Cryogenics 90 (2018) 47–51

Contents lists available at ScienceDirect

Cryogenics

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

Research paper

Degradation of the performance of an epoxy-impregnated REBCO solenoid due to electromagnetic forces

T. Matsuda[a,b], T. Okamura[a], M. Hamada[c], S. Matsumoto[d], T. Ueno[e,b], R. Piao[b], Y. Yanagisawa[b,*], H. Maeda[b]

[a] Tokyo Institute of Technology, Yokohama 226-8502, Japan
[b] RIKEN Center for Life Science Technologies, Yokohama 230-0045, Japan
[c] Japan Superconductor Technology Inc., Kobe 651-2271, Japan
[d] National Institute for Materials Science, Tsukuba 305-0003, Japan
[e] Sophia University, Yotsuya, 102-8584, Japan

ARTICLE INFO

Keywords:
REBCO coil
Circumferential stress
Degradation
Electromagnetic force

ABSTRACT

Recently, degradation of a high-field REBCO coil due to strong electromagnetic forces, has been identified. This issue is related to a conductor movement, forming a kink in the conductor body, and hence epoxy impregnation should be effective to prevent it. The purpose of this paper is to examine the effect of epoxy impregnation on *the electromagnetic force-induced degradation* of a REBCO coil. We made an epoxy impregnated solenoid coil and charged it at 4.2 K in an external field of 11 T. A notable characteristic behavior, which is different from that of a dry or paraffin impregnated coil, was observed in the coil's performance. The coil did not show any normal voltage below 408 A, at 65% on the coil load line, but it showed a sudden voltage jump at 408 A, resulted from a sudden fracture of the REBCO conductor. The outward bending, combined with a strong circumferential stress, caused the REBCO layer to fracture. Although epoxy impregnation is effective to suppress a conductor movement inside the winding, avoiding self-supported sites at a coil edge is required to eliminate degradation of the thin and flexible REBCO conductor.

1. Introduction

High temperature superconducting (HTS) $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE: rare-earth)-coated conductors are promising materials for use in high field NMRs (Nuclear Magnetic Resonance) and MRIs (Magnetic Resonance Imaging), as they have a high engineering current density of the order of > 1000 A/mm^2 at high fields (12 T@ 4.2 K) and high tolerance against a tensile stress of > 700 MPa [1–3].

However, REBCO conductors possess significantly low resistance against peeling and cleavage [4,5]. Therefore, if a REBCO coil is impregnated with epoxy resin, winding turns are tightly bonded to each other and therefore a tensile stress concentration is created at the edge of the conductor during cool-down, resulting in peeling of a REBCO conductor and degradation of the performance of the coil. [4–7]. Considerable efforts have been invested to eliminate the *thermal stress-induced degradation* of epoxy impregnated REBCO coils, as epoxy impregnation is a common process for superconducting coil fabrication. Adequate procedures are to use polyimide electrodeposited REBCO conductors [7], thermal shrink-tube insulated REBCO conductors [8], fluorine coated insulation for REBCO conductors [9] and so forth. These procedures decouple the REBCO-conductors from the epoxy resin. If a REBCO coil is fabricated by dry winding or a paraffin impregnation method, thermal stress induced degradation of the coil performance does not appear, as the REBCO conductors are not bonded to each other, and therefore peeling of a conductor during cool-down is suppressed [4].

Although it was originally considered that REBCO coils fabricated by the above-described process do not show premature quenches, we have recently identified the existence of premature quenches due to an electromagnetic force [10,11]. In one example, a high field superconducting magnet, comprised of a REBCO inner coil, a Bi-2223 middle coil, and a Nb_3Sn/NbTi outer coil, showed a premature quench, initiated from the paraffin-impregnated REBCO coil at 27.7 T (288 A) [10]. The quench current, 288 A, corresponded to the circumferential stress of 286 MPa, only $< 50\%$ of the tolerance limit of the tensile stress of the conductor. Therefore, the premature quench is not due to the excessive circumferential stress but to a previously unrecognized mechanism.

* Corresponding author.
E-mail address: yoshinori.yanagisawa@riken.jp (Y. Yanagisawa).

https://doi.org/10.1016/j.cryogenics.2018.01.002
Received 10 November 2017; Received in revised form 29 December 2017; Accepted 3 January 2018
Available online 06 January 2018
0011-2275/

Based on our previous investigations, macroscopic movement of a REBCO conductor caused by an electromagnetic force leads to permanent deformation such as buckling and kinking of the REBCO conductor, as the conductor is very thin and flexible [12,13]. It results in a decrease in the local critical current, and therefore a premature quench is initiated. The dry winding and paraffin impregnation methods are sometimes insufficient to suppress such macroscopic movement of REBCO conductors [12]. Thus, from this point of view, the epoxy impregnation method seems to be preferred to the dry-winding and paraffin-impregnation methods, which is contrary to the case of *the thermal stress-induced degradation* [4]. However, the effect of epoxy impregnation on premature quenches due to the strong electromagnetic force is still unclear.

The purpose of this paper is to investigate the effect of epoxy impregnation on premature quenches caused by an electromagnetic force, i.e. *the electromagnetic force-induced degradation*. An epoxy impregnated REBCO solenoid coil was fabricated using a polyimide-electrodeposited REBCO conductor as described above; note that such a conductor effectively removes *the thermal-stress induced degradation* in the coil performance [7]. It was charged at 4.2 K in an external magnetic field of 11 T to examine the occurrence of premature quenches by the strong electromagnetic force. Based on the results, a general classification of *the electromagnetic force-induced degradation* in the REBCO coil performance will be discussed.

