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A Study on Thermal and Electrical Stabilities of GdBCO Coils Impregnated with Epoxy Composites Using Surface-Treated Carbon Nanotube Fillers

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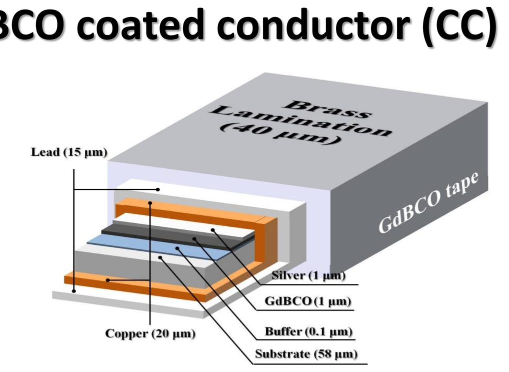
Abstract

Recently, there have been sustained efforts to develop novel epoxy composites including various fillers for improving the physical properties of the epoxy-impregnated superconducting coil. Among the various filler materials, carbon nanotubes (CNTs) have emerged as one of the promising candidates because of the high thermal conductivity as well as the superior mechanical strength. However, achieving the desired thermal and mechanical properties of CNT/epoxy composites is difficult due to poor dispersion of CNT fillers in epoxy resins. Therefore, the uniform dispersion of CNTs should be obtained through surface treatments such as acid treatment and amine treatment, to enhance the physical properties of superconducting coils impregnated with epoxy composites using the CNT fillers. In this study, the thermal and electrical characteristics of GdBCO coils impregnated with epoxy composites containing surface-treated CNT fillers were evaluated through the thermal quench, over-current, and repetitive cooling tests. In addition, the degree of dispersion of the CNT fillers in the epoxy resin was examined through scanning electron microscope (SEM) analysis.

Experimental setup

★ GdBCO coated conductor (CC)



< Schematic drawing of the GdBCO composite manufactured by SuNAM Co., Ltd. >

< Specifications of the GdBCO CC tape >

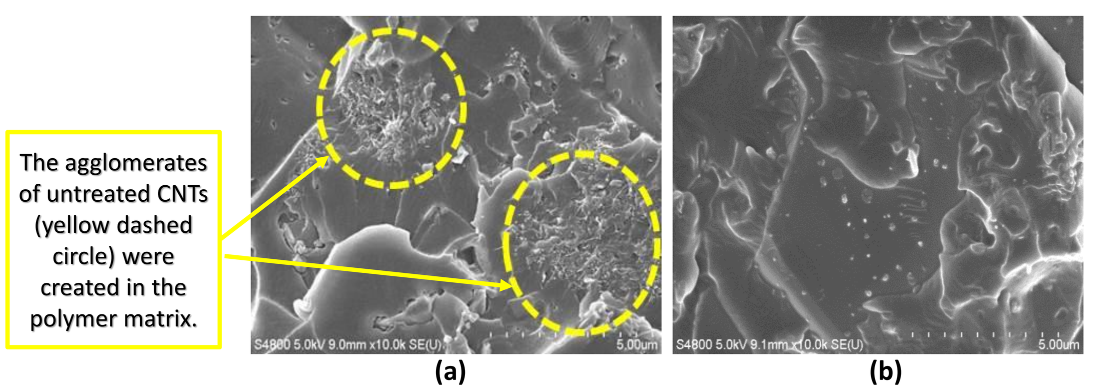
Parameters		Values
Company		SuNAM
Thickness	[mm]	0.25
Width	[mm]	4.10
Lamination		Brass
Stabilizer		Cu
Stabilizer thickness	[μm]	40
Buffer layer thickness	[μm]	0.085
GdBCO layer thickness	[μm]	1
Substrate		Hastelloy
Substrate thickness	[μm]	60

