Numerical and Experimental Investigation of the Electromechanical Behavior of REBCO Tapes

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Abstract. To fully characterize the electromechanical behavior of a Twisted Stacked-Tape Cable (TSTC) it is important to understand the performance of the individual REBCO tapes under various loading conditions. Numerical modeling and experimentation have been used to investigate the electromechanical characteristics of two commercially available REBCO tapes (SuperPower and SuNAM). Tension and combined tension-torsion experiments on single tapes have been continued, from prior preliminary studies, to characterize their critical current behavior and mechanical strength. Additionally, structural finite element analysis was performed on single tapes under tension and combined tension-torsion to investigate the strain dependence of the critical current. The numerical results were compared to the experimental findings for validation. The SuNAM experimental data matched the numerical model very well while the SuperPower tape experienced degradation at lower stress and strain than predicted in the model. The Superpower tape also displayed greater variability in critical current between different samples as compared with the SuNAM tape.

1. Introduction

The Twisted Stacked-Tape Cable (TSTC) is one method for cabling flat REBCO tapes and may be a viable option for implementing high temperature superconductors in various applications including power transmission, fusion and high-energy physics [1]-[2]. The TSTC method consists of a stack of flat REBCO tapes twisted along the axis of the stack; therefore, to fully characterize the electromechanical behavior of a TSTC conductor it is important to first determine the performance of the individual REBCO tapes under their operational loading conditions.

Several studies are available on the characteristics of REBCO coated conductors under various loading conditions including torsion [3]-[7], tension [8]-[13] and combined tension-torsion [7], [12]-[13]. These studies provide good insight into the general characteristics of REBCO tapes. Considering REBCO tapes have varying dimensions and layered compositions between manufacturers, it is important to characterize specific REBCO tapes being used for TSTC conductors as done in this work.

In this work the electromechanical behavior of two commercially available REBCO tapes from SuperPower and SuNAM have been investigated under tension and combined tension-torsion loading. Combined tension-torsion loading is of particular interest for TSTC conductors due to the twisted nature the design. Torsion originates from the twisting of the REBCO tapes for AC loss reduction; while tension occurs from differential thermal contraction and hoop forces within a magnet coil.

Tension and combined tension-torsion experiments in self-field at 77 K have been conducted and the results were evaluated using a numerical finite element model which was developed in tandem.
Together the numerical and experimental data provides unique insight into the strain dependence of the critical current for these two REBCO coated conductors.

The layered composite architecture of the SuperPower and SuNAM REBCO tapes that were used are shown in figure 1. Overall both tapes are composed of a superconducting film, buffer layers, silver layers, a non-magnetic substrate and a copper stabilizer. The SuperPower tape has a Hastelloy C276 substrate and a Zr-doped REBCO superconductor while the SuNAM tape uses a Stainless Steel substrate and a GdBCO superconductor. The dimensions and specifications of these tapes are provided in table 1. It should be noted that the width, thickness values reported are the mean values calculated from 50 measurements taken over a 350 mm long sample length. The reported critical currents are the average value from 7 SuNAM and 11 SuperPower samples tested and discussed in this paper. These calculated mean values all fall within the range provided from the manufacturers.

Table 1. Tested REBCO tapes and their measured characteristics

| Manufacturer | SuperPower | SuNAM |
|--------------|------------|-------|
| Type         | SCS4050-AP | SCN04150 |
| Processing   | IBAD-MOCVD | IBAD |
| Width        | 4.027 ± 0.057 mm | 4.062 ± 0.008 mm |
| Thickness    | 0.092 ± 0.001 mm | 0.144 ± 0.001 mm |
| Substrate (thickness) | Hastelloy C-276 (50 µm) | Stainless Steel (100 µm) |
| Stabilizer (total thickness) | Electroplated Cu (40 µm) | Electroplated Cu (40 µm) |
| Critical Current (77 K & self-field) | 112 ± 3 A | 229 ± 6 A |

Figure 1. REBCO tape architectures of SuperPower [14] top and SuNAM [15] bottom.

Figure 2. Bilinear material properties inputted into numerical ANSYS® model [14-24].

