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Experimental study on the impact of double bending at room temperature on the performance of YBCO coated conductors

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Abstract— **The performance of High Temperature Superconducting (HTS) tapes is strongly affected by the mechanical loadings they experience during manufacturing, cooldown and operation. Therefore, the development of HTS-based applications requires thorough investigations on the impact of these loadings on the critical current.**

In this work, a measurement procedure is applied to determine the critical current of a (Re)BCO tape at 77 K, after double bending at room temperature around a cylindrical mandrel. In this procedure, the tape is cooled down to cryogenic temperature, and the critical current is first measured on the straight sample. After warming the tape up to room temperature, a double bending around a cylindrical mandrel is applied in two opposite directions and the critical current is measured at the following cooldown. This analysis is repeated for different mandrel diameters in order to identify to study the impact of the curvature radius on the performance degradation. The application of one single bending at room temperature is compared to the results of the double bending procedure. The influence on the performance degradation of applying a known force to the tape during the double bending at room temperature is also experimentally analyzed.

Index Terms—**HTS tapes, Double bending, Critical current, Performance degradation, Mechanical loading.**

I. INTRODUCTION

The High Temperature Superconducting (HTS) tapes have gained increasing interest in the recent years for application in superconducting magnets [1] – [5] and power applications for the electric grid [6] – [8]. The tape production process involves several operations, such as spooling, coiling and cabling, which can determine a bending of the conductor. Since the critical current is one of the most important technical features of the conductor, determining the impact of bending on this parameter is very useful. The technical relevance of this aspect is demonstrated by the inclusion of the retained critical current after double bending in the specifications of several commercial copper oxide superconductors [9–11]. Various laboratories have developed experimental methods for studying the dependence of the critical current on tensile strain, bending and torsion of copper oxide superconductors, including BSCCO [12–15] and REBCO [16–20]. As for the BSCCO, an international round robin test was organized [21], which led to the approval of a technical standard of the International Electrotechnical Committee (IEC) related to the measurement of the retained critical current of BSCCO tapes after double bending at room temperature [22]. Such a standard has not yet been approved for the measurement of the retained critical current after double bending of REBCO tapes.

In this work, the IEC standard developed for the BSCCO conductors was adapted to the REBCO tapes, in order to analyze the impact of bending on the electrical characteristics of a plated REBCO tape developed by THEVA Dünnschichttechnik GmbH (hereafter referred to as THEVA). The validity of the experimental procedure adopted was verified by performing the measurements both at THEVA and at the University of Bologna. The bending around the fixed diameter mandrel at room temperature was performed either with or without applying a constant, controlled axial force to both ends of the tape. The impact on the tape electrical performance of applying either a single or a double bending at room temperature was studied by using several samples cut from the same tape length.

II. EXPERIMENTAL METHOD FOR THE RETAINED CRITICAL CURRENT MEASUREMENT

The tape samples used in this work are cut from a length of the TPL4121 model tape manufactured by THEVA, whose superconducting layer is composed of $GdBa_2Cu_3O_7$ (GdBCO). This 12 mm wide tape is plated with copper and silver layers; Fig. 1 shows the details of the tape cross-section. The average critical current of the virgin tape (at 77 K and in self-field) is equal to 420 A, with fluctuations of ±25% along the tape length. The experimental setups used at the THEVA laboratories and at the University of Bologna are described in the next section.

A. Measurement setup for the critical current tests

In order to measure the critical current of a tape sample, a segment of tape with a length between 30 cm and 32 cm is mounted on a rigid straight bar.

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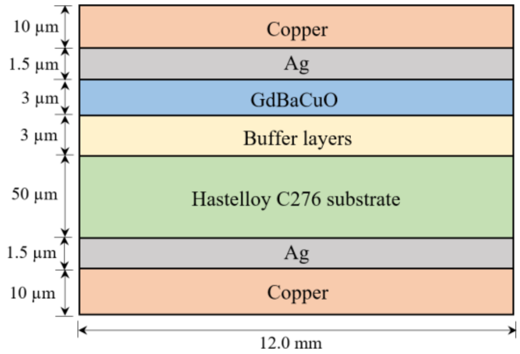

Fig. 1. Geometry of the cross-section of the THEVA TPL4121 tape, not to scale (Courtesy of THEVA).

