TRANSVERSE COMPRESSIVE STRESS, FATIGUE, AND MAGNETIC SUBSTRATE EFFECTS ON THE CRITICAL CURRENT DENSITY OF Y-Ba-Cu-O COATED RABiTS TAPES

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ABSTRACT

The electromechanical properties of (0.3 μm thick) yttrium-barium-copper-oxide (YBCO) coatings on buffered pure-nickel rolling-assisted-biaxially-textured substrates (RABiTS) were measured at 76 K and self magnetic field. YBCO coatings on buffered substrates both 50 μm and 125 μm thick were tested. Significant degradation of transport critical-current density (J_c) can occur from transverse compressive stress unless the in-plane yielding of the substrate is prevented by providing frictional support to the sample or by using substrate materials of high yield-strength. Scanning electron microscopy was used to investigate the microstructure of the samples after electromechanical testing. Isolated defective regions were found with a mixed pattern of cracks, both longitudinal and transverse to the direction of electrical-current flow. The more the degradation of J_c from electromechanical testing, the greater the density of the observed cracked regions. Also, it was found that the use of magnetic substrates in the fabrication of the YBCO coated-conductor tapes produces a significant reduction in J_c when the tapes are arranged in a stack of two or more layers. This effect is reversible upon unstacking the tapes.

INTRODUCTION

Critical-current density (J_c) in excess of 1 MA/cm^2 has been achieved in yttrium-barium-copper-oxide (YBCO) coated conductors at liquid-nitrogen temperature and self-field [1-3]. These conductors have therefore the potential for use in the construction of

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electrical devices such as power-transmission lines, transformers and motors that have high energy efficiency. The fabrication of the coated conductors in usable long-lengths, however, still requires further development. Among the most challenging design requirements for building superconducting electrical devices and electromagnets using the coated conductors are those involving mechanical properties, since the YBCO and buffer layers are inherently brittle. The tolerance of these conductors to stress and strain needs to be known for optimized cable fabrication and magnet applications. Only limited data are available on electromechanical properties of the coated conductors so far [1,4-8]. Besides axial tension, transverse compression acting on the tape may play a significant role in determining the ultimate performance of an electromagnet made of these conductors. When the magnet is energized, the resulting Lorentz force acting radially produces a hoop stress along the windings. If the magnet windings are restrained at the outer radius or with distributed reinforcement, the hoop stress is partially converted to transverse compressive stress in the windings. For large magnets such as those designed for particle accelerators, this transverse stress can reach or exceed 100 MPa. In this paper we report the first experimental results on the effects of transverse compressive stress and fatigue on J_c, obtained in thin (0.3 μm) YBCO coatings on buffered pure-nickel rolling-assisted-biaxially-textured substrates (RABiTS). Data are presented that provide an insight on the role played by critical parameters such as the yield strength of the substrate material on the tolerance of these conductors to stress.

High biaxial texture of the YBCO layer is a key requirement for achieving J_c values in excess of 1 MA/cm^2 [9]. This biaxial texture can be obtained by depositing buffer layers on randomly oriented polycrystalline substrates using ion-beam-assisted-deposition (IBAD) [1,10] or inclined-substrate-deposition (ISD) [11] processes. These buffer layers serve as templates for subsequent growth of textured YBCO film. Alternatively, RABiTS substrates with sharp macroscopic biaxial texture can be used to transmit the texture to the buffer and YBCO layers. Pure nickel is widely used as the substrate material in the RABiTS technology since it offers the required texture after adequate thermomechanical processing. However, nickel is a magnetic material. In the present work, we also report the first experimental evidence that the use of magnetic substrates can result in a reversible reduction of J_c of the tape when the tape is arranged in a stack of two or more layers. This configuration is readily used in many potential applications where one tape is wound on top of another, or crosses over another as in a braided cable. The magnetic-substrate effect provides strong motivation for the use of non-magnetic substrates in the fabrication of the coated conductors, particularly for low magnetic-field applications such as underground power-transmission lines.

