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Uniform performance of continuously processed MOD-YBCO-coated conductors using a textured Ni–W substrate

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Abstract
Second-generation coated conductor composite HTS wires have been fabricated using a continuous reel-to-reel process with deformation-textured Ni–W substrates and a metal-organic deposition process for $YBa_2Cu_3O_{7-x}$. Earlier results on 1 m long and 1 cm wide wires with 77 K critical current performance greater than 100 A cm^{-1} width have now been extended to 7.5 m in length and even higher performance, with one wire at 132 and another at 127 A cm^{-1} width. Performance as a function of wire length is remarkably uniform, with only 2–4% standard deviation when measured on a 50 cm length scale. The length-scale dependence of the deviation is compared with a statistical calculation.

1. Introduction

High temperature superconductor films, such as $YBa_2Cu_3O_{7-x}$ (YBCO), can support critical current densities (J_c) exceeding 1 MA cm^{-2} (77 K, self field) on biaxially aligned substrates with an appropriate lattice match [1, 2]. Two methods to provide such templates for the epitaxial growth of the superconductor have dominated research in the field of second-generation HTS wires. The first method uses an untextured metal substrate along with a technique to induce texture in a buffer layer such as ion-beam assisted (IBAD) [2] or inclined substrate [3] deposition. The second method begins with a textured metal substrate which is buffered with an epitaxial film for diffusion resistance and chemical compatibility with the superconductor. The rolling method used to achieve a biaxially textured substrate is called RABiTS™ [1]. Numerous methods are available for epitaxial deposition of the superconductor, including *in situ* formation of YBCO by pulsed-laser deposition (PLD) [4] and an *ex situ* reaction of a BaF_2-based precursor deposited by either electron-beam evaporation [5] or web coating of a metal-organic-based solution [6]. Results using the combination of the yttria-stabilized zirconia (YSZ) IBAD and PLD-YBCO have shown previously that critical currents (I_c) greater than 100 A cm^{-1} width can be obtained at 75–77 K on 1 m long wires [7]. However, without significant improvements in the slow texture evolution in YSZ-IBAD and the cost of laser deposition, the IBAD-PLD approach remains costly and difficult to manufacture in large volumes. High I_c performance has also been shown [8] with a lower cost approach, which combines the RABiTS™ architecture with a solution-derived (metal-organic deposition (MOD)) YBCO. To show the potential of this process for commercial production of second-generation coated conductor composite wires, we report on the excellent I_c uniformity possible on wires up to 8 m in length. Results on 10 m lengths have been reported elsewhere [9].

2. Experimental details

The coated conductor composite architecture presented in this paper consists of a textured Ni alloy substrate that is buffered with cubic oxide buffer layers and coated with an MOD-YBCO superconductor. In this case, Ni is alloyed with 5atm%W to produce a substrate with increased strength and reduced magnetism [10] compared to the standard Ni substrate widely used for RABiTS™ in the past. At room temperature, the tensile yield strength of Ni–W (145 MPa) is four times that of pure Ni (34 MPa).

The Ni–W alloy was rolled to a thickness of 75 μm and slit to 1 cm wide, before it was recrystallized in a reel-to-reel furnace to form the cube-textured template. Epitaxial buffer layers with the structure $Ni/Y_2O_3/YSZ/CeO_2$ were also deposited in a reel-to-reel format with continuous processing that is scalable to longer length. The substrate was reel-to-reel coated with a 2 μm Ni layer prior to buffer deposition. Following the deposition of Ni, a surface sulfurization process enhances the proper [100] nucleation of the yttria seed layer on the metal surface [11]. A 50 nm thick Y_2O_3 seed layer was deposited on Ni surface by reel-to-reel electron-beam evaporation. Both, the 300 nm thick YSZ barrier layer and a 30 nm CeO_2 cap layer were subsequently deposited by rf-sputtering.

Fully buffered wires were coated with a single layer of YBCO precursor by a commercial web-coating process with MOD using a trifluoroacetate (TFA)-based precursor [12]. The organic components were decomposed in a humid, oxygen atmosphere up to a temperature of 400 °C, to form a BaF_2-based precursor film with stoichiometric Cu and Y oxides for YBCO. This precursor was continuously converted to the epitaxial superconducting phase in a tube furnace in a humid, low oxygen partial pressure environment [8, 13, 14].

The resulting film thickness was 1.2 μm measured by SEM cross-section analysis, but Rutherford backscattering (RBS) data indicate that the film contains the mass for a fully dense, stoichiometric 1.0 μm film. Although RBS has an accuracy of only ±10%, we consider it more reliable than the SEM result because of the rough surface of YBCO. The typical RMS roughness is 70 nm for a 25 μm^2 surface area of YBCO. The structure was completed with a 3 μm Ag cap layer deposited by dc sputtering and an oxidation step to provide environmental protection, mechanical and electrical stability, optimum oxygen stoichiometry for YBCO and a low resistivity contact to the superconductor.

