Degradation of the performance of a YBCO-coated conductor double pancake coil due to epoxy impregnation

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Abstract

Now that YBCO-coated conductors have been commercialized, a number of YBCO coils have been developed. However, their basic performances have not been systematically investigated so far. Here, we demonstrate that of a YBCO double pancake coil. The critical current of an epoxy impregnated YBCO double pancake coil was substantially degraded, i.e. the normal voltage appears above 8 A, only 18 % of that for the dry coil. It was inferred that degradation occurs if the cumulative radial stress developed during cool down exceeds the critical transverse stress for the YBCO-coated conductor (typically 10 MPa). Under these conditions**,** the conductor was debonded at the interface between the buffer layer and YBCO layers, or fractured in the YBCO layer itself, causing cracks on the YBCO layer, resulting in a significant decline of the critical current. These negative effects are suppressed if the coils are dry wound or impregnated with paraffin, as the bonding strengths between turns are negligible and therefore turns are separated if the cumulative radial stress tends to be tensile. For non-circular coils in which epoxy impregnation is inevitable, degradation due to cumulative tensile transverse stress is still the major problem.

Keywords:

YBCO

YBCO coil

Degradation in coil performance

Epoxy impregnation

Radial tensile stress

Delamination

Thermal contraction

Lorentz force

1. Introduction

Superconducting magnets operated in the temperature range below 20 K generate enormous stresses on the conductors. It is possible to achieve a high current density through the use of commercial $YBa_2Cu_3O_{7-x}$ (YBCO)-coated conductors that can tolerate longitudinal stresses of 700 MPa [1]-[4]. Otsuka and Kiyoshi [5] demonstrated that the current density of an ultra-high field superconducting NMR magnet**,** such as that used at >1.0 GHz (23.5 T), is mainly dominated by the conductor hoop stress. Assuming a conductor hoop stress of 300 MPa in a 1.3 GHz NMR magnet design, the coil volume becomes 1/8 of that needed for a 200 MPa hoop stress. A value of the hoop stress as high as 300 MPa is only possible with YBCO-coated conductors. Thus, the superconducting coil volume is substantially reduced if we take advantage of YBCO-coated conductors.

Though a YBCO-coated conductor tolerates axial tensile stress well, it is easily delaminated and degraded by transverse tensile stress; DC van der Laan et al.[6] showed that the critical current of a YBCO-coated conductor is significantly degraded under a transverse tensile stress of 10 MPa, while it tolerates a compressive transverse stress of 120 MPa.[7,8] Thus, it is probable that such anisotropic stress tolerance affects the performance of YBCO-coated conductor circular coils.

Arp[9], Williams and Bobrov [10], and Urata and Maeda [11][12] demonstrated that coil winding, cool down and Lorentz force result in a radial-stress distribution in a circular coil such as a solenoid or double pancake [13]. The radial stress in a circular coil corresponds to the transverse stress applied to the YBCO-coated conductor. Therefore, if the cumulative radial stress exceeds the critical transverse strength such as +10 MPa, it is probable that the stress will adversely affects the YBCO-coated conductor in the coil winding, resulting in degradation of the YBCO coil performance. This phenomenon has not been reported so far in YBCO-circular coils; it is demonstrated here for a single YBCO double pancake coil operated at 77 K.

The topics investigated are as follows: (a) the effect of epoxy impregnation on the current-voltage characteristics of YBCO circular coils and (b) the microstructure of the degraded YBCO-coated conductor in the coil winding. These results will be discussed based on a structural analysis of the YBCO coil winding.

2. Experimental procedure

A double pancake coil was dry wound with a commercial YBCO-coated conductor (SuperPower Inc. SCS4050) [1] around a 3 mm thick fiber reinforced plastic

(FRP) coil form without winding tension. The YBCO-coated conductor is 4.1 mm in width and 0.1 mm in thickness; a 35 μm thick Kapton tape is adhered on an outer side of the conductor. The short sample critical current is 96 A at 77 K. The YBCO coil winding is 30 mm in inner diameter, 38 mm in outer diameter and 8.8 mm in length. The number of turns is 27×2 and the length of the YBCO-coated conductor is 5.6 m.

A single YBCO double pancake coil was energized at 77 K until the electric field in the coil exceeded 1 μV/cm, i.e. 560 μV. It was then warmed up to room temperature. The sequence of testing at 77 K and warming up to room temperature was repeated 5 times.

