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Bi-based HTS insert coils at high stress levels

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Abstract

Bi-2212 and Bi-2223 conductors from commercial sources are wound into double pancakes using the react and wind approach. One of the Bi-2223 conductors as supplied is reinforced with stainless steel strips. *I–V* characterization at 4.2 K until failure of the pancakes, in a 19 T–0.17 m cold bore magnet assembly, is performed. This gives insight in the operational limits of these conductors in conditions representative of insert magnets. The results are compared to the linear stress–strain properties of the conductors.

Keywords: React and wind; Strain; Bi-2212; Bi-2223

1. Introduction

One of the applications for HTS conductors is in magnets that, in combination with metallic superconductors, generate on the order of 25 T. Three react and wind coils are considered here with dimensions relevant to that application. Goals are understanding the role of bending strain and the effectiveness of reinforcement against Lorentz-force induced strain. A generalized plane strain model [1] is applied to estimate gradients in stress and strain. Both bending strain and Lorentz-force induced strain are highest at the inner turns, and this is where the first I_c degradation is expected. To optimize the average current density and therefore magnetic field generated by a magnet, it is desirable to use the minimum amount of reinforcement needed to keep the sum of bending and Lorentz-force induced strain below the critical value.

2. Experimental

2.1. Coils

All coils are epoxy impregnated double pancakes wound from a single piece of reacted multifilamentary conductor and equipped with multiple voltage taps and without bore tubes or other extraneous materials that have a reinforcing effect on the windings. Coils A and C rely on co-wound Kapton with adhesive for insulation, with a total thickness of about 35 μm. Coils B and C are reinforced, the latter with about twice as much steel. Co-winding with a stainless steel tape

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Table 1
Conductor and coil properties

Property	Unit	A	B	C
Conductor thickness	mm	0.19	0.19	0.243
Conductor width	mm	3.0	4.95	2.92
Conductor length	m	39.5	65	34.6
Ceramic		Bi-2223	Bi-2212	Bi-2223
Inner diameter	mm	97	106	97
Outer diameter	mm	126	147	127
Winding thickness	mm	14.5	20.5	15
# Turns		113	166	98
Reinforcement		None	Steel (co-wound)	Steel
Reinforcement thickness	μm	–	$1 * 27$	$2 * \sim 30$
Insulation		Kapton	Ceramic	Kapton
Coil height	mm	6.6	10.2	7.0

provides reinforcement for coil B. To insulate the steel, prior to winding, a 8 μm MgO-doped ZrO_2 layer is deposited using the sol–gel approach [2]. The measured Young's modulus of the steel is 207 GPa at 4.2 K. The production process for the conductor C includes a lamination step where stainless steel strips are soldered to each side of the conductor. More details are given in Table 1.

2.2. Conductor mechanical properties

2.2.1. Linear stress–strain behavior

Measured linear tensile stress–strain properties at 77 K are given in Fig. 1. For conductor C the company specifications of 78 GPa are presented. Conductor A exhibits a sharp decrease in I_c for strain levels around 0.38%, the unreinforced conductor B around 0.45%, conductor C degrades at 0.5%. Notice that unreinforced conductors become very plastic for strains slightly exceeding critical. The curve for "B+reinforcement" is calculated based on the measured properties of the material used.

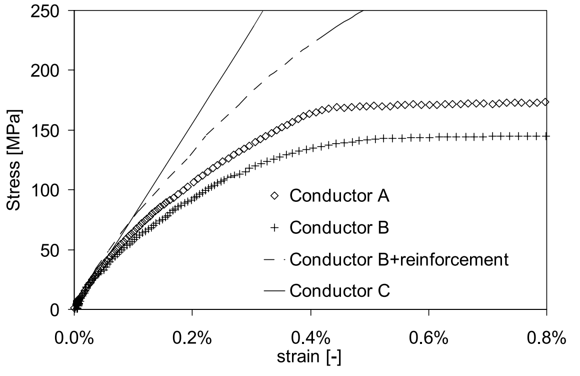

Fig. 1. Tensile stress–strain properties of all conductors at 77 K.

