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$YBa_2Cu_3O_{7-\delta}$ coated conductor cabling for low ac-loss and high-field magnet applications*

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Abstract
The electromechanical properties of $YBa_2Cu_3O_{7-\delta}$ coated conductors under high axial compressive strain are measured; they show no irreversible degradation in critical current up to −2% strain. The high degree of elasticity of the ceramic layers in these conductors is beneficial when used in high-field applications, but has not been fully exploited. The results presented here lead to the introduction of a new method of producing $YBa_2Cu_3O_{7-\delta}$ coated conductor cabling for use in low ac-loss and high-field magnet applications, where coated conductors are wound around a former with a relatively small diameter. This concept allows for full transposition of the conductors, a high cable critical current, low inductance, and a relatively high engineering current density. The feasibility of the concept is demonstrated by constructing several prototype cables and by comparing the cable critical current to that of a straight sample under axial compression.

1. Introduction

The development of $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductors for electric power applications has resulted in high critical current densities (J_c) of over 3.0 MA cm^{-2} in conductor lengths exceeding 1 km [1]. The mechanical properties have improved significantly compared to those of $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes. The axial strain (ε) at which the YBCO layer breaks (irreversible strain limit ε_{irr}) now exceeds 0.6% under tension in coated conductors [2]. A clear reversible change in J_c as a function of strain is measured before ε_{irr} is reached [2–5], which is possibly related to a fundamental change of critical temperature (T_c) and upper critical field (H_{c2}) with strain. At this time, no data exist regarding the axial compressive strain at which the YBCO layer degrades irreversibly.

Low-temperature superconducting (LTS) wires are used in high-field magnets, such as particle accelerators, that require high-current-density windings. Currently, the highest magnetic field that can be reached in these magnets is limited by the upper critical field of the superconductor, which is around 26 T at 4.2 K for Nb_3Sn. Achieving higher fields requires the use of high-temperature superconductors (HTS) with upper critical fields far exceeding those of LTS. The potentially very high elasticity of YBCO coated conductors under axial compressive strain is also beneficial for high-field magnet applications. In high-field dipole magnets [6], the conductor is placed under relatively high axial compressive strain during cool-down to mitigate the Lorenz forces that will strain the wire towards its irreversible strain limit during operation. YBCO coated conductors have recently been applied as high-field insert magnets [7], where a record total field of 26.8 T is achieved in a background field of 19 T. This magnet was constructed from simple turn, multiple layer units, so-called pancakes that were wound from a single coated conductor. Cabling of YBCO coated conductors to achieve higher currents per winding for low-inductance magnet and generator applications, and with full conductor transposition, has so far been limited to the Roebel bar design [8].

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In this paper, the behavior of the critical current (I_c) of YBCO coated conductors under high axial compressive strain of up to −2% is studied. A new concept of cabling YBCO coated conductors for high-field magnet and low ac-loss applications is introduced and a number of prototypes are constructed to demonstrate the feasibility of the concept.

2. Experimental details

The YBCO coated conductors in this study were purchased from SuperPower Inc. and consist of ceramic buffer layers deposited on a 50 μm thick Hastelloy C-276 substrate. The 1.0 μm YBCO layer was deposited on top of the buffer layers by metal–organic chemical-vapor deposition (MOCVD) [9, 10]. Grain alignment was introduced into the MgO buffer layer with ion-beam-assisted deposition (IBAD). A silver cap layer, 2–3 μm thick, was deposited on top of the YBCO layer for electrical and thermal stability. The coated conductors were then slit from a 12 mm wide tape to their final width of 4 mm. They were surround-plated with 20 μm of copper for electrical and thermal stability. The critical current density is about 2.5 MA cm^{-2}.

The dependence of the critical current on axial compressive strain of the coated conductors was measured at 76 K. The samples were soldered onto the surface of 98 wt%Cu–2 wt%Be (CuBe) and brass beams by use of 97 wt%In–3 wt%Ag solder with a melting temperature of 143 °C. The bond between the bending beam and the sample should be homogeneous and of high strength, which is ensured by soldering the copper plated samples to a copper-alloy bending beam. Axial strain was applied by bending the beams in a four-point bender, as described in more detail elsewhere [2]. The critical current was determined with a four-contact measurement having an uncertainty of about 0.5% at an electric field criterion of 1, or 10 μV cm^{-1} for the case of a double layered cable (cable 6). Strain was measured directly with strain gages that were mounted on top of the beams and on top of the sample.

