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Experimental study of yttrium barium copper oxide superconducting tape's critical current under twisting moment

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Abstract. Critical current (I_c) characteristics of 2G YBCO superconducting tape under the influence of twisting moment was experimentally investigated at varying current ramp rates in the self-field. Under a uniform twist, the degradation in the current-carrying capacity of YBCO tape up to 30% was observed at 77 K. The degradation is largely attributed to the shear stress and torsional shear strain resulting from the twisting. The superconductor to resistive transition index, n, is also found to behave in an identical manner with increase in the twisting. Finite element analysis (FEA) of the tape in the experimental configuration with twisting moment being applied on to it has been carried out in COMSOL. The torsional strain calculated analytically as per the experimental configuration matches closely with that of FEA results, which shows that the critical current degradation is a function of strain.

Keywords. Coated conductor; critical current; twisting moment; torsional strain.

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1. Introduction

Long-length, commercial-grade, high-temperature, high-amperage second-generation (2G) yttrium barium copper oxide (YBCO)-coated conductors can be fabricated through rolling-assisted-biaxially-textured-substrate (RABiTS) route at low cost. They are extensively used 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 is subjected to twist-induced strain. The strain beyond a certain limit can critically affect the transport property and can also modify the super-current carrying path in the coated conductor. Previous works on the torsional strain dependence of bismuth strontium calcium copper oxide (BSCCO) conductor showed the experimental findings on the degradation of I_c and n values [5]. All practical

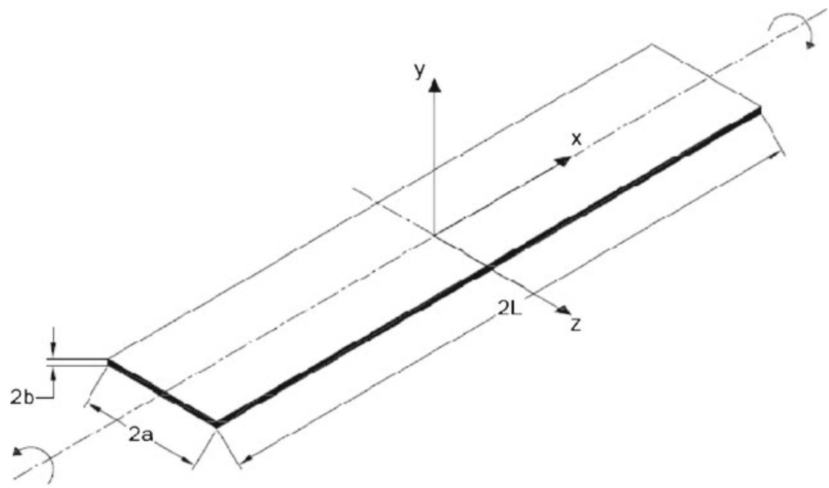

Figure 1. Schematic of the YBCO tape.

HTS-based applications are electrically charged to their respective nominal currents at a certain allowable ramp rate. Often, it is observed that the critical current is a function of the current ramp rate [6]. Faster the ramping of the current, less will be the critical current for a given field, operating temperature and strain state. In the present study, torsional strain dependence of the critical current of the coated conductor is investigated experimentally for different current ramp rates. Again, the magnitude of the stress and its distribution along the length of the conductor are studied analytically as well as by FEA simulation. In this paper, the experimental arrangement is discussed in §2. Results and theoretical analysis are discussed in §3 while FEA analysis is discussed in §4.

2. Experimental arrangement

2G high-temperature YBCO-coated conductor manufactured by American Superconductor Corporation (AMSC) contains YBCO film deposited on the oxide-buffered Ni–W alloy substrate [7]. The schematic of the tape used for the experiment is shown in figure 1 and its properties are given in table 1.

Table 1. Properties of AMSC YBCO tape.

