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Reversible axial-strain effect in Y–Ba–Cu–O coated conductors*

N Cheggour[1], J W Ekin[1], C L H Thieme[2], Y-Y Xie[3], V Selvamanickam[3] and R Feenstra[4]

[1] National Institute of Standards and Technology, Boulder, CO 80305, USA
[2] American Superconductor Corporation, Westborough, MA 01581, USA
[3] SuperPower Incorporated, Schenectady, NY 12304, USA
[4] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

E-mail: cheggour@boulder.nist.gov

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Abstract

The recently discovered reversible strain effect in Y–Ba–Cu–O (YBCO) coated conductors contrasts with the general understanding that the effect of strain on the critical-current density J_c in practical high-temperature superconductors is determined only by crack formation in the ceramic component. Instead of having a constant J_c as a function of strain before an irreversible drop when cracks form in the superconductor, J_c in YBCO coated conductors can decrease or increase *reversibly* with strain over a significant strain range up to an irreversible strain limit. This reversible effect is present in samples fabricated either with rolling-assisted biaxially textured Ni–W substrates or with ion-beam-assisted deposition on Hastalloy substrates. The reversibility of J_c with strain is observed for thin as well as thick YBCO films, and at two very different temperatures (76 and 4 K). The reversible effect is dependent on temperature and magnetic field, thus indicating its intrinsic nature. We also report an enhancement of the irreversible strain limit ε_{irr} where the reversible strain effect ends and YBCO cracking starts. The value of ε_{irr} increases from about 0.4% to more than 0.5% when YBCO coated conductors are fabricated with an additional Cu protection layer.

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

1. Introduction

Recent studies of the electromechanical properties of yttrium–barium–copper oxide (YBCO) coated conductors showed that the critical-current density J_c depends reversibly on the axial tensile strain ε up to an irreversible strain limit ε_{irr}, representing the strain at the onset of YBCO cracking [1, 2]. Instead of having a constant J_c as a function of strain before an irreversible drop when cracks form in the superconductor, J_c in YBCO coated conductors can decrease or increase *reversibly* with strain up to $\varepsilon = \varepsilon_{irr}$. Therefore, the effect of strain on the transport J_c in these practical superconductors is not determined just by crack formation in the YBCO brittle component. These results were obtained on 1 μm thick YBCO films, grown on rolling-assisted, biaxially textured substrates (RABiTS) [3, 4].

This paper presents a concise review of wide-ranging sets of data obtained for various conductor geometries and under very different temperature and magnetic field conditions, intended to describe and promote understanding of the origins of the reversible strain effect in YBCO coated conductors.

Following the discovery of the reversible strain effect in the RABiTS conductors [1, 2], we now show that this behaviour also exists in samples fabricated with the ion-beam-assisted deposition (IBAD) technique [5, 6]. Detailed analysis of the electric field (E) versus current density (J) characteristics for both RABiTS and IBAD conductors proves that the reversibility of J_c with strain is independent of the

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electric field criterion used to define J_c, at least for E between 0.1 and 20 μV cm^{-1}. Hence, this behaviour is not an artefact of the measurements. New data reveal that this reversible strain effect is also present in samples with a relatively thick YBCO layer of 2.75 μm. Furthermore, the effects of temperature and magnetic field on the reversible behaviour have been investigated by measuring $J_c(\varepsilon)$ at liquid-nitrogen and liquid-helium temperatures, in the presence of magnetic fields of intensities up to 16.5 T applied parallel to the (a, b) plane. This initial study indicates a strong dependence of the intrinsic strain effect on temperature and magnetic field. Finally, we show that the reversible strain window can be significantly widened by incorporating a Cu protection layer on the structures of both the RABiTS and IBAD coated conductors.

2. Experimental procedure

The RABiTS samples that we tested, designated with prefix 'A', had a Ni–5 at.% W substrate. YBCO was grown on the buffered substrate by the use of a BaF_2 *ex situ* process with either metal–organic deposition precursors (samples A1, A3, A4, A5, and A6) [3, 4] or evaporated precursors (sample A2) [7]. All the other samples except sample A2, for which the YBCO layer was relatively thick (2.75 μm), had an YBCO thickness t_{YBCO} of 0.8–1 μm. Samples were coated with an Ag layer (3–7 μm thick) on the YBCO side. Samples A1, A3, A4, and A6 were laminated by soldering a Cu foil on the YBCO side of the conductor for protection in case of sample quenching. The thicknesses of the Cu layer and the substrate were the same (75 μm), which geometry places the YBCO near the neutral axis of the conductor [4].

