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Ybco Superconductor Characterization under Shear Strain

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ABSTRACT

YBCO based high temperature superconductors in practical applications are subjected to shear strain. `Critical current characteristics' of such high temperature superconductors are known to get degraded in strain state. In this work, shear stresses resulting from the finite twisting of HTS tape having varying widths have been modeled using FEA analysis for different twisting angles. Supporting the findings of this model, an American Superconductor Corporation (AMSC) 2G YBCO tape of a given width has been twisted and experimentally investigated in self field for a given current ramp-rate. Under uniform twist of the YBCO tape at 77 K, the degradation in the current carrying ability up to 30% was observed. The irreversibility in the current carrying ability of HTS tape was also observed beyond the twisting angle per unit length of 25 degree/cm. The superconductor to resistive transition index, `n' is found to behave in an identical manner to the critical current as a function of twisting angle. Such degradation is largely attributed to the torsional shear strain resulting from the twisting.

Introduction

High temperature second generation (2G) commercial grade YBCO coated conductors are available now-a-days in long length for extensive uses in electrical power cable (Rutherford cable) in the form of stacked twisted HTS conductors [1-3]. Even the proposal of coated conductor in conduit cable (CCICC) employs the idea of stacked HTS conductor twisted over different transposition lengths [4]. In such applications individual HTS tape subjects to twist induced shear stress/strain. The strain beyond a certain limit can critically affect the transport property as well as can modify the super-current carrying path in the coated conductor [5]. Hence, it has become necessary to ensure the maximum tolerable shear stress/strain applied to HTS which could induce recoverable damage. Previous works on the torsoinal strain dependence of Bi-2223, YBCO coated conductor shows experimental findings on I_c degradation behavior. Finite element analyses along with theoretical co-relation also have been surveyed on torsion experiments of high temperature superconducting tapes [6-8]. In case of pure torsion, the strain induced on the tape cross-section is non-uniform and complex. However, the maximum torsional shear strain could be determined at the midpoint of the width side of the cross-section using the formula ($\varepsilon_t = t\theta/L$) [8-9].
In the present study, FEA modeling for shear stress developed on 2G YBCO tape of different widths has been considered. Further, the shear strain dependence of the critical current of coated conductor has been investigated experimentally for a high current ramp-rate.

In this paper, the FEA analysis is discussed in section-II. The experimental results and conclusion are discussed in section-III & section-IV respectively.

FEA Analysis

The finite element analysis was carried out considering a 300 mm length YBCO tapes having 4 mm, 8 mm and 12 mm widths. The parameters considered for the analysis along with tape geometry are given in the table 1.

Table 1: Properties of AMSC make YBCO tape.

Quantity	Value
Dimension, L × t	300 × 0.2 mm^2
Widths, w	4, 8, 12 mm
YBCO film thickness	0.8 µm
Substrate thickness	75 µm
Young's modulus	133.3 GPa
Poisson's ratio	0.28
Co-efficient of thermal expansion	1.5 × 10^{-5} m/mK
Temperature	80 K

Static structural type analysis is adopted for determining the longitudinal elongation and the shear stress developed due to twist at different angles. ANSYS workbench is used for simulation in which the element type is chosen by the software itself according to the type of analysis. 3-D model is used and the meshing is carried out using the same platform. Twisting moment

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from 90° to 1530° was applied at both ends of the tape in opposite directions with a step increment of 90°. For a given tape width, the maximum shear stress and the elastic strain for the full rotation of 1530° are shown in figure 1 and figure 2 along with the meshing.

Similarly, for each tape width at different rotational increment, the shear stress are calculated and presented in figure 3. The percentage of elongation in length due to shear stress and the percentage of the shear strain developed for maximum twist are tabulated in table 2 which indicates that the shear strain is more dominant as compared the shear stress.

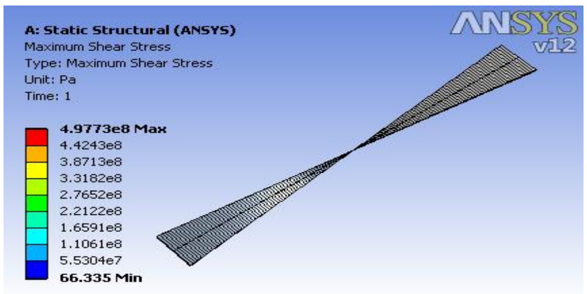

Figure 1: Shear stress after twisting the YBCO tape of 4 mm width at an angle of 1530°.

