Effect of Fatigue Under Transverse Compressive Stress on Slit Y-Ba-Cu-O Coated Conductors

Najib Cheggour, Jack W. Ekin, Cees L. H. Thieme, and Yi-Yuan Xie

***Abstract*—The slitting of wide Y-Ba-Cu-O coated-conductor tapes to a width desirable for applications allows for considerable reduction in conductor manufacturing cost. Localized damage induced at the slit edges may be tolerated provided that mechanical cracks formed in the ceramic layers do not propagate deeper inside the conductor due to mechanical forces and thermal cycling to which the strand will be subjected in actual applications. In order to evaluate the effect of slitting, we used fatigue cycling under transverse *compressive* stress. These tests simulate conditions in applications such as rotating machinery and industrial magnets. Conductors measured had a rolling-assisted biaxially textured Ni-W substrate (RABiTS), or a Hastelloy-C substrate with an ion-beam assisted deposition (IBAD) buffer template. Samples were fabricated with or without a Cu protection layer, added either before or after slitting. For all these geometries, the critical current exhibited no significant degradation during fatigue testing up to 150 MPa transverse compressive stress and 20,000 cycles. Nevertheless, these results do not imply that slitting is not deleterious to the conductor performance under other experimental conditions.**

***Index Terms*—Coated conductors, crack propagation, critical current density, fatigue cycling, IBAD, RABiTS, slitting, stress, transverse compression, Y-Ba-Cu-O.**

I. INTRODUCTION

THE rapid advancement in the development of yttrium-barium-copper-oxide (YBCO) coated conductors brings more promise than ever before that high-temperature superconductor wire will play an important role in modernizing aging electric transmission and delivery systems to satisfy the growing demand for electricity around the world [1]–[3].

Some superconductor manufacturers have opted to fabricate wide coated-conductor tapes (up to 40 mm), and then slit them to a width of typically 4 mm desired for most applications. This technique provides a considerable reduction in conductor manufacturing cost but induces damage at the slit edges, which results in a reduction (up to about 15%) of the critical-current density J_c. However, the benefits of slitting outweigh the slight reduction in J_c, provided that mechanical cracks formed in the ceramic layers at the tape edges do not propagate deeper into the conductor under the mechanical forces and thermal cycling to which the strand will be subjected in actual applications. Evaluation of the slitting damage is therefore crucial at this point of conductor development.

Manuscript received August 24, 2006. This work was supported in part by the U.S. Department of Energy, Office of Energy Delivery and Energy Reliability, and the Office of High Energy Physics.

N. Cheggour and J. W. Ekin are with the National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: cheggour@ boulder.nist.gov).

C. L. H. Thieme is with American Superconductor Corporation, Westborough, MA 01581 USA.

Y.-Y. Xie is with SuperPower Incorporated, Schenectady, NY 12304 USA.

Digital Object Identifier 10.1109/TASC.2007.897918

In order to evaluate the effect of slitting, we used fatigue cycling under transverse *compressive* stress, since previous experiments had shown this to induce crack propagation in earlier YBCO coated conductors [4], [5]. J_c was measured in samples subjected to 20,000 fatigue cycles of transverse compressive stress up to 150 MPa, which is higher than the 100 MPa benchmark commonly agreed upon for several applications. These tests simulate conditions in applications such as rotating machinery and industrial magnets, and evaluate whether fatigue exacerbates cracks by propagating them into the conductor. The measurements could also help discriminate between different slitting techniques and assess the influence of coated-conductor configurations on crack propagation. In addition, these data update our earlier reports on the effect of transverse compression on transport properties of coated-conductors [4]–[7].

II. EXPERIMENTAL PROCEDURE

A. Sample Preparation

Samples were fabricated either with rolling-assisted biaxially textured Ni-5at.%W substrates (RABiTS) [8], or ion-beam-assisted deposition (IBAD) on Hastelloy C-276 substrates [9]. In this paper, RABiTS and IBAD samples are designated with the prefix 'A' and 'B', respectively. Table I lists the 11 samples measured and gives a brief summary of the results obtained.

