Composites Part B 94 (2016) 190–196

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Effect of micro-ceramic fillers in epoxy composites on thermal and electrical stabilities of GdBCO coils

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ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form
17 February 2016
Accepted 21 March 2016
Available online 28 March 2016

Keywords:
A. Polymer-matrix composites (PMCs)
A. Particle-reinforcement
B. Thermal properties
B. Electrical properties

ABSTRACT

This paper reports the effects of ceramic fillers for epoxy composites used as impregnation materials on the thermal and electrical stabilities of three GdBCO coils impregnated with epoxy alone, with an epoxy/AlN composite, and with an epoxy/BN composite. During cool-down to 77 K, due to the high thermal conductivity of the filler materials, the coils impregnated with the epoxy composites that included the AlN and BN fillers exhibited faster cooling times than the coil impregnated with epoxy resin alone. Moreover, the addition of the filler could facilitate quench heat dissipation as well as ameliorate the discrepancy of thermal contraction between the GdBCO CC tape and the epoxy. In particular, the coil impregnated with the epoxy/BN composite exhibited superior performance in cooling, over-current, and repetitive-cooling tests. Therefore, the epoxy/BN composite could be the most effective impregnating material for the development of highly-stable superconducting rotating machines, with considerably enhanced reliability.

1. Introduction

With the rapid development of the electrical and electronic equipment industries, polymers are increasingly important for use as encapsulation materials for electronic devices in order to enhance the efficiency of thermal management [1,2]. Among the various polymers, epoxy resin is one of the most commonly used polymers due to its high moisture resistance, mechanical robustness, easy processing, excellent adhesion, and low cost [3,4].

Such effectiveness and convenience make epoxy resins suitable for use in today's high-power high-temperature superconducting (HTS) rotating applications that require high mechanical reliability and dynamic stability. In the manufacturing process for HTS rotating machines, the epoxy resin is in practical use for robust field windings which are comprised of a number of HTS racetrack-type coils— because the HTS coils encounter unwanted mechanical vibrations induced by dynamic movement as well as inhomogeneous spatial load distributions exerted by oscillatory Lorentz forces [5–7].

However, during cooling, HTS coils impregnated with epoxy resins may underperform because the coil can experience degradation of its superconducting property due to the thermal contraction mismatch between the HTS tape and the epoxy resin. Moreover, when a quench occurs in the coil, hot spots cannot be easily dissipated outwards due to encapsulation by epoxy resin with low thermal conductivity. Consequently, the HTS coil may be locally burned-out or may even sustain permanent damage [8,9].

Recently, the thermal and electrical behaviors of HTS coils impregnated with commercialized epoxy resins such as Stycast 2850 FT, CTD-521 were investigated [10,11]. However, it is essential to improve the thermal and mechanical properties of the epoxy resin for better performance in over-current and repetitive-cooling conditions. In the semiconductor industries, continuous efforts have been made to improve the physical properties of epoxy resin

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http://dx.doi.org/10.1016/j.compositesb.2016.03.065
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Table 1
Specifications of epoxy resin and filler materials.

Parameters		Stycast 2850 FT
Thermal conductivity	[W/m·K]	1.15
Coefficient of thermal expansion	[ppm/°C]	111.5

Parameters		Aluminum nitride	Boron nitride
Molar mass	[g/mol]	40.99	24.82
Average particle size	[μm]	~10	
Shape		Polygon	Hexagon
Thermal conductivity	[W/m·K]	270	300
Coefficient of thermal expansion	[ppm/°C]	4.5	0.5

by adding ceramic fillers. However, in order to utilize the epoxy/filler composite in superconducting applications, especially in HTS rotating machines, it is necessary to develop proper epoxy materials employing special fillers that enhance the thermal conductivity as well as reduce the discrepancy in thermal contraction between the HTS tape and the epoxy in over-current and repetitive-cooling conditions.

In this study, the effects of ceramic fillers for epoxy composites employing aluminum nitride (AlN) and boron nitride (BN) powders on the thermal and electrical stability of impregnated GdBCO-coated conductor coils were investigated through cool-down, over-current, and repetitive-cooling tests. Furthermore, the composition and particle dispersion of epoxy composites that include ceramic fillers were analyzed using energy-dispersive x-ray spectroscopy (EDS) and back-scattered electron (BSE) measurements.