EXPERIMENTAL

The architecture of the samples investigated in this work was sequenced, from outside in, as YBCO | CeO_2 (cap layer) | yttria-stabilized zirconia (YSZ) | CeO_2 (seed layer) | Ni. The buffer layers CeO_2 and YSZ were deposited on pure-nickel RABiTS substrates by reactive evaporation (CeO_2 seed layer) and RF magnetron sputtering (YSZ and CeO_2 cap layer). The YBCO layer was then grown on the buffered substrates using the *ex situ* BaF_2 method [12], which consists of e-beam coevaporation of Y, BaF_2, and Cu precursors, followed by appropriate post-annealing to form YBCO. The tapes were then coated with a layer of silver (1 μm thick) and annealed in oxygen at 500 °C for 0.5 hour. To maintain a low contact resistivity when soldering the current leads to the sample, an additional silver layer (10 μm thick) was deposited by thermal evaporation. For samples 1 to 4, the thickness of the nickel substrate was 50 μm, the buffer layers less than 1 μm, and the YBCO layer about 0.3 μm. Sample 5 had a nickel substrate 125 μm thick, while the other buffer and superconductor layers were kept unchanged. The samples had a width of 3 mm and a length of about 2.5 cm.

Electromechanical tests were carried out at 76 K and self-field. A detailed description of the transverse-stress apparatus has been reported elsewhere [8,13]. The stress is applied to the tape sample by means of two stainless-steel anvils. These anvils are machined flat and have smooth surface finish. Uniformity of stress over the pressed area of the sample is achieved by beveling the edges of the top anvil, and attaching it to a biaxially gimbaled pressure-foot so that this anvil conforms precisely to the bottom anvil and sample surfaces. The anvils are thoroughly cleaned with acetone and isopropanol before every sample mounting to ensure that there are no residue or dust particles between the contact surfaces of the sample and anvils. For the same reason, no flux is used for soldering the copper current-bus bars and voltage taps to the sample. The sample is cooled to 76 K in a stress-free manner [14]. Voltage-current characteristics are taken as a function of applied transverse stress up to 180 MPa, and J_c values determined at an electrical-field criterion of 1 μV/cm. The values of J_c are measured to within ± 0.5 % and transverse compressive stress to within ± 2 %. All samples presented in this work were of high quality, having initial values of J_c in excess of or close to 1 MA/cm^2 at 76 K and self-field.

STATIC TRANSVERSE COMPRESSIVE STRESS RESULTS

Three measurement modes were used. Results obtained on three different samples are summarized in FIG 1. The *monotonic-loading* mode consists of applying stress to the sample and incrementally increasing its value, without releasing the load between measurement steps. In this mode the pressing anvils provide strong frictional support to the tape, which prevents in-plane material expansion. Consequently, as shown in FIG 1, the J_c degradation is very small, less than 1 % up to about 120 MPa (Sample 1). In the *load-unload* mode, transverse stress is applied to the sample, then removed with the loading anvils still in contact with the sample, and stress reapplied at a higher value. Voltage-current curves are taken both on loading and unloading the sample to check the reversibility of J_c with stress. This test mode greatly reduces the frictional support to the sample. As a result, J_c degradation amounts to 28 % at 100 MPa, and to 39 % at 180 MPa (Sample 2). In the *lift-off* mode, after application of transverse stress, the sample is completely released, with the upper loading-anvil keeping no physical contact with the sample. In this mode, J_c degradation is the highest, reaching about 68 % at 100 MPa, and 80 % at 110 MPa (Sample 3). For the last two modes, the degradation of J_c is irreversible.

These results clearly demonstrate the importance of frictional support to the sample for preventing high and irreversible degradation of J_c. Without friction, the applied transverse stress converts into in-plane tensile strain in the sample, which could plastically deform the substrate and initiate formation of cracks in the ceramic layers. The J_c degradation occurs almost immediately, starting at stresses as small as ~ 10 MPa. In this mode, the mechanical yield strength of the substrate material is expected to play a major role in the stress tolerance of these conductors. If frictional support is provided to the sample, however, load application generates transverse stress with negligible in-plane strain in the sample. In this configuration, transverse stress has little effect on J_c in the YBCO coated-conductors (see also Ref. 8). In practice, magnet performance is expected to be between the *monotonic-loading* mode and the *load-unload* mode situations [8]. The *lift-off* mode is not a usual situation, but was used to give more emphasis to the role of friction.