2. Numerical modeling of REBCO tapes

Structural finite element analysis (FEA) using ANSYS® was done to investigate the electromechanical behavior of REBCO coated tapes under tension and combined tension-torsion loads. The FEA model was used to determine the stress and strain characteristics (elongation and load) as well as the torque magnitude of the tapes under load. The strain profile from the FEA was paired with an analytical model to predict the critical current of the sample [7]. The FEA model was customized to the exact multi-layered architecture of each type REBCO tape (SuperPower and SuNAM) so that detailed results for each constituent layer of the composite tapes can be obtained.

The REBCO tape was modeled using 3D 8-node SOLSH190 structural solid-shell elements with built in layered composite capabilities. The tape was meshed with one element through its thickness and the appropriate layer definitions and properties were defined using shell section commands (i.e. each layer of the tape {substrate, REBCO, etc} is defined within the finite element and all interlayer interactions are calculated in the element formulations). Sufficient mesh density through the width and
The length of the tape was chosen. The tensile load was applied to the ends of the tape using a surface pressure load while the rotation was applied to the ends of the tape using pilot node constraints.

The material properties for each constituent layer of the composite REBCO tapes were defined in ANSYS® using bilinear stress-strain curves. The bilinear curves are defined by a modulus of elasticity, yield strength and tangent modulus and are shown in figure 2. Care was taken to use the most accurate material properties for the substrate and copper because those materials govern the overall strength of the tapes. The buffer and REBCO superconducting layers have brittle ceramic characteristics and were modeled with linear elastic properties. For consistency, the same REBCO, copper and silver properties were defined for both tapes.

A single REBCO tape under pure tension was initially simulated to determine the mechanical stress-strain trend of the model. The bilinear material properties were modified to produce the best fit to the experimental stress-strain curve (see section 3.2 for more details). Once the material properties were accurately defined producing a model with the same mechanical characteristics as the real REBCO tape, the model was used to determine the strain dependence of the critical current for both REBCO tapes utilizing an analytical model described in [1]. The critical current degradation under pure tension for an untwisted tape was first analyzed followed by the critical current behavior under combined tension-torsion loading in order to investigate electromechanical characteristics of a twisted tape. The results from FEA modeling are compared to the experimental data in section 4.

3. Experimental Details

3.1. Experimental test probe

The tension and combined tension-torsion tests were conducted using the same experimental test probe used in prior preliminary studies [7], [25]. The tests probe is shown in figure 3. The probe is designed to simultaneously measure the axial load, elongation, torque and critical current of REBCO tapes. The probe was used to test both 100 mm and 300 mm long samples. The samples were mounted using stainless steel compression style sample holders. The current was supplied via flexible 12 mm wide high current SuperPower REBCO tapes. This was done so that the current leads did not influence the torque or axial load measurements. Two pairs of voltage taps were used to record the voltage during critical current measurements.

Figure 3. (a) Experimental test probe highlighting stainless steel structure (b) probe inside cryostat (c) Tension sample showing sample holders [D], current leads [E], extensometers [C] and voltage taps [A, B] (d) Torsion-tension sample after being removed from cryostat showing torque meter [F].
Axial displacement was applied outside the cryostat through a pull rod by a 1/40 hp permanent magnet DC electric motor (Bison 011-190-0702) and a 10 kN anti-backlash machine screw actuator (Duff-Norton M5500-124). The axial displacement of the sample was measured outside the cryostat by a 15 mm stroke linear variable differential transformer (LVDT, Omega LD621-15). Double extensometers (Nyilas-type) were used to calibrate the LVDT sensor during pure tension measurements [26]. The extensometers were not used for the tension-torsion tests due to the twist in the sample. The torsion/twist was applied to the top of the sample via the pull rod while the bottom was held by a low capacity reaction torque sensor (RTS-10 Transducer Techniques). The tensile load was measured outside the cryostat by an 1112 N (250 lb) donut style load cell (Futek LTH-350).

3.2. Mechanical stress-strain measurements
In order to define the appropriate material properties for the composite REBCO tapes in the numerical finite element model, the stress-strain behavior of the tapes was measured. The experimental stress-strain results can then be used to validate the stress-strain curve produced by the model allowing the strain dependence of the critical current in the tapes can be investigated. The mechanical stress-strain tests were done in a bath of liquid Nitrogen at 77 K using the experimental test probe defined in the previous section. A high precision load cell mounted on the pull rod at the top of the probe recorded the tensile stress while the strain of the sample was measured by Nyilas-type extensometers mounted directly on the REBCO tape and also by the LVDT mounted in the room temperature zone at the top of the probe. After the probe was cooled down in the bath of liquid Nitrogen the sample was slowly strained at a rate of roughly 3 mm/min while the load and displacement were simultaneously measured. After the onset of yielding occurred the strain was released and the sample was unloaded.

