Magnetic-Field Dependence of the Reversible Axial-Strain Effect in Y-Ba-Cu-O Coated Conductors

Najib Cheggour, Jack W. Ekin, and Cees L. H. Thieme

***Abstract*—The critical-current density J_c of an yttrium-barium-copper-oxide (YBCO) coated conductor deposited on a biaxially-textured Ni-5at.%W substrate was measured at 76.5 K as a function of axial tensile strain ε and magnetic field B applied parallel to the YBCO (a, b) plane. Reversibility of J_c with strain was observed up to $\varepsilon \simeq 0.6\%$ over the entire field range studied (from 0.05 to 16.5 T), which confirms the existence of an intrinsic strain effect in YBCO coated conductors. J_c vs. ε depends strongly on magnetic field. The decrease of $J_c(\varepsilon)$ grows systematically with magnetic field above 2–3 T, and, unexpectedly, the reverse happens below 2 T as this decrease shrinks with increasing field. The pinning force density $F_p = J_c \times B$ scaled with field for all values of strain applied, which shows that F_p can be written as $K(T, \varepsilon)b^p(1-b)^q$, where p and q are constants, K is a function of temperature and strain, $b = B/B^*_{c2}$ is the reduced magnetic field, and B^*_{c2} is the effective upper critical field at which $F_p(B)$ extrapolates to zero.**

***Index Terms*—Coated conductors, critical current, pinning force, RABiTS, reversible strain effect, scaling, YBCO.**

I. Introduction

THE reversible strain effect discovered recently in yttrium-barium-copper-oxide (YBCO) coated conductors opens up a whole new area of study of strain effects in high critical-temperature (T_c) superconductors in general and YBCO in particular [1]. In previous work, we found that the critical-current density J_c degrades reversibly with axial tensile strain ε at liquid-nitrogen temperature and self-field, up to an irreversible strain limit ε_{irr} corresponding to the onset of crack formation in the YBCO film [1]. This finding contrasts with the general understanding that the effect of strain on J_c in high-T_c superconducting composite tapes is extrinsic, driven only by crack formation in the ceramic component.

One of the questions that arise from the new finding is whether this reversible strain effect exists in the presence of a magnetic field, as in the case of low-T_c superconductors [2], [3]. To investigate this question, we measured J_c at 76.5 K as a function of axial tensile strain and magnetic field in a YBCO coating deposited on a rolling-assisted, biaxially textured Ni-5at.%W substrate (RABiTS) [4], [5]. Magnetic field, applied parallel to the YBCO (a, b) plane and perpendicular to the current-flow direction, varied from 50 mT to 16.5 T. The pinning force density $F_p = J_c \times B$ was measured as a function of magnetic field and applied strain, and the question of its scaling was studied. Besides providing insight into the origin of the reversible-strain effect, these results will also potentially have an impact on high-field applications of YBCO coated conductors such as industrial magnets, motors, synchronous condensers, and magnetic resonance imaging systems, as well as low-field applications such as power transmission lines, transformers, and fault-current limiters.

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II. Experimental

A. Sample Fabrication

The YBCO sample measured was grown on a buffered Ni-5at.%W RABiTS by the use of a tri-fluoro-acetate (TFA)-based metal-organic solution process [5], [6]. An Ag layer was then deposited on YBCO and the conductor laminated by soldering a Cu foil onto it. Thereafter the conductor, originally 10 mm wide, was slit reel-to-reel to a width of 4 mm, and a piece 3.5 cm long was used for the measurements. Thicknesses of the substrate, YBCO, and Ag layers were respectively 75 μm, 0.8 μm, and 3 μm. The thickness of Cu was 75 μm to match that of the substrate such that YBCO lies approximately at the neutral-axis of the conductor [6]. Initial J_c (at a 1 $\mu V/cm$ criterion) and n-value (representing the steepness of the voltage-current characteristic) were respectively about 1.75 MA/cm^2 and 37 at 76.5 K, which shows the high quality of the sample measured.

B. Strain Apparatus

The sample ends were soldered to two copper blocks in the strain apparatus. These blocks served the dual purpose of electrical contacts and grips for applying strain. One grip was stationary and the other could slide in a carriageway so that the sample could contract freely during cooling from room temperature to the measurement temperature. Strain was measured directly at the sample location by use of a calibrated extensometer attached to the two grips [7].