IBAD samples, designated with prefix 'B', had a Hastalloy C-276 substrate with an IBAD template. The YBCO layer was grown on the buffered substrate by the use of metal–organic chemical vapour deposition (MOCVD) [5, 6], and an Ag film (3 μm thick) was deposited on YBCO. For sample B3, a Cu layer (30 μm thick) was electroplated on the YBCO side of the conductor for protection in case of sample quenching.

The strain apparatus used for measuring J_c versus ε was designed to allow stress-free contraction of the sample when the latter is cooled from the soldering temperature to the measurement temperature [8]. The ends of the specimen were soldered to two Cu grips, which were also used for current contacts. In order to facilitate soldering, the back of the coated conductor was carefully sanded to remove any oxide layer that formed on the substrate. A corrosive flux was used to help tin the ends of the sample on the substrate side. The specimen was mounted on the apparatus with the substrate ends in direct contact with the two Cu grips. In97–Ag3 solder was used to attach the ends of the sample to the Cu grips [9]. An additional Cu piece was soldered to the top of the specimen at each end on the YBCO side and to the Cu grips in order to achieve a better injection of current into the sample and reduce current-transfer distances [10, 11]. A pair of voltage taps were soldered to the middle section of the specimen, about 5 mm apart. The distance between each voltage tap and its neighbouring current contact was several millimetres, so as to minimize current-transfer voltages that would interfere with the sample signal [10, 11]. A calibrated extensometer was attached to the two grips to measure strain applied to the coated

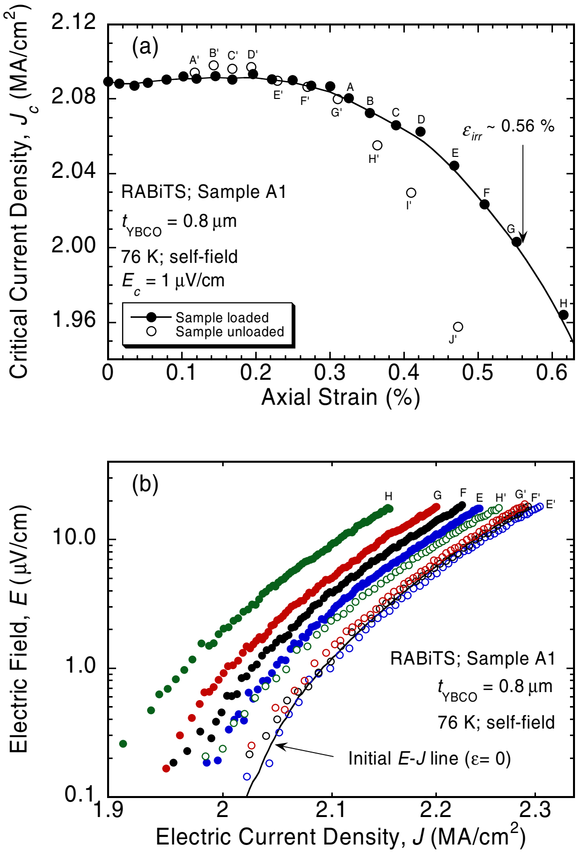

Figure 1. $J_c(\varepsilon)$ and $E(J)$ results obtained for a thin (0.8 μm) YBCO film on a Ni–5 at.% W RABiTS, with a Cu laminate layer 75 μm thick. Data when the sample was loaded and unloaded are respectively labelled with unprimed and primed letters and represented with solid and open symbols. In (b), the same colour was used to represent data for a given loaded and unloaded strain points (for example, H and H' are in green). $J_c(\varepsilon)$ and $E(J)$ exhibit reversible behaviour up to an irreversible strain limit $\varepsilon_{irr} \approx 0.56\%$. This reversible behaviour is independent of the electric field criterion between 0.1 and 20 μV cm^{-1}. $J_c(\varepsilon)$ data are from [14].

conductor. The uncertainty in the measurement of strain was about ±0.02%. The critical current I_c was determined from the voltage versus current $(V–I)$ curves with an electric field criterion of 1 μV cm^{-1}, and J_c was calculated from the cross-sectional area of YBCO. The uncertainties in I_c and the YBCO cross-section were respectively about 1% and 10%.