The holder used at the University of Bologna is entirely composed of G10, while a stainless-steel bar is adopted at THEVA. The tape is pressed onto the holder by means of a couple of copper bars screwed at the holder ends, which are in turn connected to the power supply.

At THEVA, a DC power supply (Agilent 6680A) was used, with a three-phase input and a maximum output current and voltage of 875 A and 3 V, respectively. The cable from the power supply to the sample was connected to a shunt resistor of known value (60 µΩ).

At the University of Bologna, a Keysight 6680A-J04 was used as the DC power supply and the current is measured through a coaxial shunt resistor (with a 1 mΩ resistance).

In both laboratories, the transport current in the tape is derived from the voltage drop across the shunt resistor measured with a Keithley 2700 multimeter. For the measurement of the electric field developed along the superconductor, two voltage taps are clumped onto the tape surface, thus avoiding soldering, as shown in Fig. 2. The voltage drop was measured by a Keysight 34420A nanovoltmeter. The experimental setup and the sketch of the measurement circuit adopted at THEVA are shown in Fig. 3.

The distance between voltage taps is fixed to 8 cm at the University of Bologna, while it is varied between 16.8 cm and 20.7 cm in the tests performed at THEVA.

The tape electrical characteristics is measured in self-field at 77 K in a liquid nitrogen bath. The critical current of the tape is computed from the raw data with the critical electric field criterion of 1 µV/cm (E_c). The n-value of the power law is retrieved by fitting the experimental data with the power law [23], in the range of electric field values from 0.5 to 5 µV/cm.

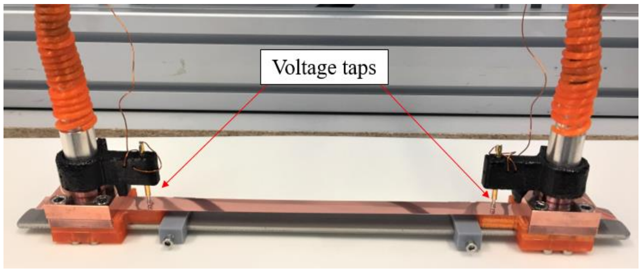

Fig. 2. Sample HTS GdBCO THEVA tape mounted on the straight holder and connected to the power supply, used at THEVA.

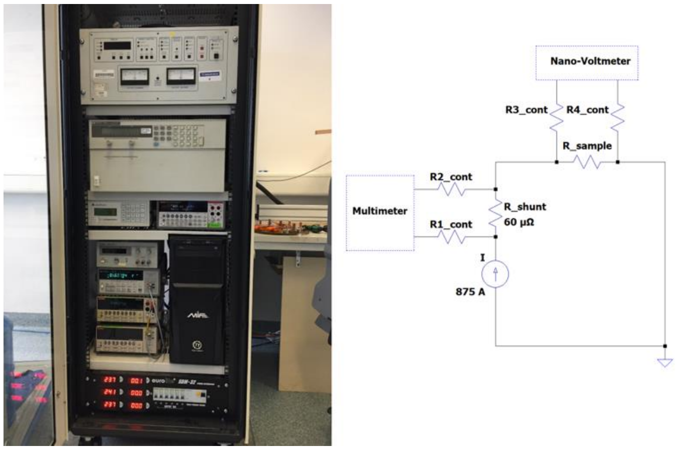

Fig. 3. Experimental setup used at THEVA for the critical current measurement. a) View and b) sketch of the measurement circuit.

B. *Procedure for the bending of the tape at room temperature*

The initial value of I_c measured on the straight virgin sample at 77 K is taken as the reference value. After this measurement, the sample is warmed up to room temperature and disconnected from the holder. Then, the bending procedure is applied at room temperature. Three types of bending procedure were applied:

a) double bending of the tape without axial force application (performed both at UNIBO and at THEVA)

b) single bending with a controlled applied force of 10 N on both tape sides, performed at THEVA

c) double bending with a controlled applied force of 10 N on both tape sides, performed at THEVA.

In procedure a), a portion of the tape is fixed to a cylindrical mandrel of known diameter using a Kapton tape. The tape is gradually bent around the mandrel, applying the bending to the entire portion of tape included between the two voltage taps (see Fig. 4a). Subsequently, the sample is gently released from all constraints. The procedure is then repeated by turning the tape on its opposite face and bending the same tape portion on the mandrel.