C. Temperature Control

The apparatus was immersed in liquid nitrogen contained in an insert dewar located inside an 18 T superconducting magnet. Since the measurements performed take several days of labor, changes in the atmospheric pressure from day to day can affect the boiling point of nitrogen. Furthermore, the hydrostatic head of nitrogen, due to its relatively high density (as compared to helium), can change the temperature at the sample location depending on how much liquid nitrogen is in the insert dewar. Hence control of temperature during the whole duration of measurements was necessary.

To monitor temperature, the vapor pressure of nitrogen was measured with a pressure sensor and regulated by the use of a *PID* (Proportional-Integral-Derivative) pressure controller coupled with a throttle valve that was connected to the dewar exhaust. A calibrated Cernox thermometer was also installed next to the sample. For effective control, temperature was raised slightly above the boiling point of nitrogen at our laboratory location (~75.7 K) by pressurizing the nitrogen bath above atmospheric pressure and heating it from the bottom to overcome temperature stratification, following a similar procedure used for measurements in liquid helium [8]. Temperature $(= 76.5\,\mathrm{K})$ was determined with an uncertainty of ±0.1 K.

D. Measurement Procedure

Voltage-current curves were measured first at zero applied strain as a function of magnetic field from 0 T to 16.5 T. Data at $\varepsilon = 0$ were taken in increasing and decreasing field to check any hysteretic behavior of J_c. Strain was then incremented by a small amount each time up to a strain of about 0.8%. At each value of ε, measurements were taken as a function of ascending magnetic field from 0.05 T to 16.5 T. The sample was periodically unloaded to nearly zero stress and measured as a function of B in order to determine the irreversible strain limit ε_{irr} beyond which the sample is permanently damaged. J_c values were calculated from the cross-sectional area of YBCO using a $1\,\mu\mathrm{V/cm}$ criterion. Uncertainties in determining the critical current I_c and YBCO cross-sectional area were respectively about 1% and 10%. Uncertainty in measuring ε was about ±0.02%.

III. Results and Discussion

A. J_c vs. B at Zero Applied Strain

The $J_c(B, \varepsilon = 0)$ data obtained in ascending and descending field are depicted in Fig. 1. At 16.5 T, J_c dropped by a factor of 46 as compared to its value in self-field. Besides, J_c was mostly reversible with field; there was only a little hysteretic behavior below 2 T that did not exceed 2%.

B. Reversible Strain Effect in Magnetic Field

A comprehensive overview of the $J_c(B, \varepsilon)$ results is presented in Fig. 2. Fig. 3 shows details of J_c vs. ε at two magnetic fields, 3 T and 16.5 T. Data obtained when the sample was loaded and unloaded are respectively labeled by corresponding unprimed and primed letters. J_c showed good reversibility with strain up to near strain point D, for which the corresponding unloaded point D' started to deviate slightly below the original $J_c(\varepsilon)$ curve. We correlate this deviation to the formation of mechanical cracks in the YBCO layer and estimate ε_{irr} to be about 0.6%. This value of the irreversible strain limit comfortably meets the axial-strain requirements for even the most demanding applications [1]. The value of ε_{irr} was similar for all fields measured.

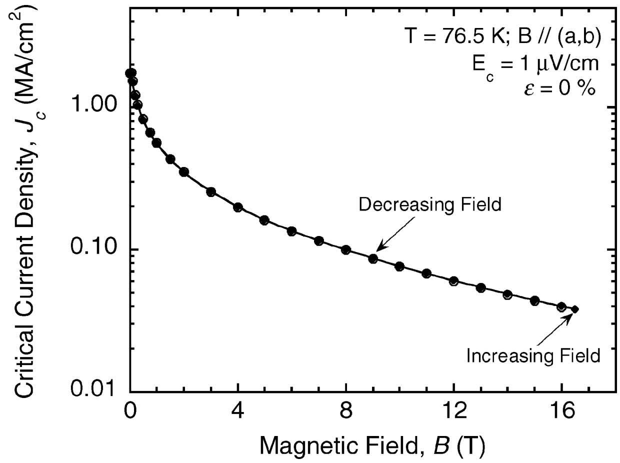

Fig. 1. Critical-current density as a function of magnetic field at 76.5 K and zero applied strain for a Cu-laminated YBCO coated conductor. Magnetic field was applied parallel to the YBCO (a, b) plane and perpendicular to the current-flow direction.