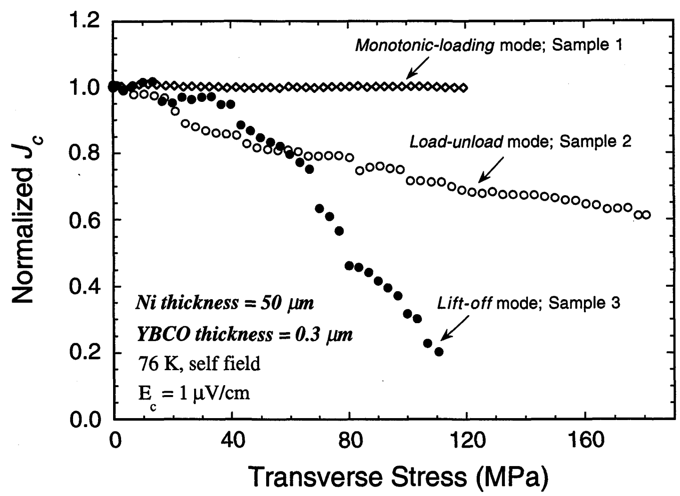

FIGURE 1. Effect of transverse stress on J_c in YBCO film on nickel RABiTS. The results obtained in different test modes illustrate the role played by friction between the sample and pressing anvils.

Results obtained on the effects of substrate work-hardening and substrate thickness are presented in FIG 2. Sample 4 was first monotonically loaded to 180 MPa. The J_c did not degrade compared to its initial value at zero load (result not shown in FIG 2). The sample was then unloaded and measured in the *load-unload* test mode up to 180 MPa. This sample exhibited much better tolerance to transverse stress than Sample 2, also measured in the *load-unload* mode. During the first monotonic loading of Sample 4 up 180 MPa, the soft nickel substrate work-hardened, after which the J_c degradation was only 6 % at 100 MPa, and 12 % at 180 MPa in the *load-unload* mode. This result lends further support to the conclusion that substrate yield-strength is playing a major role. This suggests that in magnet applications using the coated conductors on soft substrates, a good practice would be to energize the magnet to its maximum field during the first run after manufacture in order to improve the robustness of the windings against transverse compressive stress.

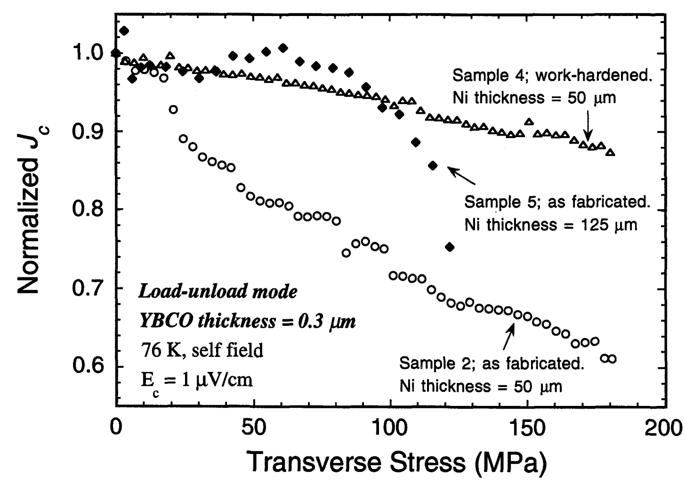

FIGURE 2. Effect of transverse stress on J_c in YBCO film on nickel RABiTS. The results illustrate the role played by substrate work-hardening and substrate thickness.

Finally, the thickness of the substrate may also play a role in the tolerance of these conductors to transverse stress. Sample 5, which has thicker Ni substrate (125 μm instead of 50 μm), was tested in the *load-unload* mode. The degradation of J_c was only about 6 % at 100 MPa, but precipitously increased to 24 % at 122 MPa (FIG 2). This result also supports the idea that substrate yielding plays a significant role in the conductor's tolerance to transverse stress since the thicker Ni-substrate has a higher in-plane yield *load*.