2. Experimental

2.1. Procedure for epoxy composite preparation

Table 1 lists the specifications of epoxy resin and filler materials. Stycast 2850 FT manufactured by Emerson and Cuming Company was used as an epoxy resin for the impregnation of HTS coils in this study. The thermal conductivity and thermal contraction coefficients of Stycast 2850 FT were 1.15 W/m-K and 111.5 ppm/°C, respectively. To improve the thermal and mechanical properties of the impregnated HTS coil, we fabricated two lab-made epoxy composites: one mixed with AlN powder, and the other mixed with BN powders. The particle shapes of AlN and BN were polygon and hexagon, respectively, and their average particle size was ~10 μm.

Table 2
Specifications of the GdBCO single-pancake coils.

Parameters		GdBCO test coil
Conductor length	[m]	2.7
Number of turns		10
Inner diameter	[mm]	80
Outer diameter	[mm]	91
Insulation material		Kapton tape
Insulation width; Thickness	[mm]	4.1; 0.05

Parameters		Coil 1	Coil 2	Coil 3
Critical current @ 77 K	[A]	125	122	126
Epoxy		Stycast 2850 FT		
Cure agent		Catalyst 23 LV		
Cure temperature		Room temperature		
Cure time	[hr]	48		
Filler material		No filler	AlN	BN
Filler content	[wt. %]	N/A	10	10

The thermal conductivities and thermal expansion coefficients of AlN and BN were 270 W/m·K, 4.5 ppm/°C and 300 W/m·K, 0.5 ppm/°C, respectively [12–19]. Epoxy composites were fabricated by the following procedures: Stycast 2850 FT (50 g) was mixed with a filler of 5 g (10 wt. %); cure agent (Catalyst 23 LV) was added into the mixture; and, the epoxy composites were stirred at 40 °C for 45 min.

2.2. Coil construction

Table 2 lists the specifications of the GdBCO single-pancake test coil. The test coil consisted of 10 turns of GdBCO coated conductor tape, with Kapton tape as the turn-to-turn insulator, wound onto a Bakelite bobbin. The inner and outer diameters of the test coil were 80 and 91 mm, respectively. The critical currents (I_c) of coils 1, 2, and 3 measured at 77 K using a 1 μV cm^{-1} criterion were 125, 122, and 126 A, respectively.

Fig. 1 shows schematic drawings of the arrangement of an E-type thermocouple (TC), voltage taps (VTs), and a circular-shaped copper foil. In order to obtain temperature profiles for the test coil during the cooling test, an E-type thermocouple (TC) was installed on the outermost layer (see Fig. 1 (a)). Voltage taps were installed at both ends of the coil to measure the total coil voltage. A 7.1-mm height copper foil was installed with a gap of 3 mm from the outer radius of the coil (see Fig. 1 (b)).

Fig. 2 shows a schematic drawing of the impregnating procedure for the test coil. Each prepared epoxy composite was used to fill the empty space between the coil and copper foil, and the coil was cured for 24 h at room temperature. Fig. 3 shows photographs of the three GdBCO coils impregnated with epoxy alone, with an epoxy/AlN composite, and with an epoxy/BN composite.