The YBCO coil was then immersed in epoxy resin (Emerson & Cuming, Stycast 1266) for several hours, and hardened in an oven at 338 K for 50hr. It was cooled to 77 K and energized until the electric field in the coil again exceeded 1 μV/cm, i.e. 560 μV. This thermal cycle was repeated 5 times.

3. Experimental results

3.1 Current-voltage characteristics

The current-voltage (*I*-*V*) characteristic of a dry double pancake coil is represented by black closed circles in Fig. 1. The normal voltage appears above 45 A and the coil critical current, corresponding to 1 μV/cm (i.e. 560 μV), is 54 A. The latter value coincides with an intersection, 52 A, between the coil load line and a short sample critical current for the YBCO-coated conductor. Therefore, no degradation appears to be present in the YBCO dry coil. The *n*-index value for the *I*-*V* curve seen in Fig. 1 is 27, equivalent to that for a short sample. These characteristics did not change after 5 thermal cycles.

The current-voltage characteristic for the epoxy impregnated double-pancake is shown by the blue open squares in Fig. 1; coil degradation is obvious**,** as the normal voltage appears above 8 A, only 18 % of that (45 A) for the dry coil, and the coil critical current is 31.5 A, 58 % of that (54 A) for dry coil. The *n*-index is as low as 3. These results demonstrate that parts of the YBCO-coated conductor in the coil winding are damaged by cool down resulting in coil degradation as the Lorentz force in this experiment is negligible small (~0.1 MPa). The critical current for damaged sections may be as low as 8 A.

The current-voltage (*I*-*V*) characteristic of a paraffin impregnated double pancake coil is represented by red open triangles in Fig.1; it will be referred later.

3.2 Microstructure of the degraded coil section

After the sequence of thermal cycles, we unwound the epoxy impregnated coil from the outer surface; voltage taps and current lead were soldered on each layer to measure the current-voltage characteristics. In this way, we could determine the damaged winding section. A schematic drawing of a current lead and voltage-tap pairs, V_1 to V_6, on the 6^{th} layer is shown in Fig. 2(a); the current-voltage curves for each voltage-tap pairs are shown in Fig. 2 (b). The normal voltages appear above 6 A for V_3, V_4, V_5, and V_6, while not for V_1 and V_2. Thus, the winding section corresponding to V_3 to V_6 is substantially degraded; this turned out to be in the 6^{th} layer.

After the current-voltage measurements, we cut out a degraded section, V_3, seen in Fig. 2(a). A wrinkle was found on the outer surface of the conductor and when we removed the edge of the conductor using sandpaper, the YBCO-coated conductor delaminated into two parts, as seen in Fig 3(a). Figure 3(b) shows the microstructure of a fracture surface of the outer part of the delaminated conductor, taken by a scanning electron microscope (SEM). Elemental composition analysis was simultaneously carried out with an energy dispersive spectroscopy (EDS). Figure 3(c), (d) and (e) show the EDS intensities for Ba (green), Ag (red) and Mg (orange). The presence of Ba corresponds to a YBCO layer, Ag to a silver surface layer on the YBCO[1] and Mg to a MgO buffer layer. As seen in Fig. 3 (c), YBCO (Ba) distributes over the fracture surface and cracks run randomly on the YBCO layer as seen in Fig. 3(b). However, Fig. 3(d) shows that the YBCO (Ba) signal is rather weak on the left side, while that of Ag is strong in that area. Furthermore, the Mg buffer layer (orange) distributes on the right side as seen in Fig. 3(e). In summary, the YBCO layer itself is fractured on the left side, while a debonding occurs at the interface between the YBCO layer and the buffer layer on the right side. Note that the coil transport current is in the horizontal direction in these figures.

Thus, we have demonstrated that in the case of epoxy impregnated YBCO-coated conductor coils, the conductor is fractured during cool down, causing cracks on the YBCO layer. They significantly degrade the critical current of the YBCO conductor over several cm in longitudinal length and the normal voltage develops at extremely low currents, as seen in Fig. 1. Similar delamination phenomenon for a YBCO coated conductor was reported by Sugano et. al..[14]

4. Discussion

4.1 Structural analysis

The radial stress distribution in an epoxy impregnated double pancake coil due to winding, cool down, and Lorentz force has been numerically analyzed. [9-12] Each of the coil form, conductor and insulator layers is regarded as an infinitely long thin cylinder, contacting elastically each other. Continuity of the radial-displacement and radial-stress at the interfaces gives a set of simultaneous equations, which is solved numerically. The physical parameters used in the numerical calculation are tabulated in Table 1.

