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Index Terms—BSCCO, HTS, torsion, YBCO.

I. INTRODUCTION

FOR APPLICATION to electrical devices, HTS conductors are requested to have not only high critical current density (J_c), but also good mechanical properties. YBCO and BSCCO 2223 conductors are available in the form of tape with large aspect ratios, typically 10 to 200. In some applications, they are subjected to torsion. This is the case of the twisted-pair cables [1], which are being developed for application to electrical transfer lines in the LHC machine. Prototype twisted-pair cables with twist pitch of 400 mm were characterized at cryogenic temperatures, in background fields of up to 9.6 T, and showed good performance [2], [3].

The effect of torsion on the critical current (I_c) of HTS conductors has been studied and reported by some authors [4]–[6]. In this paper, using an accurate description of the I_c dependence on axial strain, a self-consistent analytical expression of the I_c dependence on twist pitch is elaborated for both YBCO and BSCCO conductors. The expression takes into account the temperature dependence of the strain sensitivity. Measurements performed on tapes at 77 K and in self-field were found to be in good agreement with the analytical formulation.

II. CONDUCTORS GEOMETRY

YBCO coated conductors consist of a high strength metal alloy substrate, onto which is deposited a thin layer of YBCO.

TABLE I
DETAILS OF CONDUCTORS

Symbol	Type-1	Type-2	Type-3
Conductor	BSCCO 2223	YBCO	YBCO
Supplier	Sumitomo	SuperPower	AMSC
width (mm)	4.5	4.1	4.4
thickness (mm)	0.36	0.095	0.44
a_t (mm)	0.083	-	-
a_w (mm)	2.03	-	-

Two metal stabilizer strips can be present on both sides of the conductor. The BSCCO 2223 tape consists of superconducting filaments embedded in a silver alloy matrix. The multifilamentary area can be approximated with a rectangular shape $2a_t$ height and $2a_w$ wide. BSCCO conductors can be reinforced with metal laminations soldered onto both sides of the tape. The main features of the different conductors studied in this paper are reported in Table I.

III. ANALYTICAL EXPRESSION FOR STRAIN DISTRIBUTION INDUCED BY TORSION

Performances of HTS conductors are well known to be sensitive to uni-axial strain [7]–[9]. In order to estimate the effect of torsion on the I_c , the strain state has to be known. Based on a simplified model, the strain distribution in HTS conductors submitted to pure torsion was introduced by [6], [10]. Pure torsion loading requires that no external net force in the longitudinal direction is applied to the tape when twisted. We assume here that torsion in HTS tapes induces only longitudinal uni-axial strain. When a twist pitch T_p is applied to a thin rectangular tape of width w in pure torsion loading, the uni-strain at a distance r from the tape neutral axis is expressed as:

$$\varepsilon(r, T_p) = 2\pi^2 \frac{(r^2 - w^2/12)}{T_p^2}. \quad (1)$$

The strain in the twisted tape is inversely proportional to the square of the twist pitch and it increases with the distance from the neutral axis. The maximum strain occurs at the tape edges. Considering that the thickness of the tape is negligible with respect to the tape width, the strain at tape edge $r = w/2$ (ε_{edge}) is expressed as:

$$\varepsilon_{edge}(T_p) = \frac{\left(\frac{\pi w}{T_p}\right)^2}{3} \quad (2)$$

Manuscript received October 5, 2012; accepted November 12, 2012. Date of publication November 15, 2012; date of current version January 3, 2013. This work was supported by CERN.

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Digital Object Identifier 10.1109/TASC.2012.2228292

TABLE II
PARAMETERS VALUES OF IC FITS

Parameter	Type-1	Type-2	Type-3
I_{cm0} (A)	1205	1518	1282
T_{c1} (K)	105	97	94
m (-)	1.40	1.64	1.45
b_0 (-)	-	2821	3122
d (-)	-	4.3e-4	4.3e-4
e (-)	-	0.201	0.201
ε_{m0} (%)	-	0.23	0.44
f (-)	-	5.1e-5	5.1e-5
ε_{irr} (%)	0.38	1.1	1.1

IV. I_C DEGRADATION DUE TO UNI-AXIAL STRAIN

In self-field, the I_c dependence on strain of YBCO and BSCCO 2223 tapes has a reversible behavior up to a maximum strain value (ε_{irr}). Above ε_{irr} the percolation path of the current is modified by the yielding of the matrix materials, and an irreversible drop of I_c is observed. In the following sections, the irreversible pitch (T_{pi}) is defined as the twist pitch of a tape at which the tensile strain at tape edge reaches the ε_{irr} . The T_{pi} is expressed as:

$$T_{pi} = \pi w \sqrt{\frac{1}{(3\varepsilon_{irr})}}. \quad (3)$$

For twist pitches larger than T_{pi} , the strain in the tape cross section is lower than ε_{irr} .