CYCLIC TRANSVERSE COMPRESSIVE STRESS RESULTS

Cyclic transverse-stress tests up to 180 MPa and 2000 cycles were carried out on the same samples after the static transverse-stress measurements. Load was cycled between a given value (σ_T, generally equal to the maximum load used in the static-load testing) and near zero at a frequency of 0.33 Hz. The effect of fatigue was found to depend on the "history" of the sample (FIG 3). The results show 21 % additional J_c degradation after 2000 fatigue-cycles in Sample 2, which previously had 39 % degradation from static pressure; 3 % additional degradation in Sample 4, which had 12 % degradation; and less that 1 % fatigue degradation in Sample 1, which had no significant initial degradation. As will be shown below, mechanical cracks found in the samples after transverse stress testing are the main cause for J_c degradation in these conductors. We conclude that fatigue cycles can significantly further degrade the J_c if the sample initially contained cracks. Fatigue cycles do not appear to create new cracks in the sample if the stress amplitude is not increased much beyond what the sample experienced in the static test (Sample 1). Fatigue, however, tends to propagate the existing cracks throughout the oxide and buffer layers and hence further decrease the J_c.

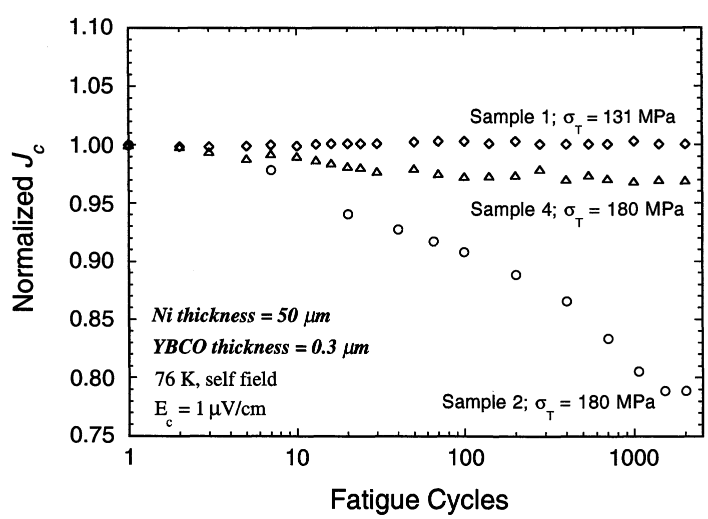

FIGURE 3. Effect of fatigue on J_c in YBCO film on nickel RABiTS. Fatigue tests were carried out on the samples after the static transverse-stress measurements. Fatigue effect was found to be important only in samples containing mechanical cracks previous to testing.

MICROSTRUCTURE STUDY

Microstructural characterization of the samples was carried out after static and cyclic transverse stress testing. Scanning electron microscopy (SEM) was used to examine the top YBCO layer of the samples. Silver was etched away to expose the YBCO layer [8]. We found isolated regions of cracks both longitudinal and transverse to the direction of electrical-current flow (FIG 4). The cracked regions are randomly distributed throughout the entire sample. These patches cover areas in the sample that are a few micrometers to more than 600 μm wide. The total degradation of J_c correlates with the crack density in these defective regions. The sections on FIG 4a where the YBCO has peeled off show that the cracks in the YBCO layer extend through the buffer layers also. From FIG 4a, the length and width of longitudinal cracks suggest that these cracks formed first, before the transverse cracks developed. FIG 4b, however, shows the opposite scenario. It must be emphasized that the ordered mosaic shown in FIG 4 is not the only feature seen in these samples. Cracks with random orientations are frequently seen also. As reported earlier [8], YBCO coatings on IBAD buffered Inconel 625 substrates showed only longitudinal cracks after similar mechanical testing. Furthermore, these cracks were located only at the samples' edges. The crack pattern, fundamentally different between RABiTS and IBAD samples, may reflect the influence of certain parameters on the robustness of the coated conductors, such as the mechanical properties of substrate material, the buffer layers, or the size of the YBCO grains.

