Remarkable weakness against cleavage stress for YBCO-coated conductors and its effect on the YBCO coil performance

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Abstract

Cleavage strength for an YBCO-coated conductor at 77 K was investigated with a model experiment. The nominal cleavage strength for an YBCO-coated conductor is extremely low, typically 0.5 MPa. This low nominal cleavage strength is due to stress concentration on a small part of the YBCO-coated conductor in cleavage fracture. Debonding by the cleavage stress occurs at the interface between the buffer layer and the Hastelloy substrate. The nominal cleavage strength for a slit edge of the conductor is 2.5-times lower than that for the original edge of the conductor; cracks and micro-peel existing over the slit edge reduce the cleavage strength for the slit edge. Cleavage stress and peel stress should be avoided in coil winding, as they easily delaminate the YBCO-coated conductor, resulting in substantial degradation of coil performance. These problems are especially important for epoxy impregnated YBCO-coated conductor coils. It appears that effect of cleavage stress and peel stress are mostly negligible for paraffin impregnated YBCO-coated conductor coils or dry wound YBCO-coated conductor coils.

Keywords:

YBCO-coated conductor

YBCO coil

Stress concentration

Cleavage

Peel

Delamination

Degradation

Stress analysis

Critical current

1. Introduction

A YBCO-coated conductor tolerates axial tensile stress as high as, and possibly higher than 700 MPa [1-3]. This is much higher than comparable stress numbers for both 1G high temperature superconductors (HTS) [4] and low temperature superconductors (LTS) [5]. If we take advantage of YBCO-coated conductors, we can increase current density in the superconducting coils thus reducing their volumes.[6] However, an YBCO-coated conductor is delaminated and degraded by a transverse tensile stress of 10-20 MPa.[7] Such anisotropic stress tolerance of the YBCO-coated conductor affects the coil performance.

In a previous paper [8], we demonstrated that an epoxy impregnated YBCO-coated conductor double-pancake coil showed substantial degradation in coil performance. This was because part of the conductor was delaminated. This was interpreted as excessive transverse stress; i.e. the cumulative transverse (radial) stress, 12 MPa, developed during epoxy cure [9] and cool down [8] degraded the conductor in the coil winding because it exceeded the tensile transverse strength, 10-20 MPa, of the YBCO-coated conductor [7]. Xie et al. [10] recently reported the transverse tensile strength for commercial YBCO-coated conductors as 40-100 MPa. Considering such higher transverse tensile strengths for recent conductors, it is necessary to examine

additional sources of stress in the coil winding.

YBCO-coated conductors used in the previous work [8] were made up of numbers of layers. [1] This can be modeled as an adhesive lap joint, where two adherends of a copper/Hastelloy layer and a silver/copper layer are bonded by the brittle adhesive of a buffer/YBCO layer. If the brittle adhesive layer, i.e. buffer/YBCO, is debonded or fractured, the YBCO conductor performance is substantially degraded.

Petrie [11] has listed five basic stress types common to adhesive joints; tensile stress, shear stress, compressive stress, cleavage stress and peel stress. Tensile corresponds to the transverse tensile stress. Cleavage occurs when an external force acts to open one edge of the adhesive assembly. Peel is similar to cleavage, while an adherend is flexible. In the case of cleavage and peel, the stress is concentrated on a small part of the adhesive bond and therefore their (cleavage and peel) strengths are much lower than the tensile strength. Therefore, both cleavage and peel are undesirable and are usually avoided in the adhesive bond assembly design. [11]

Considering the close resemblance between an YBCO-coated conductor and an adhesive joint assembly, it is probable that cleavage is undesirable in the YBCO-coated coil. However, so far the effect of cleavage on the YBCO-coated conductor has never been investigated. This paper is a report of such a study using a model experiment.

The topics investigated are (a) effect of cleavage on the critical current of the YBCO-coated conductor, (b) microstructures of the fracture surface of the YBCO-coated conductor made by a cleavage experiment and (c) the effect of slit edge on the cleavage strength of the conductor. Stress concentration in the YBCO-coated conductor loaded in cleavage is numerically analyzed by finite element software. The effect of cleavage on the performance of epoxy impregnated YBCO-coated conductor coil will be discussed.

2. Experimental procedure

The YBCO-coated conductor manufactured by SuperPower Inc. (SCS4050), 4 mm in width and 0.1 mm in thickness, was used in the experiment. It was utilized by Ion Beam Assisted Deposited (IBAD) MgO technology for the buffer layer and by metal organic chemical vapor deposition (MOCVD) for the YBCO layer. The thickness of the Hastelloy substrate, the buffer layer, the YBCO layer and the silver surface layer were 50 μm, 0.1-0.2 μm, 1 μm and 2 μm respectively and the conductor was covered with a 20 μm-thick copper plate as seen in Fig. 1(a). The original YBCO-coated conductor was slit into several conductors in the manufacturing process that was used in this experiment. The 4 mm wide conductor used in this experiment had a slit edge on

one side and an original edge on another side as seen in Fig. 1(a).

Experimental arrangement of the cleavage experiment is shown in Fig. 1(b); both an upper anvil (copper) and a lower anvil (copper) were soldered onto the YBCO-coated conductor using a Sn-3.8wt%Cu-1.0wt%Ag solder. The cleavage force is applied to the right edge of the conductor as seen in Fig. 1(b), acting so as to open the YBCO-coated conductor. The solder-bonded area was 16 (= 4×4) mm^2.