3.3. Critical current measurements
For both tension and combined tension-torsion tests, two pairs of voltage taps were used to determine the samples critical current. The primary pair of voltage taps (denoted by A in figure 3(c)) was located in the center of the sample. The secondary pair of voltage taps (denoted by B in figure 3(c)) spanned twice the distance covering the majority of the sample length. The distance between voltage taps varied with the length of the sample being tested. For 100 mm long samples, the primary and secondary voltage tap pairs spanned 40 and 80 mm long respectively. For the longer 300 mm samples, the primary and secondary voltage tap pairs spanned 100 and 200 mm long. The two sets of voltage taps were used to identify any critical current variation that may occur along the length of the sample.

During the critical current measurements, the current is slowly increased while two nanovoltmeters simultaneously record the voltage between the two voltage tap pairs. The low noise characteristic of the REBCO tapes and the accuracy of the nanovoltmeters allowed for repeatable precise determination of the critical current and n-value. The critical current presented in this work was calculated from the lower electric field criterion of 100 μV m⁻¹. The upper electric field criterion used for SuperPower tapes was 500 μV m⁻¹ while it was 200 μV m⁻¹ for SuNAM tapes, which were more prone to burning due to the larger currents they carry. A characteristic voltage versus current plot for Superpower and SuNAM samples is shown in figure 4 along with the electric field criterion for a tap span of 100 mm.

4. Results

4.1. Stress-Strain Characteristics
The stress-strain curve for SuperPower and SuNAM REBCO tapes at 77 K is shown in figure 5. The solid curves in the figure denote the experimental stress-strain results while the dashed lines indicate the stress-strain result from the structural FEA model of the layered composite tapes. The experimental tests for both tapes produced very repeatable stress-strain behavior and the curves shown in figure 5 are the average stress-strain curves from 6 tests of each tape. The bilinear material properties in the numerical model (shown in figure 2) were adjusted to produce the best fit to the experimental data, which are shown in figure 5.
The SuperPower and SuNAM tapes have different dimensions, substrates and superconducting films and were found to have different mechanical stress-strain characteristics. The SuNAM tape was found to have a 20% greater modulus of elasticity compared to SuperPower but was also found to have a lower yield stress; about 700 MPa compared to around 820 MPa for SuperPower. That being said, because the SuperPower tape has a smaller overall cross-section it actually yields at a lower tensile load (~300 N) compared to the SuNAM tape (~400 N). The SuperPower tape was also found to have a tangent modulus of nearly double that of SuNAM.

4.2. Normalized critical current behavior under pure tension

The critical current behavior of SuperPower and SuNAM tapes under pure tension is shown in the following figures. Figure 6 plots the normalized critical current versus applied tensile stress while figure 7 plots the normalized critical current versus applied tensile strain. The dashed lines in the plots indicate the predicted critical current determined from the numerical FEA strain results and the analytical model given in [1]. The predicted onset critical current degradation from the finite element model closely matches the yield strength of the tape.

The critical current trend under tension was found to be very different between the two REBCO tapes. The critical current degradation of SuNAM tape closely matched the numerical data and experienced degradation near the yield point of the tape (~700 MPa). Each SuNAM sample experience relatively close and repeatable results whereas the SuperPower tape displayed much greater variability between each sample tested. The critical current for the SuperPower tape was seen to degrade between 500-600 MPa and 0.45-0.55% strain. A few SuperPower samples did have a noticeably higher stress at the onset of critical current degradation (~700 MPa) however that was still much lower than the ANSYS® prediction based on the yield strength of the tape.
Figure 7. Normalized critical current versus applied tensile strain plots for straight samples.