The apparatus was immersed in a liquid cryogen, either liquid nitrogen at 76 or 76.5 K, or liquid helium at 4 K. For measurements in magnetic field, the liquid-cryogen Dewar was inserted inside an 18 T superconducting magnet. Strain was incrementally increased and its corresponding $V–I$ curve measured. In order to investigate the reversibility of J_c with strain, the sample was periodically unloaded to nearly zero stress, and J_c was measured for each unloaded point.

3. Intrinsic strain effect at 76 K and self-field

Figures 1 and 2 show $J_c(\varepsilon)$ and $E(J)$ results obtained for a RABiTS and an IBAD sample with thin YBCO layers (0.8 and 1 μm, respectively). Data obtained when a sample was loaded

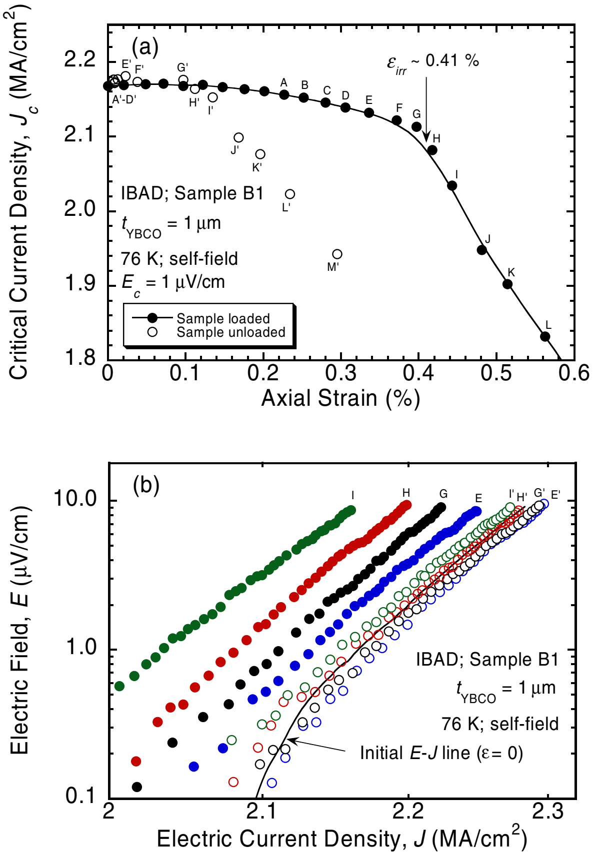

Figure 2. $J_c(\varepsilon)$ and $E(J)$ results obtained for a thin (1 μm) YBCO film on a Hastalloy C-276 substrate with an IBAD template, without a Cu protection layer. Data when the sample was loaded and unloaded are respectively labelled with unprimed and primed letters and represented with solid and open symbols. In (b), the same colour was used to represent data for a given loaded and unloaded strain points (for example, I and I' are in green). $J_c(\varepsilon)$ and $E(J)$ exhibit reversible behaviour up to an irreversible strain limit $\varepsilon_{irr} \approx 0.41\%$. This reversible behaviour is independent of the electric field criterion between 0.1 and 10 μV cm^{-1}. $J_c(\varepsilon)$ data are from [14].

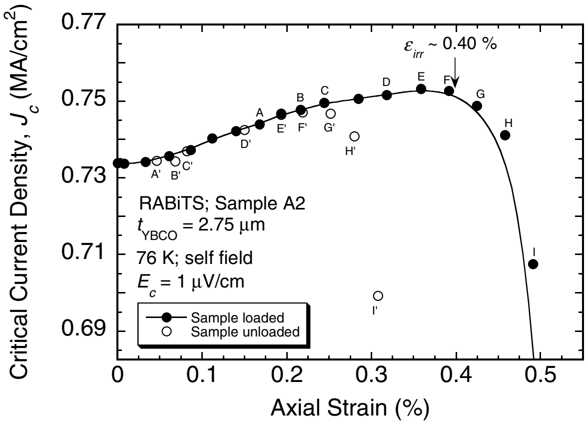

Figure 3. $J_c(\varepsilon)$ results obtained for a thick (2.75 μm) YBCO layer on a Ni–5 at.% W RABiTS, without a Cu protection layer. Data when the sample was loaded and unloaded are respectively labelled with unprimed and primed letters and represented with solid and open symbols. $J_c(\varepsilon)$ exhibits a reversible behaviour up to an irreversible strain limit $\varepsilon_{irr} \approx 0.40\%$, similar to that of thin YBCO films on RABiTS without a Cu protection layer.

