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

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A B S T R A C T

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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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.

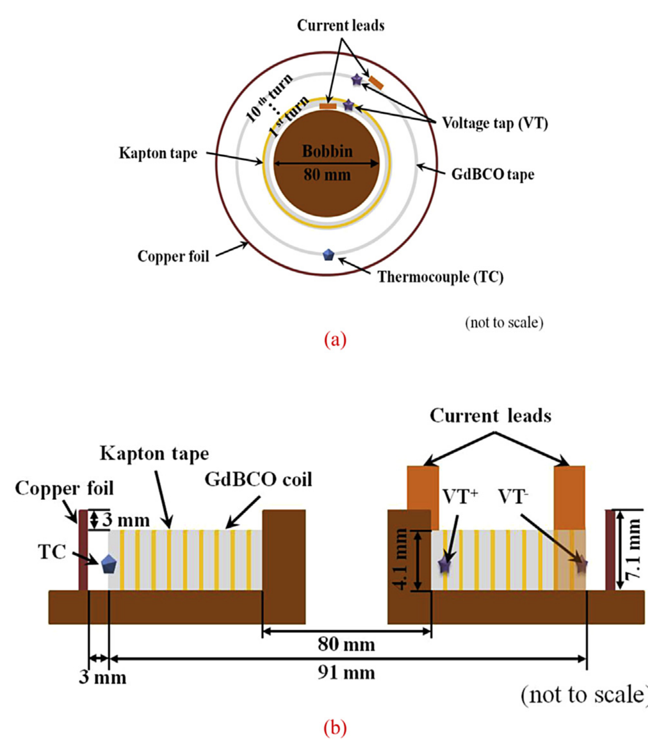

Fig. 1. Schematic drawings of the arrangement of an E-type thermocouple (TC), voltage taps (VTs), and a circular-shaped copper foil: (a) top view and (b) cross-sectional view.