All samples tested from both manufacturers were taken off of the same spool of tape and were prepared and mounted in the same manner. Care was taken during the preparation and mounting to keep everything consistent between samples. Considering this and the fact that the SuNAM tape had more repeatable data, we conclude that the variability in the SuperPower samples is real and may be explained by a microscopic slipping/shearing phenomena between layers inside the tape that causes critical current degradation before the yield point of the sample. A deeper analysis of the tapes looking at their microstructure is required. SuNAM tape may not have experience such a phenomena because it is 60% thicker and uses a different fabrication process.

4.3. Normalized critical current behavior under combined tension-torsion

The combined tension-torsion results for SuperPower and SuNAM tapes are displayed in the following figures. Figure 8 plots the normalized critical current versus applied tensile stress while figure 9 plots the normalized critical current versus applied tensile strain. The dashed lines again indicate the critical current trend predicted from the numerical FEA strain results. The tension-torsion tests were conducted first for a 200 mm twist pitch which is the twist pitch being used for current TSTC conductors [2]. Tests were also carried out for a 150 mm twist pitch to identify the influence of additional twist. The experimental critical current was normalized to the initial value for the twisted samples (200 and 150 mm twist pitch), although the initial critical currents of the twisted samples saw no difference compared to the straight samples.

Figure 8. Normalized critical current versus tensile stress plots for combined tension-torsion samples. Numerical results are shown by dashed lines and the sample twist pitch is indicated in parenthesis.

The numerical results under combined tension-torsion shown in figure 9 also indicate a very similar critical current trend compared to the pure tension model. This result was confirmed by the experimental results, which also showed that the combined tension-torsion samples saw critical current degradation around the same location with the tensile samples. The SuNAM samples for 200 and 150 mm twist pitch were almost identical and both showed degradation around 700 MPa which
again is at the yield point of the tape same as in the tension samples. The tension-torsion SuperPower samples at 200 mm twist pitch again showed a higher degree of variability as was found in the tension samples. The SuperPower samples saw an onset of degradation between 700 and 800 MPa, which matches the “best” samples from the pure tension results. Those results seem to indicate a slight improvement in critical current performance in the SuperPower tension-torsion samples but more data would be necessary to validate.

4.4. Torque behavior under combined tension-torsion
As the tensile load was applied to twisted REBCO tapes the torque was concurrently measured. Figure 10 below is a plot of the change in torque versus the axial tensile stress applied to the twisted sample. For the most part the experimental results show good agreement with the torque performance predicted by the FEA model. The results from both REBCO tapes indicate an increasing torque with increasing applied tension. Additionally, both tapes indicate that for a shorter twist pitch the change in torque under tensile load is greater. For the same tensile load the SuperPower tape experienced less change in torque compared to the SuNAM tape. Those results are consistent with previously presented data that showed the SuNAM tape had higher torque under pure torsion [3]. The SuNAM tape experienced a pronounced plateau of the torque at high stress (near its yield point), which was not observed in the SuperPower results.

5. Discussion and conclusion
In this work, we analyzed the electromechanical behavior of two commercially available REBCO tapes (SuperPower and SuNAM) under tension and combined tension-torsion loading. The characteristics of the tapes were investigated through experimentation in self-field at 77 K and by structural finite element analysis. The finite element model was initially validated by adjusting the
material properties until the numerical results matched the measured experimental stress-strain curves. Following this, the numerical FEA strain results were fit to an analytical model that predicted the critical current behavior of the tapes under tension and combined tension-torsion. These results were then evaluated against the experimental results from both REBCO tapes.

For tension, the SuNAM experimental data matched the numerical model very well and saw a degradation in critical current beginning at the onset of plastic deformation in the tape. The SuperPower tape experienced degradation at lower stress than numerically predicted and displayed greater variability between samples as compared with SuNAM. These behavior is still under investigation. Overall, TSTC conductors should be designed to remain well below the yield strength of the REBCO tapes to avoid irreversible critical current degradation.

The combined tension-torsion critical current results were found to be almost identical to the pure tension results for both tapes indicating that the combined tension-torsion has minimal effect on the critical current performance for the two tested twist pitch (200 and 150 mm). This indicates that the twist of a TSTC conductor, for a twist pitch greater than 150 mm, should not influence the critical current behavior of that TSTC conductor under axial tension. The torque characteristics of the REBCO tapes under combined tension-torsion were also investigated and were found to linearly increase with applied tension. The numerical FEA results were found to be in good agreement with the measured torque data of both manufactures’ tapes.

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