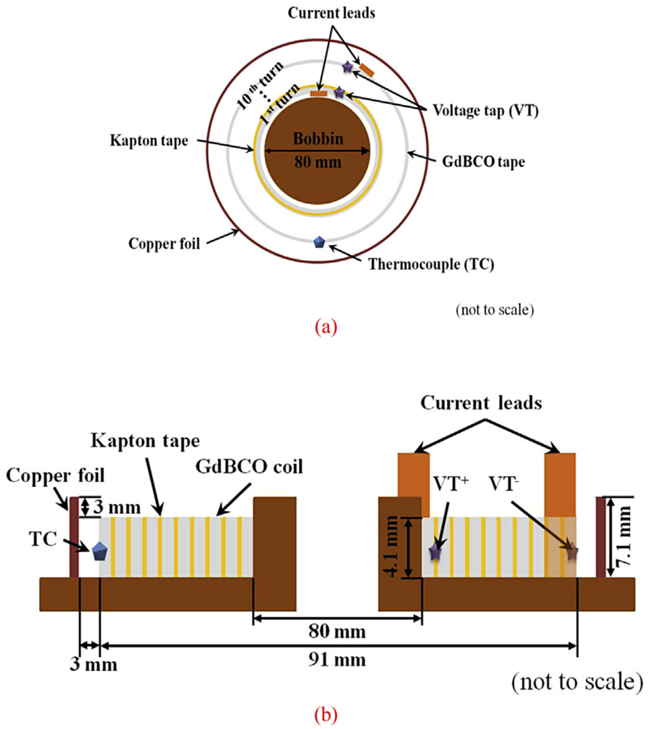


Fig. 1. Schematic drawings of the arrangement of an E-type thermocouple (TC), voltage taps (VTs), and a circular-shaped copper foil: (a) top view and (b) cross-sectional view.

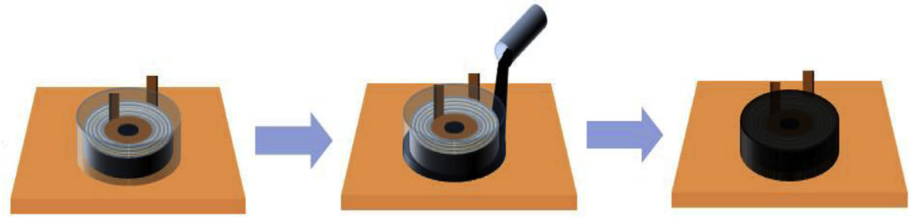


Fig. 2. A schematic drawing of the impregnating procedure for the test coil.

3. Results and discussion

3.1. *Epoxy composite*

Fig. 4 shows the energy-dispersive x-ray spectroscopy (EDS) spectra of the impregnating materials for coils 1, 2, and 3. Carbon, oxygen, and aluminum peaks were observed in the EDS spectrum, Fig. 4 (a), because Stycast 2850 FT is comprised of epoxy resin, alumina, butyl 2, 3- epoxypropyl ether, and carbon black. For the epoxy/AlN composite, a nitrogen peak was additionally detected and the intensity of the aluminum peak was relatively higher than that for the epoxy resin alone due to the addition of the AlN filler. The EDS spectrum of the epoxy/BN composite in Fig. 4 (c) clearly shows boron and nitrogen peaks. As shown in the BSE images in Fig. 5, bright spots represent the alumina and ceramic fillers and dark regions denote the epoxy resin matrix. The image confirms that the alumina and additives were homogeneously dispersed in the epoxy matrix.

3.2. *Cool-down tests*

The cool-down test was performed in a liquid nitrogen bath (LN2) to investigate the effect of the filler additions to the epoxy resin on the cooling performance of the GdBCO single-pancake coil impregnated with epoxy composites. Fig. 6 shows the temperature

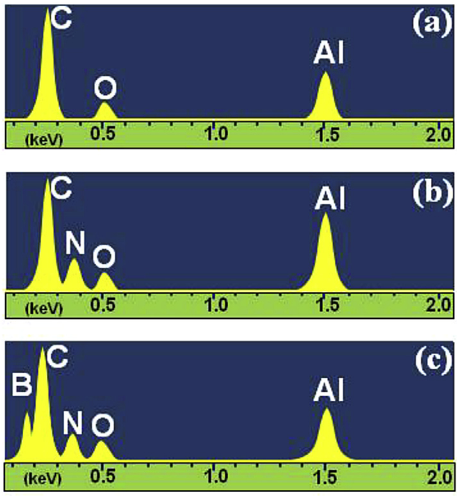


Fig. 4. EDS spectra: (a) epoxy resin, (b) epoxy/AlN composite, and (c) epoxy/BN composite.