and unloaded are respectively labelled with unprimed and primed letters and represented with solid and open symbols. For RABiTS sample A1, when strain was applied to strain point A and released, the sample snapped back to point A′ with no permanent degradation of J_c. Note that the strain did not go back to zero due to the yielding of the sample. Then when the sample was strained to point B, J_c degraded more than for point A, but still reversibly as J_c for the point B′ fully recovered to its initial value. All the points C′ to F′ retraced the $J_c(\varepsilon)$ original curve quite well (figure 1(a)), thus showing a reversible behaviour of J_c with strain. By the time the strain point G was reached, J_c degraded by a noticeable amount of approximately 4% with respect to its starting value, and yet, when strain was released from point G, J_c showed no permanent damage, since the corresponding unloaded point G′ was on the $J_c(\varepsilon)$ original curve. However, when higher strains were applied to the sample, J_c was no longer reversible upon unloading as evidenced by the points H′, I′, and J′ falling below the $J_c(\varepsilon)$ curve due to permanent damage in the sample. From the $E(J)$ characteristics in figure 1(b), it is clear that the reversibility up to point G held for all electric fields between 0.1 and 20 μV cm^{-1}. Therefore, the $J_c(\varepsilon)$ reversible behaviour is intrinsic to the sample, and is not an artefact of the measurements. The strain delimiting the two reversible and irreversible regimes is called the irreversible strain limit (ε_{irr}). ε_{irr} is correlated with the onset of mechanical crack formation in the YBCO layer, and hence it is an important parameter from an applications point of view [1, 2]. ε_{irr} appropriately quantifies the tolerance of the sample to axial strain.

For IBAD sample B1, $J_c(\varepsilon)$ and $E(J)$ also exhibited a reversible behaviour for all strain values before the strain point H (figure 2). It is around this point and beyond that the reversibility broke down. Again, the reversible behaviour was independent of the electric field criterion between 0.1 and 10 μV cm^{-1}. The difference in value of ε_{irr} between samples A1 and B1 is due solely to the fact that sample A1 had a Cu protection layer, while sample B1 did not. The effect of the Cu protection layer on the conductor's strain tolerance will be discussed in section 5.

Figure 3 presents $J_c(\varepsilon)$ data for a RABiTS sample with a YBCO thickness of 2.75 μm, about three times the thickness of all the other samples studied in this work. For sample A2, $J_c(\varepsilon)$ showed a reversible behaviour for all strains below strain point F, but became irreversible when strain was increased further. The irreversible strain ε_{irr} was about 0.4%, very similar to that for samples with a thin YBCO film and no Cu protection layer. Note that J_c rose with strain by about 2.5%, before falling rapidly when the strain was increased above ε_{irr}. Such a peak in the J_c versus strain relation was observed for several samples, but not consistently (see also figure 6). Its origin may not necessarily be entirely correlated with the release of pre-compression of YBCO when an external strain is applied to the conductor.

Coated conductors with a thick YBCO layer have the potential of carrying very high current densities, which could exceed 1000 A per cm width. However, expectations were that such a thick YBCO layer would be more prone to cracking. The results presented in figure 3 show that the electromechanical