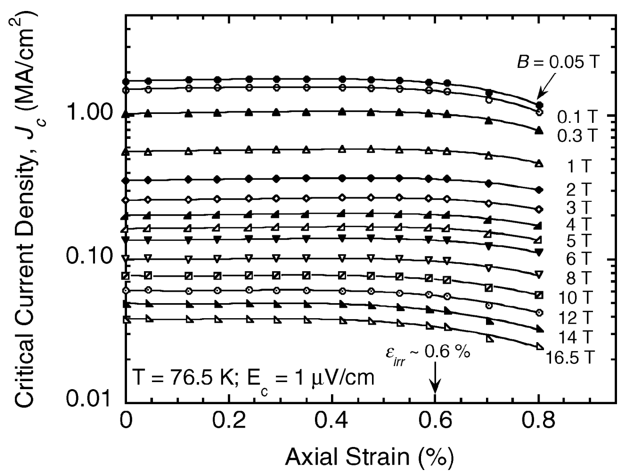

Fig. 2. An overview of $J_c(B, \varepsilon)$ data obtained at 76.5 K on a Cu-laminated YBCO coated conductor. Measurements were performed over a wide range of magnetic field (from 0.05 T to 16.5 T) and axial tensile strain (up to 0.8%). Magnetic field was applied parallel to the YBCO (a, b) plane and perpendicular to the current-flow direction.

Fig. 3(a) shows a small peak in J_c as a function of strain. In fact, we observed this J_c-peak effect in several YBCO samples at 76 K and self-field but not consistently. The origin of this behavior is still unclear but could possibly be related to the release of pre-compression of the YBCO layer by applying strain. The present data showed an increase in the J_c-peak magnitude with magnetic field up to 3 T, where it reached a value of about 4%, but then a decrease for fields above 3 T until the peak disappeared beyond 10 T (see Fig. 4). For example, Fig. 3(b) exhibits no peak in J_c at 16.5 T.

Fig. 3(b) shows a reversible degradation of J_c at $\varepsilon = \varepsilon_{irr}$ of about 11% for the field of 16.5 T.

C. Two Regimes

Normalized J_c, defined as $J_c(B, \varepsilon)/J_c(B, \varepsilon = 0)$, showed that the degradation of J_c due to strain unexpectedly shrank