3. Results and discussion

3.1. YBCO coated conductors under high axial compressive strain

Previous measurements of the critical current of YBCO coated conductors under axial compressive strain were limited to about −1% strain to avoid plastic deformation of the CuBe bending beam, at which strain level no irreversible degradation in I_c occurred [2]. In this paper, compressive strain that exceeds −1% is applied to determine at which strain the critical current degrades irreversibly, allowing a plastic deformation of the CuBe or brass bending beam. A deviation from the parabolic I_c–ε dependence is measured as soon as the strain exceeds −1% (figure 1), where I_c decreases more gradually until reduced by about 95% at about −2% strain. The reduction in I_c up to −2% compression is fully reversible, as is confirmed by partially unloading the strain (open circle in figure 1). It's assumed that the film remains undamaged at −2% compressive strain since the critical current fully recovers to its initial value after the sample is unloaded from −2% to −1% axial strain. A degradation of the current leads attached to the sample that occurs at strains exceeding −2% limits the range of the experiment. The irreversible strain limit of YBCO coated conductors under axial compressive strain therefore remains unknown, but exceeds −2%. A possible cause for this high degree of elasticity of the YBCO layer under axial compressive strain is the almost single-crystalline nature of the film.

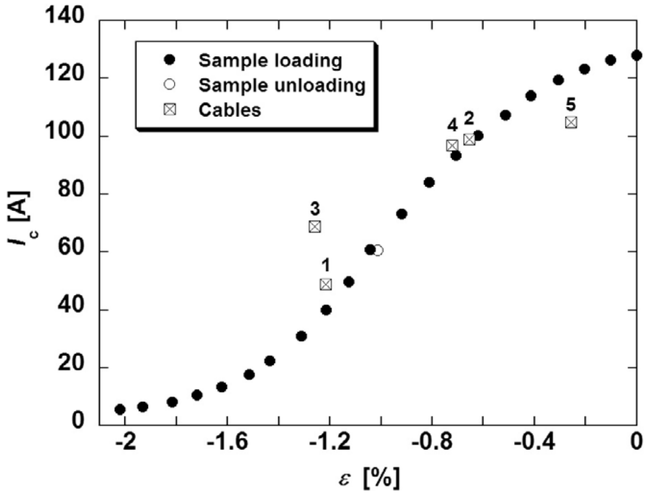

Figure 1. Critical current as a function of axial compressive strain at 76 K of a YBCO coated conductor that is soldered on a brass bending beam. The applied strain is measured directly on the surface of the sample with a strain gage. The critical currents at the calculated strain state of prototype cables (numbered) are included (below, table 1).

Three additional samples were measured to confirm the results: one of the samples was mounted on a CuBe bending beam and two were mounted on brass bending beams (results not shown here). The measured I_c-ε dependence of all four samples is comparable, although the elastic limit of the brass beams is lower (−0.95%) than that of the CuBe beam (−1.25%). The elastic limit of the bending beams at 76 K is determined by measuring the remaining strain at the surface of the beam with a strain gage after the beam is unloaded from the maximum applied strain. It is also confirmed that the applied strain is fully transferred to the YBCO layer, even at a high compressive strain of about −2%, by measuring the strain on the sample surface. Therefore it can be concluded that the inflection in the I_c-ε dependence at about −1% strain is not caused by yielding of the bending beam or the substrate of the sample. The change in shape is intrinsic to the superconducting layer, as is the case for Nb_3Sn wires; Arbelaez *et al* have recently explained this by use of the third invariant of the deviatoric strain [11].

