was perpendicular to the wide face of the tap, the $I_c$ of the short sample was 426.5 A and 291.9 A, respectively, based on a $1 \mu V \text{ cm}^{-1}$ criterion.

Constrained by the aperture of the background magnet, this paper only tests the critical performance of coils with an inner diameter of 50 mm. Figure 10 shows the critical current results of the three epoxy-impregnated coils 4, 5, and 6 at 4.2 K, 5 T and 10 T. To ensure reproducibility of the results, at least two measurements were taken for each background field setting, leaving time in between for the sample to cool down again to bath temperature.

As can be seen from figure 10, the voltages of all the coils increased dramatically when the currents were close to the critical values. When fitting the $V-I$ data with the power law, the fitted n-values were near 100, which were much higher than the values obtained from the short samples. We speculated that the temperature increasement was responsible for the voltage in coils rising so steep at 4.2 K. Epoxy impregnation could be moderate thermal insulation between the coil and liquid helium. When the coil was charged with a current around its critical value, the index loss may become non-neglectable and heat the coil, which further decreases its critical current and makes the heating more significant.

To verify this hypothesis, the charging process of ReBCO tape at 4.2 K and 10 T was simulated using the method reported in [44], assuming a charging rate of 1 A s$^{-1}$ in adiabatic conditions. In one case, the index loss was included and in the other, it was not. The resulted voltage as a function of current was plotted and shown below in figure 11, which clearly showed the influence of the index loss on the voltage and demonstrated our assumption. Consequently, the n-values of the coils were not shown in figure 10.

According to the $1 \mu V \text{ cm}^{-1}$ criteria critical currents, the $I_c$ values of the IR-3, CTD-101K, and MY750 impregnated coils were 423.4 (0.994 $I_c$), 400.9 (0.942 $I_c$), and 421.6 A (0.990 $I_c$), respectively, at 4.2 K and 5 T (figure 10(a)). These correspond to a 0.6%, 5.8%, and 1.0% degradation in the current-carrying capabilities of the short sample. The IR-3 impregnated coil exhibited superior stability and magnetic properties.

After discharging the coil, a similar experiment was then performed in a background field of up to 10 T and the test results were depicted in figure 10(b). Comparing the critical current with the short tapes, the $I_c$ for IR-3 impregnated coil was 294.1 A (1.008 $I_c$), which corresponds to an increase of the current-carrying capabilities of 0.75%, and the $I_c$ for MY750 impregnated coil was 290.9 A (0.997 A), which corresponds to a degradation of the current-carrying capabilities of 0.34%. However, in the case of the CTD-101K impregnated coil, the voltage signals of the coil were too noisy to detect and the $I_c$ value did therefore not get. The above results implied that impregnation of the KI REBCO DP coils with the IR-3 and MY750 did not result in detectable degradation of the current-carrying capabilities. The high fracture toughness of IR-3 and MY750 which could cause fewer or no cracked areas in the REBCO layer may be the reason for this phenomenon [34].

To validate whether the epoxies impregnated coils after the 4.2 K run resulted in critical current degradation or not, the $I_c$ of the impregnated coils were then measured again at 77 K in self-field. The test results are shown in figure 12, and the n-values are given in the legend. Comparing the $I_c$ values and n values of the impregnated coils before the test at 4.2 K in figure 6, we can see that all of the $I_c$ values and n values before and after the 4.2 K tests were almost the same. This further proved that the current-carrying capacities of the impregnated ReBCO coils
were maintained after the 4.2 K, 10 T tests, which are important for their application in the operation of future high field magnet systems.

We also calculated the radial stresses of the IR-3 impregnated coil at 4.2 K produced by electromagnetic and thermal forces. The parameters of the coil model were the same as those of the 77 K in self-field. The sample holder constructed using fiberglass reinforced G10 was used to fix the coils during the V-I measurements (figure 13(a)). The simulation result of the coil charged at 294 A under the background field of 10 T is shown in figure 13(b). Same as cases reported in many works of literature, the maximum transverse tensile stress was at the edge of the conductor. The maximum stress applied to the conductor layer was about 15 MPa for tension. But the average tensile stress applied to the conductor was below 10 MPa. No significant Ic degradation was found in the test results, proving that delamination should not happen to the above IR-3 impregnated HTS coils.

4. Conclusion

The effects of a newly developed high toughness epoxy resin IR-3 on the thermal and electrical stabilities of KI REBCO DP coils both in the self field at 77 K and magnetic field up to 10 T at 4.2 K were investigated. Compared with CTD-101K and another toughness epoxy MY750, the following conclusions were obtained.

At 77 K in self-field, the IR-3, CTD-101K, and MY750 impregnated REBCO coils can avoid performance degradation after repeated cooling tests. Over-current test results showed that all the impregnated coils exhibited almost the same thermal and electrical stabilities. Additionally, the IR-3 impregnated coil enabled well cooling performance between liquid nitrogen and the coil according to the fast cool-down test.

Under 4.2 K with 5 T and 10 T background fields, the IR-3 impregnated coil showed superior electrical stability and also maintained its current-carrying capability.

FE simulation results exhibited that the IR-3 impregnated coil could avoid degradation problems due to delamination under the tension stress of about 15 MPa.

IR-3 exhibits high toughness, long-pot life, good mechanical strength, and acceptable radiation resistances. It has the potential as an impregnating material for HTS coils.
Next, more work will be carried out for larger IR-3 impregnated HTS coils under high background magnetic field with high stress. On the one hand, we will try different types of HTS tapes. On the other hand, we will clarify the exact reasons for avoiding performance degradation from a more mechanistic level.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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