Parameter	Value
YBCO film thickness	0.8 μm
Substrate thickness	75 μm
Overall dimensions ($2L \times 2a \times 2b$)	$300 \times 4 \times 0.2$ mm^3
Young's modulus (E)	133.3 GPa
Poisson's ratio (ν)	0.28

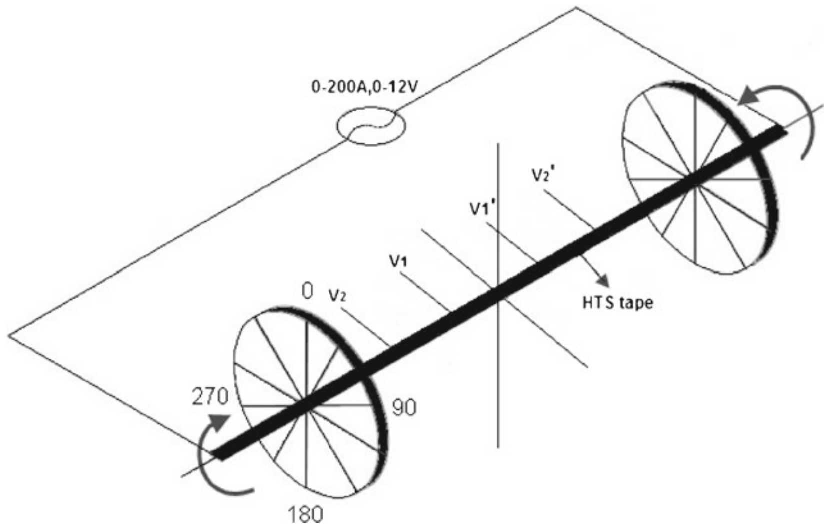

Figure 2. Experimental set-up for I_c measurement under twisting.

The complete experimental set-up is shown in figure 2. YBCO-coated conductor of 300 mm length was clamped tightly to hylam supports which were connected to suitable knob arrangements at both the sides outside the cold bath so as to avoid removing the sample out of the cold bath whenever there was a need to change the twist angle. Thus, the effect of thermal cycling on the tape was avoided. The knobs could be rotated on either direction to provide prefixed twist-induced strain. The sample tape was connected to current leads via flexible copper braids which would also get twisted along with the sample tape. Thus, the stress concentration at the edge of the tape was eliminated using the intermediate flexible copper braid between the sample tape and the current leads. These copper braids were dipped in LN_2 bath to avoid evolution of local hot spots.

The twist angle θ was increased up to 1680° with constant rotational angle interval. Two voltage terminals with sufficient lengths were soldered at the centre of the tape width, 5.0 cm and 10.0 cm away from the middle node so that during twisting of the tape, additional stress should not be developed due to the voltage terminals. These two

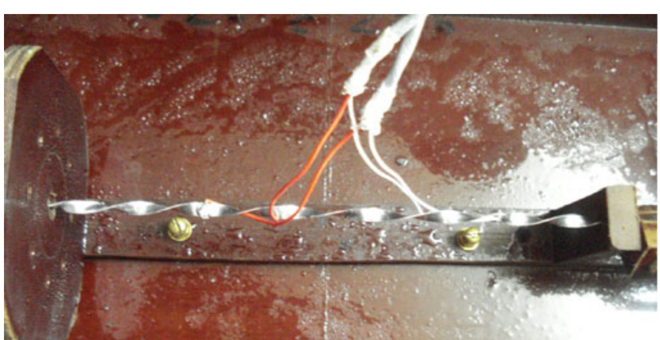

Figure 3. Photograph of YBCO tape at 1530° twist angle.