For the RABiTS, YBCO (0.8 μm thick) was deposited on a 75 μm thick buffered Ni-5at.%W substrate (up to 40 mm wide) by the use of a BaF_2 *ex situ* process with metal-organic deposition precursors (MOD). A 3 μm thick layer of Ag was added to the YBCO. Two types of samples were investigated in this work: (a) the neutral-axis specimens, where a 75 μm thick Cu foil was soldered to the YBCO side of the tape; then the conductor was slit to a width of 4 mm (samples A1–A5); (b) the 3-ply samples, where the tape was first slit to a 4 mm width, and then two 50 μm thick Cu foils (4.4 mm wide each) were laminated to the conductor, one foil on the YBCO side and the other on the substrate side (samples A6 and A7).

IBAD samples include a 100 μm thick Hastelloy C-276 substrate (up to 12 mm wide) with an IBAD yttria-stabilized zirconia (YSZ) buffer template, on top of which an YBCO layer (1.1 μm thick) was grown by the use of metal-organic chemical vapor deposition (MOCVD). A 3 μm thick layer of Ag was added to the YBCO. Three types of samples were studied: (a) a sample slit to a 4 mm width, not Cu-plated (sample B1); (b) a sample electroplated with a 20 μm thick Cu layer on each of the YBCO and substrate sides—thereafter the sample was slit to 4 mm width (sample B2); (c) samples were first slit to a width of 4 mm, and then a Cu layer was electroplated on all 4 sides

TABLE I
DESCRIPTION OF RABiTS AND IBAD YBCO SLIT COATED-CONDUCTORS TESTED

Sample No.	Fabrication process	Substrate; t_s[a] (μm)	t_{Cu}[a] per side (μm)	Process of Cu addition and slitting	Maximum stress σ_{TM} (MPa)	J_c degradation from monotonic loading to σ_{TM}	Number of fatigue cycles applied	J_c degradation from fatigue cycling
A1	RABiTS/ MOD	Ni-5at.%W; 75	75	Neutral-axis; tape slit *after* Cu-lamination	75	2 %	21,000	1.5 %
A2	″	″	75	″	100	< 1 %	20,000	< 1 %
A3	″	″	75	″	100	< 1 %	20,050	< 1 %
A4	″	″	75	″	150	< 1 %	20,000	< 1 %
A5	″	″	75	″	150	1.4 %	20,000	< 1 %
A6	″	″	50	3-ply; tape slit *before* Cu-lamination	150	< 1 %	20,000	< 1 %
A7	″	″	50	″	150	< 1 %	20,000	< 1 %
B1	IBAD/ MOCVD	Hastelloy C-276; 100	0	Not Cu-plated; tape slit	100	< 1 %	20,200	< 1 %
B2	″	″	20	Cu-plated on YBCO and substrate sides; tape slit *after* Cu-plating	100	< 1 %	20,000	< 1 %
B3	″	″	20	Cu-plated *all* sides; tape slit *before* Cu-plating	100	< 1 %	20,000	< 1 %
B4	″	″	20	″	150	< 1 %	20,000	< 1 %

Summary of the results obtained on the effect of transverse-compressive stress and fatigue cycling. Measurements were performed at 76 K in self-field.
[a] t_S, t_{Cu}: thicknesses of substrate and Cu layers, respectively.

of the conductor—the Cu layer was 20 μm thick all around the tape (samples B3 and B4).

B. Transverse-Compressive-Stress Apparatus

Each sample was cut to a length of 25 mm. Two copper leads were attached to the tape ends and a pair of voltage taps soldered to its middle. One of the current leads was stationary and the other was free to flex so as to ensure stress-free cooling of the sample from room temperature to liquid-nitrogen temperature [10]. The sample was positioned at the bottom end of the apparatus between two flat stainless-steel anvils used to apply transverse compressive stress to the specimen [6]. The load was transmitted to the sample via a stainless steel rod, attached to a calibrated 13 kN load cell at the top end of the apparatus to measure the applied force. During measurements, the bottom anvil was in direct contact with the back of the sample (substrate side), while the top anvil was positioned in the middle area of the tape between the voltage taps. Uniformity of stress over the compressed area of the conductor was achieved by attaching the top anvil to a biaxially gimbaled pressure-foot so that this anvil conformed precisely to the bottom anvil and sample surfaces [6]. The top anvil was made wider than the tape and its edges beveled in order to avoid stress concentrations.