★ Procedure for epoxy composite preparation

< Specifications of the epoxy resin and filler used in this study >

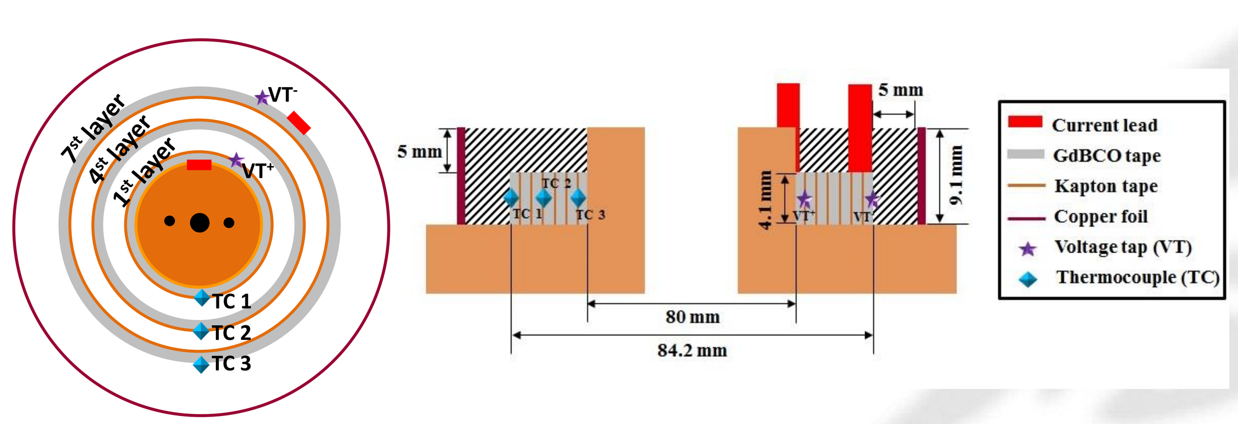
Parameters		Stycast 2850 FT
Company	[m]	Emerson and Cuming Co.
Thermal conductivity*	[W/m·K]	1.15
Coefficient of thermal expansion*	[ppm/°C]	111.5
Parameters		**CNT**
Company		Sigma-Aldrich, Korea
Categorized		Multi-Walled Carbon Nanotube
Outer diameter × length	[nm × μm]	6-9 × 5
Thermal conductivity*	[W/m·K]	~ 3000
Coefficient of thermal expansion* (for the radial direction; for the longitudinal direction)	[ppm/°C]	-1.5;7.5

*obtained at 293 K



< FESEM images of (a) epoxy/untreated CNT composites (10,000×) and (b) epoxy/acid-treated CNT composites (10,000×)>

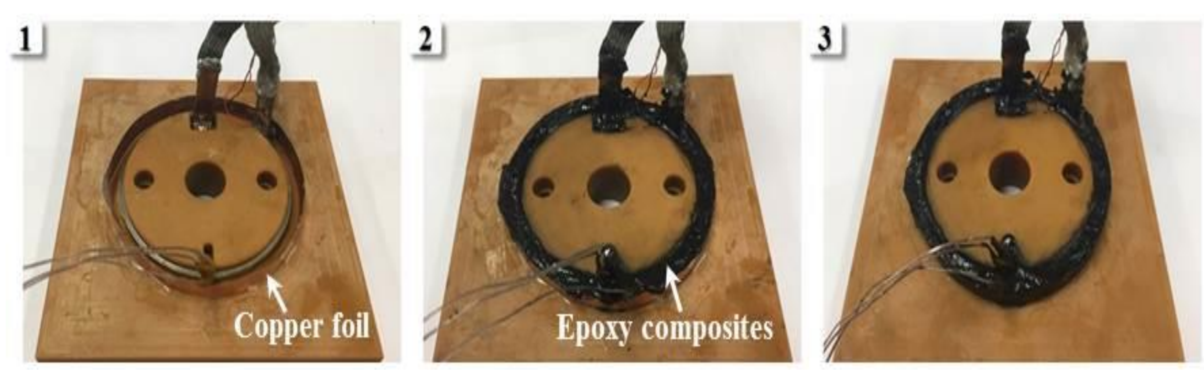
★ Coil construction



< Schematic drawings of the arrangement of an E-type thermocouple (TC), voltage taps (VTs), and a copper foil: (a) top view and (b) cross-sectional view >

