Influences of Electro-plated Copper on Tensile Strain- and Stress- Tolerance of Critical Current in DyBCO Coated Conductor

Shojiro Ochiai, Hiroshi Okuda, Michinaka Sugano, Kozo Osamura, and Werner Prusseit

Abstract—**The present work was carried out to reveal the influence of plated copper onto the substrate tape constituting of $DyBa_2Cu_3O_{7-\delta}$, MgO, Ag and Hastelloy C-276 on the stress-strain behavior, and tensile strain- and tensile stress- tolerance of critical current at 77K. From the analysis of the stress-strain relation of the copper-plated tape at 77K, it was shown that the copper plated at room temperature is yielded in tension at 77K due to the higher coefficient of thermal expansion of copper than that of substrate tape. The plated copper gave compressive strain to the substrate tape and hence the superconducting layer at 77K, due to which the strain tolerance of critical current was improved. The observed improvement of strain tolerance with increasing volume fraction of plated copper was described quantitatively from the viewpoint of the stress balance at 77K between the substrate tape and yielded copper. The tolerant strain increased but the tolerant stress decreased with increasing copper volume fraction. Such a trade-off correlation between the tolerant strain and tolerant stress was described well by modeling analysis.**

Index Terms—**Coated conductor, Copper plating, Strain- and stress- tolerance of critical current, Cracking**

I. Introduction

SUPERCONDUCTING composite tapes and wires are subjected to thermal, mechanical and electromagnetic stresses/strains in fabrication and service. For RE(Y, Sm, Dy)$Ba_2Cu_3O_{7-\delta}$ coated conductors, it has been shown that when tensile strain is applied, the critical current is reversible up to the irreversible strain at which cracking occurs in the superconducting RE(Y, Sm, Dy)$Ba_2Cu_3O_{7-\delta}$ layer, but beyond the irreversible strain, the critical current decreases irreversibly with increasing applied strain due to the extension of cracking [1]–[11]. For safe and reliability, high irreversible strain and hence high strain-tolerance is required.

For the YBCO coated conductor, it has been shown that addition of copper layer enhances the irreversible axial-strain limit [1]. However, the stress-strain relation of the copper layer-added tape (hereafter noted as composite tape) has not been studied in detail. The stress bearing capacity per unit cross-sectional area of the copper-added composite tape is reduced with increasing volume fraction of copper due to the softer nature of copper than the substrate tape. Thus, it is required to reveal the influence of volume fraction of copper not only on strain-tolerance but also on stress-tolerance of the critical current.

The aims of the present work are (i) to analyze the stress-strain relation of the composite tape to reveal the stress state in the substrate tape and added-copper layer, (ii) to estimate experimentally the change in tolerant strain and tolerant stress of critical current with copper-layer addition and (iii) to describe the trade-off relation between the tolerant strain and tolerant stress (the higher the tolerant strain, the lower becomes the tolerant stress) by modeling analysis of the stress-strain relation of the composite tape.

In the present work, the $DyBa_2Cu_3O_{7-\delta}$ (DyBCO)/Hastelloy C-276 coated conductor, prepared at THEVA, Germany [12] was used as the substrate tape. A thin silver layer of 0.5 μm in thickness had been plated to solder the voltage taps for measurement of critical current under no applied strain. This substrate tape has the following mechanical features. When the substrate tape alone is pulled in tension, the Hastelloy C-276 that had been exposed at the deposition temperature (963K in this case) exhibits discontinuous yielding similarly to the Lüders band extension [4], [5], as shown in the stress-strain curve at 77K in Fig.1. As silver layer is soft and is thin (0.5 μm in thickness) in comparison with the total thickness (96.6 μm), its contribution to total stress is negligible. As Hastelloy C-276 (90 μm in thickness) occupies the most part of the cross-section (96.6 μm), it mostly controls the stress-strain relation. The discontinuous yielding initiates in the elastic deformation range shown in the circle in Fig.1, causing arrayed multiple micro-cracking in the DyBCO layer as shown in Fig.2. Such a cracking causes reduction in critical current [4], [5], [11]. The tensile strain at initiation of cracking corresponds to the irreversible strain of critical current. Thus, for improvement of

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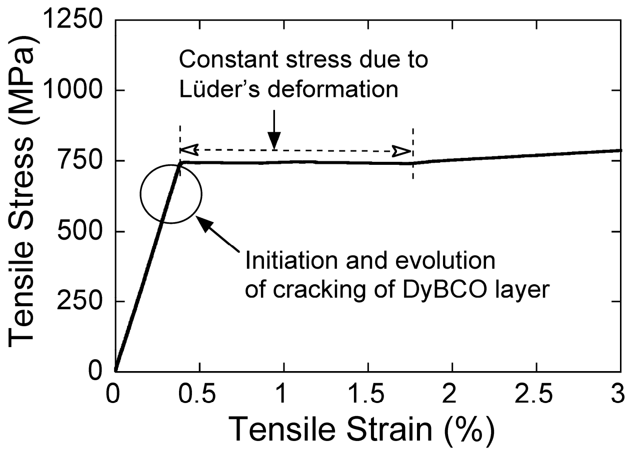

Fig. 1. Stress-strain curve at 77K of as-supplied sample without copper. Cracking of the superconducting layer initiates and evolutes, and accordingly critical current decreases in the strain region indicated in the circle.