C. Measurement Procedure

During the cooling of the specimen to the liquid-nitrogen temperature of 76 K, the top anvil was not in contact with the sample in order to avoid applying load to the tape during the cooling. Once the sample was cooled, the top anvil was lowered to make contact with the conductor. Transverse compressive stress σ_T was then applied and gradually increased, and voltage-current (V–I) curves measured for various values of stress in order to estimate the effect of static compressive stress on J_c. In this process, we used only the *monotonic-loading* mode [4]–[7], which consists of applying stress to the sample and incrementally increasing it without releasing the load between measurements steps, up to a certain maximum value of stress σ_{TM} at which the sample is subsequently subjected to fatigue cycling. As we showed in [4]–[7], the monotonic-loading mode generates the least degradation of J_c (and hence the fewest cracks) as compared to the *load-unload* or *lift-off* modes, where the force is released between the measurements steps, and the top anvil is either kept in physical contact with the sample (*load-unload* mode) or separated from it (*lift-off* mode). Differences between the three modes stem from the fact that, in the monotonic-loading, the pressing anvils provide good frictional support to the specimen, and hence limit formation of mechanical defects [4]–[7]. The aim of using the monotonic-loading mode in this experiment was to avoid inducing new mechanical cracks in the YBCO layer (other than those formed from tape slitting) from the stress build-up before the start of fatigue cycling. This procedure would ascribe the effect of fatigue cycling almost exclusively to the propagation of cracks that originated from conductor slitting.

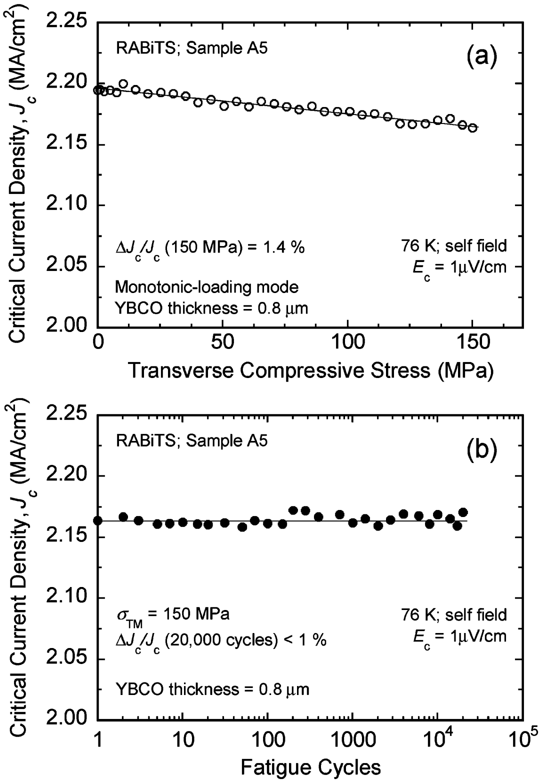

Fig. 1. Dependence of critical-current density J_c on (a) transverse compressive stress and (b) fatigue cycling up to 150 MPa and 20,000 cycles, in a neutral-axis YBCO RABiTS slit coated-conductor. Both effects are negligible, showing that transverse compression and fatigue cycling do not exacerbate edge cracks induced by conductor slitting.

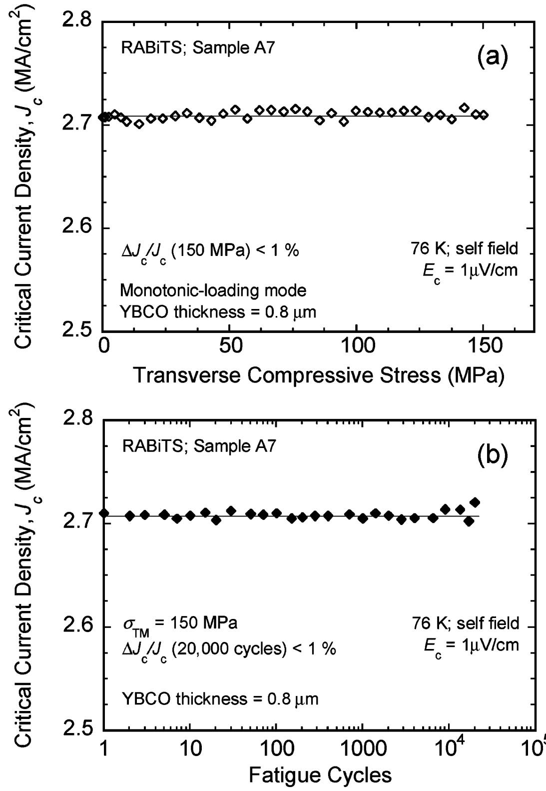

Fig. 2. Dependence of critical-current density J_c on (a) transverse compressive stress and (b) fatigue cycling up to 150 MPa and 20,000 cycles, in a 3-ply YBCO RABiTS slit coated-conductor. Both effects are negligible, again showing that transverse compression and fatigue cycling do not exacerbate edge cracks induced by conductor slitting.