The apparatus for the cleavage experiment at cryogenic temperature (77 K) is shown schematically in Fig. 1 (c). An upward force pulls the upper-right end of a lever arm, loading a cleavage force on the YBCO-coated conductor. This action is generated and controlled by a pneumatic system installed on top of the apparatus. The cleavage force is measured by a load cell installed in the pulling rod. The distance between the pulling rod and the conductor center is 10.8 mm. Displacement of the pulling rod was measured by a displacement gauge installed on a top flange. An acoustic emission (AE) sensor was attached to the fiber reinforced plastic base rod on which the lower anvil was bolted; the AE sensor measures acoustic waves generated by conductor delamination. Both terminals of the conductor were soldered to current leads connected to a DC power supply. A pair of voltage taps was attached to the conductor.

Several load/unload cycles were repeated; for each cycle, the maximum

upward force exceeds the last peak value by a certain amount of force. The load/unload cycle was repeated until the conductor was completely delaminated. The critical current for the conductor was measured after unloading the upward force.

Fracture surfaces formed by cleavage experiments were examined with a scanning electron microscope (SEM) and by energy dispersive spectroscopy (EDS).

3. Experimental results

3.1 Delamination of the YBCO-coated conductor by cleavage experiments

Figure 2 (a) shows a cleavage force vs. vertical displacement plot; the cleavage force is applied to the slit-edge of the YBCO-coated conductor. The right-hand vertical axis gives a corresponding nominal cleavage stress. The nominal cleavage stress is defined as the cleavage force divided by the area of the solder bond to the upper anvil. During the 1st run (#1) and the 2nd run (#2), the curve was elastic; i.e. it is reversible and few AE events appear. The conductor critical current seen in Fig. 2 (c) coincides with the initial critical current.

In the 3rd run (#3), the cleavage force vs. displacement curve shows a bend at point (A); its cleavage force is 7.0 N corresponding to the nominal cleavage stress of 0.44 MPa. A train of AE events appears simultaneously. During unloading of the

cleavage force, the force-displacement curve is linear and no AE event appears. The critical current decreased to 100 A. Thus, it is clear that delamination of the YBCO-coated conductor starts to occur above point (A), extending with cleavage force. The extension stops during unloading of the force.

In the 4th run (#4), the cleavage force vs. displacement curve is elastic at first but upon exceeding the last maximum force of 8 N (i.e. 0.5 MPa) at point (B), intensive trains of AE events begin to appear and the force-displacement curve shows a steep bend, becoming nearly horizontal with the cleavage force of 6 N (i.e. the nominal cleavage stress equals to 0.38 MPa). The behavior lasts to the point (C) seen in Fig. 2 (a), where the conductor is completely delaminated; the critical current at point (C) is zero.

This demonstrates that the YBCO-coated conductor delaminates at a nominal cleavage stress as low as 0.5 MPa. This remarkable weakness against the cleavage stress is due to stress concentration on a small part of the YBCO-coated conductor in the case of cleavage fracture. Note that the nominal cleavage stress defined here might not be directly comparable to the reported transverse strength[7,10], as the stress concentration factor in this experiment changes with the length of the lever arm.

3.2 Microstructure of the fracture surface formed by cleavage experiments

A picture of a typical fracture surface formed in a cleavage experiment at 77 K is shown in Fig. 3(a). Tin on the left is due to solder on the copper. Figure 3(b) shows a microstructure of the fracture surface examined by SEM, while Fig. 3(c) shows EDS for solder. The fracture surface contains Hastelloy, demonstrating that the buffer/YBCO/silver/copper layer is stripped off from the Hastelloy substrate by the cleavage experiment.

Based on these results, the mechanism of delamination involved in these cleavage experiments and seen in Fig. 2 is interpreted as follows:

(1) Debonding of the buffer/YBCO/silver/copper layer from the Hastelloy substrate starts to occur from the slit edge of the conductor where the opening tensile stress is concentrated. The debonded zone gradually extends with cleavage force, resulting in a bend in the force-displacement plot at point (A) as seen in Fig. 2(a) and AE pulses as seen in Fig. 2(b).

(2) The cleavage force is concentrated at the copper surface plate as the debonding progresses to copper plate fracture at point (B) in Fig. 2(a), resulting in a steep bend in the plot. The fracture line seen in Fig. 3(a) is due to this copper fracture.

(3) Striping off the buffer/YBCO/silver/copper layer proceeds with time; vertical YBCO lines seen in Fig. 3(b) are due to stripping off the layer and the discrete AE pulse trains

seen in Fig. 2(b) suggest a stick-slip motion of the process. The layer is completely removed at point (C) in Fig. 2 (a).

3.3 Effect of slit edge of the YBCO-coated conductor on the cleavage strength

Another cleavage experiment was conducted at 77 K where the left edge and the right edge of the YBCO-coated conductor seen in Fig. 1(b) were reversed; i.e. a cleavage force was applied to the original edge of the conductor instead of the slit edge. The cleavage force vs. displacement plot in this case is shown by the brown line in Fig. 4(a), while that for the slit edge by a green line; Figure 4(b) shows AE events in the former case, i.e. original edge. The brown line is linear elastic at first and abruptly drops at point (D); the cleavage force at this point is 20 N, corresponding to the nominal cleavage stress of 1.25 MPa. Prior to reaching point (D), only several AE events appear as seen in Fig. 4(b) suggesting that debonding of the buffer/YBCO/silver/copper layer from Hastelloy and fracture of the copper plate occur simultaneously at point (D) as seen in Fig. 4(a). The nominal cleavage strength, 1.25 MPa, for the original edge of the YBCO-coated conductor is 2.5-times higher than that, 0.5 MPa, for the slit edge.

The cleavage force vs. displacement plot becomes horizontal with a cleavage force of 6 N (0.38 MPa). Stripping off the buffer/YBCO/silver/copper layer from the Hastelloy substrate was confirmed by a metallurgical microscope.

The abrupt drop at point (D) seen in Fig. 4(a) demonstrates that the cleavage stress required to strip off the buffer/YBCO/silver/copper layer is several-fold lower than that required for the initial debonding and copper fracture. In the case of the slit edge, the difference is small since the cleavage strength is low and therefore an abrupt drop does not appear as seen in Fig. 2(a). This result suggests that once the stripping process starts, it propagates easily to reach the end of the fracture.