3.2. Cabling of YBCO coated conductors

Their very high elastic limit under axial compression enables YBCO coated conductors to be used in configurations that previously were considered impossible. For instance, the conductors can be cabled by winding them with the YBCO

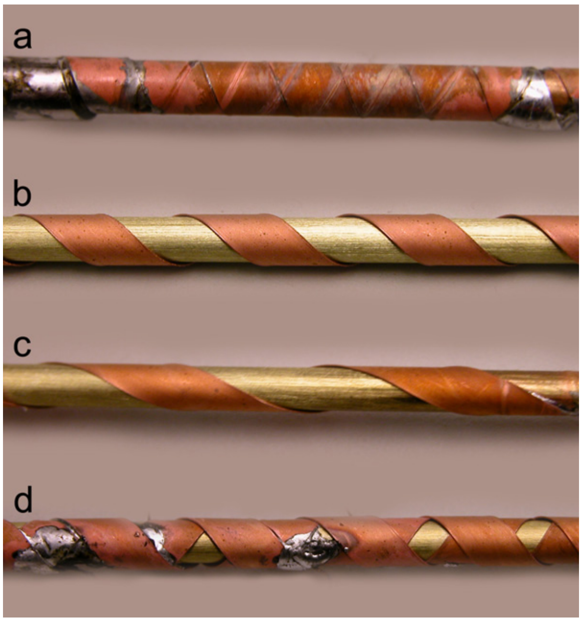

Figure 2. Prototype cables prepared by winding a single YBCO coated conductor around a brass former, 3.19 mm in diameter, with twist pitch (a) 9 mm, (b) 20 mm, (c) 40 mm, and (d) by winding two layers of conductors with 18 mm twist pitch.

(This figure is in colour only in the electronic version)

layer in compression on a round former (i.e., with the YBCO layer positioned towards the inside), similar to some superconducting transmission cables [12], but with a much smaller radius. A compressive strain of 2% in the YBCO layer corresponds to a winding radius of only 1.25 mm, as follows from the following equation:

$$\varepsilon(r) = \frac{-t}{2r}. \tag{1}$$

Here, t is the thickness of the substrate on which the YBCO layer is deposited (50 μm in this case) and r is the bending radius. The center of the conductor always experiences zero strain, independent of bending radius. This strain-free axis is called the neutral axis [13].

To demonstrate the cabling concept, five single conductor cables and one double layer cable have been prepared. The YBCO coated conductors were wound around a brass rod of 3.19 mm (1/8 inch) outer diameter, with various twist pitches p (see figure 2). Both ends of the conductors are soldered to the rod. The critical current of the conductor cables was measured at 76 K and depends on the initial I_c (between 125 and 135 A), the radius of the former, and the twist pitch. Notably, I_c is higher for larger twist pitch lengths: $I_c = 49$ and 69 A at 9 mm pitch (cables 1 and 3), $I_c = 97$ A at 20 mm pitch (cable 4), and $I_c = 105$ A at 40 mm pitch (cable 5), as listed in table 1. Twisting the conductor around the former results in a full transposition and a reduced ac-loss of the cable.

The coated conductor in cable 2 was laminated by soldering a 50 μm thick copper strip to the YBCO side before it was wound around the brass rod, there by moving the YBCO layer closer towards the neutral axis of the conductor, and

Table 1. Specifications of the cable prototypes.

	Twist pitch (mm)	I_c (A)	$\varepsilon_{\mathrm{YBCO}}$ (%) (equations (2))
Cable 1	9	49	−1.28
Cable 2[a]	9	99	−0.71
Cable 3	9	69	−1.28
Cable 4	20	97	−0.78
Cable 5	40	105	−0.32
Cable 6[b]	18	214	Layer 1: −0.86 Layer 2: −0.85

[a] The conductor was laminated on the YBCO side with 50 μm of copper.
[b] The critical current of the double layer cable was determined at 10 μV cm^{-1}.

significantly reducing the strain in the YBCO layer. Placing the YBCO layer closer to the neutral axis results in a relatively high I_c of 99 A when the conductor is wound around the brass former with a twist pitch of 9 mm, compared to the same cable arrangement of cables 1 and 3 that were prepared without lamination.

Cable 6 consists of two layers, each containing a single coated conductor. The first conductor is wound directly on the brass rod with a twist pitch of about 18 mm, while the second conductor is wound in the opposite direction with the same twist pitch over the first conductor. The critical current of the cable is 214 A at an electric field criterion of 10 μV cm^{-1}. The critical current could not be determined at a lower criterion due to the relatively small separation between the voltage contacts and the ends of the tapes in the cable.