Once the maximum stress $\sigma_{\rm TM}$ is reached, the load was cycled between $\sigma_{\rm TM}$ and near zero at a frequency of 1 Hz, and V–I measurements made (when stress was at $\sigma_{\rm TM}$) at various stages of cycling. The number of fatigue cycles (about 20,000) was ten times more than that in our previous reports [4]–[6].

All data were acquired in self-field. Values of critical current I_c were determined from V–I curves at an electrical-field criterion E_c of 1 $\mu\mathrm{V/cm}$. Critical current and transverse compressive stress were accurate to within 1% and 3%, respectively. Values of J_c were calculated from those of I_c by using the cross-sectional area of the YBCO layer. Uncertainty in estimating the YBCO cross section was about 10%.

III. Results and Discussion

A succinct summary of the results obtained is depicted in the last four columns of Table I, where the total degradation of J_c from the static stress application, and then the subsequent fatigue testing to about 20,000 cycles, is tabulated for all samples measured. More detailed descriptions of the effect of the monotonic-loading of transverse compression and fatigue cycling on J_c are shown for selected samples in Figs. 1–4 for both RABiTS and IBAD YBCO coated conductors.

The monotonic build-up of stress to $\sigma_{\rm TM}$ has minimal effect on J_c Figs. 1(a) and 2(a): 1.4% in the case of sample A5, and nonexistent in sample A7. This shows that our goal of minimizing formation of new cracks before fatigue cycling was achieved for all samples measured (see also Table I). This also

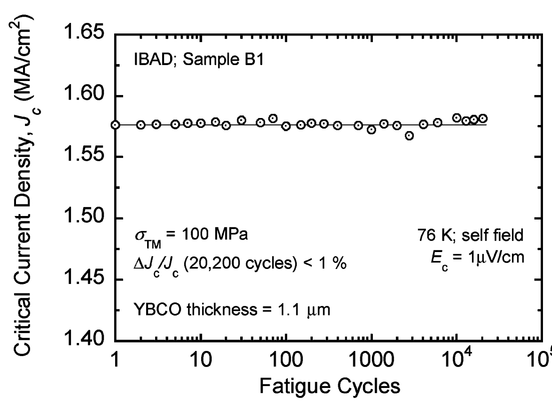

Fig. 3. Dependence of critical-current density J_c on fatigue cycling under transverse compressive stress up to 100 MPa and 20,200 cycles, in a non-Cu-plated YBCO IBAD slit coated-conductor. The fatigue effect is negligible, showing that propagation of edge cracks induced by conductor slitting is extremely limited.

confirms that transverse compression has little intrinsic effect on J_c of YBCO, possibly due to the fact that the critical temperature T_c does not change significantly from compressing the YBCO lattice along its c-axis [11].

The effect of fatigue cycling is depicted in Figs. 1(b) and 2(b) for the RABiTS neutral-axis and 3-ply architectures, and in Figs. 3 and 4 for the IBAD conductors with and without a Cu-plated layer. All data obtained show that, independently of RABiTS or IBAD, conductor geometry, or the sequence of Cu

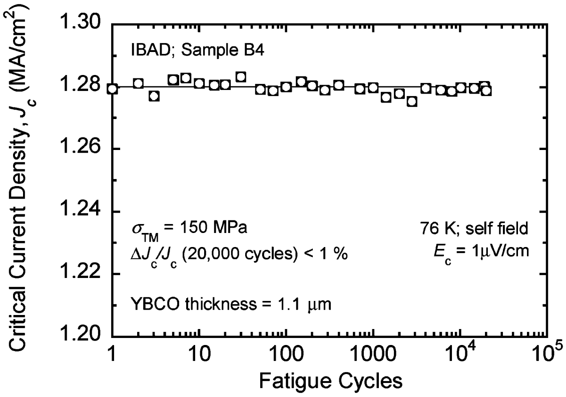

Fig. 4. Dependence of critical-current density J_c on fatigue cycling under transverse compressive stress up to 150 MPa and 20,000 cycles, in a Cu-plated YBCO IBAD slit coated-conductor. Again, the fatigue effect is negligible, showing that propagation of edge cracks induced by conductor slitting is extremely limited.