Silver and copper layers were etched off by immersing the YBCO-coated conductor in a solution of NH_3:H_2O_2=1:1.[12] The SEM picture taken of the slit-edge of the conductor is seen in Fig. 5 (a); the slit edge shows a saw-tooth pattern and many cracks and micro-peels exist, which are made in the slitting process of the conductor. On the contrary, in the case of the original edge of the conductor as seen in Fig. 5(b), the edge is smooth and there are no cracks and micro-peels. Thus the extremely low cleavage strength for the slit edge is due to cracks and micro peels on the edge since they act to initiate debonding. D. C. van der Laan et al.[7] also reported an effect of the slit edge on the transverse tensile strength of the YBCO-coated conductor.

Figure 6 compares dispersion of the cleavage strengths for original edges and slit edges of the YBCO-coated conductor at 77 K and at room temperature. The cleavage strength of the YBCO-coated conductor is shown by the open circle, while the

cleavage strength when the debonding occurs at the solder joint between the anvil and the conductor is shown by ×. We see wide deviation of the cleavage strength for the original edge between 77 K and room temperature, although it is several-fold higher than that for a slit-edge; e.g. the maximum cleavage strength is >2.1 MPa, where the inequality sign is necessary as the debonding occurs at the solder joint. The result also demonstrates that if we use an YBCO-coated conductor with original edges on both sides, the cleavage strength for YBCO-coated conductors will be enhanced, resulting in more suppression of degradation of the YBCO-coated conductor coil performance due to excessive cleavage stresses.

4. Discussion

4.1 Stress concentration under cleavage experiment

Stress distribution in the YBCO-coated conductor under cleavage experiment was numerically analyzed using finite element software Abaqus; the linear elastic calculation was made in the stress analysis. A 2D-mesh was generated for a cross-sectional configuration of the experimental apparatus as shown in Fig. 7(a): The upward force of 8 N was applied to the upper right end of the lever arm while the bottom plane of the YBCO-coated conductor was restrained. Contour plot of the normal

stress σ_z in the vertical direction under 8 N is also shown in Fig. 7(a); tensile stress appears on the right edge of the conductor, while compressive stress is on the left edge of the conductor. Figure 7(b) traces $\sigma_{z,}$ vs. horizontal position along the conductor width. The peak tensile stress appearing on the right edge of the conductor, i.e. at point (E) as seen in Fig. 7(b), is 12.7 MPa and is 25.4 fold higher than the nominal cleavage stress of 0.5 MPa.

Based on the stress concentration factor of 25.4 and cleavage stresses seen in Fig. 6, the peak stress for the original edge of the conductor is estimated to be in the range from 30 MPa to >53 MPa. This estimated strength is consistent with the transverse tensile strength, 40-100 MPa, recently reported by Xie et al.[10]. On the contrary, based on Fig. 4, the peak stress at point (E) in Fig. 7(b) for the slit edge is in the range 8 to13 MPa.

4.2 Effect of cleavage on the performance of YBCO-coated conductor coils

Cleavage stress tends to appear for epoxy impregnated YBCO-coated conductor double pancake coils; a numerical example is given for thermal stress due to cool down for an epoxy impregnated double pancake coil. The coil parameters are the same as for the epoxy impregnated coil described in the previous paper [8]. They are 30 mm in inner diameter, 38 mm in outer diameter, 8 mm in height and have a number of

turns of 23×2. The YBCO-coated conductor is 4 mm in width and 0.1 mm in thickness and the coil form is assumed to be epoxy resin, 3 mm in thickness with inter-layer insulations of 70 μm thickness. The stress distribution in the coil is calculated by the finite element software Abaqus. Linear elasticity is assumed in the calculation. The coil is axis-symmetric. Table 1 lists physical parameters for materials used in the calculation.

Figure 8 shows the generated mesh of the double pancake coil and deformed shape and contour plot of the radial stress, σ_r, due to thermal contraction. Thermal shrinkage of the coil form pulls the inner layers of the coil winding in the axial direction (i.e. the z direction) and in the radial direction (i.e. the r direction), deforming the inner layers of the coil as seen in Fig. 8. This results in radial stress concentration on the outer edge of the inner layers as shown by the orange and yellow colors acting as the cleavage stress. The local stress intensity is ~70 times larger than the average stress intensity in the coil which will delaminate the YBCO-coated conductor. The stress concentration factor is much reduced, if we use a coil form with lower thermal contraction than epoxy resin or if we remove the coil form after epoxy impregnation.

In the previous paper [8], degradation of the performance of an epoxy impregnated YBCO-coated conductor double pancake coil was interpreted as being due to excessive radial tensile (i.e. transverse) stress in the coil winding suggesting here that

additional stress concentration appearing on the edge of the conductor due to cleavage and peel stress, developed during epoxy cure, cool down and coil charging, might assist degradation in YBCO epoxy impregnated coils. More investigations are being made in this regard.

If the YBCO-coated conductor coil is impregnated with paraffin wax, development of cleavage stress and peel stress is unlikely, since paraffin wax is easily fractured by the applied stress. This is also the case for dry wound YBCO-coated conductor coils. Therefore the effect of cleavage stress and peel stress are mostly negligible for paraffin impregnated YBCO-coated conductor coils and for dry wound YBCO-coated conductor coils.

As discussed above, if we use an YBCO-coated conductor with original edges on both sides, its cleavage strength will be enhanced, resulting in better suppression of degradation due to cleavage stress and peel stress for the conductor coils. This is especially true for epoxy impregnated YBCO-coated conductor coils.