A. YBCO

The reversible I_c dependence on uni-axial strain in YBCO tapes has been reported [7], [8]. For coated conductors, the ε_{irr} is reported to be in the range 0.5%–1.1% [7], [8], corresponding to irreversible pitch values of respectively 103 mm and 69 mm for 4 mm wide conductors. The ε_{irr} of the tapes has been reported to be temperature independent in the range 20 K–77 K [7]. Experimental data on $I_c(\varepsilon)$ in compressive or tensile strain regime at various temperatures are well described by a power law expression [7], [8]. For a tensile strain above ε_{irr} a sharp decrease has been reported. The I_c dependence on of coated conductors can be expressed as:

$$I_c(T, \varepsilon) = I_{cm}(T) \left[1 - b(T) |\varepsilon - \varepsilon_m(T)|^2 \right] \quad \forall \varepsilon \leq \varepsilon_{irr}$$

$$I_c(T, \varepsilon) = 0 \quad \forall \varepsilon > \varepsilon_{irr}. \quad (4)$$

The parameter $b(T)$ expresses the strain sensitivity of the material, and $\varepsilon_m(T)$ is the strain at which $I_{cm}(T)$ is maximum. The temperature dependence of the parameters b , ε_m and I_{cm} is expressed as:

$$b(T) = b_0 + d \exp(eT) \quad (5)$$

$$\varepsilon_m(T) = fT - \varepsilon_{m0} \quad (6)$$

$$I_{cm}(T) = I_{cm0} (1 - T/T_{c1})^m. \quad (7)$$

The optimized parameters for Type-2 and Type-3 conductors are reported in Table II.

Fig. 1. YBCO and BSCCO I_c dependence on uni-axial strain. Measurements taken from [7]–[9] are compared with expressions (4) and (9).

B. BSCCO 2223

In BSCCO 2223 conductors, the decrease of I_c with strain is linear. The slope of the decrease is temperature dependent [9], being stiffer close to T_c . For Type-1 conductors, ε_{irr} is 0.38% in tension [9], corresponding to a T_{pi} of 132 mm. For a strain beyond ε_{irr} , the irreversible reduction of I_c is sharp. In tension, at 0.05% above ε_{irr} the I_c of the tape is reduced from 0.95 I_{c0} to 0.2 I_{c0} [11]. In compression, an irreversible strain has also been reported [9]. Here we assume that the ε_{irr} in compression and tension has the same value. When the conductor is twisted, the center of the tape ($r = 0$) under compression reaches the ε_{irr} threshold for a pitch value T_{pic} expressed as:

$$T_{pic} = \pi w \sqrt{\frac{1}{(6\varepsilon_{irr})}}. \quad (8)$$

The I_c dependence on strain of BSCCO conductors is expressed as:

$$I_c(T, \varepsilon) = I_{cm}(T) (1 - b(T)\varepsilon) \quad \forall |\varepsilon| \leq \varepsilon_{irr}$$

$$I_c(T, \varepsilon) = 0 \quad \forall |\varepsilon| > \varepsilon_{irr}. \quad (9)$$

The parameter $b(T)$, which relates to the strain sensitivity of the material, has been reported to be 6.0 and 9.7 at temperatures of respectively 65 K and 76 K [9]. The parameter values of the I_c dependence on temperature for Type-1 conductor are reported in Table II.

In Fig. 1, the expressions (4) and (9) are compared with measurements reported in [8], [9]. For both YBCO and BSCCO conductors below ε_{irr} there is a good agreement (within 1%) between the two curves and the measured values. For YBCO conductors, the irreversible reduction of I_c is well described by the parameterization. For BSCCO conductors, the reported I_c is underestimated for strains larger than ε_{irr} .