< Specifications of the superconducting test coil >

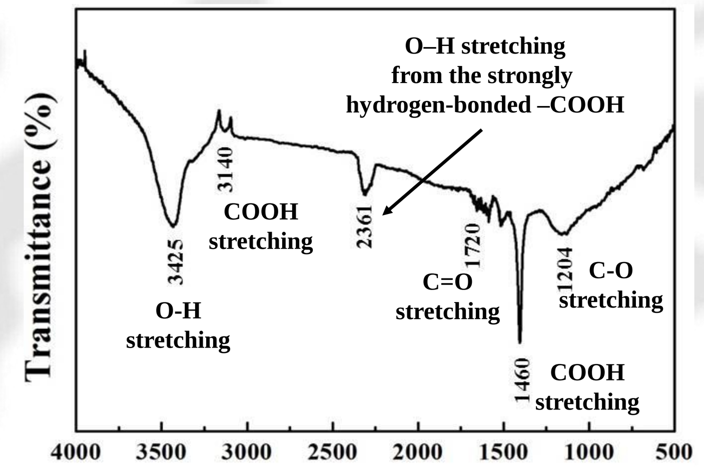
Parameters		GdBCO test coil	
Conductor length	[m]	1.8	
Inductance	[μH]	8.8	
Number of turns		7	
Inner diameter	[mm]	80	
Outer diameter	[mm]	84.2	
Insulation material		Kapton tape	
Insulation width; Thickness	[mm]	4.1; 0.06	
Parameters		**Coil 1**	**Coil 2**
Critical current @ 77 K	[A]	156	
Epoxy		Stycast 2850 FT	
Curing agent		Catalyst 23 LV	
Curing temperature		Room temperature	
Curing time		24	
Filler material		Untreated CNTs	Acid-treated CNTs
Filler content	[wt. %]	0.5	
Epoxy Thickness	[mm]	5	



< Photographs of the test coil during the impregnation procedure >

Results & discussion

★ Fourier transform infrared (FTIR) spectroscopy analysis

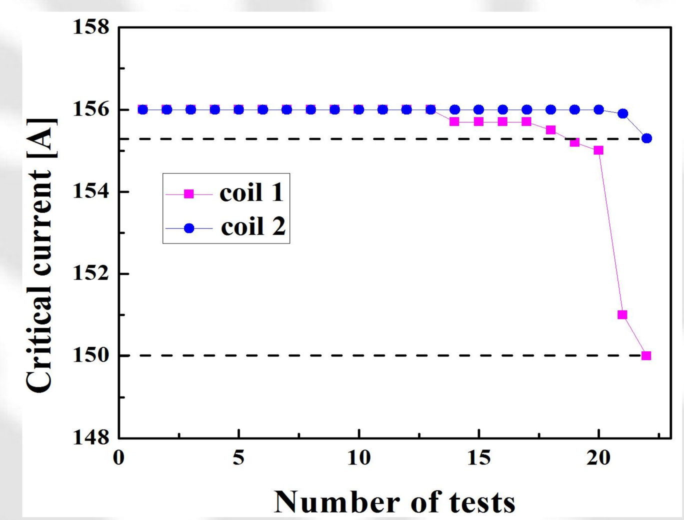


COOH stretching : 1460, 3140
C-O stretching : 1204
C=O stretching : 1720
O-H stretching : 3425
O-H stretching from the strongly hydrogen-bonded –COOH : 2361

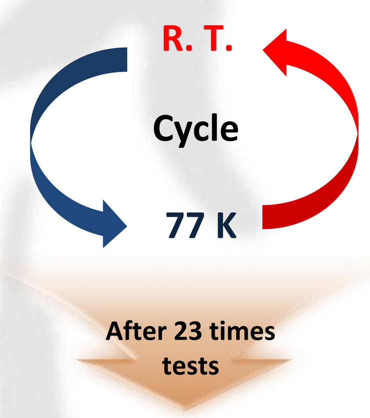
Carboxylic acid have successfully formed at the surface of acid-treated MWCNTs.

< FTIR spectrum of acid-treated multi-walled carbon nanotubes (MWCNTs) >

★ Repetitive-cooling test



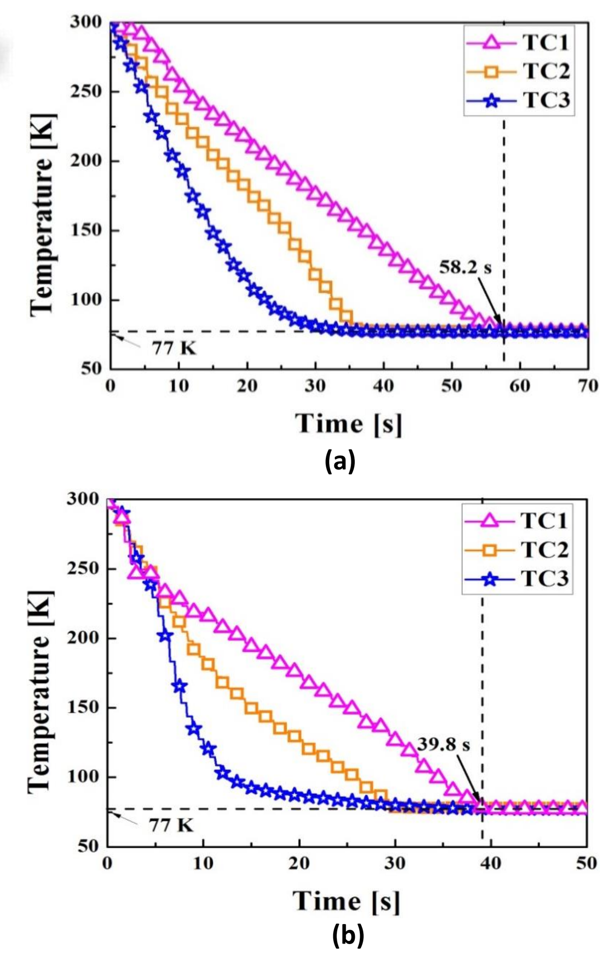
< Repetitive-cooling test results for coils 1 and 2 >