2. Experimental details

The REBCO conductor was a commercial product of SuperPower Inc. (SCS4050). A polyimide-coating was electrodeposited on the surface of the conductor by Mitsubishi Cable Industries Inc. The thickness of the polyimide-coating was ~10 µm.

A solenoid coil was wound with the REBCO conductor. The physical parameters of the coil are listed in Table 1; 80.0 mm in inner diameter, 81.0 mm in outer diameter and 94.8 mm in height. A wet winding process with epoxy (STYCAST 2850 FT) was employed, as vacuum impregnation was difficult owing to the small space between turns and layers. A small roughness appeared on the cured coil surface, as the conductor was very thin and flexible. The coil was charged in liquid nitrogen before the test at 4.2 K in an external magnetic field.

Fig. 1 shows a load line of the REBCO coil under an external magnetic field of 11 T, generated by a NbTi/Nb_3Sn coil installed in the National Institute of Materials Science (NIMS). The intersection between the load line and the short sample critical current gives the coil critical current of 621 A, which corresponds to 1553 A/mm^2 in conductor current density, 11.574 T in magnetic field and 718 MPa in circumferential stress.

After the magnet was cooled to 4.2 K, the outer coil was charged to 11 T and then the REBCO coil was charged. The coil current, coil voltages and central magnetic field were recorded during the coil charge/discharge test.

Table 1
Parameters of the REBCO coil.

	Unit	Value
Conductor		
REBCO conductor	–	SuperPower SCS4050
Width: thickness (bare)	mm	4.0: 0.1
Insulation	–	10 µm-thick polyimide
Critical current at 77 K	A	65
n value at 77 K	–	24
Coil winding		
ID: OD: Length	mm	80.0: 81.0: 94.8
Conductor length	m	24
Total number of turns	–	92
Number of layers	–	4
Coil constant	mT/A	0.928
Maximum B_zJR at 400 A in 11 T	MPa	440
Self inductance	mH	0.413

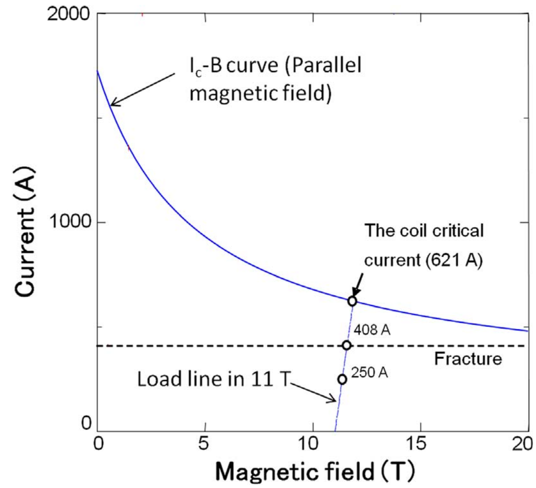

Fig. 1. The load line of the REBCO solenoid coil in an external magnetic field of 11 T. Conductor damage appears at 408 A, 65% on the coil load line. When the coil is discharged, the normal voltage remains in the range from 410 A to 250 A, showing a reduction in critical current by 61%.

3. Experimental results

3.1. The coil performance at 77 K under a self-field

Fig. 2 shows the voltage vs. current characteristic for the REBCO coil at 77 K. The coil critical current of 65 A can be seen in Fig. 2. Thus, *thermal stress-induced degradation* in the coil performance was suppressed by the polyimide electrodeposition as we expected [7].

3.2. The coil performance at 4.2 K in an external field of 11 T

Fig. 3(a) shows the coil voltage vs. current characteristic at 4.2 K in an external magnetic field of 11 T. The coil was in the superconducting state below 406 A as shown by the open red circle. The coil voltage suddenly jumped to 0.9 mV at 408 A as shown by the transient voltage signal in Fig. 3(b); the time duration of the voltage jump was as short as < 40 ms. The current, 408A, was only 66% on the coil load line as seen in Fig. 1. The corresponding circumferential stress for the conductor is 469 MPa, 67% of the tolerable tensile stress of 700 MPa. As the coil voltage becomes nearly constant at 1.15 mV from 408 A to 410 A, the voltage jump is not due to a thermal runaway but to the sudden failure of the REBCO conductor due to the electromagnetic force; it originated from an abrupt reduction in the local critical current, giving rise to the sudden rise of the normal voltage. To determine the degraded

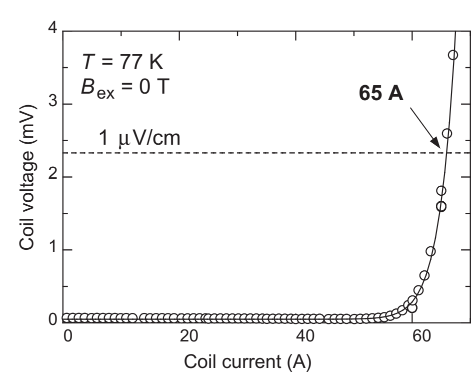

Fig. 2. The voltage vs. current characteristic at 77 K in the self-field. There is no degradation in the coil performance due to cool down.