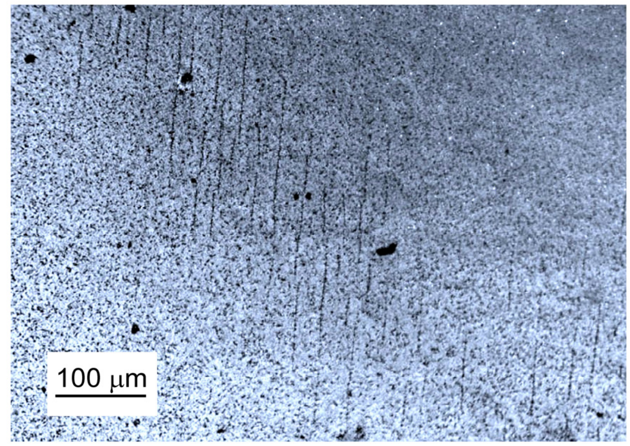

Fig. 2. An example of appearance of multiple micro-cracking.

strain tolerance of critical current, the initiation of cracking shall be retarded.

In the present work, copper was electro-plated at room temperature onto the substrate tape to retard the initiation of cracking, where copper was expected to give compressive strain on the substrate tape during cooling from room temperature to cryogenic temperature (77K in this work) since copper has higher coefficient of thermal expansion than Hastelloy C-276 [13]. Also it is noted that, when the substrate tape without plated copper is tested under applied tensile strain, quenching occurs after several percent-reduction in critical current, due to the progress of multiple cracking near the gripped portion and due to the small thickness of silver layer [4], [5]. With copper plating, the variation in critical current with applied tensile strain could be measured successfully for wide range of applied strain and for wide range of critical current [11]. Copper plays not only to improve the irreversible strain but also to give shunting circuit for imposed current, suppressing quenching [11].

II. Experimental Procedure

The DyBCO coated conductor prepared by THEVA [12], consisting of Hastelloy C-276 substrate (thickness 90 μm), MgO buffer layer (3.3 μm) deposited by ISD process, MgO cap layer (0.3 μm), DyBCO superconducting layer (2.5 μm) and silver layer (0.5 μm), was used as the substrate tape. The critical current of the substrate tape at zero applied strain was ~210 A.

Copper was electro-plated onto the substrate tape at room temperature with an electrolyte composed of $CuSO_4 \cdot 5H_2O$:225g/ℓ, H_2SO_4:35mℓ/ℓ and distilled water. In order to plate copper uniformly onto the substrate tape, as an anode, a pure copper plate with an original thickness 0.2 mm was wound to a shape of round tube and was placed into the bath as to surround the substrate tape. The volume fraction of the plated copper, V_{Cu}, was 0.427 and 0.546, where the thickness of the plated copper at each side was 36 μm and 59 μm for V_{Cu}=0.427 and 0.546, respectively.

Uniaxial tensile strain was applied to the specimen at 77 K with an Instron type testing machine. The specimen was gripped by the chucks made of copper, which also worked as current electrodes during measurement of critical current. To reduce the stress concentration within and near the grips, indium foils were inserted between the specimen and grips. For measurement of strain of the specimen, a couple of very light Nyilas [14] - type extensometers with a gage length 20 mm were attached directly to the specimen. The voltage taps for measurement of voltage (V) – current (I) curves were soldered with a spacing of 15 mm within the gage length of the extensometers. The $V – I$ curves under various applied tensile strains were measured with the usual four-probe method at 77 K in a self magnetic field.

The critical current I_c was estimated with a criterion of 1 μV/cm from the measured $V – I$ curve at each applied strain. Also, stress was monitored with a load cell at each applied strain. The stress (σ_C) – strain (ε_C) relation and critical current (I_c) – strain (ε_C) relation were measured for two specimens with V_{Cu}=0, three specimens with V_{Cu}=0.427 and three specimens with V_{Cu}=0.546.

III. Results and Discussion

A. Stress-Strain Curve

The stress (σ_C) and critical current (I_c) were measured at the same time at each tested strain (ε_C). Figure 3 shows representative stress (σ_C) – strain (ε_C) relation. In all specimens tested, the σ_C increased almost linearly with ε_C. The substrate tape (V_{Cu}=0) deforms elastically, as has been shown in Fig.1. From the slope, the Young's modulus E_{ST} of the substrate tape was estimated to be 216 GPa. As the composite tape was composed of the substrate tape and plated copper, two-component-model was used for analysis of the stress-strain relation of the composite tape, with which the influence of copper addition on stress-strain curve and stress state of each component were extracted as shown below.