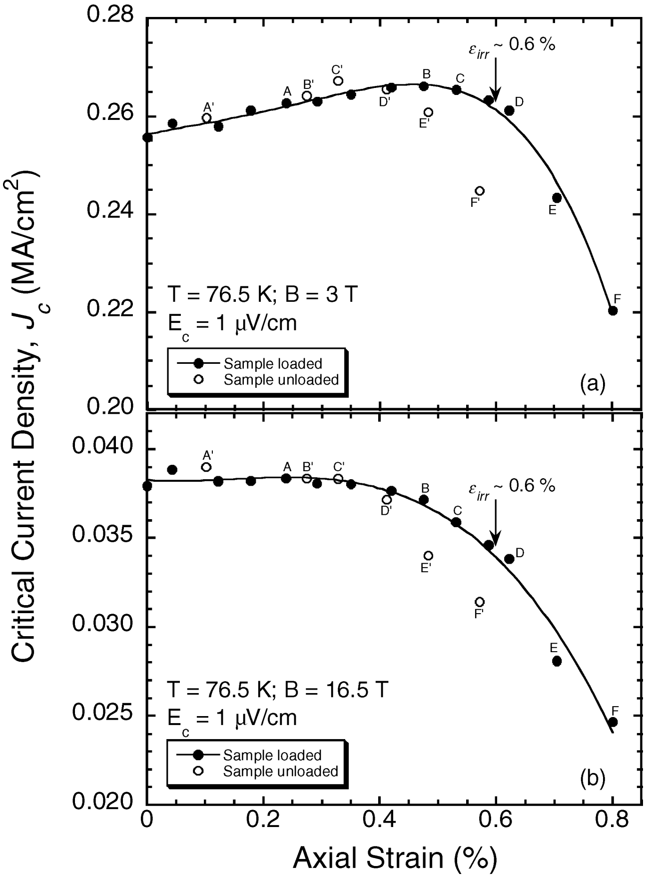

Fig. 3. Critical-current density as a function of axial tensile strain at 76.5 K for a Cu-laminated YBCO coated conductor, in magnetic fields of (a) 3 T and (b) 16.5 T, applied parallel to the YBCO (a, b) plane. Data when the sample was loaded and unloaded are respectively labeled by corresponding unprimed and primed letters. The irreversible strain limit ε_{irr} is about 0.6%, mostly independent of magnetic field.

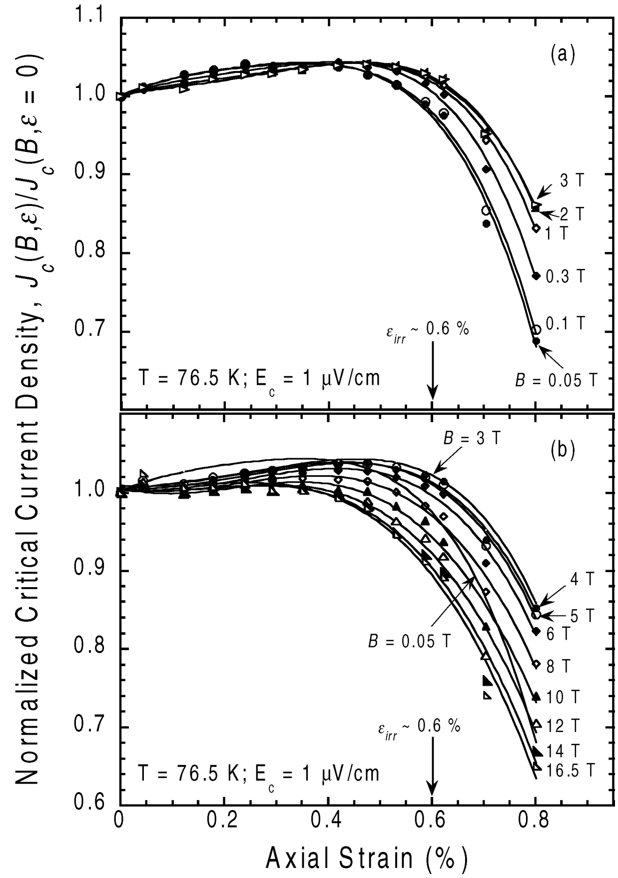

Fig. 4. Normalized critical-current density as a function of axial tensile strain at 76.5 K for a Cu-laminated YBCO coated conductor, both in low (0.05 T to 3 T) and high (3 T to 16.5 T) magnetic fields. J_c degradation unexpectedly shrinks with magnetic field from 0.05 T to about 2–3 T. Above 3 T, the reverse occurs as this degradation grows systematically with increasing field up to 16.5 T, where it reaches its maximum.

with magnetic field from 0.05 T to about 2–3 T [Fig. 4(a)]. Above 3 T, the reverse occurred as this relative degradation grew systematically with increasing field up to 16.5 T, where it reached about 11% at $\varepsilon = \varepsilon_{irr}$ [Fig. 4(b)]. This finding will have an impact on both low- and high-field applications. The relatively strong dependence of the reversible degradation on magnetic field demonstrates the intrinsic nature of the effect in YBCO. Note however that the degradation of J_c with strain is not significant at strains below 0.4%, but rather as the irreversible strain limit is approached or exceeded. The maximum reversible degradation of 11% (at 16.5 T) may possibly vary from sample to sample. More measurements are required to clarify this point.