5. Conclusions

Cleavage strength for an YBCO-coated conductor at 77 K was investigated with a model experiment. Conclusions are as follows:

(a) The nominal cleavage strength for the slit edge of the YBCO-coated conductor is extremely low typically being 0.5 MPa. This is due to stress concentration on a part of the conductor in the case of cleavage fracture. Debonding by cleavage stress occurs at the interface between the buffer layer and the Hastelloy substrate, and after debonding, the critical current for the YBCO-coated conductor is zero.

(b) The cleavage strength for the slit edge of the conductor is several-times lower than that for an original edge of the conductor. This is due to cracks and micro-peel existing on the slit edge.

(c) Cleavage stress and peel stress should be avoided in the coil winding, as they easily delaminate the YBCO-coated conductor resulting in substantial degradation of the coil performance. This is especially true for the epoxy impregnated YBCO-coated conductor coil. We have demonstrated that the cleavage stress on the coil edge might result in delamination of the YBCO-coated conductor.

Acknowledgments

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Figure Captions:

Figure 1. (a) Configuration of the YBCO-coated conductor manufactured by SuperPower Inc.; (b) schematic arrangement of the cleavage experiment; (c) schematic diagram of the apparatus for cleavage experiment at cryogenic temperature (77 K).

Figure 2. (a) The cleavage force vs. displacement plot. Right vertical axis corresponds to the nominal cleavage stress, defined as the upward force divided by the solder-bonded area; the cleavage force is applied to the slit edge of the YBCO-coated conductor; (b) AE event vs. vertical displacement plot for four consecutive load/unload cycles of the cleavage force; (c) the critical current vs. displacement plot, where the critical current is measured after unloading the cleavage force.

Figure 3. (a) Picture of the fracture surface made by cleavage experiment for YBCO-coated conductor; the cleavage force is applied to the slit edge of the conductor; (b) microstructure of the cleavage fracture surface taken by SEM; (c) EDS intensities for Solder (Sn), YBCO(Ba) and Hastelloy (Ni) on the fracture surface.

Figure 4. The cleavage force vs. displacement plot for the original edge of the YBCO-coated conductor (green line) and that for the slit edge of the conductor (brown line).

Figure 5. (a) SEM picture of a slit edge of the YBCO-coated conductor and (b) that of

an original edge of the YBCO-coated conductor. Both copper plate and silver layer were etched out, by immersing the conductor in a solution of NH_3:H_2O_2=1:1.

Figure 6. Deviation of cleavage strength for the original edge and the slit edge of the YBCO-coated conductor; the measurements are made at 77 K and room temperature.

Figure 7. (a) 2D mesh generated for finite element structural calculation and a contour plot of the normal stress, σ_z, parallel to the vertical direction under **a** cleavage force of 8 N; (b) normal stress σ_z vs. horizontal position along the conductor width.

Figure 8. Generated mesh of the stress analysis due to thermal contraction for the YBCO-coated conductor coil; the deformed shape and contour of the radial stress are also shown.

1 Table caption:

2 **Table 1.** Physical parameters used in the stress analysis

3

Figure(s)

