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Research on the health monitoring of ReBCO tape using fiber Bragg grating sensors

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Abstract. Epoxy resin is used to enhance the mechanical properties, insulation, and thermal conductivity of superconducting magnets. However, the multi-layer structure of second-generation high-temperature superconducting (ReBCO) tapes causes significant mechanical anisotropy. During curing and cooling, stress concentration arises due to the differing shrinkage rates of each layer, with epoxy resin shrinking much more than the ReBCO tape. This leads to strong stresses on the conductor, potentially causing cracks, spalling, or fractures in the superconducting layer, which degrade the critical current. In this study, fiber Bragg grating (FBG) sensors were used to monitor strain during epoxy curing and cooling processes, and the critical current was measured before and after curing. Results showed that pure epoxy resin curing and cooling to 77 K introduced about 14,334 μ strain, reducing the critical current by 52 A after five thermal cycles. By impregnating the epoxy resin with glass fiber cloth, residual strain was significantly reduced to less than 2500 μ strain, with almost no degradation in critical current. Additionally, embedded FBGs were used for quench detection, and the results demonstrated that detection sensitivity strongly depends on the FBG's distance from to the quench point.

1. Introduction

High-temperature superconducting (ReBCO) tapes represent a significant advancement in the field of superconductivity, offering enhanced performance in high-magnetic fields applications like MRI machines, particle accelerators, and power transmission systems. Unlike traditional superconductors requiring near-absolute zero temperatures, ReBCO tapes operate at higher temperatures, around 77 K, achievable with liquid nitrogen. However, challenges remain regarding their mechanical integrity and stability under operational conditions.

The first challenge for ReBCO tapes is their mechanical anisotropy due to the multi-layered structure, where each layer exhibits distinct mechanical and thermal properties. During cooling, differential thermal contraction causes stress concentrations between layers[1], further exacerbated by epoxy resin, which has much larger cooling shrinkage than the ReBCO tape[2]. This mismatch induces significant residual strain, potentially leading to various structural failures within the ReBCO tape. Takematsu et al.[3] identified the mismatch between epoxy and the conductors can cause peeling and cleavage stresses concentration on the conductor. Potential issues include cracking, spalling, or even complete fracture of the superconducting layer. This mechanical degradation directly affects the tape's electrical performance[4]. Gao et al.[5,6] demonstrated through finite element modeling that thermal mismatch stresses during cooling significantly impact the mechanical behavior of epoxy-impregnated ReBCO coils and cannot be ignored in electromagnetic structure analysis. Therefore, understanding the impact of curing residual strain and cooling shrinkage is essential to ensure the performance and reliability of superconducting magnets.

Quench detection is another critical aspect of ensuring the operational stability and safety of superconducting systems, especially as ReBCO magnet coils are highly susceptible to localized heating due to their low quench propagation velocities, often leading to burn-out. Traditional voltage-based detection methods used in low-temperature superconductors are less effective for ReBCO, as voltage signals typically appear only after irreversible damage. Early detection of local thermal "hot-spots" is therefore preferable. Recently, fiber optic sensors of quench detection have been suggested. Chen et al.[7] used FBG sensors for high-precision strain measurements to detect quench onset and propagation. Maximilian Fisser et al.[8] proposed a hotspot detection system using ultra-long FBG technology and a signal processing algorithm. Erica E Salazar et al.[9] successfully demonstrated rapid and reliable temperature perturbation detection in VIPER cables using FBG and ULFBG sensors under quenching-like conditions at the SULTAN facility.

To solve these problems, this research focuses on employing FBG sensors for health monitoring of ReBCO tapes. FBG sensors are highly sensitive to strain and temperature variations, making them useful for real-time monitoring of the internal states of ReBCO tapes during manufacturing and operation process. We monitored the strain of the ReBCO tape during curing and cooling process, and measured the critical current before and after the epoxy resin curing. Also, we have explored the use of the embedded FBGs for quench testing.