D. Scaling of the Pinning Force Density

The pinning force density $F_p = J_c \times B$ was plotted in Fig. 5 for all the values of strain measured. It is well established that, for most of the technological low-T_c superconductors, F_p can be described as $K(T,\varepsilon)b^p(1-b)^q$, where K is an arbitrary function of temperature and strain, $b = B/B^*_{c2}$ is the reduced magnetic field, and B^*_{c2} is the effective upper critical field at which $F_p(B)$ extrapolates to zero [2], [3], [7], [9], [10]. In this work we attempted to apply this expression to the data in order to see whether a scaling of F_p can be achieved in

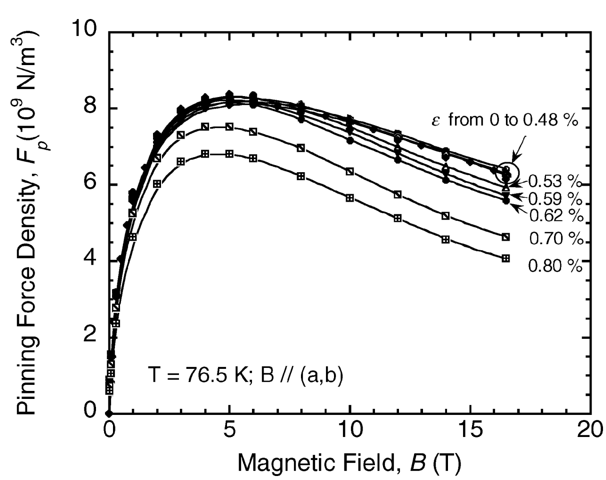

Fig. 5. Pinning force density as a function of magnetic field at 76.5 K for a Cu-laminated YBCO coated conductor for various values of axial tensile strain up to 0.8%.

YBCO. A global fit to the data was used following the procedure described in [3] and [10]. p, q, and B^*_{c2} were treated as fitting parameters. However, since we were able to measure the peak value of the pinning force F_{pm} [which occurs at a reduced field $b_m = p/(p+q)$] for all the strains (Fig. 5), it was possible to determine $K = F_{pm}\, b_m^{-p}(1-b_m)^{-q}$ and not declare it as fitting

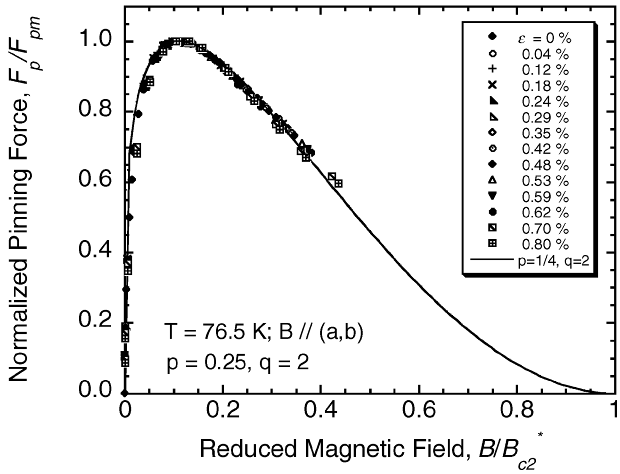

Fig. 6. Normalized pinning force density as a function of reduced magnetic field ($b = B/B_{c2}^*$) at 76.5 K for a Cu-laminated YBCO coated conductor for various values of axial tensile strain up to 0.8%. B_{c2}^* is the effective upper critical field at which $F_p(B)$ extrapolates to zero. Data show scaling of the pinning force density with reduced field for all the values of strain measured. The continuous line represents a function proportional to $b^{0.25}(1-b)^2$.

parameter. This gave the advantage of reducing the number of variables. A good fit to the data was obtained with $p = 0.25$ and $q = 2$. Fig. 6 shows the success of the scaling, which results in a single curve of normalized F_p as a function of reduced magnetic field for all applied strain values.

IV. Conclusion

Practical high-T_c superconductor composites were, for nearly two decades, thought to have no intrinsic strain effect on their transport properties, unlike their low-T_c superconductor counterparts. In this work we demonstrated that the YBCO-coated conductors do actually have a significant intrinsic strain effect at liquid-nitrogen temperature that is strongly dependent on magnetic field. Moreover, the pinning force density F_p was found to scale with the reduced field $b = B/B_{c2}^*$ such that F_p can be written as $K(T,\varepsilon)b^p(1-b)^q$, where p and q are constants, and K is an arbitrary function of temperature and strain. These results open up an exciting new area of study of intrinsic strain effects in high-T_c superconductors. Questions relating to B_{c2}^* dependence on strain, influence of temperature, and effect of field orientation with respect to YBCO crystallographic axes (particularly $B//c$) will be addressed in future publications.

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