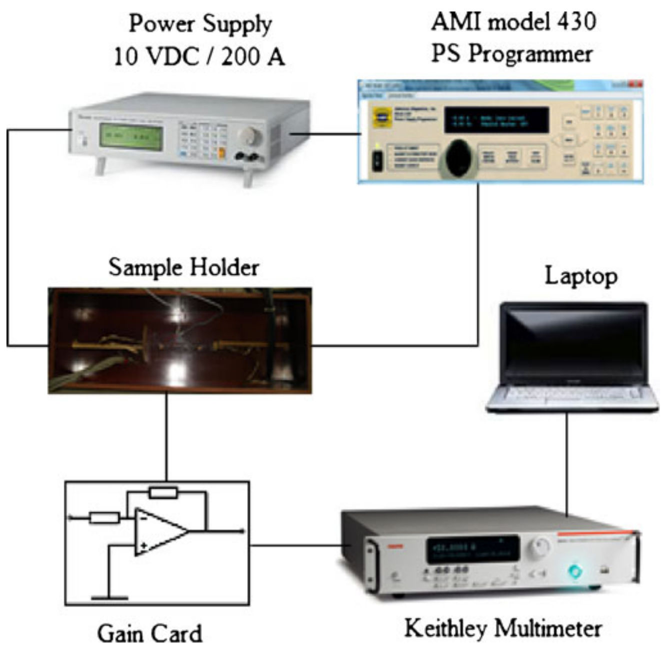

Figure 4. Data acquisition schematic for I_c measurement.

voltage terminals were used for measuring the critical current I_c at each subsection. The experiment was repeated for ramp rates ranging from 1.0 A/s to 5.0 A/s for each twisting interval. The uniform twisting of the tape at a particular experimental angle is shown in figure 3.

A schematic of the data acquisition set-up for this experiment is shown in figure 4. For a particular rotational angle θ, the transport current I was driven by unipolar AMI XFR (0–200 A, 0–12 V) DC power supply. Current I was ramped through AMI programmer (Model 430) up to its maximum amplitude and then ramped down to zero. Voltage limit in the programmer was kept at a value greater than the voltage calculated using $V = L(\mathrm{d}I/\mathrm{d}t) + V_o$, where V_o is the voltage drop across the power lead which was measured to be less than 2 V.

During the ramp-up and ramp-down phases, the data relating to potential differences across the voltage contacts and the transport current were acquired using Keithley Multimeter (Model 2750 Integra Series) and the values were stored in a computer. The sampling frequency of this Keithley Multimeter is 84 ms per data point. The multimeter was connected to LABVIEW installed PC via general purpose interface bus (GPIB). One precision signal conditioning card was used to amplify the voltage signals corresponding to the two voltage contacts to a measurable level. I–V measurement was carried out using the standard four-probe method.

3. Results and theoretical considerations

The typical I–V characteristics are plotted for the current ramp rates ranging from 1.0 A/s to 5.0 A/s for an arbitrarily chosen twist angle of 990°. The typical electric field criterion

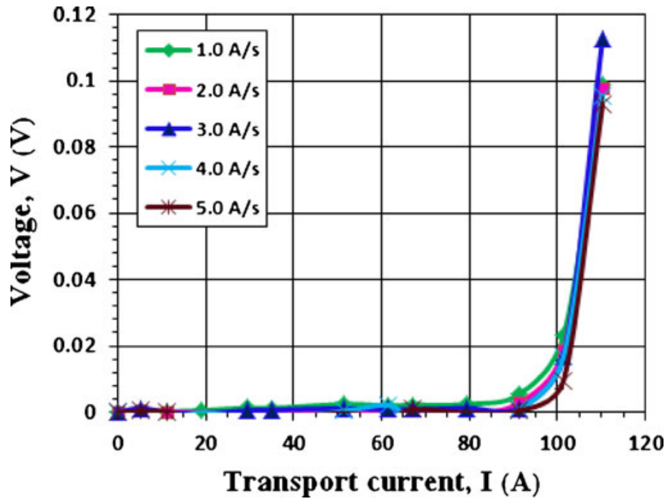

Figure 5. Consolidated I–V characteristic for 990° twist angle for various ramp rates.

of 1 μV/cm for the critical voltage V_c is employed to determine I_c value. The change in ramp rates in transport current does not have a significant effect on the critical current (I_c) value as depicted in the consolidated I–V characteristics as shown in figure 5.