To explain the difference in measured I_c values of the cables wound with different twist pitches, the strain in the YBCO layer of the tape is calculated. The thickness c of the 20 μm copper that is plated on top of the YBCO layer is added to the 1.59 mm radius of the brass former. It is also assumed that the tape is wound tightly around the former, eliminating any gap between former and tape. The strain in the YBCO layer along the direction of the current ($\varepsilon_{\mathrm{YBCO}}$) can be calculated from the radius of the former and the twist pitch by calculating the length of the path of the YBCO layer l_{YBCO} and the length of the path of the neutral axis l_{neutral} over half a twist pitch $\frac{p}{2}$, as shown in figure 3. Since the neutral axis is strain-free, its length remains constant (independent of bending radius or twist pitch) and the YBCO layer is placed under axial compression:

$$\varepsilon_{\mathrm{YBCO}}(r, p) = \frac{(l_{\mathrm{YBCO}} - l_{\mathrm{neutral}})}{l_{\mathrm{neutral}}}$$

$$= \frac{\sqrt{\frac{1}{4}p^2 + (r+c)^2 4\pi^2}}{\sqrt{\frac{1}{4}p^2 + (r+c+\frac{1}{2}t)^2 4\pi^2}} - 1. \tag{2}$$

The critical currents of the cables are compared to that of a straight coated conductor under axial compression. The additional compressive strain that the conductor experiences upon cool-down when soldered to the bending beam has to be taken into account in this comparison. The additional compressive strain is not introduced into the conductor of the cable, since the conductors are not continuously soldered. The

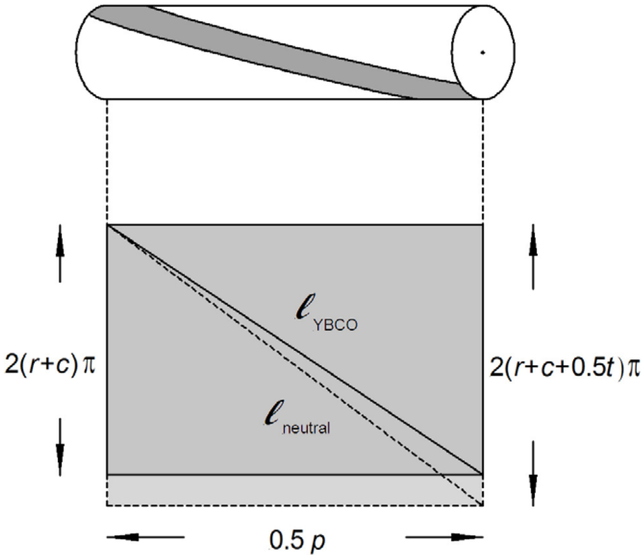

Figure 3. Schematic of the different path lengths between the YBCO layer and the neutral axis of a coated conductor that is wound around a former with twist pitch p.

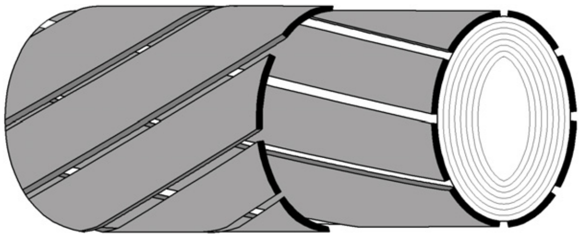

Figure 4. Schematic of a multi-layer cable, showing how each layer is configured out of multiple conductors.

compressive pre-strain is determined with a strain gage that is mounted on the sample. The sample that is soldered on the beam experiences an additional compressive strain of -0.06%.

A direct comparison between the critical current of a straight sample and those of the cables is made in figure 1. The strain in the YBCO layer of the conductors in the prototype cables is far less than -2% (equations (2)) at which the reduction in I_c is still fully reversible. This leaves room for additional compressive strain in the YBCO layer, for instance, by winding the tape around a former with an even smaller radius. The slight difference between I_c of the cables and that of a straight sample under compression can be caused by a number of factors. First, it is assumed in the strain calculation that the conductor is wrapped tightly around the brass former. The actual strain in the YBCO layer will be reduced when a small gap exists between conductor and former (see figure 2). Second, there is slight variability in I_c over the length of the tape. Critical currents between 125 and 135 A have been measured in the tapes that were used for cabling. A third cause of the deviation between the critical currents of the cables and the straight sample could be the difference in self-magnetic-field at the tape surface that depends on the different configurations.