2.2.2. Bending strain

After heat treatment and spooling, each conductor has a specific curvature when in a relaxed state, free of external strain. Upon bending to the diameters used in the coils and release, the conductors relax to a diameter between the original and to which is was bent, indicating that the bending process is partially elastic, partially plastic [3]. Assuming the plasticity corresponds to plastic yield of the matrix, based on the absence of I_c degradation, the surface strain on the conductor as bent can be estimated from the difference between the bent and relaxed diameter. The ratio of that strain and the pure elastic strain, corrected for the initial curvature, is taken as the degree of elasticity. Since the filaments are not on the surface, the calculated maximum tensile strain on the filaments, $\varepsilon_{\mathrm{BEND,MAX}}$ is obtained by scaling the surface strain with the ratio of the thickness of the filament zone over the total thickness. The results are summarized in Table 2.

Table 2
Conductor bending properties

Property	Unit	A	B	C
Degree of elasticity	%	75	84	>99
$\varepsilon_{\mathrm{BEND,MAX}}$	%	0.13	0.09	0.12

3. Results and discussion

All reported I_c measurements are performed at 4.2 K using the 10^{-4} V/m criterion and in a background magnetic field of 19.2 T at the windings of the HTS coils. The operating current I_{op} is cycled between zero and increasingly higher peak values, as high as thermal stability allows. Average Lorentz-force induced stress in the windings, $\sigma_{\text{L-ave}}$, is calculated using the peak operating current, total number of turns and the winding cross section as detailed in Table 1. The corresponding stress and strain at the inner turns, $\varepsilon_{\text{L-inner}}$ are estimated to be 12% above the average for coils A and C, 19% for coil B. The engineering current density is defined as the critical current divided by the product of conductor thickness and width. An overview of coil properties is given in Table 3 and Fig. 2.

Significant degradation occurs in the inner turns of *coil A* at 74 A, using a 10% I_c reduction as criterion. This corresponds closely to the 0.38% limit for linear strain at cryogenic temperature minus the calculated $\varepsilon_{\text{BEND,MAX}}$ of 0.13%.

The strain-induced degradation of I_c spreads from the inner turns outward with increasing operating current, as presented in Fig. 3. Each voltage taps covers a section identified by the radial distance to the inner turn of the coil and location in either the top or bottom pancake. The degradation progresses less then 3.4 mm from the inner turn with an increase of average stress from 96 to 105 MPa.

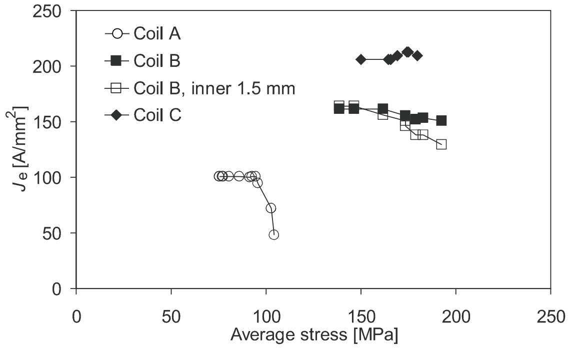

Fig. 2. Relation between the engineering current density and the average Lorentz-force induced stress in the windings in a 19 T background field. Lines are a guide to the eye. The datapoint at the lowest stress for each curve corresponds to I_c.

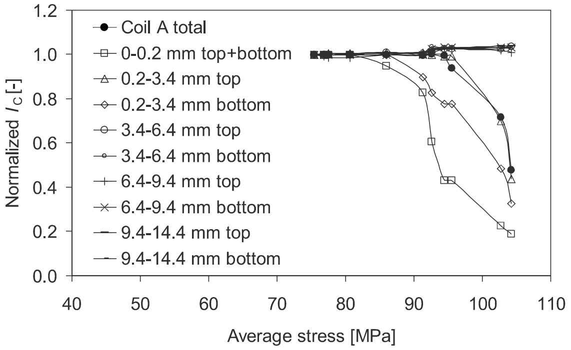

Fig. 3. Normalized critical current versus average coil stress for sections of coil A, identified by radial distance from inner diameter and top/bottom pancake. Lines are a guide to the eye. Sections beyond 3.4 mm show no degradation and differ insignificantly from each other.