Figure 1

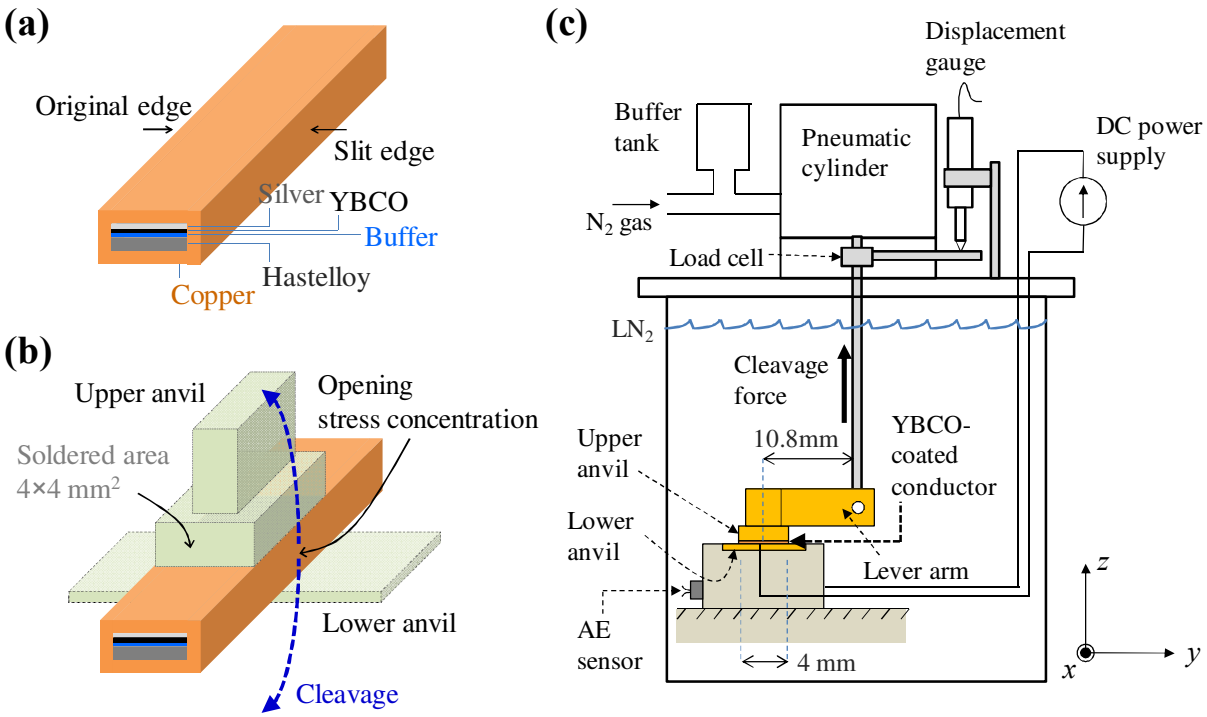

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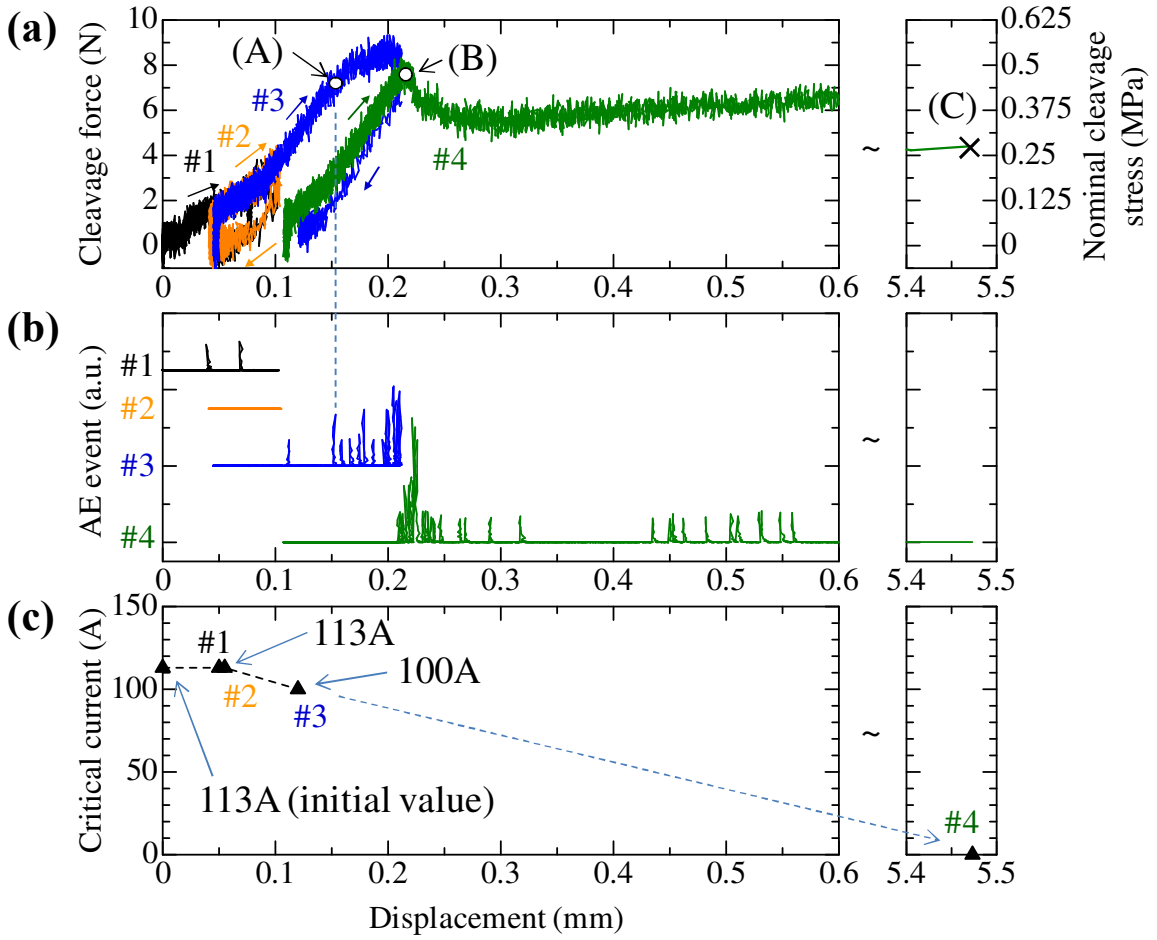
Figure 2