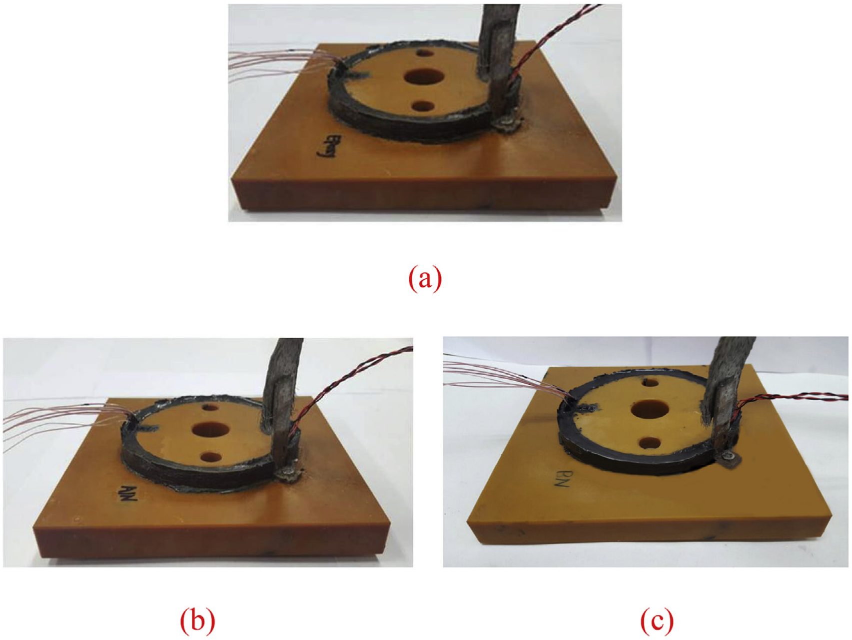


Fig. 3. Photographs of the GdBCO test coils impregnated with: (a) epoxy alone, (b) epoxy/AlN composite, and (c) epoxy/BN composite.

traces for the coils obtained during the cool-down from room temperature to 77 K. The times required to reach 77 K for coils 1, 2, and 3 were 468.1, 429.8, and 356.3 s, respectively, which indicated that the cooling times for coils 2 and 3 were faster than that for coil 1 because the addition of AlN and BN fillers facilitated heat transfer between LN2 and the GdBCO coils. In addition, coil 3 (epoxy/BN composite) exhibited superior performance in the cooling test, implying that the addition of BN filler could be a more effective method to enhance the thermal conductivity of epoxy resin.

3.3. *V*–*I* characteristics

Fig. 7 shows the *V*–*I* curves of the test coils before and after impregnation. The critical current (I_c) values were measured in a LN2 bath (at 77 K) using a criterion of 1 μV/cm. Before impregnation, the I_c values of coils 1, 2, and 3 were 125, 122, and 126 A, respectively. After impregnation, a 3.2% lower I_c value was observed in coil 1 (121 A), whereas coil 2 (122 A) and coil 3 (126 A) showed no change. The test results implied that coils 2 and 3 experienced no degradation in their superconducting properties due to the addition of ceramic fillers, which ameliorated the thermal contraction mismatch between the GdBCO CC tape and epoxy.

In contrast, a 3.2% lower I_c value of coil 1 suggests that the use of epoxy resin without any ceramic fillers caused a degradation in the superconductivity due to the mechanical stresses induced by the discrepancy in thermal contraction between the GdBCO CC tape and the epoxy.

3.4. Over-current tests

Fig. 8 shows the over-current test results for the test coils. During the over-current testing, the supply current was increased at a charging rate of 1 A/s, and then maintained at each target current. When the total voltage of the coils reached 1.2 mV, the test was stopped to prevent the coils from being damaged.

For coil 1, at 1.00 I_c, the total voltage initially started to increase at 113 s, rapidly reached 0.23 mV and remained at 0.25 mV, as shown in Fig. 8 (a); the test results at 1.01 and 1.02 I_c exhibited similar voltage traces with higher voltage and constantly remained at 0.34 and 0.50 mV, respectively. The constant voltages at each value indicated thermal equilibrium between the cooling by LN2 and Joule heating induced by the over-current.