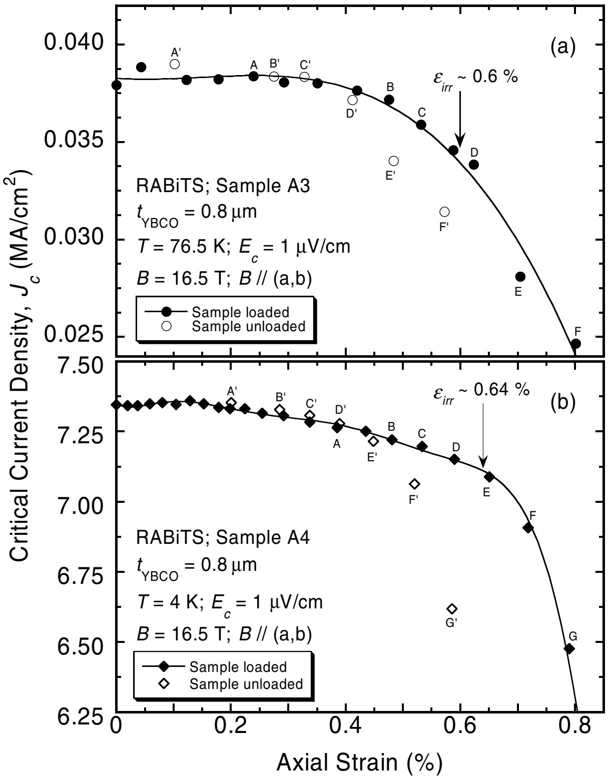

Figure 4. $J_c(\varepsilon)$ results obtained for a Cu-laminated YBCO coated conductor with a Ni–5 at.% W RABiTS, at (a) 76.5 K and (b) 4 K, in the presence of a magnetic field of 16.5 T applied parallel to the (a, b) plane. Data when the sample was loaded and unloaded are respectively labelled with unprimed and primed letters and represented with solid and open symbols. $J_c(\varepsilon)$ exhibits reversible behaviour at both temperatures. The influence of strain on J_c within the reversible regime appears to diminish with decreasing temperature. $J_c(\varepsilon)$ data at 76.5 K are from [2].

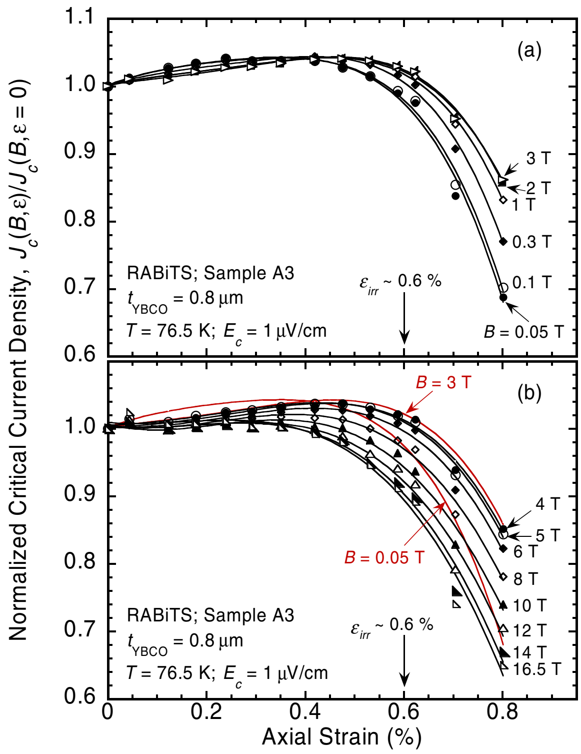

Figure 5. Normalized critical-current density as a function of axial tensile strain at 76.5 K for a Cu-laminated YBCO coated conductor with a Ni–5 at.% W RABiTS, both in low (0.05–3 T) and high (3–16.5 T) magnetic fields. The sensitivity of J_c to strain unexpectedly diminishes with magnetic field from 0.05 T to about 2–3 T. Above 3 T, the reverse occurs as this sensitivity grows systematically with increasing field up to 16.5 T. Data are from [2].

properties of coated conductors remain intact even when the thickness of the YBCO layer is increased to 2.75 μm. This result is of relevance for applications requiring high currents, such as power transmission lines, and should clear the way for more development of thick YBCO coated conductors.

The reversible strain effect described in this section contrasts with the general perception that the effect of strain on J_c in practical high-temperature superconductors is determined only by crack formation in the ceramic component. We speculate that the source of this intrinsic strain effect is a reversible strain field broadening around misalignment dislocations at the grain boundaries [1], which could lead to a reversible narrowing of the channels conducting the supercurrent from grain to grain.