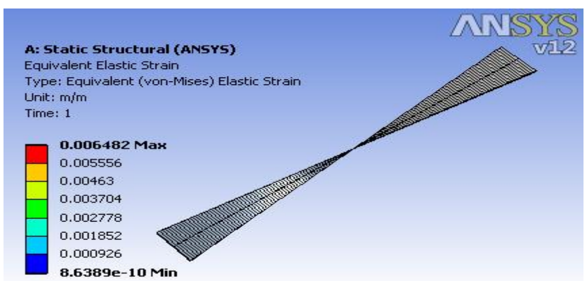

Figure 2: Elastic strain after twisting the YBCO tape of 4 mm width at an angle of 1530°.

Table 2: Maximum change in length in % along with maximum shear strain in % for different widths YBCO tape.

Strip width (mm)	Longitudinal elongation (%)	Shear strain (%)
4	0.648	1.78
6	0.753	1.78
8	0.806	1.78

Experimental and results

AMSC make YBCO tape of 300 mm length and 4 mm width was clamped tightly to hylum supports on both sides using nut-bolt arrangement in order to avoid the free shrinking along its longitudinal length during twisting. Then, it was fixed to rotating knob arrangements of the cold bath provided at both ends for twisting. These knobs rotated in either direction to provide prefixed twist induced strain. The sample tape is connected to current leads via flexible copper braids which also get twisted along with the sample tape and hence the stress concentration at the edge of the tape could be eliminated. The entire arrangement was dipped into LN_2 bath to avoid evolution of local hot spots.

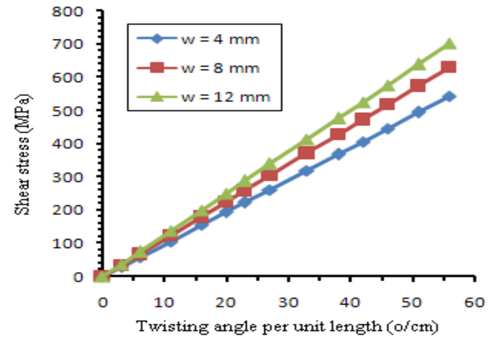

Figure 3: Shear stress calculated by FEA analysis for YBCO tape of different widths of different twist angle per unit length.

The twist angle θ is increased up to 1530° with constant rotational angle interval. Two voltage tap method was adapted to check the homogeneity of the critical current 'I_c' degradation behavior along the gauge length. These voltage taps with sufficient lengths soldered at the centre of the tape width at 5.0 cm and 10.0 cm apart from the middle node. The experiment was repeated with reversing the twisting angle at lower value in order to check the reversibility of 'I_c'. Data acquisition schematic is shown in figure 4.

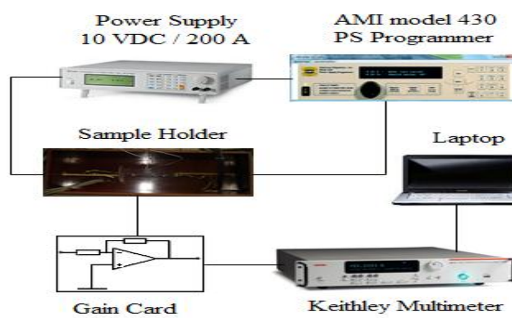

Figure 4: Data acquisition schematic for $I_c$measurement.

For a particular rotational angle 'θ', the transport current '*I*' is driven by unipolar *AMI XFR* (0-200A, 0-12V) DC power supply. Current '*I*' is ramped through AMI programmer (*Model 430*) up to its maximum amplitude and then ramp down to zero. Voltage limit in the programmer is kept greater than the voltage calculated using $V = L\,(dI/dt) + V_o$, The voltage drop `V_o' is dropped across the power lead which is measured to be less than 2*V*. During the ramp-up and ramp-down phases, the voltage drops at the two junctions and transport current are acquired in KeithleyMultimeter (*Model 2750 Integra Series*). The sampling frequency of this KeithleyMultimeter is 84 ms per data point. The multimeter is connected to LABVIEW installed PC via GPIB interface. One precision signal conditioning card is used to amplify the voltage signals corresponding to two voltage taps into measurable level. I-V measurement is pursued using standard four probe method. The typical electric field criterion of 1.0 μV/cm for critical voltage (V_c) is employed to determine 'I_c' value. The critical current 'I_{c0}' for the virgin untwisted tape at θ = 0° was found to be 105 A. The 'I_c' value was measured for each twisting angle 'θ' and then normalized by the virgin critical current 'I_{c0}'. The normalized critical current values I_c/ I_{c0} for the twist angles per unit length was plotted as shown in figure 5.