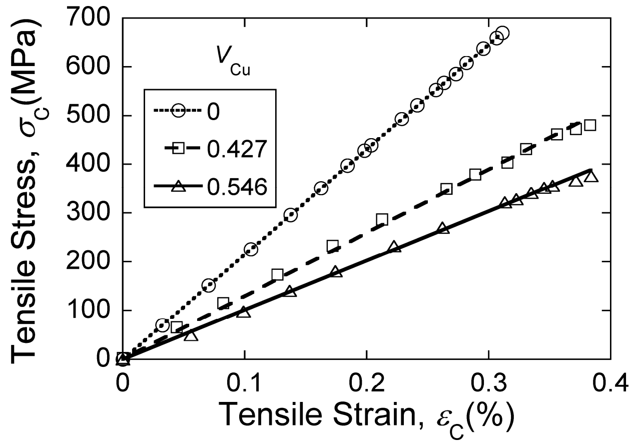

Fig. 3. Measured tensile stress σ_C – strain ε_C relation at 77 K of the specimens with V_{Cu}=0, 0.427 and 0.546.

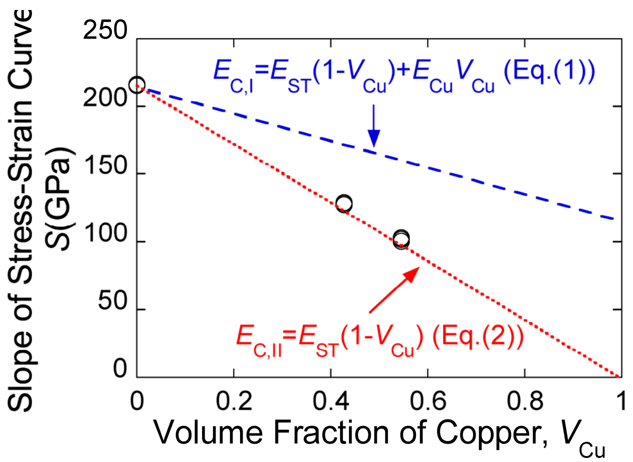

Fig. 4. Slope values in the stress-strain relation in Fig.1, plotted against copper volume fraction V_{Cu}.

The measured stress-strain relation can be used to estimate the stress state at ε_C=0%, as follows. If the copper deforms elastically, the Young's modulus of the composite tape, $E_{C,I}$ is expressed by

$$E_{C,\,I} = E_{ST}(1 - V_{Cu}) + E_{Cu}V_{Cu} \tag{1}$$

where E_{ST} (=216 GPa as stated above) and E_{Cu} (=117 GPa [15]) are the Young's moduli of the substrate tape and copper, respectively. On the other hand, if the copper deforms plastically and if the strain hardening is low in comparison with Young's modulus, the Young's modulus $E_{C,II}$ of the composite tape is approximately expressed by

$$E_{C,\,II} = E_{ST}(1 - V_{Cu}) \tag{2}$$

Slope (S) in the stress-strain relation of each tested specimen was read and was plotted against copper volume fraction V_{Cu} in Fig.4. The slope values of the specimens with V_{Cu}=0.427 and 0.546 are almost equal to $E_{C,II}$. The slight difference is

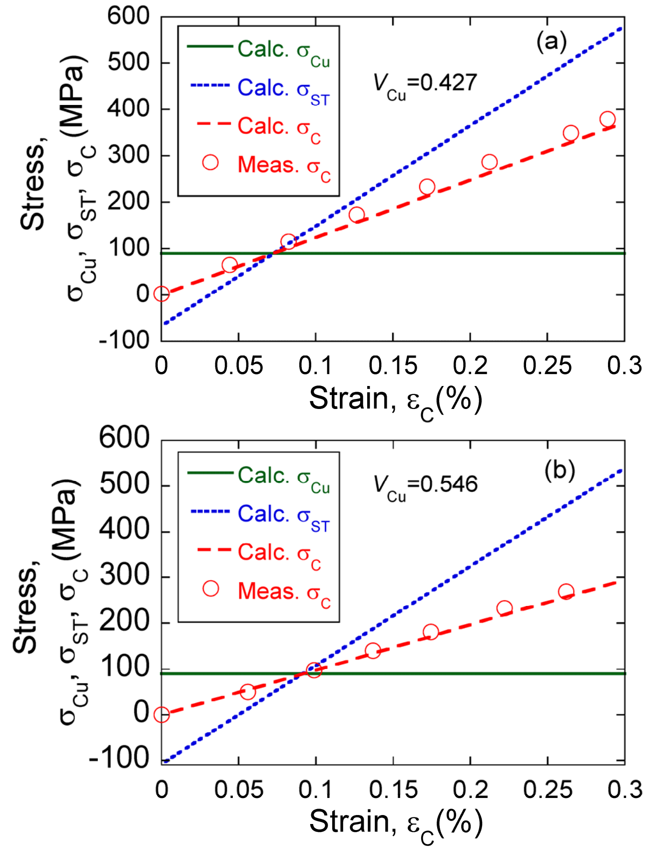

Fig. 5. Calculated stress (σ_{ST}) of the substrate tape and stress (σ_{Cu}) of cupper, stress (σ_C) of the composite tape as a function of strain (ε_C) of the composite, together with the measured σ_C – ε_C relation for comparison with calculated one. (a) V_{Cu}=0.427. (b) V_{Cu}=0.546.

attributed to the strain hardening of copper. This result clearly shows that copper has been yielded in tension before test. Namely, the residual stress of copper is almost equal to yield stress.