The radial stress distribution due to cool down in the double pancake is shown in Fig. 4(a); the effects of winding and Lorentz force are neglected in the calculation, as the winding tension is negligible and the Lorentz force is small. Due to large thermal contractions of the interlayer insulator and the FRP coil form, a tensile radial stress develops in the coil winding. It has a peak of +4.5 MPa in the 10^{th} layer; the peak stress is close to the delamination strength of +10 MPa for the YBCO-coated conductor under transverse tensile stress.[6] Furthermore, the radial position of the peak is close to that of the degraded layer found experimentally and displayed in Fig. 3. Thus, we infer that if a YBCO coil is epoxy impregnated, the tensile radial stress developed during cool down delaminates the YBCO-coated conductor in the coil winding.

If the winding tension is sufficiently large, such as 100 MPa, the cumulative radial stress is compressive over the double pancake after cool down as seen by the circles in Fig. 4(b); the cumulative radial stress here is the sum of the compressive radial stress due to winding (squares) and the tensile radial stress due to cool down.

Thus, it is probable that the YBCO double pancake is not delaminated after cool down.

A similar scenario is applicable to the Lorentz force; if the cumulative radial stress due to winding, cool down and Lorentz force exceeds the critical transverse stress, typically +10 MPa, the YBCO-coated conductor is delaminated instantly and thus the coil voltage jumps abruptly, as seen in the coil quenching of low temperature superconducting magnets. [9-13] In the next coil charge, the coil current for the superconducting-normal transition will be significantly reduced.

4.2 Effect of dry winding and paraffin impregnation

In the case of a YBCO dry double-pancake, the turns are separated if the cumulative-radial stress tends to be tensile, as there is no bonding strength between turns.[15] Even if compressive radial stresses appears in the coil winding, the YBCO-coated conductor is highly tolerant to them,[7,8] and they do not harm the coil performance.

We impregnated another YBCO double pancake with paraffin. The result is seen by the red open triangles in Fig. 1; the coil attained a short sample critical current without degradation. As the bonding strength of paraffin is negligible small, the turns are separated easily by a small amount of tensile cumulative radial stress; therefore, degradation does not appear also in this case.

Thus, dry winding and paraffin impregnation instead of epoxy impregnation seem to be effective to avoid coil degradation. However, in case of non-circular coils such as a race track and an accelerator dipole, epoxy impregnation is inevitable, and therefore degradation due to cumulative tensile transverse stress remains the major problem for the magnet. Further investigations must be made in this regard.

5. Conclusions

(1) The critical current of epoxy impregnated circular coils wound using YBCO-coated conductors are substantially degraded in use. Degradation occurs if the cumulative radial stress developed due to winding, cool down and Lorentz force exceeds the critical transverse stress for the YBCO-coated conductor**,** typically +10 MPa.

(2) The YBCO conductor is fractured at the interface between the buffer layer and the YBCO layer, or at the YBCO layer itself, causing cracks on the YBCO layer resulting in significant decline of the critical current. This results in an extremely early superconducting-normal transition of the current-voltage curve for the circular coil.

(3) Dry winding and paraffin impregnation suppress degradation as the bonding strength between turns is negligible and therefore turns are separated if the cumulative radial stress tends to be tensile.

(4) For non-circular coils in which epoxy impregnation is inevitable, degradation due to cumulative transverse tensile stress is still the major problem.

Acknowledgments

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Reference

1. C. Weber, Status of 2G HTS wire technology development and manufacturing at SuperPower, *Presentated at the EPRI Superconductivity Conference*, Oak Ridge, TN, USA, November 12-13, 2008.
2. W. Xiaorong, P. Soren, D. Daniel, G. Arno, C. Dan, S. GianLuca, F. Helene, Application of YBCO tape conductors to high-field accelerator magnets, Presented at the 21st International Conference on Magnet Technology, 5AO-04, Hefei, China, Octover 18-23, 2009.
3. M. Sugano, K. Osamura, W. Prusseit, R. Semerad, T. Kuroda, K. Ito, and T. Kiyoshi, Reversible strain dependence of critical current in 100A class coated conductor, *IEEE Trans. Appl. Supercond.* **15**, 2005, 3581-3584.
4. N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Freeman and A. Goyal, Reversible axial strain effect and extended strain limits in Y-Ba-Cu-O coating on deformation-textured substrates, *Appl. Phys. Lett.* **83**, 2003, 4223-4225.
5. A. Otsuka and T. Kiyoshi, High field magnet design under constant hoop stress, *IEEE Trans. Appl. Supercond.* **18**、2008, 1529-1532.
6. D. C. van der Laan, J. W. Ekin, C.C. Clickner, T. C. Stauffer, Delamination strength