The variation of the normalized critical current as a function of the twist angle per unit length for ramp rates ranging from 1.0 A/s to 5.0 A/s is shown in figure 6 over a range of

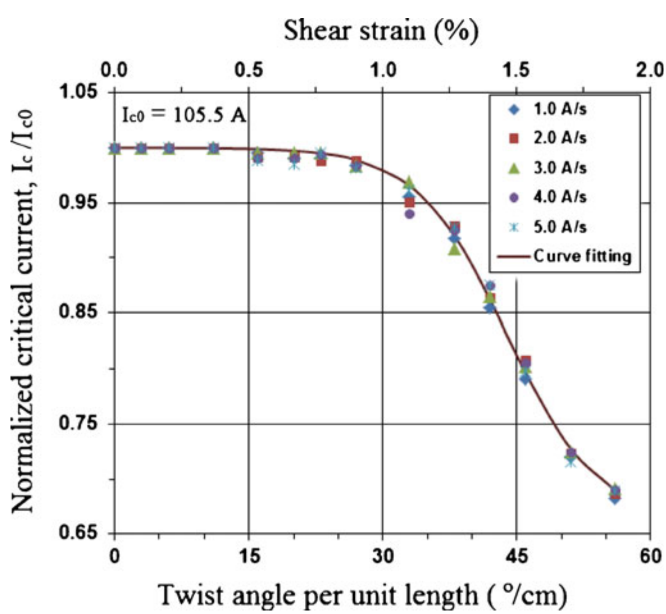

Figure 6. Variation of normalized critical current (I_c/I_{c0}) as a function of twist angle per unit length for different ramp rates.

twist angles ranging from 0°/cm (virgin sample) to 56°/cm (maximally twisted sample). An empirical formula was proposed and established using a curve fit expressed in eq. (1) to account for these experimental observations

$$I_c = I_{c\_min} + \frac{I_{c\_max} - I_{c\_min}}{1 + e^{(\theta - \theta_{mean})/\Delta\theta}}, \tag{1}$$

where θ_{mean} is the twist angle per unit length corresponding to the average normalized critical current value of $0.5(I_{c\_max} + I_{c\_min})$, I_{c_max} is the normalized critical current of the untwisted tape, I_{c_min} is the normalized critical current at the maximum twist angle per unit length, $\Delta\theta$ is the interval of values of twist per unit length.

Figure 6 shows that there is not much change in the I–V characteristic of the coated conductor with the ramp rate for a given torsional strain. It also indicates that there is no substantial degradation in I_c when the twist angle per unit length is increased up to 16°/cm and there is only a very small degradation in I_c when the twist angle per unit length is increased from 16°/cm to 27°/cm. A rapid degradation of I_c/I_{c0} occurred when the twist angle per unit length is increased beyond 27°/cm. After exposing the tape to such high stain, irreversible phenomena were observed in the tape, when it was untwisted. Experiment showed that the degradation in I_c was reversible up to the twist angle per unit length of 25°/cm, beyond which the degradation is irreversible. The experimental data illustrating the irreversibility in the critical current is shown in figure 7.

The n value for the coated conductor was also studied as a function of torsional strain. It was 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

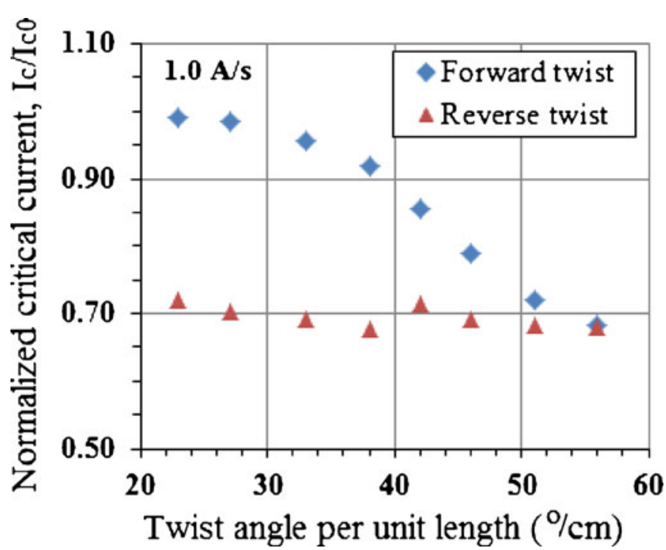

Figure 7. Normalized critical current (I_c/I_{c0}) as a function of twist angle per unit length representing the irreversibility of the twisted tape.