The assumption that the critical current of the conductor wound around a former with a twist pitch p is fully determined by the strain parallel to the current, and acting along the length of the conductor may not be correct. In case the reversible change in I_c with strain is caused by a change in critical temperature (and by a change in upper critical field), strain oriented perpendicular to the current may play an important role as well, which has not been taken into account here.

High-current cables can be constructed by adding additional layers of conductor to reach the current levels needed for specific applications (see figure 4). A flexible normal conducting former could be used to ensure enough flexibility in the final stack. For instance, starting with a former of 3.19 mm outer diameter as in the prototypes, the first layer could consist of two 4 mm wide conductors wound in parallel, since the circumference of the former is about 10 mm. By adding additional layers, the circumference increases by at least $0.2\pi = 0.63$ mm per layer (assuming a conductor thickness of 0.1 mm). The fourth layer could consist of three 4 mm wide tapes in parallel, since the circumference is now 12.5 mm. Assuming a large twist pitch, a cable of 7 mm diameter can be constructed in the following way: 3 layers of 2 conductors in parallel, 6 layers of 3 conductors, 6 layers of 4 conductors, and 4 layers of 5 conductors. The total amount of 4 mm wide conductors in this configuration is 68, which corresponds roughly to a critical current of 6800 A at 76 K (100 A per conductor), hereby ignoring the magnetic field generated by the transport current. Also, the decrease in strain in each additional layer is ignored in this calculation.

The coated conductor used in the prototype cables has a critical current of approximately 1000 A at 4.2 K in self-field, based on the assumption that the self-field I_c is increased by a factor of 10 when the conductor is cooled from 76 to 4.2 K. Based on measurements on similar coated conductors, the critical current would be a little more than 100 A at 16 T with the magnetic field oriented parallel to the c-axis of the tape, and roughly 750 A at 16 T with the field parallel to the ab-plane [14]. Since all conductors in the cable will experience a wide range of magnetic field angles, the critical current of the cable is expected to be at least 6800 A at 16 T and 4.2 K. The engineering current density (J_e) of the cable is expected to be about 175 A mm^{-2} in the absence of current sharing between conductors. This is in the range needed for high-field magnet applications designed to operate in the range between 15 and 25 T and that requires a J_e between 140 and 200 A mm^{-2}. The I_c and J_e at high temperatures can be significantly raised by introducing artificial pinning centers in the conductor [7, 15], although not much effort has been spent to improve pinning at 4.2 K. Limited data on the effect of strain on the critical current of YBCO coated conductors in the presence of a magnetic field has become available [16, 17]. Since no data exists on how axial compressive strain affects the critical current at 4.2 K in the presence of a magnetic field, and the mechanism behind the in-field strain effect remains unknown, it is currently impossible to estimate how strain would affect the performance of the cable under its operation conditions as described in this paper.

Current sharing between individual coated conductors will raise I_c in the presence of a magnetic field, and most likely improve the stability of the cable. Changing the thickness of the copper may also be required, especially that of the copper layer on the YBCO side of the conductor. The overall conductor thickness could be left unchanged, even with the addition of copper on the YBCO side, by reducing the copper thickness on the substrate side, or lowering the thickness of the substrate.

4. Conclusions

Measurements of the critical current of YBCO coated conductors on Hastelloy substrates under high axial compressive strain showed no irreversible degradation. The critical current degraded reversibly by 95% at −2% compressive strain. The high degree of elasticity of YBCO coated conductors makes them well suited for use in high-field magnets, where thermal contraction of the assembly places the conductor under axial compressive strain at cool-down.

Several prototype cables for low ac-loss and magnet applications have been prepared by tightly winding the coated conductor with the YBCO layer in compression around a brass former with a 3.19 mm outer diameter. No irreversible degradation of the tape occurs at this bending radius, since the strain in the YBCO layer is far less than −2%. The critical current of the cables as a function of twist pitch was calculated and the total I_c under operation in a magnetic field at 4.2 K was estimated, demonstrating the feasibility of this concept.

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