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The strain effect on critical current in YBCO coated conductors with different stabilizing layers

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Abstract
The tensile strain dependences of the critical current (I_c) in $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductors fabricated by using the rolling-assisted biaxially textured Ni–W substrates (RABiTS)–pulsed laser deposition (PLD) method were examined at 77 K and in self magnetic field. Cu and stainless steel layers were used as stabilizers to the YBCO coated conductor, and the effects of stabilizing layers on the strain tolerance of I_c were investigated, compared with the case without a stabilizing layer. The lamination of stabilizer produced an increase in the yield strength and strain tolerance of I_c in coated conductors. All YBCO coated conductors tested showed a reversible strain effect and a peak in the relation between I_c and applied strain. The peak strain of I_c and the irreversible strains for I_c degradation were enhanced when the YBCO coated conductor was laminated with a stabilizing layer. For the case laminated with a stainless steel layer, I_c recovered reversibly until the applied strain reached to about 0.5% and showed its peak at a strain of 0.42%, comparing to the case without a stabilizing layer, which were 0.21% and 0.18%, respectively. It can be predicted that the lamination of a stabilizing layer produced a significant residual compressive strain to the YBCO film during cooling to 77 K, which influenced the axial strain tolerance of YBCO coated conductors. Therefore, the I_c–tensile strain relation in YBCO coated conductors could be explained by a two-stage deformation; stage I is the region where YBCO film behaves elastically and I_c recovers when the stress is released. Stage II is the region where I_c decreases irreversibly attributable to the cracking induced in the YBCO film due to the significant plastic deformation of the substrate or the stabilizing layer.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The development of high-temperature superconducting wires has widened their application fields to electric utility devices and industrial magnets [1]. Recently, some achievements have been reported in high transport critical current density, J_c, and long lengths of $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductors [2, 3]. However, in practical application of superconducting wire to devices such as magnets, motors, generators and power transmission cables, HTS tapes including BSCCO tapes and coated conductors (CC) will be subjected to various kinds of stress/strain [4, 5].

Table 1. Lamination conditions of stabilizing layer to YBCO coated conductor.

Stabilizing materials	Pure Cu, stainless steel (316L)
Stabilizing layer thickness	80 μm for pure Cu 70 μm for stainless steel
Solder melting temperature	220 °C
Lamination solder thickness	20 μm
Stabilizing material dipping speed	9 cm min^{-1}
Stabilizing layer lamination temperature	250 °C

The investigation of critical current (I_c)–strain/stress behaviours of YBCO coated conductors will be of great significance in the design of superconducting devices, especially in the aspect of their reliability. Up to now, the I_c degradation mechanism and the strain tolerance of Bi-2223 in BSCCO tapes have already been established: I_c degradation is caused by the initiation of cracks in the superconducting filaments and the subsequent crack growth [6]. However, the I_c degradation mechanism in YBCO coated conductors has not been established yet [7, 8]. There are recent reports on the critical current characteristics in YBCO coated conductors under tension and transverse compression at 77 K. Cheggour *et al* have investigated the effect of strengthening the substrate on the stress or strain tolerance of I_c [9, 10]. A reversible strain effect on I_c and a larger irreversible strain for I_c degradation when Cu layer was laminated to YBCO coated conductors which were fabricated by using MOD-RABiTS and MOCVD-IBAD processes were observed [9]. Also, Sugano *et al* investigated the intrinsic strain effect on I_c and reported that there existed a reversible variation of I_c with applied strain [11, 12]. They found that the irreversible strain depended upon the buffer layer in the RE-123 and YBCO coated conductors fabricated by the IBAD-PLD process [12].

However, some expectations about the strain/stress effects on I_c in coated conductors still remained to be solved as given in the following (1) Does any coated conductor structure show reversible variations of I_c with applied strain (because the reversible strain effect of I_c is helpful to improve the performance of superconducting wires or conductors)? (2) How much influence do the mechanical properties of substrate and stabilizing layers have on the strain effect of I_c in coated conductors? (3) How can we describe the I_c degradation behaviour of coated conductors properly?