of YBCO coated conductors under transverse tensile stress, *Supercond. Sci. Technol.*, **20**, 2007, 765-770.

7. N. Cheggour, J.W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman, Transverse compressive stress effect in Y-Ba-Cu-O coatings on biaxially textured Ni and Ni-W substrates, *IEEE Trans. Appl. Supercond.*, **13**, 2003, 3530-3533.
8. N. Cheggour, J.W. Ekin, C. L. H. Thieme and Yi-Yuan Xie, Effect of fatigue under transverse compressive stress on slit Y-Ba-Cu-O coated conductor, *IEEE Trans. Appl. Supercond.*, **13**, 2003, 3530-3533.
9. V. Arp, Stresses in superconducting solenoids, *J. Appl. Phys.* **48**, 1977, 2026-2036.
10. J. E. C. Williams and E. S. Bobrov, magnet system of the 500MHz NMR spectrometer at the Francis Bitter National Magnet Laboratory: II. Disturbances, quenches, and training, *Rev. Sci. Instru.***52**, 1981, 657-661.
11. M. Urata and H. Maeda, Relation between radial stress and quench current for tightly wound dry solenoids, *IEEE Trans. on Magnetics* **MAG-23**, 1987, 1596-1599.
12. M. Urata and H. Maeda, Stabilization of superconducting dry solenoids, *IEEE Trans. Magn.*, **25**, 1989, 1528-1531.
13. H.Maeda, M. urata, H. Ogiwara, S. Miyake, N. aoki, M. Sugimoto and J. Tani,

Stabilization for wind and react Nb_3Sn high field insert coil, *Proc. of the 11th International Conf. on Magnet Technology*, 1989, 1114-1119 .

14. M. Sugano, T. Nakamura, K. Shikimachi, N. Hirano, and S. Nagaya, Stress tolerance and fracture mechanism of solder joint of YBCO coated conductors, *IEEE Trans. Appl. Supercond.* **17**, 2007, 3067-3070.

15. M. N. Wilson, Superconducting Magnets, Clarendon Press Oxford, 1983.

Figure Captions:

Figure 1. Current-voltage (*I*-*V*) characteristics obtained for a single YBCO-coated conductor double pancake. The *I*-*V* curve for epoxy impregnated coil shown by the blue open squares shows a significant degradation in the critical current**,** while those for a dry coil (black closed circles) and a paraffin impregnated coil (red open triangles) coincide with that of a short sample.

Figure 2. (a) A schematic of a current lead and voltage taps soldered on the 6th layer. (b) Current-voltage curves taken for voltage-tap pairs; $V_{3,}$ $V_{4,}$ V_5 and V_6 show significant degradation, while those for V_1 and V_2 do not show degradation.

Figure 3. (a) A wrinkle on the 6th layer of the YBCO-coated conductor, which was found when we unwound the coil. The YBCO–coated conductor fractured into two just after its edge was removed by sandpaper. (b) Microstructure of the fractured surface for the outer part of the degraded conductor taken by SEM. Element distribution on the fractured surface for (c) Ba in the YBCO, (d), Ag in the surface layer and (e) Mg in the MgB_2 buffer layer. The coil transport current is in the horizontal direction.

Figure 4. (a) The calculated radial stress distribution in the coil winding due to cool down from room temperature to 77 K. The stress shows a tensile peak of +4.5 MPa at the 10th layer. (b) The calculated cumulative radial stress distribution in the coil winding

due to winding, with a winding tension of 100 MPa, and cool down. The compressive stress dominates over the coil winding at 77 K.