2. Experimental Design

The critical current of ReBCO tape is tested by the special structure, as shown in Fig. 1. The current conduction unit is designed to transport the current to ReBCO, with a wire being installed with it together by a Cable lug. To reduce the resistance between the current conduction unit and ReBCO, the indium is installed between these two components. The stainless steel fastener, thin at both

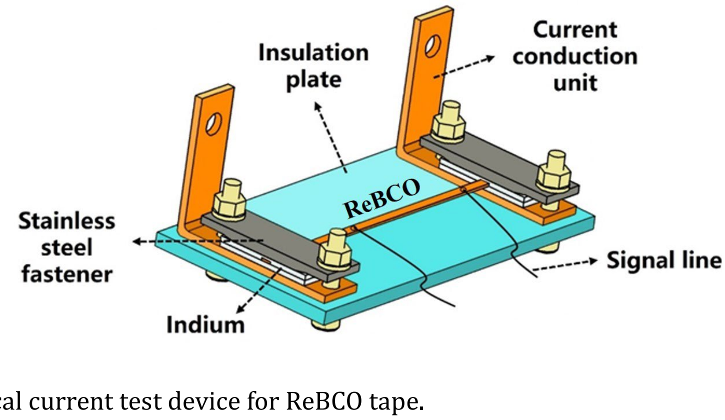

Figure 1. Critical current test device for ReBCO tape.

ends, is composed to compress ReBCO tightly. The voltage is tested by the nanovoltmeter connected to the signal line. In this experiment, the current value corresponding to the voltage rising to 1μV/cm is defined as the critical current.

For pure epoxy resin, ReBCO tape and FBG sensors are loaded directly into a silicone mold and then poured into epoxy resin for curing. For the use of glass fiber reinforcement, the vacuum pressure impregnation method as shown in the Fig. 2 is used.

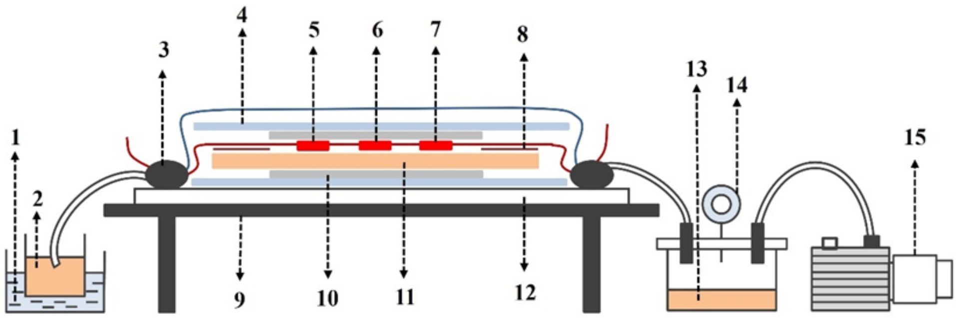

Figure 2. Schematic diagram of vacuum impregnation epoxy resin process.1-Water bath heating container; 2- Epoxy resin; 3-Sealing strip; 4-Release cloth; 5-FBG 1; 6-FBG 2; 7-FBG 3; 8-Polyimide tape; 9-Digital display heating plate; 10-Glass fiber cloth; 11-ReBCO; 12-Glass plate; 13-Resin collector; 14-Vacuum gauge; 15-Vacuum pump.

The water bath heating container (1) is designed to heat up the Epoxy resin (2) to facilitate its good liquidity. The sealing strip (3) is installed on the glass plate (12) and wrapped into a large rectangle for sealing the epoxy resin. Resin collector (13), with a vacuum gauge (14), is utilized to recycle epoxy resin under the drive of vacuum pump (15) during the impregnation process. Release cloth (4) is laid on the glass plate to separate the impregnated components from the glass plate. Three FBGs (5), (6) and (7) are arranged on the superconducting tape ReBCO (11) to measure the strain at these three points. A layer of glass fiber cloth (10) is laid on both the upper and lower sides to facilitate the infiltration and bonding of epoxy resin, while also reducing the cooling shrinkage rate of epoxy resin to a certain extent.

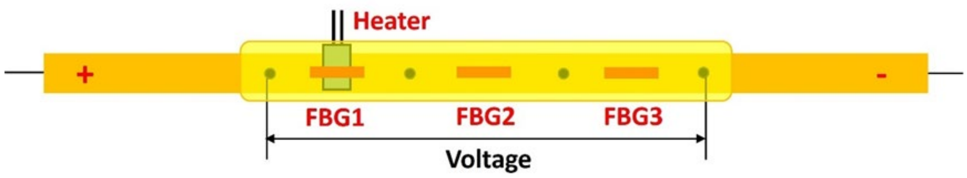

Figure 3. Schematic diagram of quench detection.