3. Results

Second-generation HTS wires of 7.5 and 8.0 m length were produced in a continuous process using nominally the same conditions used with the above described methods and architecture. Figure 1 shows I_c at 77 K, self field, for both wires, A (7.5 m) and B (8.0 m), measured at 50 cm intervals using the standard 1 $\mu V\ cm^{-1}$ criterion. End-to-end I_c performance, also determined at a 1 $\mu V\ cm^{-1}$ criterion, was

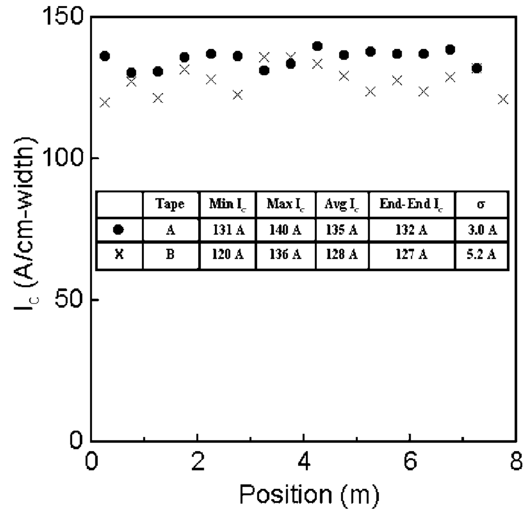

Figure 1. Critical current as a function of length, measured at 50 cm intervals, for the 7.5 and 8.0 m long YBCO superconducting wires measured at 77 K, self field.

132 and 127 A cm^{-1} width for A and B, respectively. The inset in figure 1 provides I_c statistical data for both wires. The 3.0 A cm^{-1} width standard deviation (σ) of I_c, measured for wire A, is the highest uniformity yet reported on any second-generation wire of this length [15, 16]. Wire B is a replicate of A with nearly the same I_c and only slightly higher variability. The higher variability translates to a smaller 'n value', where n is the exponent of a power law fit to the end-to-end I–V curve near I_c, with wire B giving an exponent of 16 compared to 23 for wire A.

Texture of the substrates, deposited buffer layers, and YBCO is compiled in table 1 as derived from the pole figures. The in-plane YBCO texture of the two wires differ by 0.5°, but due to its global nature, pole figure analysis does not reveal the local texture, which is the important metric in determining J_c. To predict the macroscopic J_c explicitly, it would be necessary to map grain boundary misorientations of the entire wire, specify the dependence of the grain boundary J_c on misorientation angle (θ) and calculate the network solution. Statistical approaches to this have been reported that assume a random grain distribution related to a particular in-plane full-width half maximum (FWHM). Limiting path calculations of long-range current percolation by Specht *et al* [17] model a conductor with a FWHM of 6°, with a simple cutoff in the grain boundary J_c above a critical angle $\theta_c = 5°$, corresponds to the experimental results for high J_c films on bicrystal substrates. They find the maximum reduction in macroscopic J_c over 1000 m is only about 10%, for a conductor that is at least 100 grains wide. These conclusions are supported in the recent work of Nakamura *et al* [18]. In the case of a 0.4 cm wide commercial size conductor, the wire is about 100 grains wide for a typical Ni-5atm%W substrate with a grain size of 40 μm. Hence, the current model based on a random grain distribution predicts no significant reduction in J_c for the RABiTS-based approach when scaled to commercial width and length.

Next we compare the measured dependence of I_c on the voltage tap distance with a simple extension of the statistical calculations by Specht *et al*. Since the I–V response curve is non-linear for HTS films, a small region anywhere between

Table 1. In-plane ($\Delta\Phi$) and out-of-plane (ΔX) textures of buffer layers derived from pole figures. Full-width half-maximum values are in degrees. The Y_2O_3 and CeO_2 peaks overlap enough to be indistinguishable.

Wire A (7.5 m)	$\Delta\Phi$ (degrees)	ΔX (degrees)	Wire B (8.0 m)	$\Delta\Phi$ (degrees)	ΔX (degrees)
Ni-5atm%W	6.6	6.3	Ni-5atm%W	6.8	6.8
YSZ	6.2	5.5	YSZ	5.8	4.6
Y_2O_3/CeO_2	6.0	6.0	Y_2O_3/CeO_2	5.5	5.6
YBCO	6.1	4.8	YBCO	5.6	4.6

Table 2. Comparison of critical current data for different segment lengths of wire A from position 4.8 to 5.8 m as presented in figure 1. The standard criterion of 1 μV cm^{-1} was used.