Not only for both mechanical and electrical stability but also for environmental protection for easy handling, it is required to laminate coated conductors with a metal layer called a stabilizer, which produces a composite neutral axis architecture in which the YBCO layer would be located in the neutral plane between the oxide buffered metallic substrate and the laminated stabilizer. The architecture allows the wire to meet operational requirements including stress at cryogenic temperature, winding tension applied, mechanical bending requirements, and thermal and electrical stability under fault conditions. Therefore, the effect of stabilizer on the electro-mechanical property of YBCO coated conductors should be clarified, although some results have already been reported on the Cu layer laminated YBCO coated conductor fabricated by the RABiTS-MOD method [9].

In this study, the strain effects on the critical current of YBCO coated conductors fabricated by the RABiTS-PLD method were investigated. The effect of stabilizing layer on the strain characteristics of I_c in the YBCO coated conductors was examined to understand the reversibility of the strain/stress effect of I_c. Finally, we tried to discuss the damage mechanism in YBCO coated conductor using n-value behaviour.

2. Experimental procedures

2.1. Samples

A YBCO coated conductor was fabricated by the pulsed laser deposition (PLD) process on the RABiTS substrate at KERI, which has the structure of Ag/YBCO/CeO_2/YSZ/Y_2O_3/Ni substrate. A Ni–3 at.% W tape with a thickness of 50 μm and a width of 10 mm was used as the substrate. YBCO coating films were formed by the PLD method. Critical currents before laminating the stabilizing layer to the YBCO coated conductors reach more than 100 A in a length of 1 m, which corresponds to the critical current density of about 0.7 MA cm^{-2}.

The lamination of stabilizing layers to YBCO coated conductors was performed by a continuous dipping soldering process at KERI. As stabilizing materials, pure Cu and stainless steel (316L) were adopted. The lamination conditions of the stabilizer are listed in table 1.

2.2. Experimental details

Tensile tests of YBCO coated conductors were conducted at 77 K using a hydraulic-servo material testing machine (Instron 8516, load-cell capacity 5 kN). The total length of the specimen and the gauge length between the gripping holders were 80 and 40 mm, respectively. The specimen was fixed at both ends to the upper and lower gripping holders, as shown in figure 1. The upper gripping holder was attached to the load-cell through a universal joint and the lower one was set on the fixture of the loading frame, which was connected to the ram of the testing machine. The specimen was cooled in a stress-free manner using a connecting structure, which gives a clearance of 2 mm [13]. The structure was inserted on the lower part to relieve the thermal contraction which occurred during cooling and to remove any bending or twisting loads on the specimen expected during gripping. For testing at 77 K, the test fixture including the specimen was slowly cooled down to 77 K, taking about 10 min. The strain applied to the coated conductors was measured using double extensometers which were directly attached to the specimen [13]. From the obtained stress–strain curves, the Young's modulus and the yield strength, σ_y, could be determined.

For I_c measurement during tensile tests, GFRP sheets were inserted between the specimen and the gripping holder for electrical insulation. Voltage taps were attached at the central region of the specimen with a separation of 20 mm. I–V curves were measured using the four-probe method at 77 K in self-field, and I_c was defined by a 1 μV cm^{-1} criterion. During loading in tensile tests, I_c was measured at specific strain or stress levels after stopping the testing machine intermittently, and also after lowering the load to 10 N (referred to as 'unloading' in this paper) each time to check whether the I_c recovers reversibly. I_c was normalized by the I_{c0} value

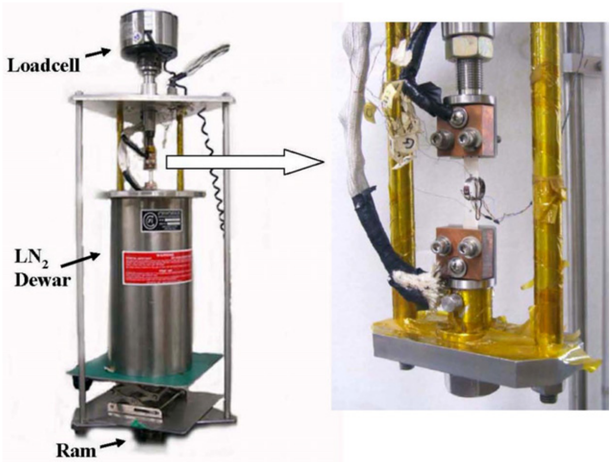

Figure 1. Appearance of the apparatus used in tensile tests of coated conductors at 77 K.