After the vacuum impregnation, the chain of FBGs, used for strain measurement, can be directly utilized for the quench detection. The working current of ReBCO is set to 100 A. To characterize the quench, a Heater as the “hot spot”, is attached to the ReBCO. Then the chain of FBGs and the Heater, along with the ReBCO, are solidified together by vacuum impregnation of epoxy resin. FBG 1 sits directly above the Heater, while FBG 2 and FBG 3 are located 1.5 cm and 3 cm away from the Heater. The voltage of ReBCO is also measured, being compared with FBGs.

3. Results and Discussion

3.1 Strain and Degradation

The real-time strain responses during the curing processes of pure epoxy resin and glass fiber reinforced composite are shown in Fig. 4(a) and 4(b), respectively. The residual strain of the curing and cooling process is summarized in Table 1. We can see that the addition of glass fiber greatly reduces the residual strain after curing and cooling of epoxy resin. The total strain of pure epoxy resin is nearly 6 times that of glass fiber reinforced condition.

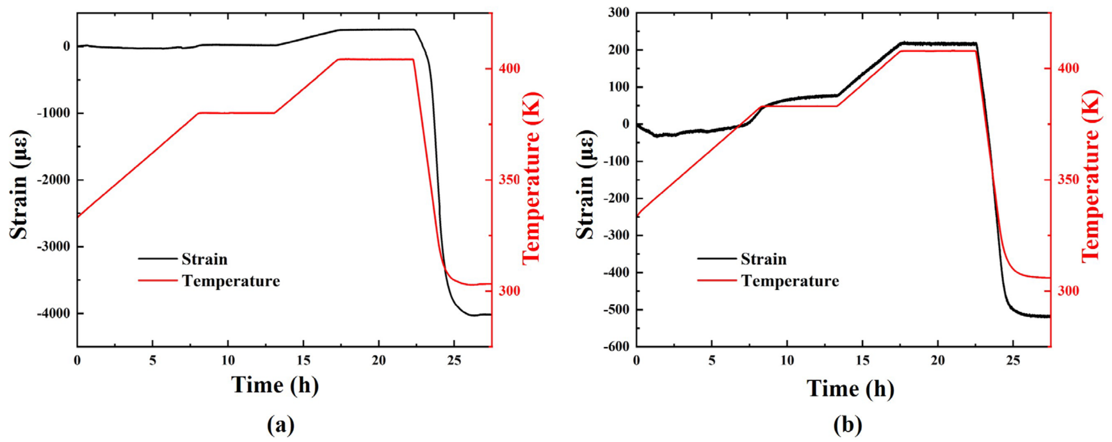

Figure 4. Strain responses during curing process: (a) pure epoxy resin, (b) glass fiber reinforced composite.

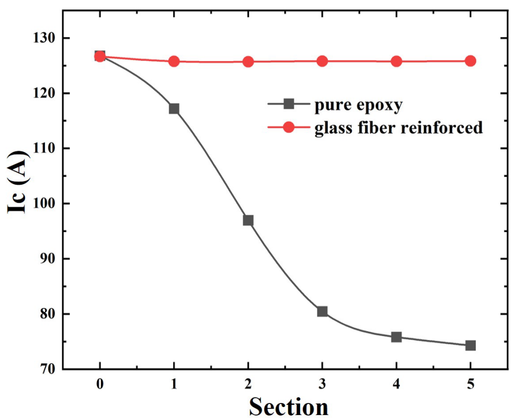

Figure 5. Ic degradation in each of the five thermal cycles.

Table 1. Residual strains after curing and cooling processes.

	Residual strain/μ	Strain at 77 K/μ	Total strain/μ
Pure epoxy	-4032±15	-10302±18	-14334±33
Glass fiber reinforced	-537±4	-1952±5	-2489±9

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The I_c degradation in each of the five times of thermal cycles is shown in Fig. 5. For ReBCO cured by pure epoxy resin, the I_c drop is very significant, especially in the first three thermal cycles, where the I_c decreases by 46 A. The degradation value of the last two thermal cycles gradually decreased, and after five times, the total degradation was 52 A. In the case of glass fiber reinforcement, the I_c is reduced by less than 1 A only during the first thermal cycle, and there is almost no degradation in the subsequent thermal cycles.