< The normalized I_c values of coils after the 23th test >

	Values
Coil 1	0.962 I_c
Coil 2	**0.996 I_c**

★ Cool-down tests

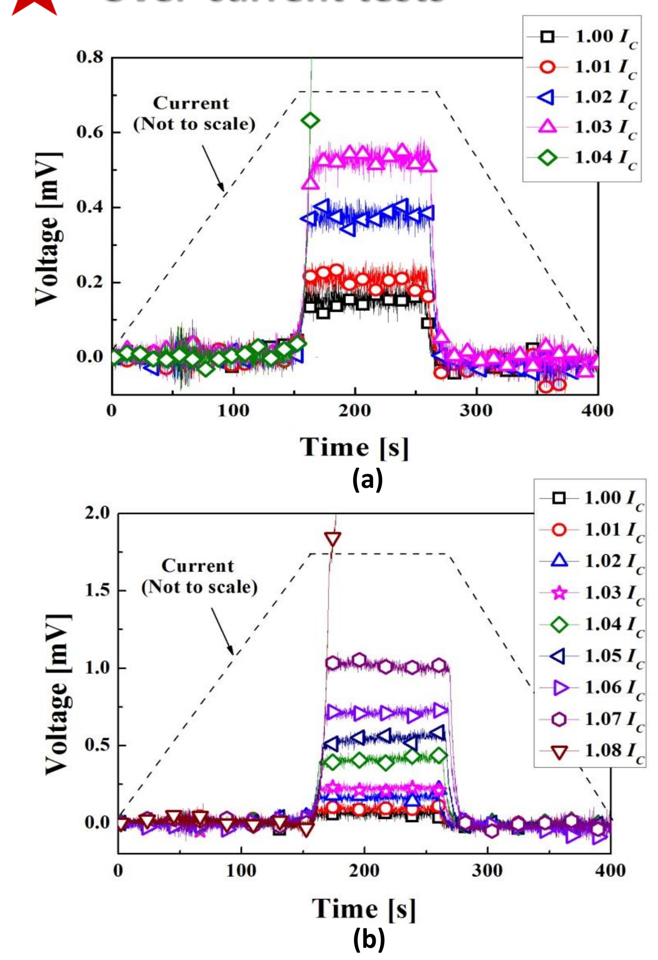


< Cooling test results for coil 1 (a) and coil 2 (b) obtained during cool-down from room temperature to 77 K >

< Results of cool-down tests >

	Total cooling time (to 77 K)
Coil 1	58.2 sec
Coil 2	**39.8 sec**

★ Over-current tests



< Over-current test results for coil 1 (a) and coil 2 (b) >

< The thermal runaway current of test coils>

	Values
Coil 1	1.04 I_c
Coil 2	**1.08 I_c**

Conclusion

★ From the FTIR spectrum, the carboxylic acid was confirmed to have successfully formed at the surface of acid-treated MWCNTs. Moreover, the images from scanning electron microscope (SEM) analysis indicated that uniform dispersion of CNTs could be achieved because of the carboxylic acid formed on the CNT surfaces.

★ In the cool-down and over-current tests, the coil impregnated with the epoxy/acid-treated CNT composite exhibited the superior performance due to enhanced thermal conductivity, which allowed effective cooling and heat transfer in the impregnated coil.

★ The repetitive-cooling test results indicated that the reduced degradation for the coil impregnated with epoxy/acid-treated CNT composite was attributed to the smaller difference between the CTE of GdBCO tape and epoxy composite.

Overall, the **addition of surface-treated CNTs to the epoxy composites** may be beneficial for achieving **highly stable** and **mechanically dense superconducting coils** with high thermal conductivities and low CTEs.