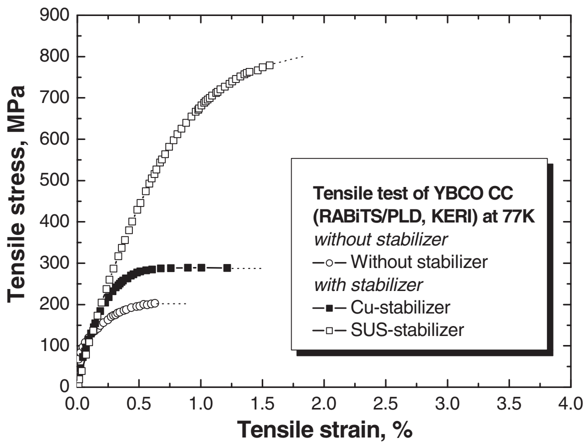

Figure 2. Stress–strain curves of YBCO coated conductors with and without stabilizer at 77 K.

obtained at the as-cooled state. From the I–V curve obtained, the n-value was also calculated by a linear fitting in the voltage range of 0.2–5.0 μV cm^{-1}.

3. Results and discussion

Figure 2 shows the stress–strain curves of YBCO coated conductors with and without stabilizer at 77 K. The lamination of stabilizing layers produced a significant increase in the yield strength as compared with the case without stabilizer. Depending upon the stabilizing materials used, the improvement of strength varied; the one stabilized with the stainless steel layer showed 3.8 times higher yield strength exhibiting strain hardening. But the case of the Cu layer stabilized one showed only 1.8 times higher yield strength and there was no strain hardening, representing an elastic–perfect plastic behaviour.

Figure 3 shows the change of I_c as a function of applied tensile strain in YBCO coated conductors with and without stabilizer. (a) The case without stabilizer; (b), (c) specimens stabilized with Cu and stainless steel layers, respectively.