3.2 Quench Detection by Embedded FBG

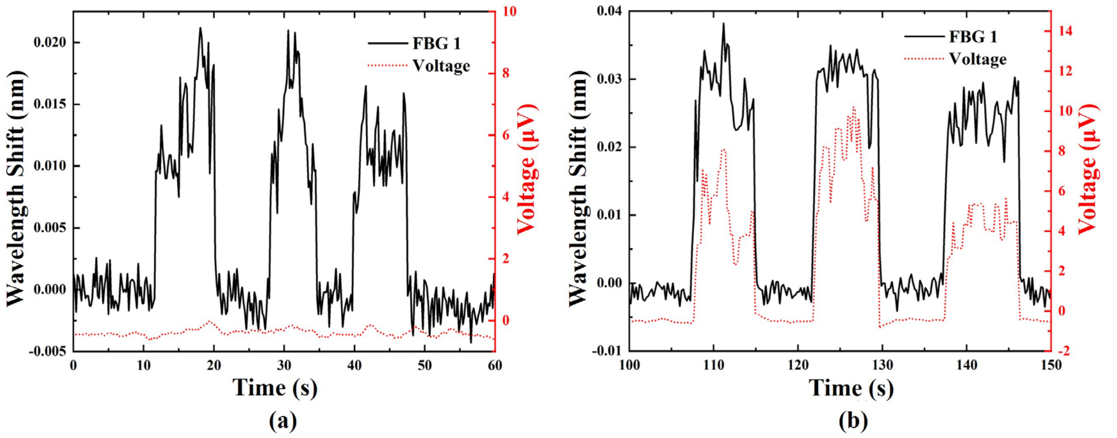

Figure 6. Quench voltage and wavelength shift during heat pulse at Iop=100 A: (a) The heating pulse power is 0.288 W, (b) The heating pulse power is 0.329 W.

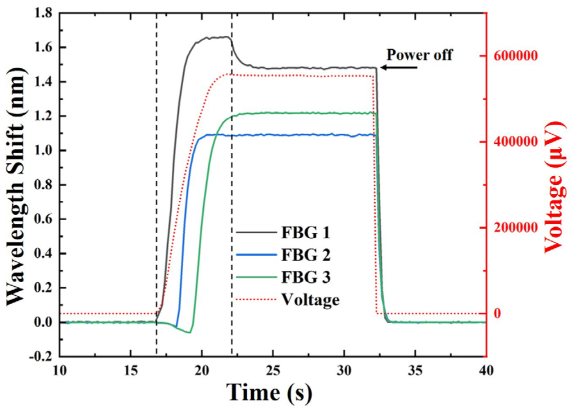

Figure 7. Quench voltage and wavelength shift during heat pulse at Iop=100 A: (a) The heating pulse power is 0.288 W, (b) The heating pulse power is 0.329 W.

Three heat pulses with two different powers: 0.288 W and 0.392 W, are applied to the Heater. The results of the FBG and voltage signals are shown in Fig. 6. Under the lower power, the voltage remains basically unchanged, failing to detect the heat, while FBG 1 shows a signal change immediately once the heat is input to the Heater. This illustrates FBG is more sensitive to quench detection. However, FBG 2 and FBG 3 show no wavelength change. These two sensors are at relatively long distance from the heater, resulting in not being affected by the heat pulse timely.

With a larger heat input of 0.657 W, all three FBGs show wavelength changes. FBG 1 has the fastest response and the strongest signal. FBG 2 and FBG 3 subsequently response, and both show a slight decrease in wavelength before rising. This is due to the first expansion of FBG 1, which causes the posterior position to be temporarily squeezed and contracted. When the heat is transferred to FBG 2 and FBG 3, the wavelengths of the two sensors are starting to increase. After the end of the heat input, the wavelengths shift of the three FBGs do not return to 0. This indicates that after a relatively high heating power, the HTS tape cannot be restored to the original superconducting state. Also, the signals of FBGs are affected by the coupling of strain and temperature, so the decoupling analysis should be carried out in the future.

4. Conclusion

In order to understand the effects of curing residual strain and cooling shrinkage on the electrical properties of ReBCO tape, we tested the strain response of pure epoxy resin and glass fiber reinforced composites using the FBG method, and tested the critical current degradation after 5 times of thermal cycles. In addition, we continued to attempt quench detection using the embedded FBGs. The conclusions are as follows:

1. The addition of glass fiber greatly reduces the residual strain after curing and cooling of epoxy resin, so that the degradation of the Ic of the ReBCO tape is also greatly reduced.
2. At lower quench energies, the signal of the voltage cannot be detected, but the FBG, which happens to be on the hot spot, is able to detect a noticeable wavelength shift.
3. The quench detection is highly dependent on the distance of the FBG from the quench point. And the wavelength shift is a complex phenomenon caused by the coupling of temperature and strain.

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