Noting the copper-induced residual strain of the substrate tape in the composite as $\Delta\varepsilon_{ST,r}$, yield stress of copper as $\sigma_{Cu,y}$, stress of composite as σ_C and strain of composite as ε_C, and ignoring the strain hardening of copper, we can express the σ_C as a function of ε_C in the form;

$$\sigma_C = E_{ST}(1 - V_{Cu})(\varepsilon_C + \Delta\varepsilon_{ST,\,r}) + \sigma_{Cu,\,y}V_{Cu} \tag{3}$$

The terms $E_{ST}(\varepsilon_C+\Delta\varepsilon_{ST,r})$ and $\sigma_{Cu,y}$ in Eq.(3) are the stresses at applied strain ε_C of the substrate tape and copper in the composite tape, respectively. As σ_C=ε_C=0 before test, Eq.(3) is reduced to

$$E_{ST}\left(1 - V_{Cu}\right)\Delta\varepsilon_{ST,\,r} + \sigma_{Cu,y}V_{Cu} = 0 \tag{4}$$

Equation (4) means that the tensile yield stress of copper is balanced with the compressive stress of the substrate tape at ε_C=0%. Thus, the residual strain of the substrate tape (=residual strain of DyBCO layer) at 77K induced by copper plating at room temperature is expressed as

$$\Delta\varepsilon_{\mathrm{ST,\,r}} = -\left(\frac{\sigma_{\mathrm{Cu,\,y}}}{E_{\mathrm{ST}}}\right)\left(\frac{V_{\mathrm{Cu}}}{1-V_{\mathrm{Cu}}}\right) \tag{5}$$

As shown in the next sub-section, the yield stress of copper $\sigma_{\mathrm{Cu,y}}$ is estimated to be 88.4 MPa. Substituting $\sigma_{\mathrm{Cu,y}}$=88.4 MPa into Eq.(5), E_{ST}=216GPa and corresponding V_{Cu} value (0.427 and 0.546), we have $\Delta\varepsilon_{\mathrm{ST,r}}$. Then substituting the known values of E_{ST}, $\sigma_{\mathrm{Cu,y}}$, V_{Cu} and $\Delta\varepsilon_{\mathrm{ST,r}}$ into Eq.(3), we have stress-strain curves of the composite tape, substrate tape in the composite and copper in the composite for the corresponding V_{Cu}. The result is shown in Fig.5. The measured stress-strain relations are described satisfactorily. The slight difference between the measured and calculated relations could be attributed to the strain hardening of copper.

When a material of higher yield stress like brass is adopted as stabilizer and when it deforms elastically during cooling from room temperature to cryogenic temperature, Eqs.(2) − (5) cannot be used for estimation of stress of composite conductor. In such a case, elastic analysis is needed. It is noted that the concept in the present work can be used for formulation of stress in elastic state and the elastic stress state can be analyzed in a similar manner.

B. Estimation of Tolerant Strain of Critical Current

The variation of I_c as a function of ε_C in the reversible strain range has been investigated for wide variety of RE(Y, Sm, Dy)BCO samples [1] – [11]. The reported results show that the shape of I_c-ε_C curve is dependent on the species of RE(Y, Dy, Sm), fabrication process and microstructure, residual strain and so on. Concerning the present substrate tape without plated cupper, it has been shown that I_c decreases almost linearly [4], [5], [11]. However, it is not sure whether the I_c − ε_C relation is linear or slightly curved. This point makes it difficult to determine the irreversible limit. In the present work, the strain tolerance was defined in a simplified manner, as follows.

Figure 6 shows the measured change in normalized critical current I_c/I_{c0} (I_{c0}: critical current at ε_C=0%) with strain ε_C in the substrate tape alone (without copper). In this experiment, in order to distinguish the irreversible and reversible states, stress was unloaded by around 80 MPa (around 0.04%) at A, B and C. The end of the unloading is shown with A', B' and C'.

The following features are found in Fig.6.

(1) In the early stage (ε_C=0 ~ 0.25%), the I_c/I_{c0} value decreases almost linearly with increasing strain, as shown with a dotted line. In this strain range, the I_c/I_{c0} value at A' is on the linear dotted line obtained in the loading process. This means the critical current is reversible at least up to A.