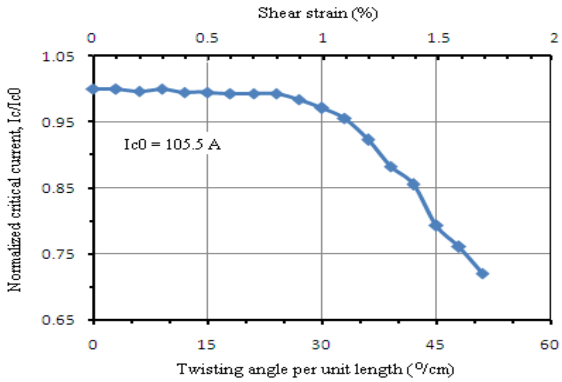

Figure 5: Behavior of normalized critical current (I_c/I_{c0}) with respect to twist angle per unit length.

Figure 5 indicates the absence of substantial I_c/I_{c0} degradation corresponding to θ/L between 0 to 24 (°/cm) whereas a gradual I_c/I_{c0} degradation was observed between 27 to 36 (°/cm). A rapid degradation of I_c/I_{c0} occurred beyond 36 (°/cm). After exposure the tape to such high stain, irreversible phenomena are observed in the tape, when untwisted. The reversible phenomenon in the critical current of the tape was observed when it is exposed to the twist angle per unit length up to 25 (°/cm).
The 'n' value behavior of the coated conductor as function of torsional strain was also investigated. It is estimated from the empirical power law relation $V/V_c = (I/I_c)^n$. As the exponent 'n' is linked with the current flowing through the superconducting core, it gets affected by the imposed torsional strain on the tape. The gradual yet significant transition from superconducting state to resistive state of the tape is reflected in the normalized 'n/n_0' value versus thetwist angle per unit length plot as shown in figure 6.

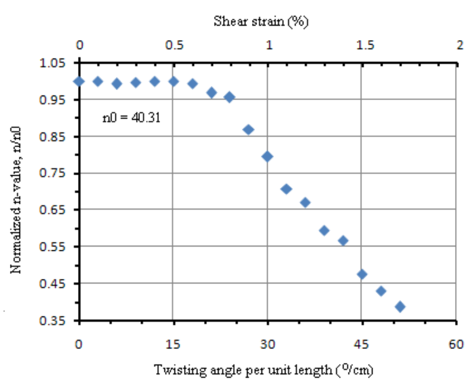

Figure 6: Normalized (n/n_0) behavior of YBCO tape for different twist angle per unit length.

The n-value for the untwisted tape i.e. at θ = 0° was found to be 40.31.Then n-values were normalized to 'n/n_0'values for all the twist angles per unit length using standard procedure. Figure 6 shows the normalized 'n/n_0'-value for untwisted and straight conductor is 1.0 and remains almost constant up to twist angle per unit length of 15. Thereafter, it attenuated in a fashion such that it follows the same trend as that of I_c degradation behavior. After degradation of the tape, the microstructure study was carried out using SME image of a nodal portion of the twisted sample as shown in figure 7. It indicates the torsion induced damage in the microstructure of the tape which could have resulted in the degradation of the superconductor film and the current is shared in the resistive alloy material causing I_c and 'n'-value deterioration.

Conclusion

From FEA analysis and the experiment, we observed that the critical current I_c degradation of YBCO tape occurrs due to the torsional strain only after a definite strain value. Thereafter, degradation is gradual as the strain increases. Finally, the I_c value falls suddenly indicating the deterioration in the transport property YBCO tape. In similar fashion, 'n'-valve behavior of YBCO tape follows I_c degradation characteristic. Also, it is observed from FEA analysis that the degradation does not depend on the tape width. Since the elongation does not have significant contribution as compared to shear strain, the wider tape is not too much sensitive to the twisting.

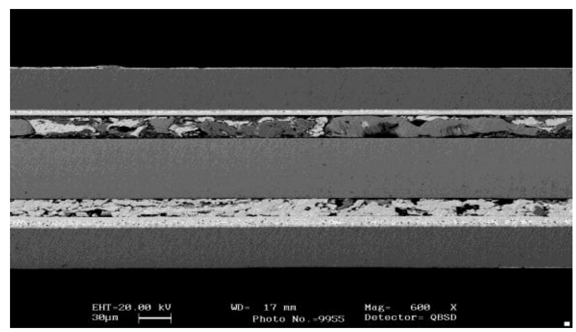

Figure 7: SEM images of the twisted sample showing crack at the interlayer portion of the twisted sample.

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