4. Temperature and magnetic field effects on the intrinsic strain behaviour

Having presented data on the reversible behaviour of $J_c(\varepsilon)$ at 76 K and self-field, we now consider how this effect depends on temperature T and magnetic field B. Figure 4 depicts results obtained on the RABiTS sample A3 measured at 76.5 K, and the RABiTS sample A4 measured at 4 K, in a magnetic field of 16.5 T applied parallel to the (a, b) plane for both samples. The results show that J_c also behaves reversibly with strain in the presence of a magnetic field, up to a certain strain limit ε_{irr}. Moreover, this reversible strain effect is present at 4 K, a temperature far below the critical temperature of YBCO. Note that the total J_c drop-off at $\varepsilon = \varepsilon_{irr}$ was about 11% at 76.5 K, whereas that at 4 K was only about 3.5%. This suggests that the effect of strain on J_c within the reversible regime may be dependent on temperature. The influence of strain appears to diminish with decreasing temperature.

The effect of magnetic field is more complex. Figure 5 shows $J_c(\varepsilon)$ for sample A3 at 76.5 K, in fields from 0.05 to 16.5 T. We discerned opposite behaviours in the low-field regime (0.05–3 T; figure 5(a)) and the high-field regime (3–16.5 T; figure 5(b)). While the change of $J_c(\varepsilon)$ above a strain of 0.4% systematically increases with magnetic field between 3 and 16.5 T, the sensitivity of J_c to strain actually decreases with increasing magnetic field for fields between 0.05 and 3 T. More investigations are required to understand the origin of this change in behaviour between the low- and high-field regimes. Also, the pinning force density $F_p = J_c \times B$ was found to scale with magnetic field for all the strains applied to the sample [2], similar to the behaviour of many of the low-temperature practical superconductors [8, 12, 13].

The dependence of the reversible strain effect on temperature and magnetic field is further evidence that this effect is intrinsic to the YBCO coated conductors.

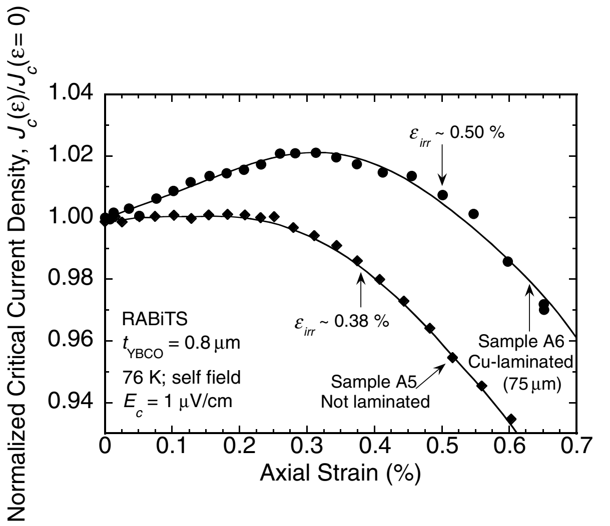

Figure 6. Normalized critical-current density as a function of axial tensile strain at 76 K and self-field for YBCO coated conductors with a Ni–5 at.% W RABiTS, with and without a Cu-laminated layer. The irreversible strain limit ε_{irr} improved substantially for the Cu-laminated RABiTS coated conductors.

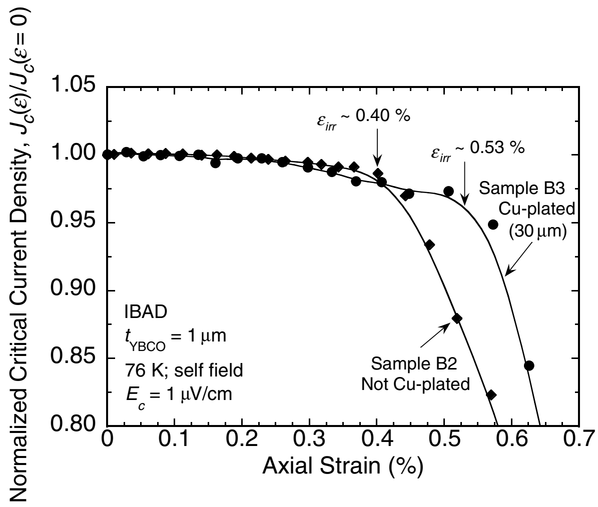

Figure 7. Normalized critical-current density as a function of axial tensile strain at 76 K and self-field for YBCO coated conductors with a Hastalloy C-276 substrate and an IBAD template, with and without a Cu-plated layer. The irreversible strain limit ε_{irr} improved substantially for the Cu-plated IBAD coated conductors.