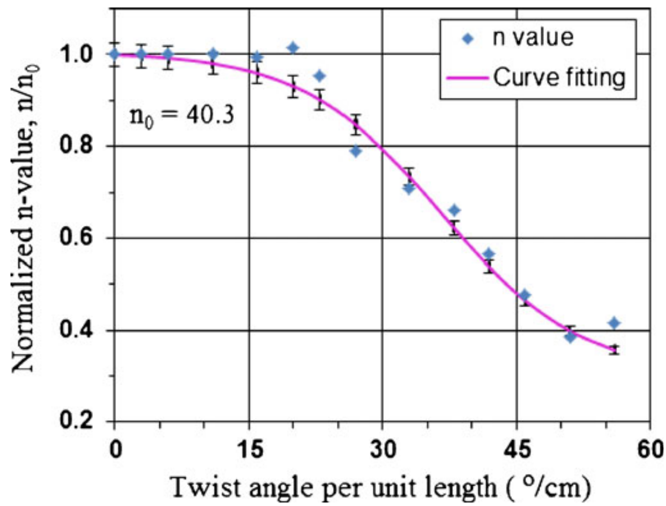

Figure 8. Variation of n/n_0 of YBCO tape as a function of twist angle per unit length.

superconducting state to resistive state of the tape is reflected in the variation of the normalized n/n_0 value as a function of the twist angle per unit length plot as shown in figure 8.

Thus, the n/n_0 values were estimated for all the twist angles per unit length for 1.0 A/s ramp rate using standard procedure with a possible maximum error of about 3% in the estimation of the n/n_0 values. Figure 8 shows the normalized n/n_0 value, which remains almost constant up to a twist angle per unit length of 16°/cm; it decreases as the twist angle per unit length is increased further following a trend similar to that observed for the degradation of I_c. The empirical formula (1) established for the case of critical current may also be used for fitting the experimental data on variation of n/n_0 with twist angle per unit length. Figure 9 shows the SEM image depicting the torsion-induced damage in the

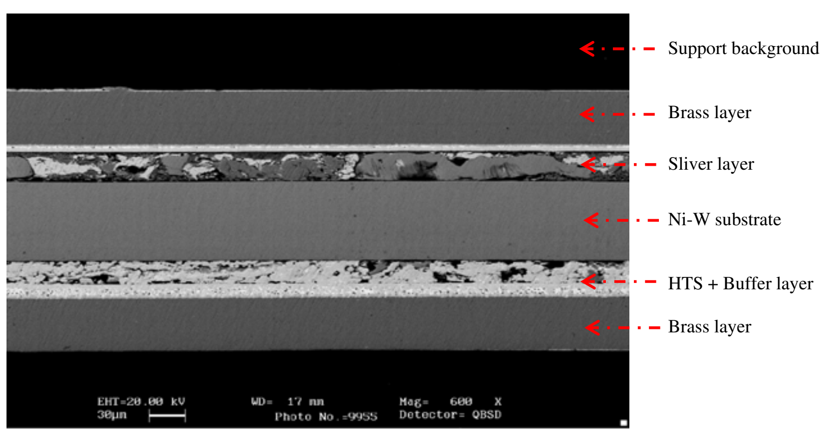

Figure 9. SEM images of the twisted sample showing crack at the interlayer portion of the twisted sample.

microstructure of the tape. The damage results in the degradation in the superconductor film and the current is shared in the resistive alloy material causing a deterioration in the values of I_c and n.

The maximum shear stress τ_{max} developed [8] in the YBCO tape due to the twisting is calculated using the equation

$$\tau_{max} = \frac{M_t}{8ab^2}(3 + 1.83\alpha + 2.66\alpha^2 - 5.41\alpha^3 + 2.73\alpha^4), \quad (2)$$

where $\alpha = b/a$ is the aspect ratio of the tape, M_t is the twisting moment, $2a$ is the width of the tape and $2b$ is the thickness of the tape.