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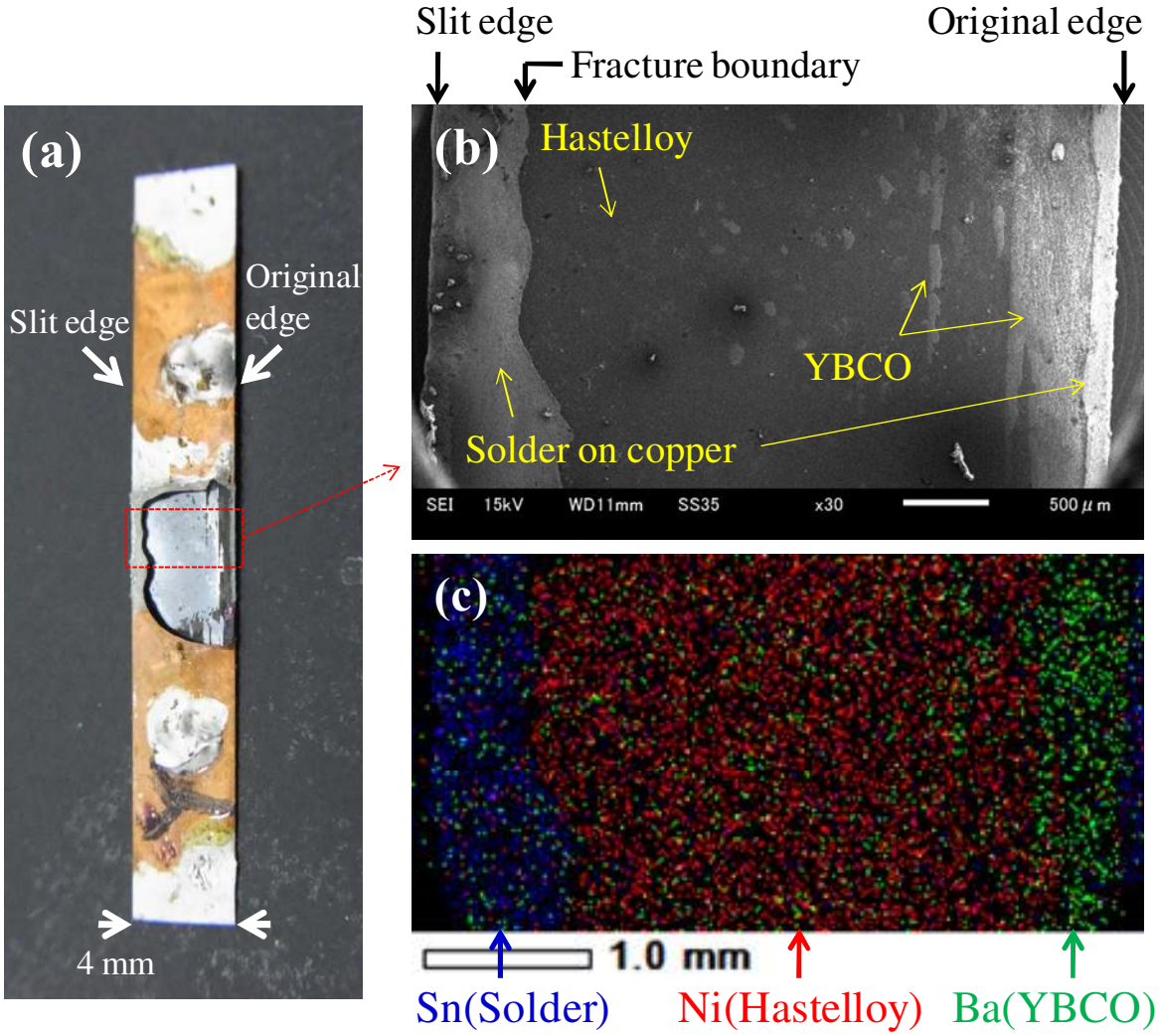
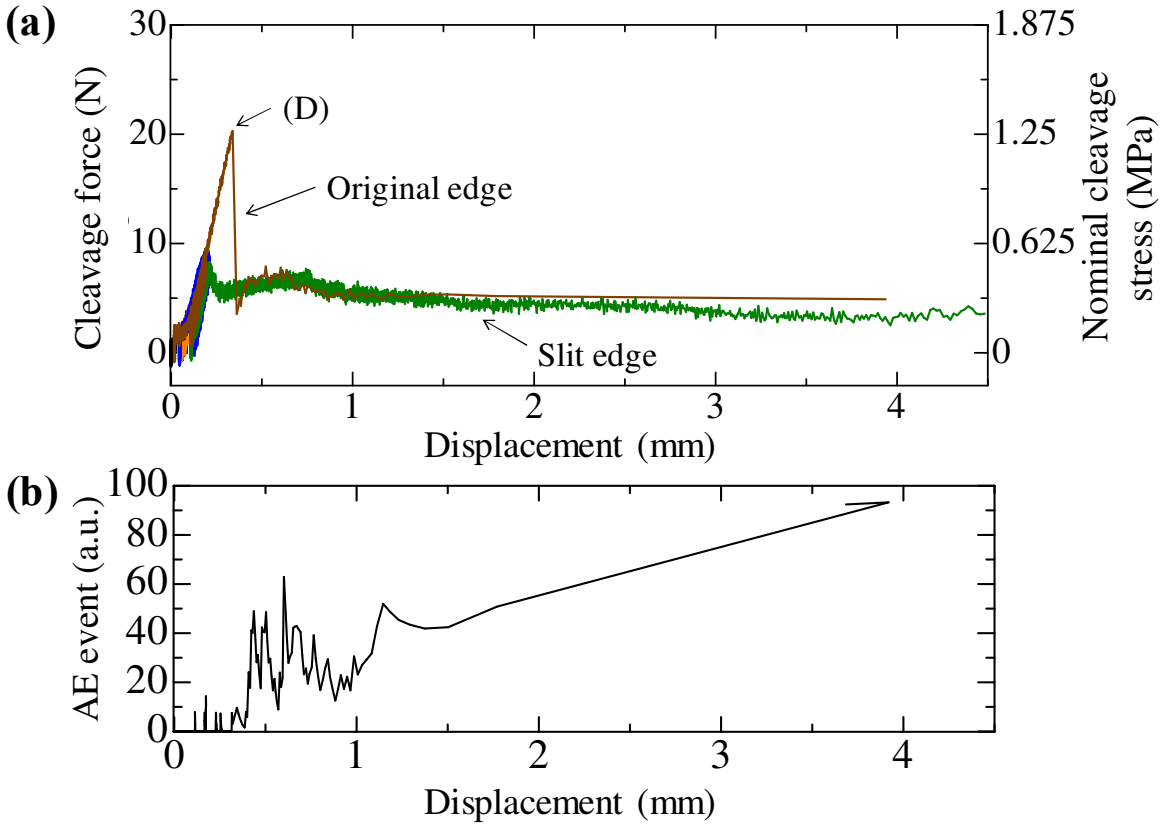
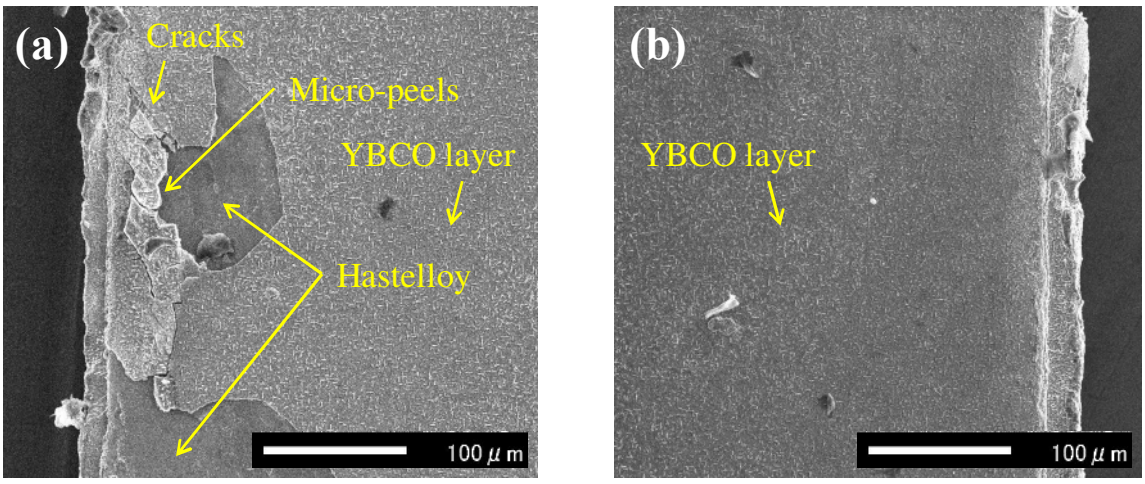