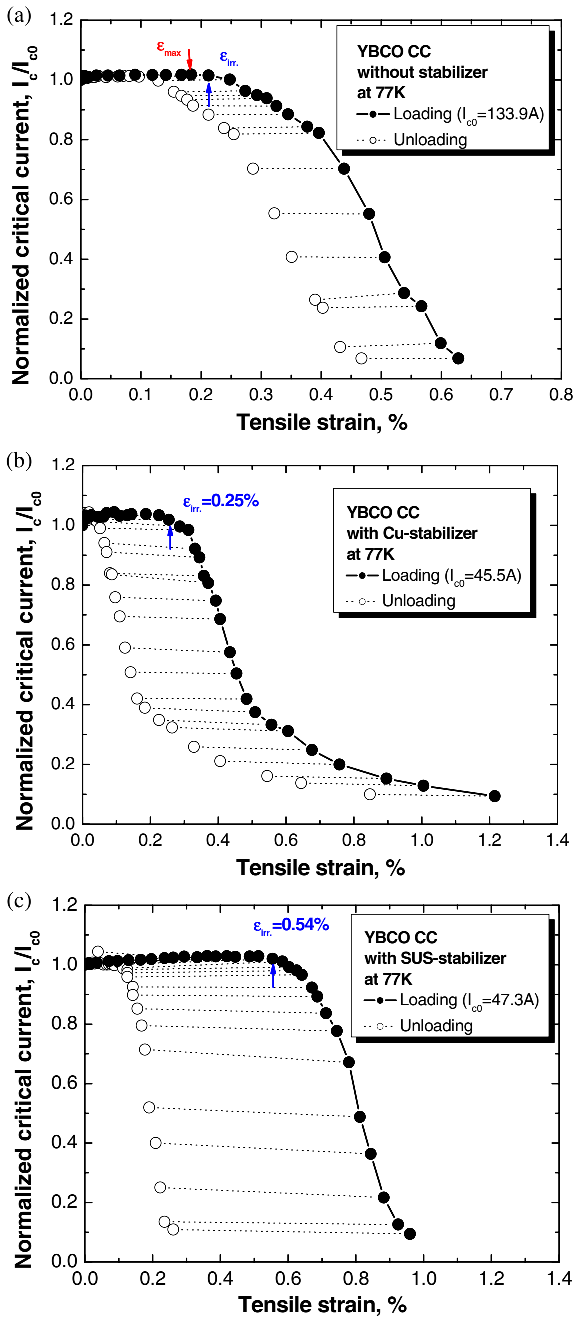

Figure 3. I_c/I_{c0}–applied tensile strain relation of YBCO coated conductors fabricated by the RABITS-PLD method. (a) Without stabilizing layer; (b) with pure-Cu stabilizer; (c) with stainless steel stabilizer.

Firstly, in all specimens tested, I_c increased initially with increasing applied strain, reached a peak value, and varied reversibly. Then, I_c started to degrade with further increase of strain. The strain at the peak I_c, ε_{max}, was defined. The peak I_c and ε_{max} varied depending on the stabilizing material adopted. From the magnified I_c/I_{c0}–strain relations shown in figure 4, in all YBCO coated conductors tested, the enhancement of I_c at ε_{max} was less than 5% of I_{c0}. They represent an intrinsic strain effect of I_c in YBCO coated conductors, similar to the case of Nb_3Sn [12, 14].

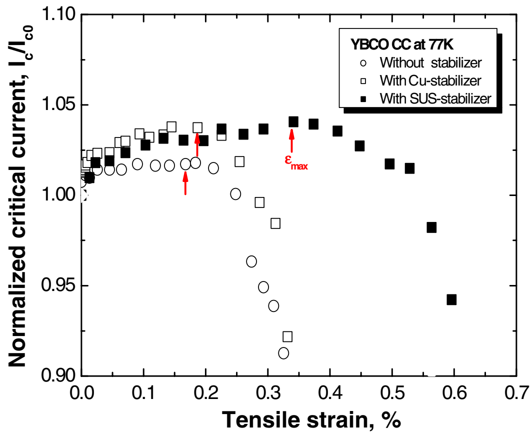

Figure 4. Magnified I_c/I_{c0}–tensile strain relations of YBCO coated conductors.

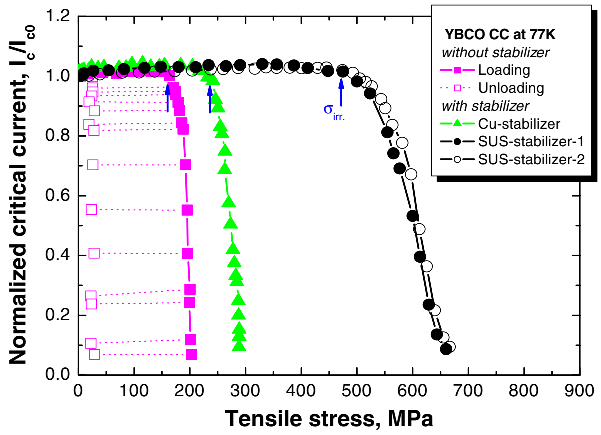

Figure 5. I_c/I_{c0}–applied tensile stress relation of YBCO coated conductors with and without stabilizers.

Table 2. Mechanical properties at 77 K and electro-mechanical properties of YBCO coated conductors fabricated by RABiTS-PLD.