5. Extension of the intrinsic strain window with the addition of a Cu layer

State-of-the-art coated conductors are now fabricated with an additional Cu layer in their architecture so as to improve their electric and thermal stability, which is beneficial for protecting the conductors during possible thermal run-away events. This Cu layer is added by lamination at around 200 °C or electroplating at room temperature. We found that Cu has an additional important advantage in that it enhances the tolerance of the coated conductors to axial strain [14]. Figures 6 and 7 compare $J_c(\varepsilon)$ behaviours for conductors with and without Cu, for both RABiTS and IBAD. The irreversible strain limit increases from about 0.4% to more than 0.5%, which makes the coated conductors more suitable for some particular and more demanding designs of generators requiring a strain tolerance of about 0.4% [15].

It might be assumed that Cu provides a low-resistance shunt for the current to circumvent defects such as cracks in the YBCO layer, and hence appears to artificially increase the strain at which irreversibility is first noticed. However, figure 1(b) clearly shows that the reversibility of $J_c(\varepsilon)$ is independent of the electric field criterion used to estimate J_c. Therefore, the enhancement of ε_{irr} in samples with the added Cu layer unambiguously holds for E at least as low as 0.1 μV cm^{-1}. This provides strong evidence that the improvement of ε_{irr} with the addition of a Cu protection layer is real, and not a consequence of current shunting.

The differential thermal contraction between Cu and that of either Ni–5 at.% W or Hastalloy C-276, when the sample is cooled from the lamination or electroplating temperature to the measurement temperature, was demonstrated to account for only a small part of the improvement of ε_{irr} that we measured experimentally [14]. Other research has shown that the addition of ductile laminates to a ceramic material increases the fracture toughness of the brittle ceramic component [16]. Such a mechanism is also believed to operate in the Cu-layered YBCO RABiTS and IBAD coated conductors [14]. By mechanically reinforcing crack initiation sites in the YBCO film, the Cu layer improves the fracture toughness of YBCO and thus inhibits or delays the formation of cracks.

The fracture toughening in the ceramic/metal laminates was shown to be more effective with the use of high-yield-strength metals [16]. For the Cu-laminated YBCO RABiTS, the average value of ε_{irr} at 76 K, calculated for samples A1, A3, and A6 (figures 1, 4(a), and 6), is about 0.55%. At 4 K, ε_{irr} is a bit higher, about 0.64% (figure 4(b)). The thermal contraction of any given material in the conductor being very similar for the range of temperature between 76 and 4 K [9], the differential thermal contraction between Cu and the other substrate materials is not expected to noticeably change ε_{irr} at 4 K in comparison to its value at 76 K. The increase in the yield strength of Cu at 4 K as compared to 76 K, however, could make Cu more effective in improving the fracture toughness of YBCO, which could explain the additional enhancement of ε_{irr} between 4 and 76 K.

These results indicate that Cu improves ε_{irr} of the coated conductors through both the differential thermal contraction and crack arresting mechanisms.

6. Conclusion

A review of the reversible strain effect in the YBCO coated conductors was presented. Wide-ranging sets of data confirm the existence of a reversible behaviour of J_c with axial strain for both the RABiTS and IBAD conductors, at liquid-nitrogen and liquid-helium temperatures, and in the presence of a magnetic field from self-field to 16.5 T (applied parallel to the (a, b) plane). The reversibility of J_c with strain is observed for thin as well as thick YBCO films. This reversibility is independent of the electric field criterion for defining J_c, at least between 0.1 and 20 μV cm^{-1}. Moreover, a strong dependence of $J_c(\varepsilon)$ on both temperature and magnetic field provides further evidence of the intrinsic character of the effect. Therefore, the effect of strain on the transport J_c is determined not only by the mechanical cracking of YBCO, as was previously shown for practical high-temperature superconductors, but also has an intrinsic component to it. We also demonstrated that the reversible strain window can be widened to suit most applications of coated conductors by adding a Cu protective layer to their structure. The Cu layer puts the YBCO film under additional pre-compressive strain upon cooling and enhances its fracture toughness.

Acknowledgments

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