In procedure b), a portion of the tape is bent around the mandrel, under a simultaneous application of a 10 N force on both ends of the tape. The force is applied by means of two dynamometers (see the sketch in Fig. 4b). During the single bending,

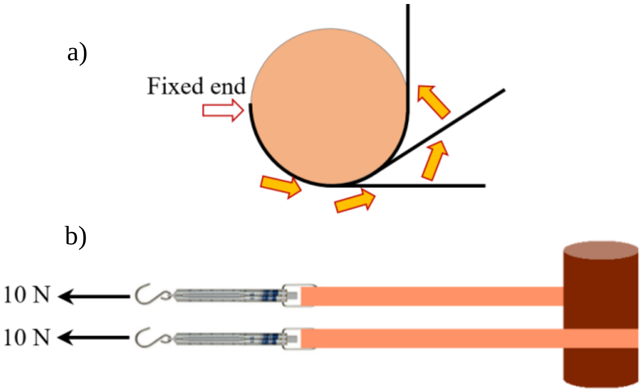

Fig. 4. Bending procedure performed a) without any tensile force application and b) with a constant and controlled applied force of 10 N.

the side of the tape with copper and metal substrate (bottom side in Fig. 1) is kept in contact with the mandrel; therefore, the HTS layer in the middle tape portion is subjected to a tensile strain.

In procedure c), the same bending of procedure b) is repeated on the other side of the tape, to study a double bending under the application of the same controlled force of 10 N.

In all cases, after the bending procedure at room temperature, the tape is straightened, pressed again onto the sample holder, and cooled down in liquid nitrogen to measure its retained critical current and *n-value*.

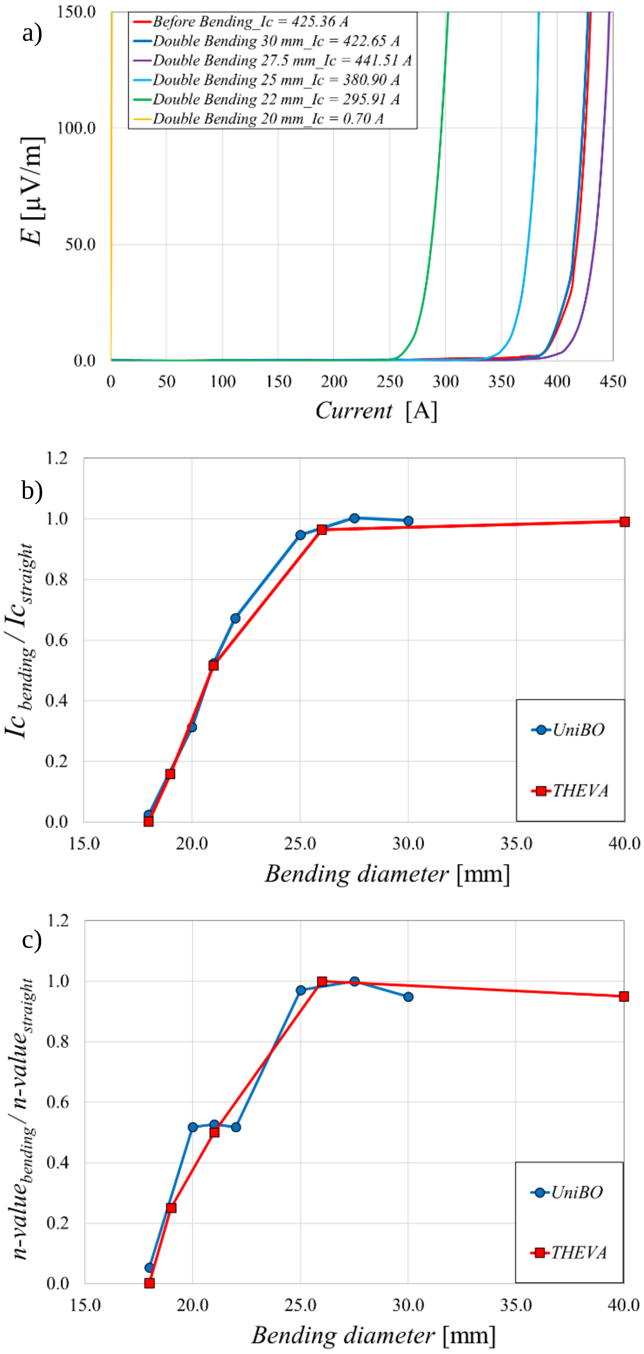

Fig. 5. (a) Electric field profiles and ratios of the (b) I_c and (c) *n-value* measured after the double bending procedure with different diameters, compared to the values measured before bending the THEVA TPL4100 tape samples.