(2) When unloading starts at B, the I_c/I_{c0} at B' does not recover to the linear dotted line. This means that the critical current at B is not reversible and the irreversible strain is in the strain range between A and B. This strain range is characterized by the large drop in the slope of I_c/I_{c0} − ε_C relation in comparison with the dotted linear line. At higher applied strain

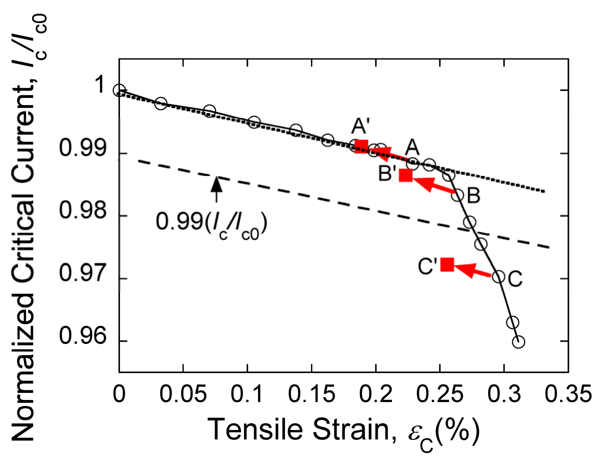

Fig.6. Change in I_c/I_{c0} with strain ε_C in loading-unloading process in a specimen without copper. A, B and C refer to the start of unloading, and A', B' and C' refer to the end of unloading around by 0.04% from A, B and C, respectively.

(C), the irreversible behavior is more clearly found as shown by the low I_c/I_{c0} value at C'.

As shown above, the candidate of the strain range of reversible limit could be detected from the sharp drop in slope of I_c/I_{c0}−ε_C diagram, while it is still not clear whether the I_c/I_{c0}−ε_C relation is surely linear or not. Also it is noted that the difference in I_c/I_{c0} value between B' and the value on the linear dotted line at the strain B'(ε_C=0.223%) is around 0.002, which is very small. Experimental error can be included in such a small value. In the present work, for estimation of tolerant strain of critical current, an alternative criterion other than the exact reversible limit was used as follows.

As shown in Fig.6, the sharper drop in I_c/I_{c0} − ε_C diagram in comparison with the liner dotted line refers to the reversible strain limit. If we take 99% I_c/I_{c0} offset line (broken line in Fig.6) of the measured I_c/I_{c0} − ε_C relation in the reversible strain range, we can identify the tolerant strain value as the cross-point of the measured I_c/I_{c0} − ε_C curve and the 99% line. This 99% I_c/I_{c0} offset line criterion is useful in practice as shown below.

Figure 7 shows the measured change in normalized critical current I_c/I_{c0} with tensile strain ε_C in the specimens with V_{Cu}=(a) 0, (b) 0.417 and (c) 0.546. Though the I_c/I_{c0} − ε_C curves are different among specimens, the I_c/I_{c0} values of all specimens commonly decreased almost linearly with increasing strain ε_C and then dropped sharply. The tolerant strain $\varepsilon_{C,t}$ obtained by the "99% I_c/I_{c0} offset line criterion" is indicated with an arrow for each specimen. Once the $\varepsilon_{C,t}$ value is obtained, the tolerant stress $\sigma_{C,t}$ at the corresponding $\varepsilon_{C,t}$ value can be read from the stress-strain relation, as typically shown in Fig.8.

Figure 9 shows the measured values of the tolerant strain $\varepsilon_{C,t}$ and tolerant stress $\sigma_{C,t}$, plotted against volume fraction of copper (V_{Cu}). The $\varepsilon_{C,t}$ increases but $\sigma_{C,t}$ decreases with increasing V_{Cu}. In the next subsection, this result is analyzed quantitatively by using the result of analysis of the stress-strain curves (Subsection III.A).