Figure 1

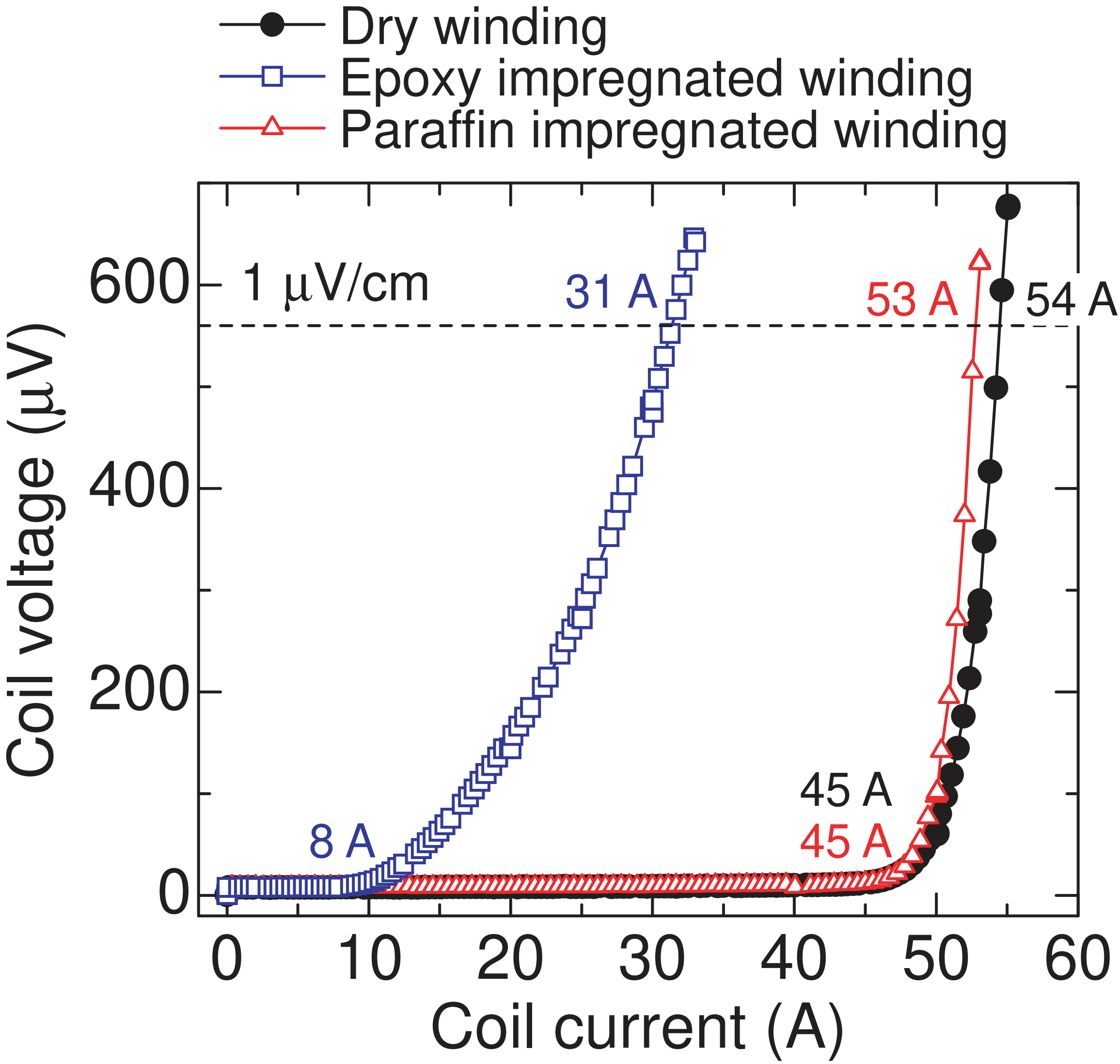
Dry winding
Epoxy impregnated winding
Paraffin impregnated winding
1 μV/cm
31 A
53 A
54 A
8 A
45 A
45 A
Coil voltage (μV)
Coil current (A)
0
200
400
600
0
10
20
30
40
50
60