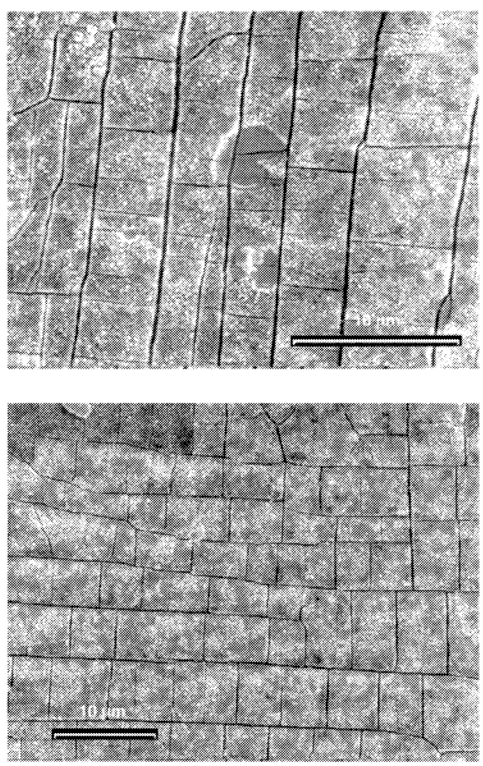

FIGURE 4 (a and b). Scanning electron micrographs of the YBCO layer of RABiTS samples, after static and cyclic transverse-stress testing, showing multi-patterned cracks in the YBCO and buffer layers. The vertical axis of the images coincides with the direction of the electrical current applied to the sample.

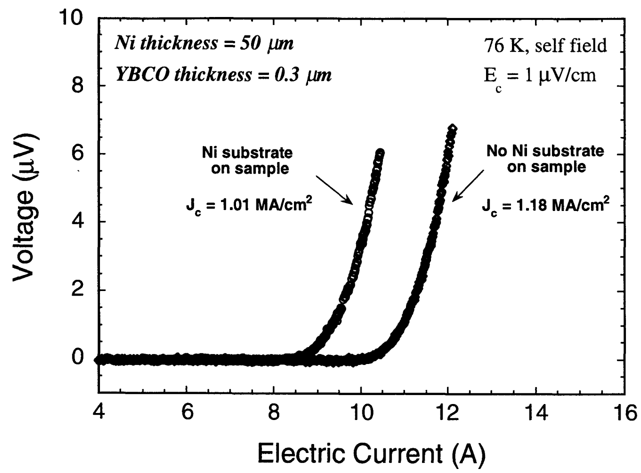

FIGURE 5. Experimental evidence of a significant drop in J_c of the coated conductors when YBCO film is sandwiched between two magnetic substrates.

MAGNETIC SUBSTRATE EFFECT

A reversible drop in J_c was measured in the YBCO coated conductors on nickel RABiTS when a nickel substrate was placed on top of the tape (FIG 5). This arrangement is common in many potential applications of these conductors such as winding one tape over another in a coil, or where one tape crosses over another in a braided cable. In such applications, the YBCO film would be sandwiched between two magnetic nickel substrates. The J_c was found to drop by about 15% for the sample geometry tested here (critical current around 11 A). The interaction of the top and bottom nickel layers increases the perpendicular component of magnetic flux at the superconductor film edges [15]. Consequently, J_c is reduced due to the enhanced perpendicular component of the magnetic field. Removing the top nickel substrate restores the J_c to its original value. That is, this phenomenon is reversible. This magnetic-substrate effect is significant, particularly in self-field situations such as power-transmission line applications. This result suggests that non-magnetic substrate materials are required to prevent significant loss of J_c.

CONCLUSION

A survey of the effect of transverse stress in the YBCO coated conductors on pure-nickel RABiTS has been presented. The degradation of J_c from transverse stress can be significant unless the in-plane yielding of the substrate is prevented by providing frictional support to the sample or by using high yield-strength substrate materials. The in-plane material expansion results in the formation of multi-patterned cracks in the YBCO and buffer layers.

Experimental evidence has been given for the first time that shows significant loss in J_c in situations where one tape is wound on top of, or crosses over another, if a *magnetic* substrate is used. Sandwiching the YBCO film between two magnetic layers increases the magnetic field at the tape edges, and hence reduces J_c. These results emphasize the need for development of non-magnetic substrates with higher yield-strength for RABiTS technology.

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