Figure 4


(a)
Cleavage force (N)
Nominal cleavage stress (MPa)
(D)
Original edge
Slit edge
Displacement (mm)
(b)
AE event (a.u.)
Displacement (mm)

Figure(s)

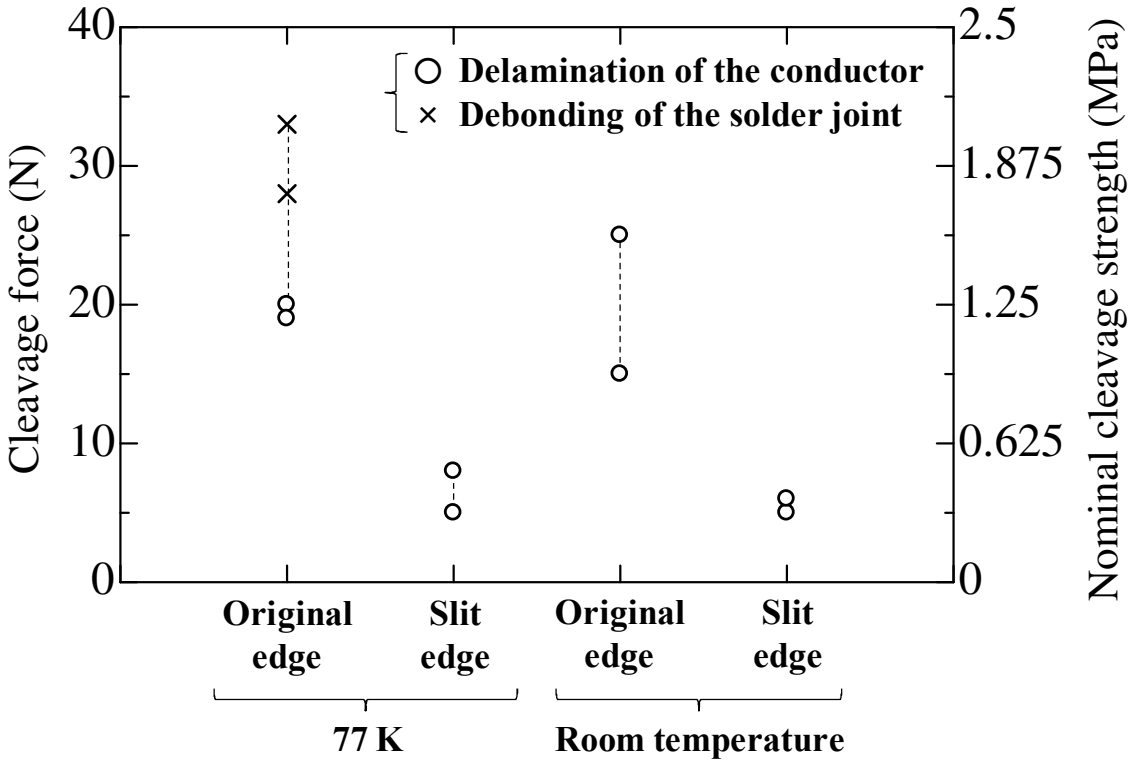
Figure 5



Slit edge

Original edge

Figure 6


Cleavage force (N)
Nominal cleavage strength (MPa)
40
30
20
10
0
2.5
1.875
1.25
0.625
0
Delamination of the conductor
Debonding of the solder joint
Original edge
Slit edge
Original edge
Slit edge
77 K
Room temperature

Figure(s)