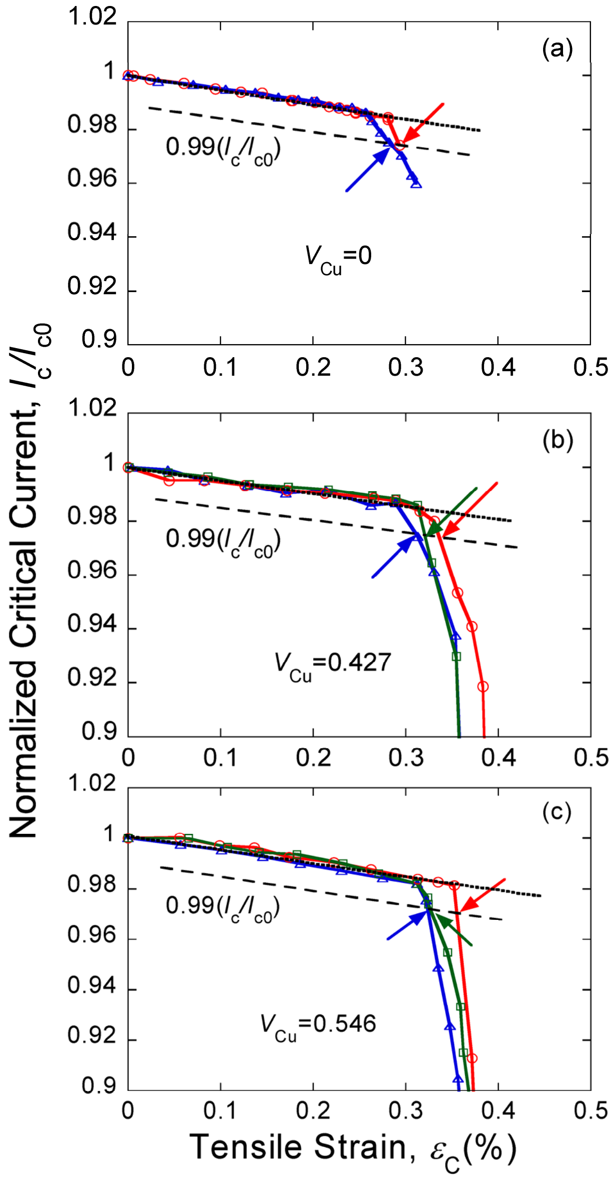

Fig. 7. Measured change in normalized critical current I_c/I_{c0} with tensile strain ε_C in the specimens with V_{Cu}=(a)0, (b)0.417 and (c)0.546. The strain tolerance $\varepsilon_{C,t}$ is shown with an arrow for each specimen.

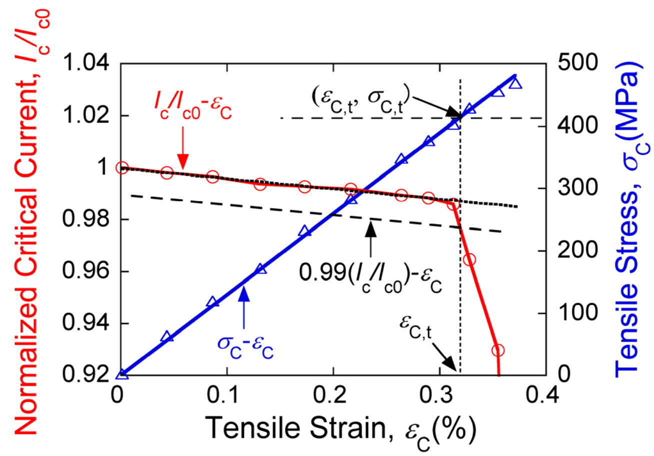

Fig. 8. An example of determination of $\varepsilon_{C,t}$ and $\sigma_{C,t}$ from the measured I_c/I_{c0} – ε_C and σ_C – ε_C relations.

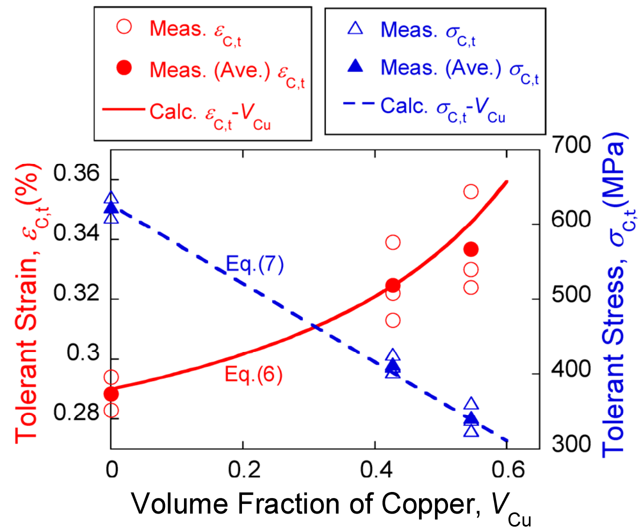

Fig. 9. Measured tolerant strain $\varepsilon_{C,t}$ and tolerant stress $\sigma_{C,t}$ plotted against volume fraction of copper (V_{Cu}). The solid curve and broken line refer to the analyzed $\varepsilon_{C,t}$ – V_{Cu} and $\sigma_{C,t}$ – V_{Cu} relation, respectively.

C. Influence of Plated Copper Amount on Strain- and Stress- and Load- Tolerance of Critical Current, and Trade-off relation between Strain Tolerance and Stress Tolerance

The residual strain $\Delta\varepsilon_{ST,r}$ of the substrate tape at 77K in the composite introduced by the plated copper is given by Eq.(5). Noting the tolerant strain of the substrate tape alone as $\varepsilon_{ST,t}$, corresponding to the value of $\varepsilon_{C,t}$ at V_{Cu}=0 in Fig.9, the tolerant strain $\varepsilon_{C,t}$ of the composite tape is given by $\varepsilon_{C,t}$= $\varepsilon_{ST,t}$ – $\Delta\varepsilon_{ST,r}$. Substituting $\Delta\varepsilon_{ST,r}$ given by Eq.(5) into this relation, we have

$$\varepsilon_{C,t} = \varepsilon_{ST,t} + \left(\frac{\sigma_{Cu,y}}{E_{ST}}\right)\left(\frac{V_{Cu}}{1-V_{Cu}}\right) \tag{6}$$