V. I_C DEPENDENCE ON TWIST PITCH

The longitudinal strain induced in a twisted tape is not uniform, and the I_c is calculated by integrating the critical current density (J_c) over the tape cross section. For twist pitches

smaller than T_{pi} part of the tape is beyond ε_{irr} threshold. The location of the points with respect with neutral axis where $\varepsilon = \varepsilon_{irr}$ will be named irreversible distance (r_{irr}), which is expressed as:

$$r_{irr} = \sqrt{\varepsilon_{irr} \left(\frac{T_p^2}{(2\pi^2)} \right) + w^2/12}. \quad (10)$$

A. YBCO Conductors

In coated conductors, the superconducting layer is about 1% of the tape thickness. The HTS layer is considered to be located at the tape mid-thickness. The strain is assumed to be constant across the HTS thickness. For twist pitches larger than T_{pi} , the I_c dependence on the twist pitch of YBCO tapes is obtained by integrating (4) over the conductor width, and it is given as:

$$I_c(T_p, T) = I_{cm}(T) \left[1 - b(T)\varepsilon_m(T)^2 - \frac{b(T)c^2w^4}{180} \right]. \quad (11)$$

For twist pitches lower than T_{pi} , the integration of (4) leads to the expression:

$$I_c(T_p, T) = \frac{I_{cm}(T)}{w} \sqrt{\frac{4\varepsilon_{irr}}{c} + \frac{w^2}{3}} \times \left\{ 1 - \frac{b(T)}{270} [54\varepsilon_{irr}^2 + 270\varepsilon_m(T)^2 + 30c\varepsilon_m(T)w^2 + c^2w^4 - 6\varepsilon_{irr}(30\varepsilon_m(T) + cw^2)] \right\} \quad (12)$$

with $c = 2(\pi/T_p)^2$. In both expressions (11) and (12) the conductor width plays a major role in the reduction of I_c .

B. BSCCO Conductors

The strain across the thickness of the multi-filamentary area is considered to be uniform since a_w is large compared to a_t . In addition, the multi-filamentary area is considered to lie over the full conductor with $a_w = w/2$. For pitches larger than T_{pi} , the integration over the tape section leads to the expression:

$$I_c(T_p, T) = I_{cm}(T). \quad (13)$$

For twist pitches in the range $T_{pic} \leq T_p \leq T_{pi}$ the I_c dependence on pitch is expressed as:

$$I_c(T_p, T) = \frac{I_{cm}(T)}{w} \sqrt{\frac{\varepsilon_{irr}}{c} + \frac{w^2}{12}} \left(2 - \frac{2b\varepsilon_{irr}}{3} + \frac{bcw^2}{9} \right). \quad (14)$$

For twist pitches lower than T_{pic} the model is no more able to predict the behavior of Type-1 conductors under torsion. An empirical formulation that covers the full range of pitches is proposed:

$$\begin{aligned} I_c(T_p, T) &= I_{cm}(T) & \forall T_p > T_m \\ I_c(T_p, T) &= I_{cm}(T) [1 - h(T_m - T_p)^{2.5}] & \forall T_p \leq T_m \end{aligned} \quad (15)$$

with $T_m = 150$ mm and $h = 130$.

Fig. 2. (top) Schematic view and (bottom) illustration of the set-up used for measuring the I_c dependence on twist pitch. A Type-3 conductor with a length of 300 mm and a twist pitch of 42 mm is shown on the set-up.

Fig. 3. Measurements of I_c dependence on twist pitch of HTS tapes.

VI. EXPERIMENTAL RESULTS

Measurements of the I_c reduction induced by torsion in HTS tapes were carried out at CERN with a purpose built set-up. The HTS samples were clamped in rotating copper chucks 260 mm distant. An artist view of the set-up is presented in Fig. 2. At one end of the tape, all degrees of freedom were blocked, whereas at the other end the rotational and longitudinal translation degrees of freedom were released. The tape was twisted by applying the desired angle of twist at room temperature. Motivation for applying the twist at room temperature is to reproduce the process of cabling [2]. Two voltage taps were soldered on the HTS tape at 240 mm distance. The presence of the voltage taps was not perturbing locally the twist of the samples.

The I_c was measured according to the electric field criterion of $1 \mu\text{V/cm}$. The I_c at 77 K and in self-field of the sample was first measured before loading (I_{c0}). The sample was then twisted applying progressively decreasing twist pitches, and each time the I_c was measured at 77 K. The I_c values obtained after loading were normalized to I_{c0} . The results of the measurements are reported in Fig. 3.

VII. RESULTS AND DISCUSSION

From the measurements reported in Fig. 3, we can derive that the twist pitch corresponding to a 95% I_{c0} retention is 114 mm for Type-1 and 80–90 mm for Type-2 and Type-3 conductors.

Fig. 4. Dependence on twist pitch of the I_c of HTS tapes at 77 K in self-field: measurements are compared to the analytical formulations.

These values correspond to the irreversible twist pitch of the conductors. The reduction of I_c for lower twist pitches is then more pronounced. The twist pitch corresponding to a 70% I_{c0} retention is 60 mm for Type-1, 65 mm for Type-2 and 57 mm for Type-3 conductors.