III. RESULTS AND DISCUSSION

A. *Double bending procedure without applied force*

The tape response to the double bending is assessed by repeating the procedure with mandrels of decreasing diameter, replacing the tape sample with a virgin tape as soon as a degradation of its electrical properties is found.

Fig. 5a shows the tape electrical characteristics after the double bending without applied force on mandrels of different diameters. Since the critical current is different for the various samples tested, the figure reports the electrical characteristics of the virgin sample characterized by the critical current value closest to the average of the set of samples. Figs. 5b and 5c show respectively the critical currents and *n-values* measured on the THEVA TPL4121 tape samples after the double bending at room temperature. The results are reported as a ratio with respect to the reference values obtained on the straight sample before bending. This normalization allows one to compare the results obtained on samples taken from sections with different electrical properties.

It can be noticed that the tape critical current progressively decreases starting from the critical diameter of 25 mm and drops to zero after bending around a 17.5 mm diameter mandrel. The tape *n-value* also decreases with decreasing the mandrel diameter, with a trend which resembles that of the critical current. Its degradation is not as regular as that of the critical current; this may be due to the fact that its value is affected by a greater uncertainty due the best fitting procedure. Finally, Fig. 3 shows the very good agreement between the measurements carried out at the University of Bologna and at the THEVA laboratories on samples taken from the same lot; this confirms the validity of the procedure and the accuracy of the measurements performed with different experimental setups.

B. *Single versus double bending procedure under controlled applied force*

The impact of applying a single or a double bending performed under the 10 N applied force (procedures b) and c) described in Section II) is analyzed here. The results, shown in Fig. 6, were obtained at the THEVA laboratories; for these measurements, each sample was subjected to repeated bending over mandrels of decreasing diameter, regardless of the possible critical current reduction.

It is worth noting that the tape samples behave differently from each other, revealing that the degradation of their electrical properties can be more or less pronounced depending on the sample characteristics. The curves of the critical current values vs mandrel diameter after single or double bending appear similar (Figs. 6a, 6b). In both cases, the tapes undergo no detectable degradation for diameters above 26 mm, with the exception of one sample subjected to double bending. At the diameter of 21 mm, the ratio between the critical current measured before and after the double bending is included between 0.99 and 0.84, while a wider range, down to 0.7, is found in the case of single bending. Reducing the mandrel diameter, the samples are completely degraded for diameters of 17 and 18 mm.