Figure 10 shows the plot of the measured values of the tolerant strain $\varepsilon_{C,t}$ against $V_{Cu}/(1 - V_{Cu})$. The slope corresponds to $\sigma_{Cu,y}/E_{ST}$ (Eq.(6)). As E_{ST} has been estimated to be 216 GPa, the value of $\sigma_{Cu,y}$ can be obtained from the slope value. The $\sigma_{Cu,y}$ of the present specimens was 88.4 MPa. With this value, the measured stress-strain was described satisfactorily, as has been shown in Fig.5. Also substituting $\sigma_{Cu,y}$=88.4MPa, average of measured $\varepsilon_{ST,t}$ values(0.289%) and E_{ST}=216GPa into Eq.(6), we have $\varepsilon_{C,t}$ – V_{Cu} relation, as shown with a solid curve in Fig.9. The calculated $\varepsilon_{C,t}$ – V_{Cu} relation satisfactorily describes the experimental result.

The tolerant stress $\sigma_{C,t}$ corresponds to the stress at $\varepsilon_C = \varepsilon_{C,t}$ (= $\varepsilon_{ST,t} - \Delta\varepsilon_{ST,r}$). Substituting $\varepsilon_C = \varepsilon_{ST,t} - \Delta\varepsilon_{ST,r}$ into Eq.(3), we have the tolerant stress $\sigma_{C,t}$ in the form;

$$\sigma_{C,t} = E_{ST}\varepsilon_{ST,t}(1-V_{Cu}) + \sigma_{Cu,y}V_{Cu} \tag{7}$$

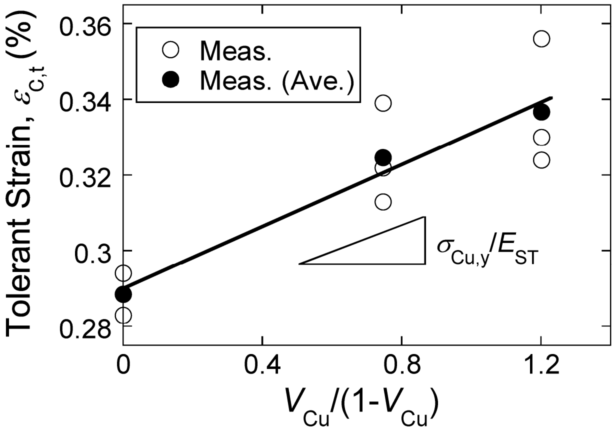

Fig. 10. Plot of the measured tolerant strain $\varepsilon_{C,t}$ against $V_{Cu}/(1-V_{Cu})$.

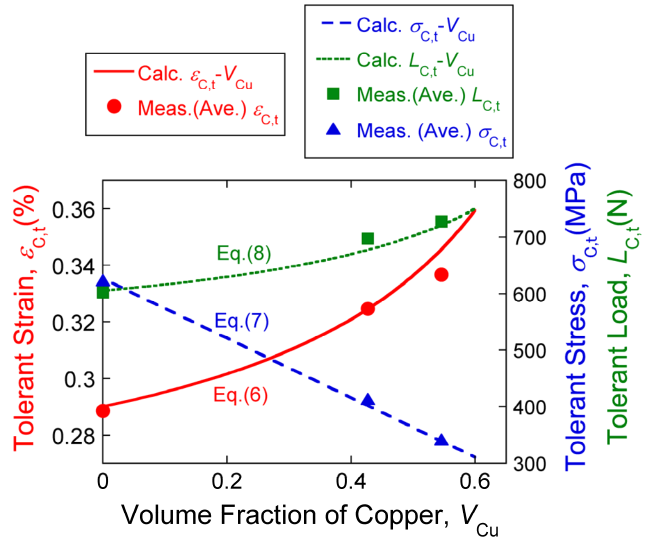

Fig.11 Measured average values of tolerant strain $\varepsilon_{C,t}$, tolerant stress $\sigma_{C,t}$ and tolerant load $L_{C,t}$, plotted against volume fraction of copper (V_{Cu}). The solid curve, broken line and dotted curve refer to the calculated $\varepsilon_{C,t}-V_{Cu}$, $\sigma_{C,t}-V_{Cu}$ and $L_{C,t}-V_{Cu}$ relations by Eqs.(6), (7) and (8), respectively.

Equation (7) means that $\sigma_{C,t}$ decreases linearly with increasing volume fraction of copper V_{Cu}. Substituting the aforementioned values of E_{ST}=216GPa, $\varepsilon_{ST,t}$=0.289% and $\sigma_{Cu,y}$=88.4 MPa into Eq.(7), we have the $\sigma_{C,t}-V_{Cu}$ relation, as shown with a broken line in Fig.9. The experimental result and the feature of linear decrease of $\sigma_{C,t}$ with V_{Cu} are satisfactorily described by this calculation. In this way, the trade-off relation between the tolerant strain-copper volume fraction and the tolerant stress-copper volume fraction (the tolerant strain increases but the tolerant stress decreases with increasing copper volume fraction) was described satisfactorily.