Figure 2

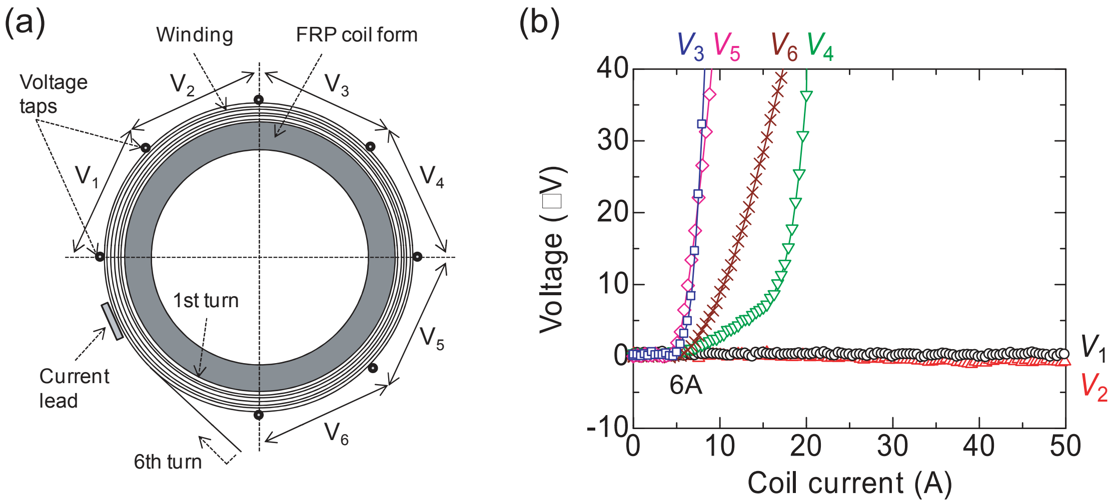
(a)
Winding
FRP coil form
Voltage taps
V2
V3
V1
V4
1st turn
V5
Current lead
V6
6th turn
(b)
V3 V5 V6 V4
Voltage (□V)
40
30
20
10
0
-10
V1
V2
6A
0
10
20
30
40
50
Coil current (A)

Figure 3.

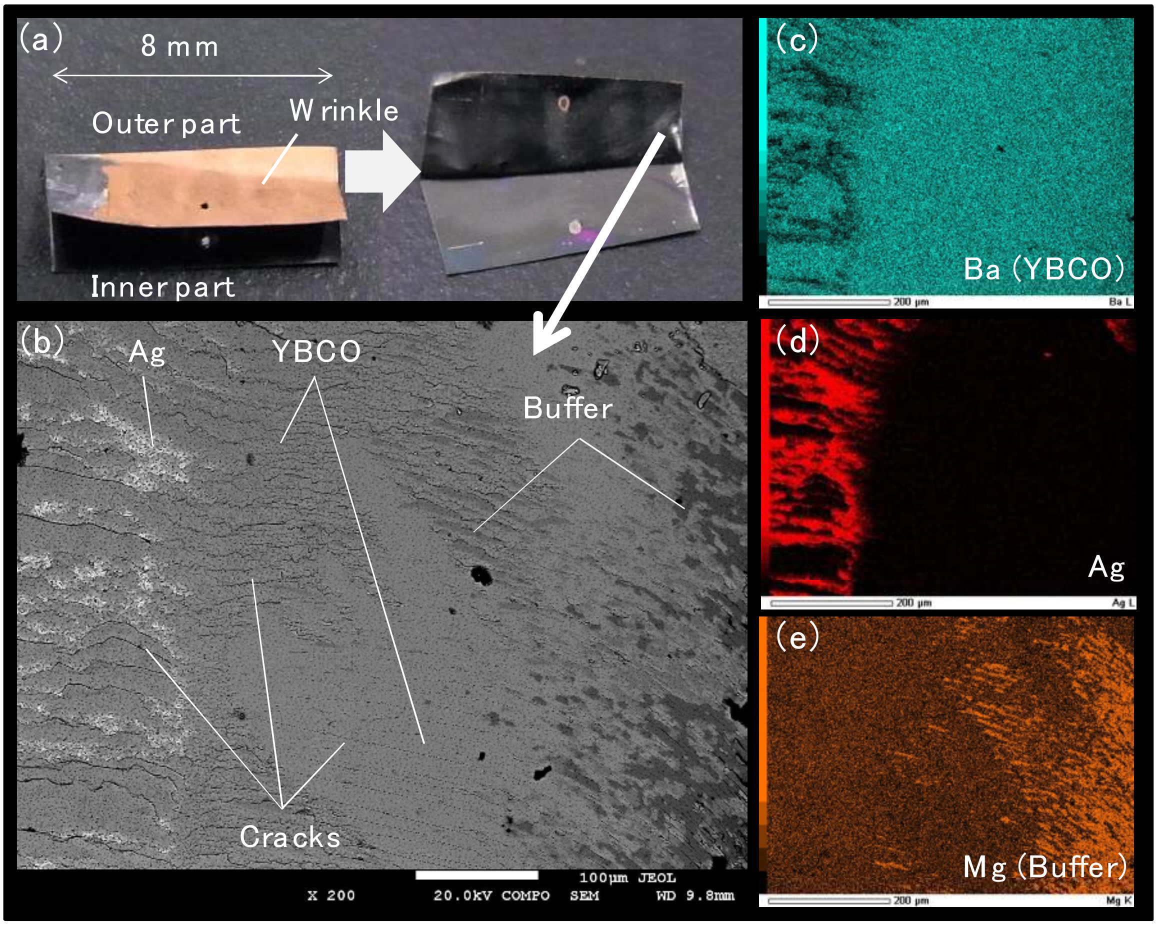
(a)
8 mm
Outer part
Wrinkle
Inner part
(b)
Ag
YBCO
Buffer
Cracks
100μm JEOL
X 200
20.0kV COMPO
SEM
WD 9.8mm
(c)
Ba (YBCO)
(d)
Ag
(e)
Mg (Buffer)