addition and tape slitting, fatigue cycles under transverse compressive stress up to 150 MPa and 20,000 cycles have negligible effect on the transport properties of YBCO conductors. Hence, under this experimental mode, cracks generated at the tape edges from slitting are not exacerbated and their propagation into the conductor is extremely limited. In short, static and cyclic transverse compressive force does not seem to present a problem for coated-conductor applications, at least up to 150 MPa and 20,000 cycles.

IV. Conclusion

Several YBCO RABiTS and IBAD slit conductors were investigated under transverse compressive stress up to 150 MPa and 20,000 fatigue cycles. Specimens studied had different geometries and fabrication processes. Independent of the fabrication technique, the data demonstrate that damage at the conductor edges from slitting does not become worse under these experimental conditions that simulate applications such as industrial magnets.

The negligible effect of fatigue in slit samples shows the robustness of the coated conductors under these specific experimental conditions. Nevertheless, the results obtained do not signify that slitting is harmless to the conductor performance under any circumstances. Slitting may still potentially weaken the conductor under other mechanical stresses such as transverse *tension* [12] or thermal cycling.

References

[1] R. M. Scanlan, A. P. Malozemoff, and D. C. Larbalestier, "Superconducting materials for large scale applications," *Proceedings of the IEEE*, vol. 92, pp. 1639–1654, October 2004.

[2] D. U. Gubser, "Superconductivity: An emerging power-dense energy-efficient technology," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 2037–2046, December 2004.

[3] A. P. Malozemoff, "The new generation of superconductor equipment for the electric power grid," *IEEE Trans. Appl. Supercond.*, vol. 16, pp. 54–58, March 2006.

[4] N. Cheggour, J. W. Ekin, C. C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, D. F. Lee, D. M. Kroeger, and D. K. Christen, "Transverse compressive stress, fatigue, and magnetic substrate effects on the critical current density of Y-Ba-Cu-O coated RABiTS tapes," *Adv. Cryo. Eng.*, vol. 48, pp. 461–468, 2002.

[5] N. Cheggour, J. W. Ekin, C. C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, and N. Rutter, "Effect of transverse compressive stress on transport critical current density of Y-Ba-Cu-O coated Ni and Ni-W RABiTS tapes," *Ceramics Trans.*, vol. 140, pp. 157–170, 2003.

[6] J. W. Ekin, S. L. Bray, N. Cheggour, C. C. Clickner, S. R. Foltyn, P. N. Arendt, A. A. Polyanskii, D. C. Larbalestier, and C. N. McCowan, "Transverse stress and fatigue effects in Y-Ba-Cu-O coated IBAD tapes," *IEEE Trans. Appl. Supercond.*, vol. 11, pp. 3389–3392, 2001.

[7] N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman, "Transverse compressive stress effect in Y-Ba-Cu-O coatings on biaxially textured Ni and Ni-W substrates," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 3530–3533, June 2003.

[8] M. W. Rupich, D. T. Verebelyi, W. Zhang, T. Kodenkandath, and X. Li, "Metalorganic deposition of YBCO films for second-generation high-temperature superconductor wires," *MRS Bull.*, vol. 29, pp. 572–578, August 2004.

[9] V. Selvamanickam, Y. Xie, J. Reeves, and Y. Chen, "MOCVD-based YBCO-coated conductors," *MRS Bull.*, vol. 29, pp. 579–582, August 2004.

[10] P. E. Kirkpatrick, J. W. Ekin, and S. L. Bray, "A flexible high-current lead for use in high-magnetic-field cryogenic environments," *Rev. Sci. Instrum.*, vol. 70, pp. 3338–3340, 1999.

[11] U. Welp, M. Grimsditch, S. Fleshler, W. Nessler, J. Downey, G. W. Crabtree, and J. Guimpel, "Effect of uniaxial stress on the superconducting transition in $YBa_2Cu_3O_7$," *Phys. Rev. Lett.*, vol. 69, pp. 2130–2133, 1992.

[12] D. C. van der Laan *et al.*, U.S. Department of Energy Annual Peer Review. Washington, DC, July 2006.