Materials	Mechanical properties		Strain/stress tolerances		
	E (GPa)	σ_y (MPa)	ε_{max} (%)	ε_{irr} (%)	σ_{irr} (MPa)
YBCO CC without stabilizer	90	157	0.18	0.21	156
YBCO CC with Cu-stabilizer	86	280	0.25	0.25	240
YBCO CC with SUS-stabilizer	104	590	0.42	0.44–0.56	470

In order to examine the reversibility of I_c with applied strain, loading and unloading processes of applied tensile strain and stress were repeated. The data measured in the unloaded state were plotted in the figures and connected by a dotted line to the state before unloading. From this result, it is possible to determine the reversible strain limit, ε_{irr}, by unloading, not using a 1% or 5% degradation point as in BSCCO tapes [15]. As shown in figure 3(a), which corresponds to the tape without stabilizer, I_c was recovered even after loading up to 0.21%. The strains for the peak I_c and the reversible strain limits for YBCO coated conductors are tabulated in table 2. With further increase of strain, I_c degraded rapidly, but it was not recovered any more after unloading. Even when the I_c dropped up to 10% of I_{c0}, quenching did not occur. This indicates that the protective layer of Ag had enough thickness to prevent burn-out of YBCO film [12]. It can be found that the lamination of stabilizing layers to YBCO coated conductors produced a significant improvement of ε_{max}, which resulted in an enhancement of the strain tolerance of I_c, directly related to the performance of the conductors. These results indicate that they might produce a larger pre-compressive strain to the YBCO film during cool-down, which is beneficial for extending ε_{irr}, also acting as a crack arrester. Until the ε_{irr}, I_c changed reversibly without cracking or damage on the YBCO film. However, after ε_{irr}, the I_c degradation behaviours were similar, regardless of the existence of stabilizer or the stabilizing material adopted. The lamination of stabilizer produced a shift of the I_c–strain curves toward higher strain tolerance when compared with the case without stabilizer of figure 3(a); the stabilizing layer with larger yield strength produced a higher strain tolerance of I_c. This explains indirectly that the Ni–3 at.% W substrate also contributed to deform the YBCO film uniformly, relieving the localized strain concentration occurring around the crack induced on the YBCO film. The addition of a stabilizing layer to the YBCO coated conductor did not change the damage initiation and growth behaviour in the YBCO film. At a strain exceeding the ε_{irr}, there existed a relatively rapid I_c degradation with increase of strain in the YBCO coated conductor tapes without stabilizer, but it showed a substantial enhancement of the reversible strain limit, ε_{irr}, of the YBCO coated conductors when a Cu or a stainless steel layer was incorporated by lamination.

Therefore, the I_c degradation behaviour of YBCO coated conductors fabricated by the RABiTS-PLD method could be classified into two stages as follows. Stage I is the region where the YBCO film behaved elastically and the I_c was recovered when the stress was removed. Stage II is the region which was attributed to cracking in the YBCO film due to the plastic deformation of the substrate or the stabilizing layer.

The change of I_c against the applied tensile stress was measured simultaneously. Figure 5 shows the change of I_c as a function of the applied stress in YBCO coated conductors with and without stabilizers. Similar to figure 3, initially, I_c increased slightly with the applied stress and recovered reversibly, but degraded abruptly after the peak I_c. The reversible limit stress, σ_{irr}, is defined and tabulated in table 2. It can be seen that through the lamination of stabilizing layers, σ_{irr} was enhanced from 156 MPa in the case without stabilizer to 240 MPa for the Cu layer laminated one, and 470 MPa for the stainless steel layer laminated one, except for the stainless steel layer stabilized one in which the I_c degradation after σ_{irr} was gradual due to the occurrence of strain hardening. The I_c degradation after the σ_{irr} occurred rapidly despite a small increase in the applied stress, which is different from the I_c–strain relation in which the I_c degraded slowly with increase in the applied strain. The lamination of stabilizers to YBCO coated conductors produced an increase in the stress tolerance. This result suggests that the RABiTS-PLD processed coated