Figure 7

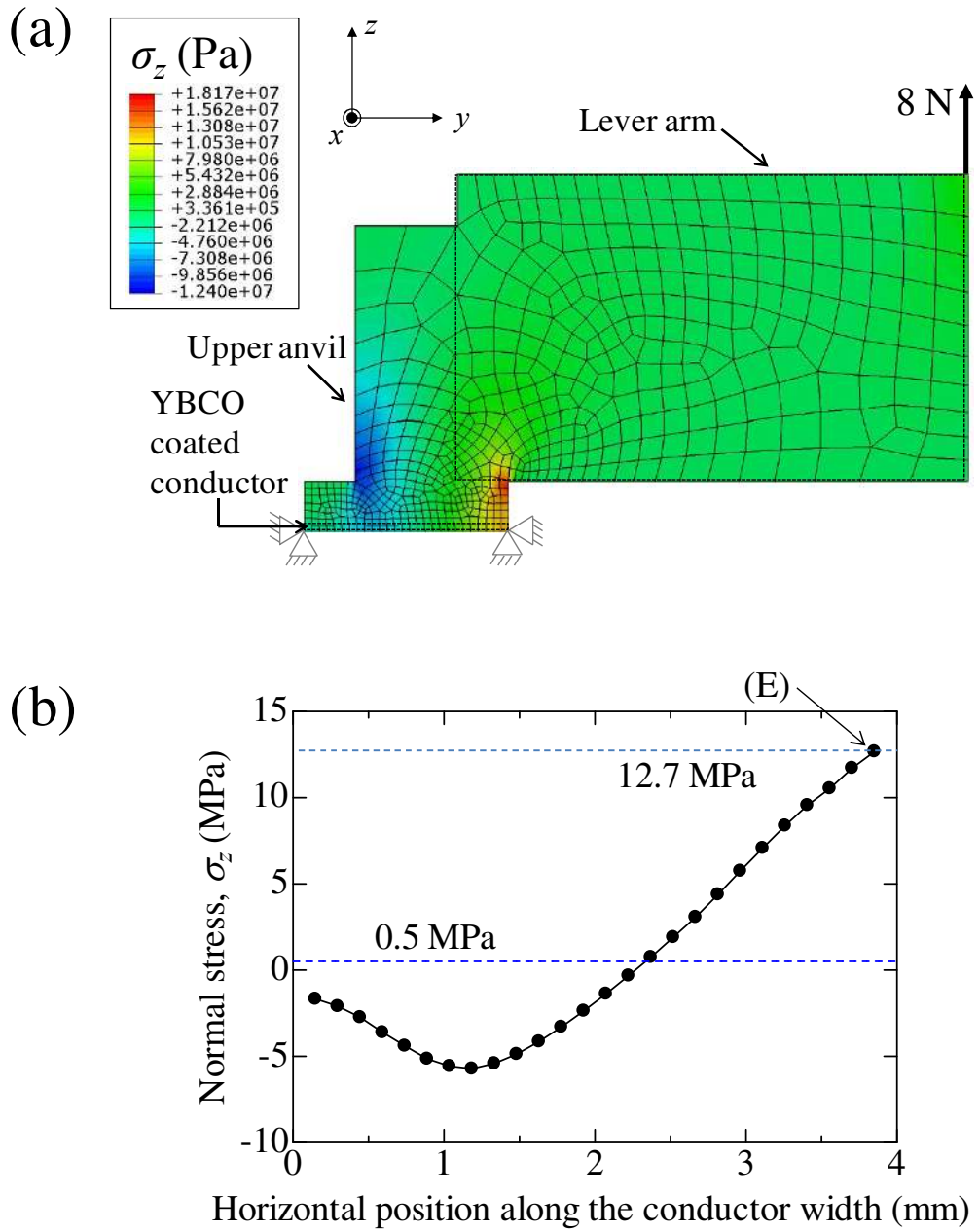


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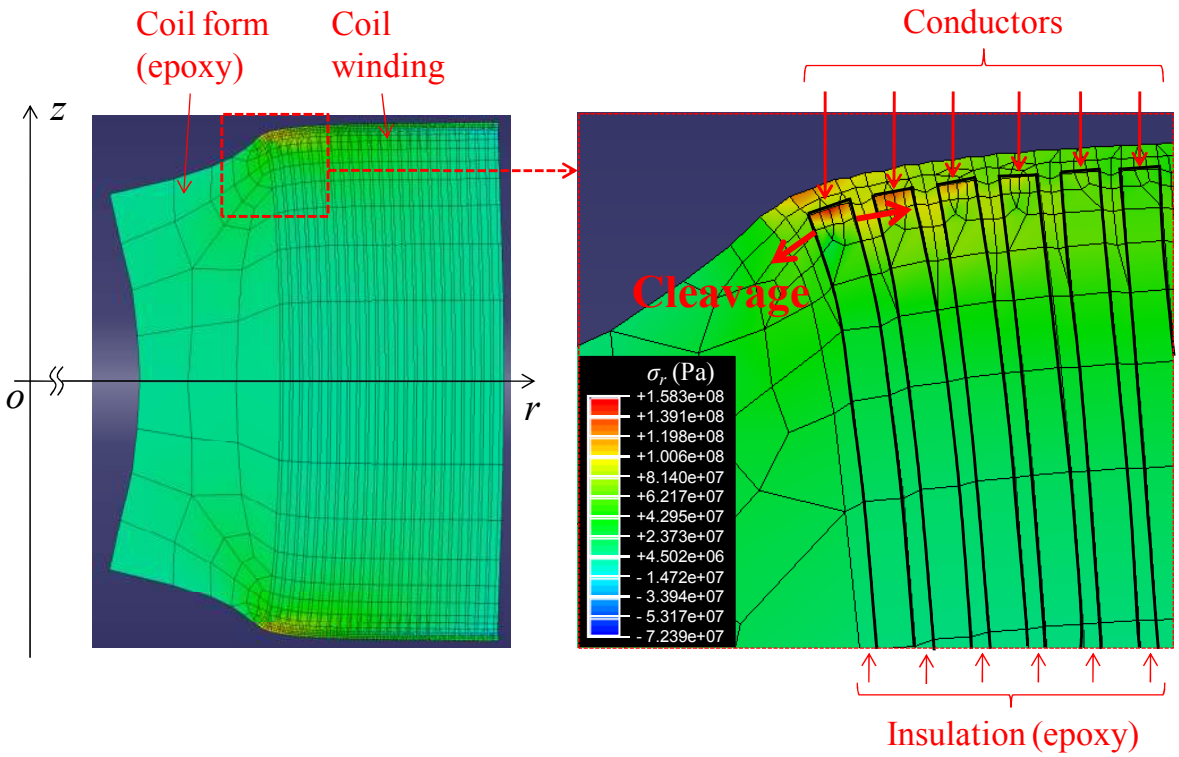
Figure 8



Table(s)

Table 1

Materials	Young's modulus (Pa)	Thermal contraction
YBCO-coated conductor	2×10^{11}	-0.00211
Epoxy for coil form and inter layer insulator	6×10^{9}	-0.0102