Figure 4.

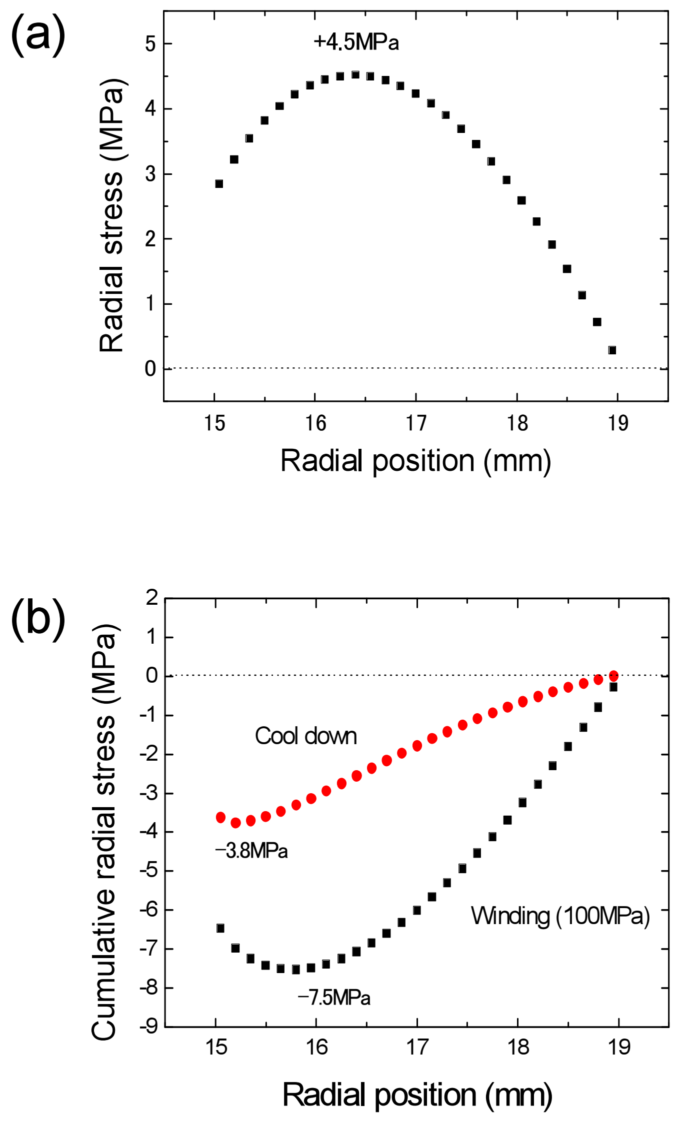
(a)
+4.5MPa
Radial stress (MPa)
Radial position (mm)
(b)
Cool down
−3.8MPa
Winding (100MPa)
−7.5MPa
Cumulative radial stress (MPa)
Radial position (mm)

Table 1.

Materials	Young's modulus (Gpa)	Thermal contraction
Fiber-reinforced plastic coil form		
lengthwise	1.8×10^{10}	-0.00211
crosswise	14×10^{10}	-0.00638
YBCO-coated conductor	2×10^{11}	-0.00211
Inter-layer insulation(Kapton)	6×10^{9}	-0.0102