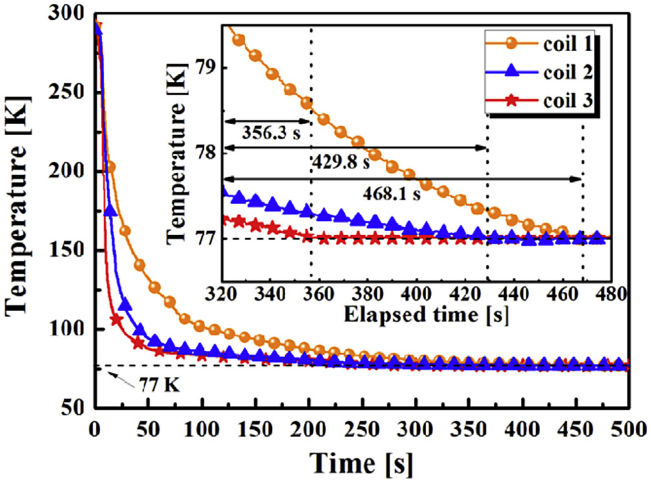
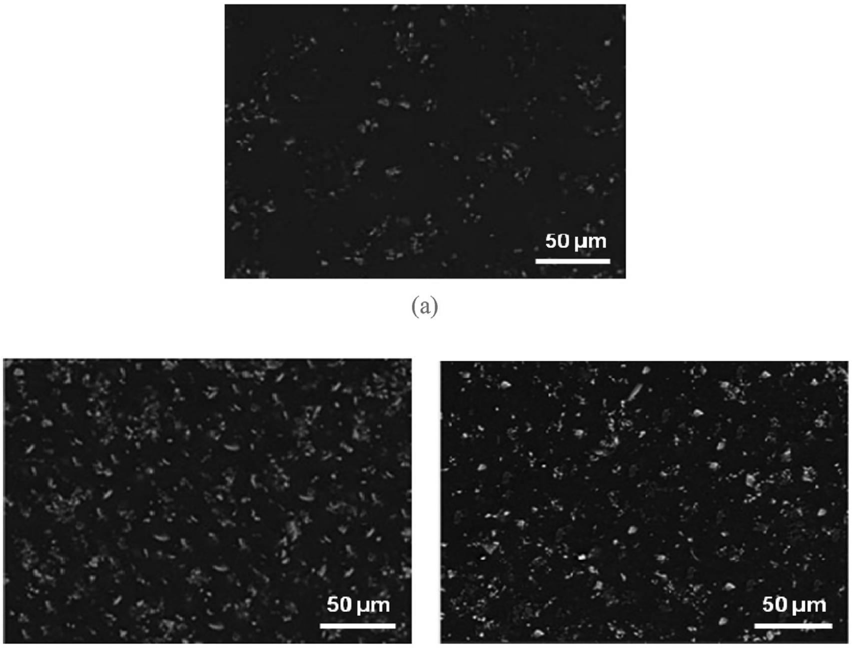


Fig. 6. Temperature traces of the test coils obtained during cool-down from room temperature to 77 K. The inset graph provides an enlarged view for easy comparison.



(a)

(b)

(c)

Fig. 5. BSE images: (a) epoxy resin, (b) epoxy/AlN composite, and (c) epoxy/BN composite.

However, when the supply current increased further to 1.03 I_c, the voltage continuously increased, indicating the occurrence of a thermal runaway phenomenon that might cause permanent damage to the coil.

The currents that caused thermal runaway in voltage were 1.04 and 1.06 I_c, for coils 2 and 3, respectively, which were higher than for coil 1 (1.03 I_c). These results implied that the addition of AlN and BN fillers improved the thermal conductivity of epoxy resin, which allowed hot spots to be dissipated more effectively in the event of a quench. In particular, the high thermal runaway current (1.06 I_c) for coil 3 demonstrated that BN could be the most effective filler to improve the thermal and electrical stability of the coil in over-current conditions.