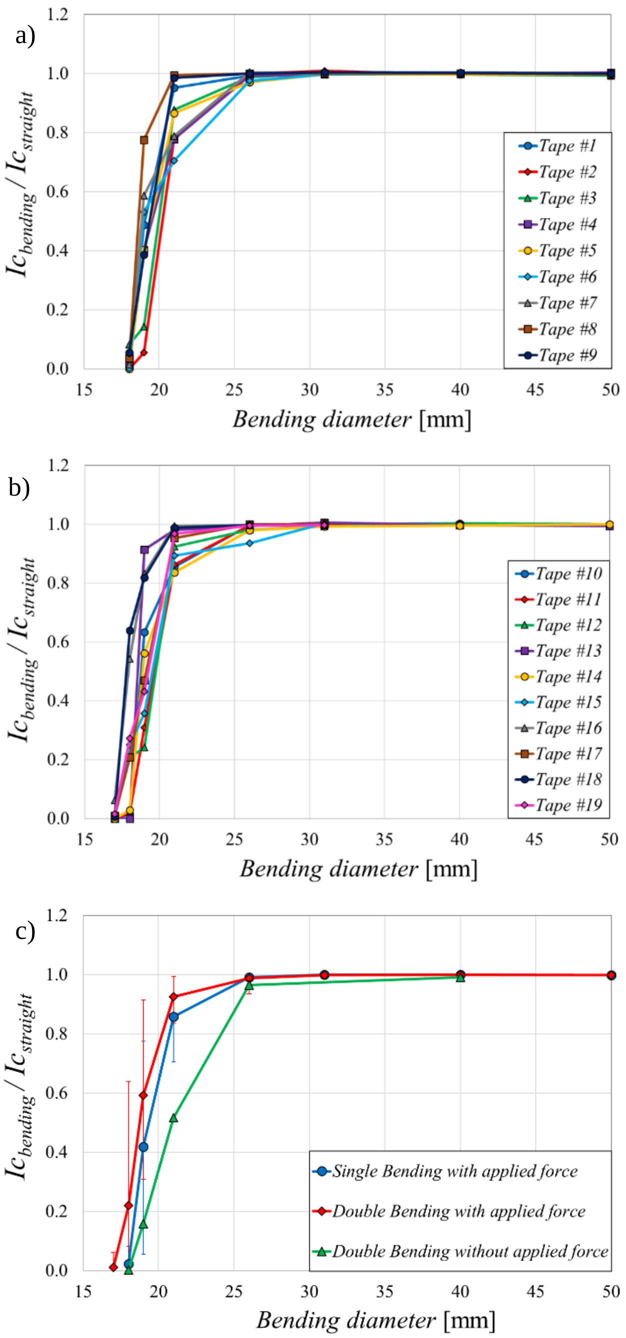

Fig. 6. I_c normalized with respect to the reference value measured on the virgin samples of the THEVA TPL4100 tape, measured (a) after the double bending procedure and (b) after the single bending procedure, both applied with a 10 N applied force. (c) Mean curves obtained with different samples at THEVA, for the three different bending procedures.

This gradual reduction of the tape electrical properties significantly differs from the abrupt drop of performance found with the same procedure on a different 4 mm wide REBCO tape manufactured by SUNAM (see [18]). In the case reported in [18], the tape critical current drops from its reference value to zero with decreasing the bending diameter over a very short range, from 15 mm to 12.5 mm.

Fig. 6c reports the average of the curves measured with the 9 samples subjected to single bending with an applied force, the average of the curves of the 10 samples subjected to double bending with an applied force, and the curve obtained at THEVA after the double bending with no applied force of a single sample. The error bars reported in the plot correspond to the difference between the highest and the lowest value of the ratio $Ic_{bending}/Ic_{straight}$ measured on the different samples in the two sets of tests. The curves obtained through the averaging are very close to each other. The degradation found with single bending seems slightly more severe than that found with the double bending. However, considering the spread of values obtained with different samples, the difference between the two curves is not meaningful. This result implies that the single bending under the applied 10 N force is sufficient to degrade the tape performance; the second bending in opposite direction does not further affect the critical current.

A somewhat more severe degradation was found for the sample subjected to a double bending without applied force with respect to both curves obtained with the applied force. However, a direct comparison between the measurements with and without force is not possible. In the tests performed without the applied force, the whole portion of tape included between the voltage taps is bent around the mandrel. In the tests performed by applying a controlled force, this type of winding is not feasible, so that only a short portion of the tape is bent around the mandrel. Bending longer tape portions might increase the damage of the tape and could explain the more severe degradation found in the measurements performed after bending without applied force.

IV. CONCLUSION

This paper reports an experimental analysis on the impact of bending loads on the electrical characteristics of a plated 12 mm wide GdBCO tape produced by THEVA. The measurement procedure developed allows one obtaining reliable results, with a very good agreement between the data obtained in the two laboratories involved in this study. Based on a comparative approach, three bending procedures have been tested, applying a double bending with no applied force and both single and double bending with a 10 N applied force. In all cases, both the critical current and the *n-value* of the tape degrade gradually with decreasing the bending diameter. The irreversible performance degradation starts for bending diameters below 25 mm and becomes complete for bending diameters below 18 mm.

Different samples of the same tape exhibit a rather similar behavior, with a spread of results which seems compatible with the inherently not repeatable nature of a degradation process.

No significant difference has been found between applying a single or a double bending procedure, both with a controlled applied force, at the same bending diameter. This result indicates that the first bending performed with the superconducting layer in tensile state is sufficient to determine the degradation of the tape electrical characteristics. Although a more severe degradation is found in the samples subjected to double bending with no applied force compared to the procedures with an applied force, a direct comparison is not possible. In fact, different lengths of the tape are involved in the two bending procedures.

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