Wire A	1 cm	5 cm	10 cm
Minimum I_c (A)	130	135	135
Maximum I_c (A)	155	148	146
Average I_c (A)	144	143	143
Standard deviation (A)	4.4	3.6	3.1
Standard deviation (%)	3.1	2.5	2.2

the voltage taps can be a dominant source of the voltage. This results in a situation where the variation of I_c on any length of wire will increase with measurements at shorter voltage taps. Here, the full I–V curve of a 1 m length of wire A was measured at 1 cm intervals. The voltage data were then summed up together to produce full I–V curves at different length scales, for which the I_c was determined. Statistical results, including the maximum, minimum, algebraic average and standard deviation are presented in table 2 for 1, 5 and 10 cm intervals using the 1 μV cm^{-1} criterion for all data. Measurements taken at 1 cm intervals over 1 m, give a standard deviation (σ) of 4.4 A cm^{-1} width which translates to a 3σ variation of 13.2 A cm^{-1} width or $\pm$9.2% of the mean I_c. As expected, data for 5 and 10 cm segments show a decreasing σ, 3.6 and 3.1 A cm^{-1} width, respectively.

We compare these results with calculations extending the model of Specht *et al* by the variation in I_c expected from percolation at different length scales. As described in the model, a YBCO film with FWHM $\Delta\Phi = 6.5°$ can be modelled by a hexagonal array of grains, in which a random 80% of the grain boundaries are conducting with the simple approximation that grains are either strongly linked and carry the full intragranular J_c or are completely nonconducting (80% corresponds to the expected fraction of strongly linked grains when the grain boundary angle cutoff is 5°). A 1 cm × 5 cm segment with a 50 μm grain size would consist of an array, 200 grains wide and 1000 grains long. In the case of a 250 m wire with 5000 such segments, I_c is found to be 48% of the intragranular value, with a standard deviation $\sigma = 3.6\%$ of the mean.

Now we consider the scaling of σ with wire length. The statistical variation in I_c for n cm segments is simulated by choosing I_c for each 5 cm segment from a Gaussian distribution with the calculated $\sigma = 3.6\%$; overall I_c for the longer wire is that of its worst segment assuming an infinitely sharp I–V curve (infinite index value n). The procedure was repeated 10^6 times. Figure 2 shows the calculated dependence of variation in segment length for the range of 1 to 1000 cm. Also plotted in figure 2 are the measured data compiled in table 2. The measured data clearly fall below the calculated curve. Interestingly, the results are better than the calculations.

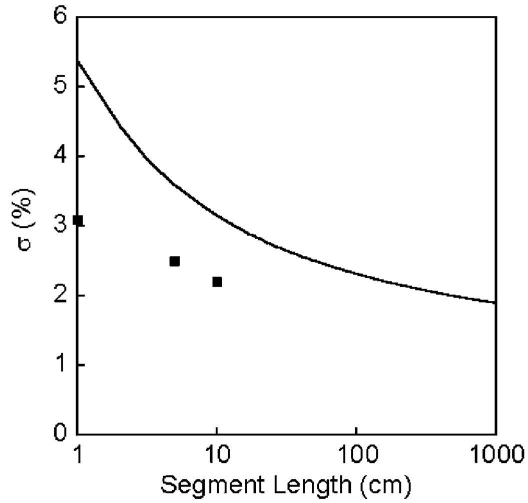

Figure 2. Solid line shows per cent standard deviation versus segment length, calculated by assuming a random distribution of grain boundary misorientations for a wire, 1 cm wide with 50 μm grains [15]. Standard deviations determined from different measurement segment lengths from 1 m of measurements taken on wire A are plotted for comparison.

There are multiple possible reasons for this discrepancy. An important assumption in the model is the infinitely sharp I–V curve, ignoring the more forgiving voltage criterion with finite index value characteristic of HTS materials. Further refinements of the models are required to include more complete J_c versus angle dependence and measured grain boundary misorientation distribution from Kikuchi mapping, which could be non-Gaussian, showing short-range texture correlations. The benefit of a refined model would be the ability to look at deviation from expected behaviour for identifying the defects or variations corresponding to a particular length scale, and in turn revealing valuable process control issues. A more fundamental understanding may be found by plotting the I_c distribution over shorter length segments to study the possibility of clustering resulting from a non-Gaussian grain boundary distribution.

4. Conclusion

In this work, the second-generation coated conductors fabricated with a low-cost RABiTS approach, in conjunction with a solution-based MOD-YBCO process, produced very uniform, high performance wires up to 8.0 m long. This work extends the processing length while maintaining the uniformity seen previously on 1 m wires. These results and statistical calculations indicate that the present processing methodology can be extended to commercial 1 km lengths with adequate uniformity and without significant loss of overall I_c.

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