3.5. Repetitive-cooling test

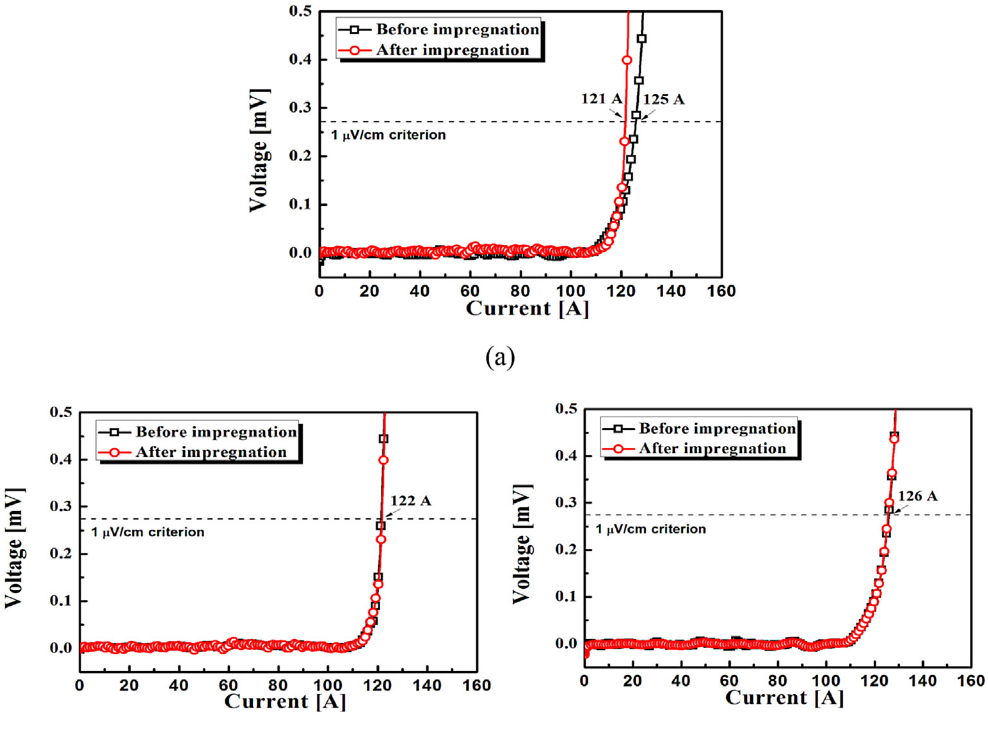
In order to examine the effect of filler materials on the thermal contraction between the GdBCO tape and epoxy composites, repetitive-cooling tests were conducted through the following steps: cool the coil to 77 K; measure the I_c value of the coil; warm the coil to room temperature; and carry out the prior three steps repetitively.

Fig. 9 shows the results from the repetitive-cooling testing for coils 1, 2, and 3. For accurate comparison, the measured I_c value for each coil was normalized to its initial value. The normalized I_c values for coils 1, 2, and 3 after the 20th test were 0.898, 0.983, and 0.991 I_c, respectively. This result indicated that coils 2 and 3 showed 1.6 and 0.8% degradation in their I_c values, which was much less than that of coil 1 (9.9%). The reduced degradation in coils 2 and 3 was attributed to the addition of AlN and BN fillers that ameliorated the discrepancy in thermal contraction between the GdBCO CC tape and the epoxy resin. Overall, the epoxy/BN composite may be preferable as an impregnating material to improve the reliability of coils in circumstances involving repetitive cooling.

4. Conclusion

In order to investigate the effects of ceramic fillers for epoxy composites on the thermal and electrical stabilities of epoxy-impregnated coils, cool-down, over-current, and repetitive-cooling tests were performed on three GdBCO coils impregnated with epoxy alone (coil 1), with epoxy/AlN composite (coil 2), and with epoxy/BN composite (coil 3). The cool-down test results showed that the times required to reach 77 K for coils 1, 2, and 3 were 468.1, 429.8, and 356.3 s, respectively, indicating that the coils impregnated with epoxy/filler composites had better cooling performance compared to the coil impregnated with epoxy alone. This was because the addition of AlN and BN fillers for epoxy composites facilitated heat transfer between the liquid nitrogen and the GdBCO coils.

In over-current tests, the currents that caused thermal runaway in voltage were 1.04 and 1.06 I_c, for coils 2 and 3, respectively, which were higher than for coil 1 (1.03 I_c), indicating that the heat transfer property in the impregnated GdBCO coil was enhanced by the addition of AlN and BN fillers to the epoxy resin. Furthermore, the repetitive-cooling test results indicated that coils 2 and 3 experienced 1.6 and 0.8% degradation in their I_c values, which was much less than that of coil 1 (9.9%). The reduced degradation of the coils