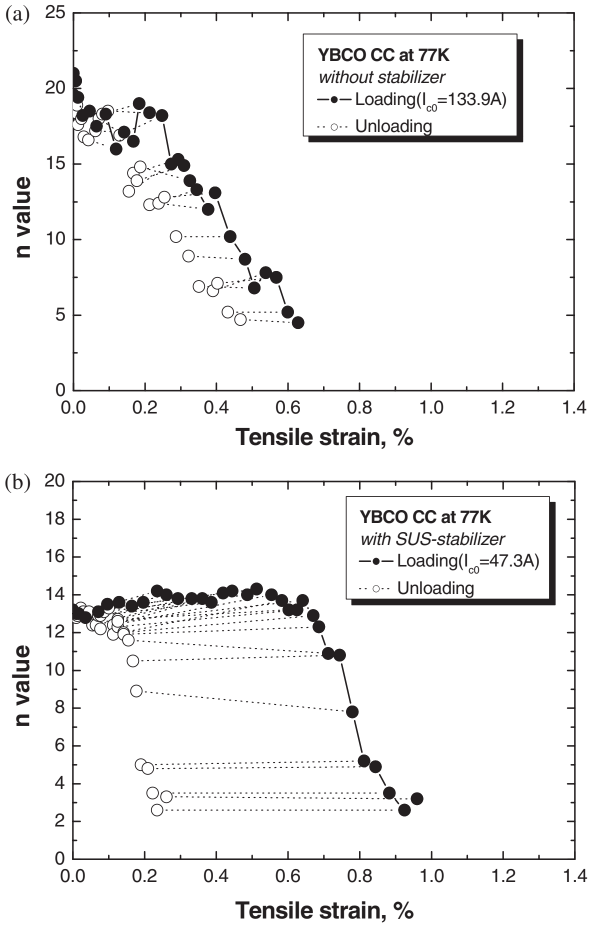

Figure 6. Relation between the n-value and applied strain of YBCO coated conductor fabricated by RABiTS-PLD. (a) Without stabilizer, (b) with stainless steel stabilizer.

conductor has smaller stress tolerance than the IBAD buffered tape on Hastelloy [7].

Figures 6(a) and (b) show the tensile strain dependence of the n-value in YBCO coated conductor. (a) Shows the case without stabilizer, (b) shows specimens stabilized with the stainless steel layer. As a whole, the n-value–applied strain relation behaved similarly to the I_c–applied strain one, regardless of the adoption of stabilizer. Since the YBCO coated conductor is similar to monofilament tape, the morphology of micro-cracks developed will have an influence on the I–V curve. On the other hand, the n_0-values measured in the unstrained state showed somewhat low value as compared with ones known for the RABiTS YBCO coated conductor tapes, which might have resulted from the drop of uniformity of YBCO film due to the application of multi-passes in the PLD method. In the elastically deformed region, the n-value recovers when the applied strain is removed. This indirectly explains that the damage behaviour in RABiTS-PLD processed YBCO film under tensile loading behaves based on the two-stage deformation described above. This means that it has partial connections even if some damage has already occurred in the YBCO film, although further efforts are needed to clarify the damage mechanism through damage morphology observations.

4. Conclusions

Effects of stabilizing layers on the tensile strain dependences of the critical current in YBCO coated conductors fabricated by the RABiTS-PLD process were examined at 77 K and in self-field. In the YBCO coated conductors, I_c increased slightly with applied strain, having a peak in the range of 0.18–0.42%, and varied reversibly. Lamination of stabilizing layers of pure Cu or stainless steel resulted in the enhancement of both ε_{max} and ε_{irr} in YBCO coated conductors, because the stabilizing layer might have produced a much larger pre-compressive strain onto the YBCO film during cool-down. I_c changed reversibly without cracking or damage on the YBCO film. Therefore, the I_c degradation behaviour in YBCO coated conductors fabricated by the RABiTS-PLD method could be divided into a two-stage deformation. Stage I: YBCO film behaved elastically and I_c recovered when the stress was removed. Stage II: I_c degradation can be attributed to cracking in YBCO film due to the plastic deformation of the substrate or the stabilizing layer.

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