The twisting moment along the axis of the tape is given by

$$M_t = GJ\frac{\theta}{2L}, \quad (3)$$

where

$$G = \frac{E}{2(1+\nu)} \quad (4)$$

is the modulus of rigidity of the composite material and

$$J = ab^3\left(\frac{16}{3} - 3.36\alpha\left(1 - \frac{\alpha^4}{12}\right)\right) \quad (5)$$

is the polar moment of inertia of the tape section.

Similarly, the maximum torsional shear stain ε_t developed at the midpoint of the width side of the cross-section can be evaluated as

$$\varepsilon_t = \frac{b\theta}{L}, \quad (6)$$

where L is the length of the YBCO tape which is subjected to the entire range of twist angles.

The variation of the critical current I_c with increase in torsional shear strain given by eq. (6) is shown in figure 6. It may be noted that initially the shear strain has only a nominal effect on the magnitude of the critical current and, as the shear strain increases beyond a threshold, the critical current is sharply degraded.

4. FEA analysis

The geometrical details of the tape considered for FEA analysis are listed in table 2. The beam element in COMSOL multiphysics assumes all the beam element properties and idealizes the actual tape cross-section into a single line. The thermal stress acting on the composite tape under operational conditions (77 K) has not been taken into account. The load condition assumes only torsion-induced stress. The mid-node of the beam has been set fixed against rotational and translational degrees of freedom. The analytically calculated twisting moments for different twist angles were applied as edge load at both ends of the beam in opposite directions.

It was observed that the maximum torsional shear stress is concentrated near the fixed nodes of the beam. Using eqs (2) and (3), the maximum shear stress and twisting moment

Table 2. Parameters of YBCO tape considered for FEA analysis.

Parameter	Value
Tape length	300 mm
Cross-section area	0.8×10^{-6} m^2
Density of the tape	6000 kg/m^2
Moment of inertia in weak direction	1.06×10^{-14} m^4
Moment of inertia in stiff direction	3.2×10^{-12} m^4
Torsional constant	1.03×10^{-14} m^4
Torsional section modulus	5.33×10^{-11} m^3

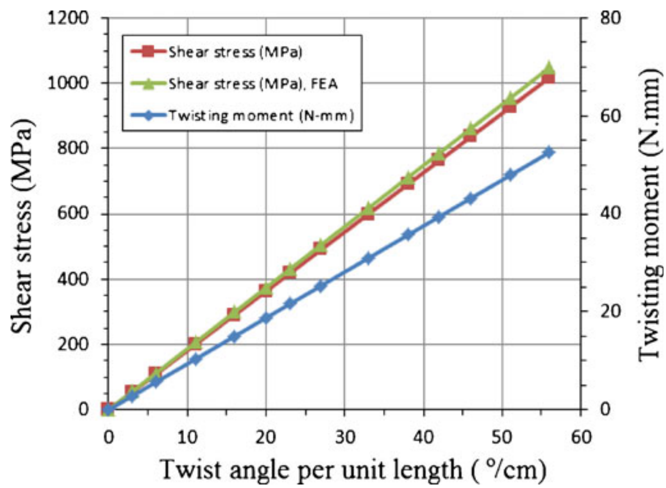

Figure 10. Variation of the shear stress and twisting moment as a function of twist angle per unit length.

for the experimental angles are calculated and shown in figure 10 along with the shear stress obtained using FEA model. The stress obtained by the simulation is in good agreement with the analytical results of the shear stress with an approximate deviation of 3% at higher values of twisting moment which is due to the fact that nonlinear torsional effects are not taken into account in the analytical result.

5. Conclusion

From this experiment, we observed that the degradation of the critical current I_c of the YBCO tape under torsional strain occurred only after the torsional strain exceeded a threshold value. Then it is degraded gradually as the torsional strain increased further and then I_c value fell suddenly indicating a deterioration in the transport property of the YBCO tape. Similarly, n value of the YBCO tape has shown to follow a characteristic similar to that followed by the degradation of the critical current I_c as the twist angle per unit length is increased. It is also observed that the ramp rate does not have any significant effect on the critical current of the composite tape.

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