Application of a uniform twist in a Type-2 conductor is difficult because of the high aspect ratio of the cross section. During twisting, the conductor tends to form a network of bands with large torsion, oriented at 45 degrees from the longitudinal direction of the tapes. To ensure more uniform twist, the coated conductor was twisted together with a 0.2 mm thick copper strip. This is representative of the cabling process in the twisted-pair YBCO cables [1].

For all conductors most of the reduction of I_c occurs at pitches lower than T_{pi} . The major part of the I_c reduction with pitch is arising from the irreversible reduction of I_c with strain.

The analytical expressions (11) to (15) computed using the parameters in Table II are reported in Fig. 4 and compared with the measurements. For all three types of samples the parameterization works well over the full range of pitch values. The analytical formulations, which have been validated with the experiments, can be extrapolated to lower temperatures and different widths of coated conductors. For the tapes studied, the I_c reduction due to twisting is mostly induced by a strain exceeding the ε_{irr} threshold. Since this threshold is quasi-temperature independent, only a small temperature effect on the $I_c(T_p)$ dependence is expected. In addition, the strain sensitivity of BSCCO and YBCO at lower temperatures is weaker leading to a weaker twist dependency of I_c .

VIII. CONCLUSION

For both BSCCO 2223 and YBCO conductors, an analytical formulation of the I_c dependence on torsion has been introduced. Measurements of I_c dependence on the twist pitch have been performed at 77 K and in self-field on different conductors with a purpose built set-up. The I_c was observed to be reduced to 95% of the un-strained value for twist pitches of 114 mm for BSCCO tapes, and 80–90 mm for YBCO tapes. The analytical description has been validated with the measurements performed. The reduction of performance was identified to be caused mainly by irreversible degradation of I_c at the tapes edges. At lower temperatures, a slightly lower sensitivity to twist is expected.

ACKNOWLEDGMENT

The authors thank A. Gharib and J. Hurte for the preparation and instrumentation of the measuring set-up.

REFERENCES

- [1] A. Ballarino, "Alternative design concepts for multi-circuit HTS link systems," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 980–983, 2011.
- [2] A. Ballarino, J. Fleiter, J. Hurte, M. Sitko, and G. Willering, "First tests of twisted-pair HTS 1 kA range cables for use in superconducting links," *Phys. Proc.*, vol. 36, pp. 855–858, 2012.
- [3] Y. Yang, E. Young, W. Bailey, C. Beduz, and A. Ballarino, "First electrical characterization of prototype 600 A HTS twisted-pair cables at different temperatures," *Phys. Proc.*, vol. 36, pp. 1337–1342, 2012.
- [4] H. S. Shin and K. Katagiri, "Critical current degradation behaviour in Bi-2223 superconducting tapes under bending and torsion strains," *Supercond. Sci. Technol.*, vol. 16, pp. 1012–1018, 2003.
- [5] H. S. Shin, J. R. C. Dizon, T. H. Kim, D. W. Ha, and S. S. Oh, "Critical current degradation behavior in YBCO coated conductors under torsional strain," *IEEE Trans. Appl. Supercond.*, vol. 17, pp. 3274–3277, 2007.
- [6] M. Takayasu, L. Chiesa, L. Bromberg, and J. V. Minervini, "HTS twisted stacked-tape cable conductor," *Supercond. Sci. Technol.*, vol. 25, p. 014011, 2012.
- [7] D. C. van der Laan and J. W. Ekin, "Large intrinsic effect of axial strain on the critical current of high temperature superconductors for electric power applications," *Appl. Phys. Lett.*, vol. 90, p. 052506, 2007.
- [8] M. Sugano, K. Shikimachi, N. Hirano, and S. Nagaya, "The reversible strain effect on critical current over a wide range of temperatures and magnetic fields for YBCO coated conductors," *Supercond. Sci. Technol.*, vol. 23, p. 085013, 2010.
- [9] D. C. van der Laan, J. F. Douglas, C. C. Clickner, T. C. Stauffer, L. F. Goodrich, and H. J. N. van Eck, "Evidence that the reversible strain effect on critical current density and flux pinning in Bi₂Sr₂Ca₂Cu₃O_x tapes is caused entirely by the pressure dependence of the critical temperature," *Supercond. Sci. Technol.*, vol. 24, p. 032001, 2011.
- [10] S. Timoshenko, *Strength of Materials*, 3rd ed, vol. 2. New York: Van Nostrand, 1955, p. 288.
- [11] N. Ayai *et al.*, "Electrical and mechanical properties of DI-BSCCO type HT reinforced with metallic sheaths," *IEEE Trans. Appl. Supercond.*, vol. 19, pp. 3014–3017, 2009.