In *coil B*, the first degradation is observed at the inner turns (0–1.5 mm radially) with an operating current of 168 A. At 180 A the degradation is still limited to 10%, and in the inner turns only. The inner turns degrade further and the complementing sections of each pancake show minor degra-

Table 3
Coil properties at 19 T, 4.2 K

Property	Unit	Coil A	Coil B	Coil C
Initial I_c	A	59	152	146
I_{op} at 10% degradation	A	74	168	–
Corresponding $\sigma_{\text{L-ave}}$, $\varepsilon_{\text{L-inner}}$	MPa/%	86/0.24	173/0.36	–
Corresponding $\varepsilon_{\text{L-inner}} + \varepsilon_{\text{BEND,MAX}}$	%	0.37	0.45	–
Maximum I_{op}	A	82	200	175
Maximum $\sigma_{\text{L-ave}}$, $\varepsilon_{\text{L-inner}}$	MPa/%	105/0.27	193/0.39	180/0.26
Final I_c	A	28	142	148

dation of about 1% at the maximum operating current of 200 A.

Coil C carries a similar I_c of 146 A at 19 T. No strain-induced degradation is observed up to 175 A, only a slight I_c increase due to changes in the magnetization state.

The results for coil A shows that, when the maximum filament strain is calculated as the sum of elastic part of the bending strain and Lorentz-force induced strain, the strain at the onset of I_c degradation in this unreinforced Ag–alloy matrix coil corresponds to the critical strain for the conductor in uniaxial tension. Reinforcement is required for similar conductor with the higher current densities typically required of insert coils [4].

For coil B, 10% degradation in inner turns due to bending and Lorentz-force induced strains is expected at around 180 A, assuming a 0.45% critical strain based on uniaxial strain test of the conductor at 77 K. However, the onset is at a signifiantly lower current, and the slope of I_c versus stress is less then expected. It is possible that a stress concentration due to winding imperfections at the transition turn between the pancakes causes premature but limited I_c degradation. The slight 1% I_c degradation for the sections outward of 1.5 mm from the inner turns at the maximum operating current indicates that that section of the windings has reached its strain limit and an increased rate of degradation is expected for higher stress levels.

Considering that the strength of conductor B is less then conductor A, the reinforcement is effective in increasing the tolerable stress level.

Since the materials present in coil B before impregnation tolerate temperatures of several hundred °C, the option exists to release almost all bending strain through annealing. Thereby insert coils with much smaller inner diameters, limited by the diameter at which bending strain induced degradation occurs, can be wound using the same conductor and reinforcement.

Coil C did not degrade at the highest achievable average stress of 180 MPa, at an operating current 20% above I_c. The estimated maximum strain at the inner turns, $\varepsilon_{\text{L-inner}} + \varepsilon_{\text{BEND,MAX}}$, is 0.38%. This conductor can be applied at higher stress/strain levels. Alternatively, depending on the application, the average current density and field generation can be improved using thinner reinforcement.

4. Summary

Three HTS coil are characterized in a 19.2 T background magnetic field, two of which use reinforcement.

The onset of degradation can be modeled accurately for unreinforced coils.

Co-wound steel is effective in reducing Lorentz-force induced strain, as are steel strips laminated to bare conductor before coil winding. All observed strain induced degradation begins at the inner turns, where both the bending strain and Lorentz-force induced strain are highest. The degradation begins at operating currents well above I_c. Stress tolerance and current densities in the reinforced coils are useful for HTS insert coils.

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