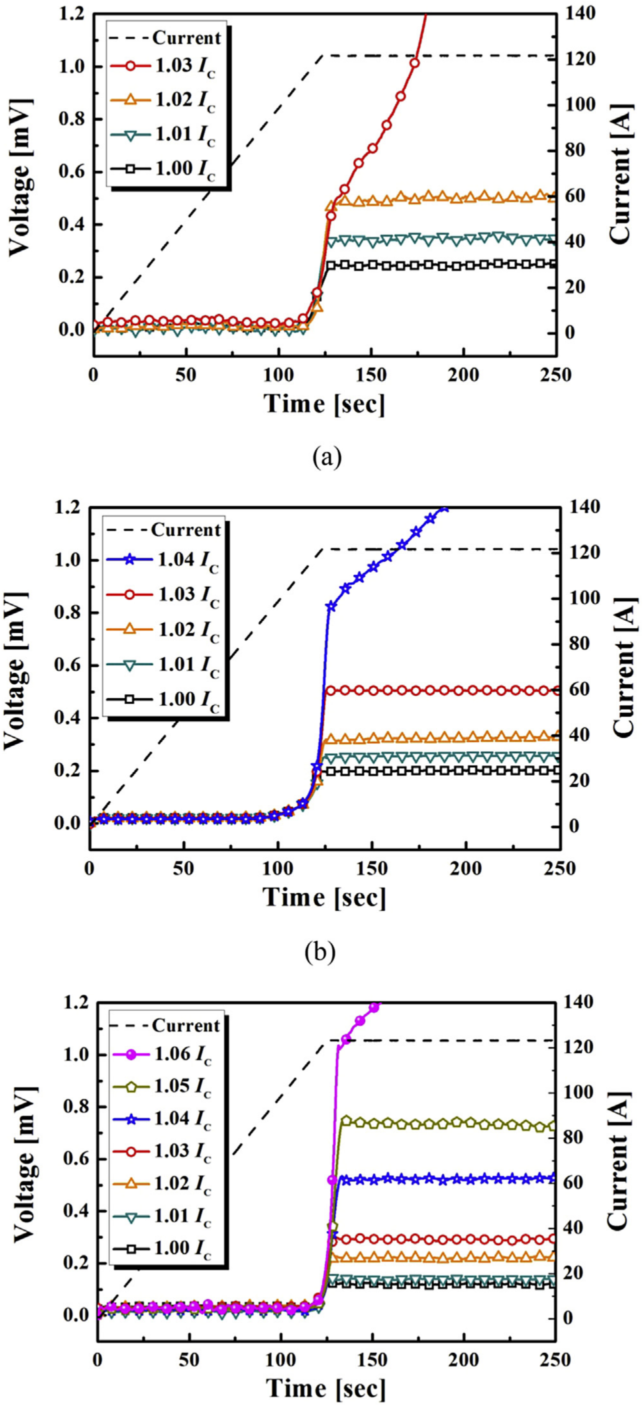


(a)

(b)

(c)

Fig. 7. *V*–*I* curves of the test coils measured at 77 K, before and after impregnation with epoxy composites: (a) coil 1, (b) coil 2, and (c) coil 3.



(a)

(b)

(c)

Fig. 8. The over-current test results of coil 1 (a), coil 2 (b), and coil 3 (c).

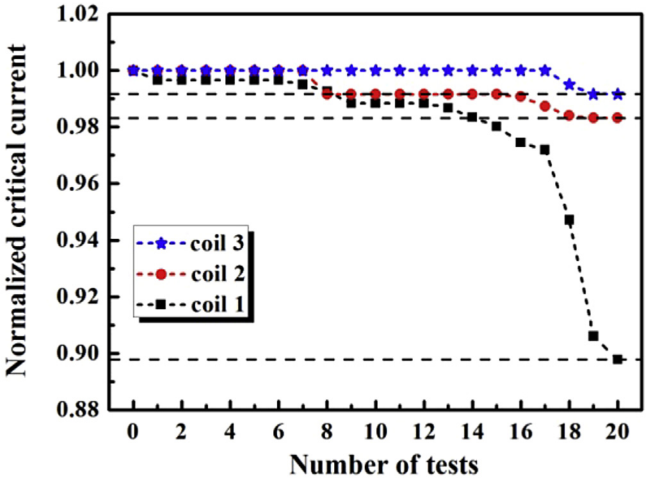


Fig. 9. Repetitive-cooling test results for coils 1, 2, and 3.

impregnated with epoxy/filler composites was attributed to the addition of AlN and BN fillers, which ameliorated the discrepancy in thermal contraction between the GdBCO CC tape and the epoxy resin. Overall, the coil impregnated with the epoxy/BN composite exhibited superior performance during cooling, over-current, and repetitive-cooling tests. Therefore, the epoxy/BN composite could be the most effective impregnating material for the development of highly-stable superconducting rotating machines with considerably enhanced reliability.

Acknowledgment

This work was supported by the Materials and Components Technology Development Program of KEIT [10053590, Development of MgB_2 wire and coils with high critical currents and long length for superconducting medical·electric power equipment].

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