As shown above, the tolerant stress $\sigma_{C,t}$ decreases with increasing volume fraction of copper (V_{Cu}). For description of influence of copper amount on tolerant mechanical property, the tolerant load $L_{C,t}$ at tolerant strain $\varepsilon_{C,t}$ is also important. Noting the cross-sectional area of the substrate as A_{ST}, $L_{C,t}$ is expressed as

$$L_{C,t}=\sigma_{C,t}A_{ST}/(1-V_{Cu}) \tag{8}$$

Substituting the calculated $\sigma_{C,t}-V_{Cu}$ relation shown in Fig.10, A_{ST}=9.66×10^{-7} m^2 into Eq.(8), we have $L_{C,t}$ as a function of V_{Cu} as shown in Fig.11. The $\varepsilon_{C,t}-V_{Cu}$ and $\sigma_{C,t}-V_{Cu}$ relations in Fig.10 and the measured average values of $\varepsilon_{C,t}$, $\sigma_{C,t}$ and $L_{C,t}$ are also shown in Fig.11 for reference. The following features can be read from Fig.11. (a) The $L_{C,t}$ increases with increasing V_{Cu} in contrast to the decrease in $\sigma_{C,t}$ with V_{Cu}. From the viewpoint of load, copper plating gives advantage. (b) The increase in $L_{C,t}$ with V_{Cu} is, however, not large due to the softer nature of plated copper; $L_{C,t}$ increases from around 600 N at V_{Cu}=0 to around 750 N at V_{Cu}=0.6. The increment is around 25% though the cross-sectional area of the composite tape increases by 2.5 times at V_{Cu}=0.6 in comparison with that of the substrate tape alone. (c) On the other hand, the decrement in $\sigma_{C,t}$ with V_{Cu} is far large; $\sigma_{C,t}$ decreases from around 600 MPa at V_{Cu}=0 to around 300 MPa at V_{Cu}=0.6. The decrement is around 50 %. The decrement in $\sigma_{C,t}$ is far sensitive to the amount of plated copper in comparison with increment in $L_{C,t}$. (d) Summarizing these results, the copper plating is useful to raise $\varepsilon_{C,t}$ and $L_{C,t}$ but the trade-off relation between $\varepsilon_{C,t}$ and $\sigma_{C,t}$ shall be optimized to realize high mechano-electrical performance tape. The present approach and the obtained $\varepsilon_{C,t}-V_{Cu}$, $\sigma_{C,t}-V_{Cu}$ and $L_{C,t}-V_{Cu}$ diagram as in Fig.11 could be a useful tool for structure design of composite tapes from mechanical viewpoint when refined.

The concept of 99% I_c/I_{c0} offset line (Figs. 6, 7 and 8) for estimation of tolerant strain is only applicable to the conductor whose I_c/I_{c0}varies linearly with strain. For the conductors that show curved behavior of I_c/I_{c0} with strain, the approach, recently developed by Goodrich et al. [16] to determine precisely the irreversible strain limit through measurement of critical current under loading – partial unloading process and polynomial fit to the experimental result, could be applied. Once the irreversible strain limit is obtained, the approach proposed in the present work can extensively be used by replacing the tolerant strain obtained by the 99% I_c/I_{c0} offset method in the present work by the irreversible strain limit. With such an approach, the irreversible stress- and load- limits and trade off-relation between the irreversible strain and irreversible stress could be estimated more precisely for wide variety of conductors.

IV. Conclusions

Influences of plated copper onto the substrate tape on the stress-strain behavior and tensile strain (and stress)-tolerance of critical current at 77K in $DyBa_2Cu_3O_{7-\delta}$ -coated conductor was studied experimentally and analytically with a proposed simple model. Main results are summarized as follows.

(1) From the analysis of the stress-strain relation at 77K, it was shown that the copper plated at room temperature is yielded in tension at 77K, mainly due to the higher coefficient of thermal expansion of copper than that of substrate (Hastelloy C-276).

(2) The plated copper gave compressive strain to the superconducting layer at 77K, due to which the strain tolerance of critical current was improved. It increased with increasing volume fraction of plated copper, which was accounted for from the viewpoint of the stress balance at 77K between the substrate-tape and yielded copper.
(3) Due to the softer nature of copper in comparison with the substrate tape, stress tolerance of critical current decreased with increasing volume fraction of plated copper, while the load tolerance increased. The measured values of tolerant stress and tolerant load were described satisfactorily by the present modeling.
(4) The trade-off relation between the tolerant strain-copper volume fraction and tolerant stress-copper volume fraction (the tolerant strain increases but the tolerant stress decreases with increasing copper volume fraction) was described by the present approach.

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