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Development of Ag-Sheathed Bi(2223) Tapes with Improved Microstructure and Homogeneity

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The development of the fabrication process of Ag-sheathed Bi(2223) tapes has been carried out in order to improve their transport and mechanical properties, as required by the power applications which are so far under study. Critical current density values of 28 kA/cm^2 at 77 K have been achieved on long multifilamentary Bi(2223) tapes, with a fabrication process that has been successfully employed in the fabrication of samples longer than 50 m. The microstructure and homogeneity of Ag-sheathed multifilamentary Bi(2223) tapes has been markedly improved by employing an alternative deformation technique. In a substantial part of the fabrication process, swaging, drawing, and rolling have been replaced by deformation with an active turks-head machine, which allows the deformation of rectangular shaped wires. At present, critical current densities in excess of 25 kA/cm^2 at 77 K have been achieved on long samples prepared with this technique. Moreover, innovative filament configurations have been employed for the fabrication of square-shaped Bi(2223) wires with reduced anisotropy and with critical current densities exceeding 20 kA/cm^2 at 77 K.

KEY WORDS: Applications of high-T_c superconductivity; power-in-tube process; Bi-based superconductors; critical current density.

1. INTRODUCTION

The standard powder-in-tube technique has been successfully employed for the fabrication of Ag-sheathed Bi(2223) tapes, with critical current densities well above 20 kA/cm^2 at the liquid nitrogen temperature and over long lengths (>10 m) [1–3]. However, practical applications of these conductors in industrial devices require a further improvement of their transport properties. One of the delicate factors affecting the critical current density of Bi(2223) tapes is the nonuniform current flow and distribution inside the superconducting core, observed both in mono- and multifilamentary samples [4–6]. The origin for such behavior was partly found in the deformation process employed for the fabrication of multifilamentary tapes: It is usually observed that filaments near the tape center are more compressed by the cold rolling process than those near the outer silver sheath. In order to solve such a problem, an alternative deformation technique was therefore introduced in the PIT method, with the aim of further improving the filament homogeneity in multi-core tapes. Within this new procedure, the standard cold rolling process has been replaced with an innovative four-roll deformation, which allows a simultaneous reduction of thickness and width of rectangular shaped wires. The improvement of filament homogeneity has been analyzed by performing preliminary measurements of the local critical current distribution with the strip-cutting technique [7]. Finally, the active turks-head machine was also employed for preparing rectangular- and square-shaped Bi(2223) wires with substantially reduced anisotropy of the transport properties.

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2. EXPERIMENTAL

The superconducting tapes we investigated in this work were multifilamentary Ag-sheathed Bi

(2223) tapes prepared by the powder-in-tube process [8]. Standard tapes were prepared with calcined powders of nominal composition $Bi_{1.80}Pb_{0.40}Sr_{2.00}$-$Ca_{2.20}Cu_{3.00}O_x$ packed inside pure 12.7 × 8.0 mm Ag tubes of about 120 mm in length, that were afterwards deformed by swaging and drawing to hexagonal wires of 0.71 mm of apothem. The multifilamentary configuration was prepared by stacking 37 pieces of hexagonal wires inside a 10.0 × 9.0 mm Ag tube, that was deformed again by swaging, drawing, and rolling to a 10–15 m long tape of about 200–250 μm in thickness and 3–3.5 mm in width. The final reaction of the tape was carried out inside tubular furnaces equipped with furnace liners in order to assure the required stringent homogeneity of the temperature. The typical high temperature process consisted of two heat treatments in air at temperatures between 835 and 840°C, with an additional rolling compaction needed to further enhance the oxide density.

Multifilamentary tapes were also alternatively prepared by means of two-axial rolling deformation. The prototype active turks-head machine that was employed is schematically represented in Fig. 1. The four independent, motor-driven rolls are placed in a special configuration that allows simultaneous deformation of a wire (of up to 15 mm × 15 mm in size) in two perpendicular directions. This process has the clear advantage of allowing the deformation of rectangular shaped wires of, in principle, indefinite length. New procedures for the preparation of multifilamentary Bi(2223) tapes have therefore been introduced. Calcined powders are filled inside round silver tubes of 8 mm inner diameter and of wall thickness between 1 and 2 mm. These tubes are first reduced as usual by swaging and drawing down to wires of about 1.5 mm in diameter, and then they are deformed by the active turks-head machine into square shaped wires of about 1 × 1 mm. Several pieces of these wires are stacked into square-shaped tubes of various sizes (of up to 12 × 12 mm in size) with wall thickness of about 1 mm. After a short treatment at 600–650°C, the tubes were immediately deformed by the active turks-head machine, the thickness and width of the tubes being reduced at the same time in steps of about 50 μm per pass. When a size of about 3 mm × 3 mm was reached, the tape width was then kept fixed, while the thickness was further reduced to 0.2–0.3 mm, in steps of 30–50 μm per pass. The resulting tape was then reacted with the same process employed for the standard ones.

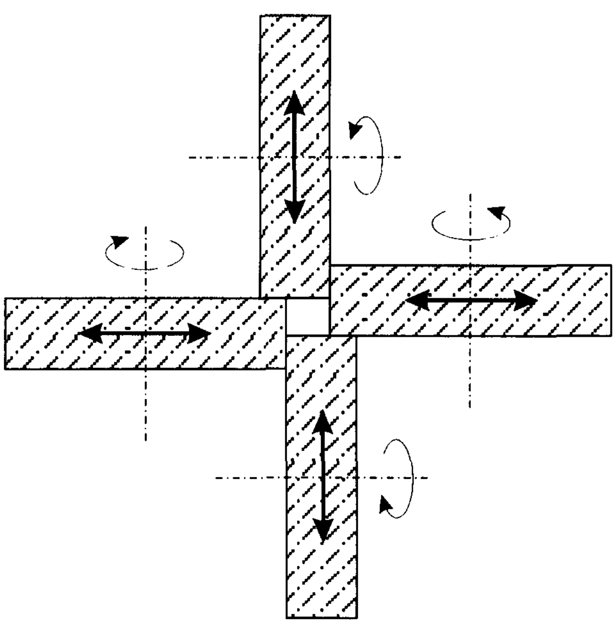

Fig. 1. Schematic representation of the active turks-head machine. The four independent rolls can be adjusted for simultaneous biaxial deformation of rectangular wires.

The transport critical current densities were measured at 77 K by the standard four-probe method, the usual criterion of 1 μV/cm being introduced for the determination of j_c from the I–V curves. The critical current in the applied magnetic field was measured on 5 cm long tapes, and their homogeneity was verified within 15 equally spaced voltage contacts. The magnetic field was applied with variable orientation with respect to the tape direction.

3. RESULTS

The modification of the PIT process we studied in this work was focused on the improvement of the filament homogeneity in multicore tapes. The microstructure of the tapes we fabricated was analyzed first by SEM. Typical transverse cross sections of a standard tape with 37 filaments as well as of a four-roll deformed tape with 45 filaments are shown in Fig. 2. It is evident that in the latter the filaments near the tape center as well as those at the lateral sides underwent similar deformation stresses, due to the additional pressure applied on the tape by the horizontal rolls. In the standard PIT processed tapes, instead, the filaments located at the tape center turned out to be much more compressed than those near the outer silver sheath layer. Moreover, by active turks-head deformation much higher superconducting fill factors can be reached in Bi(2223) tapes

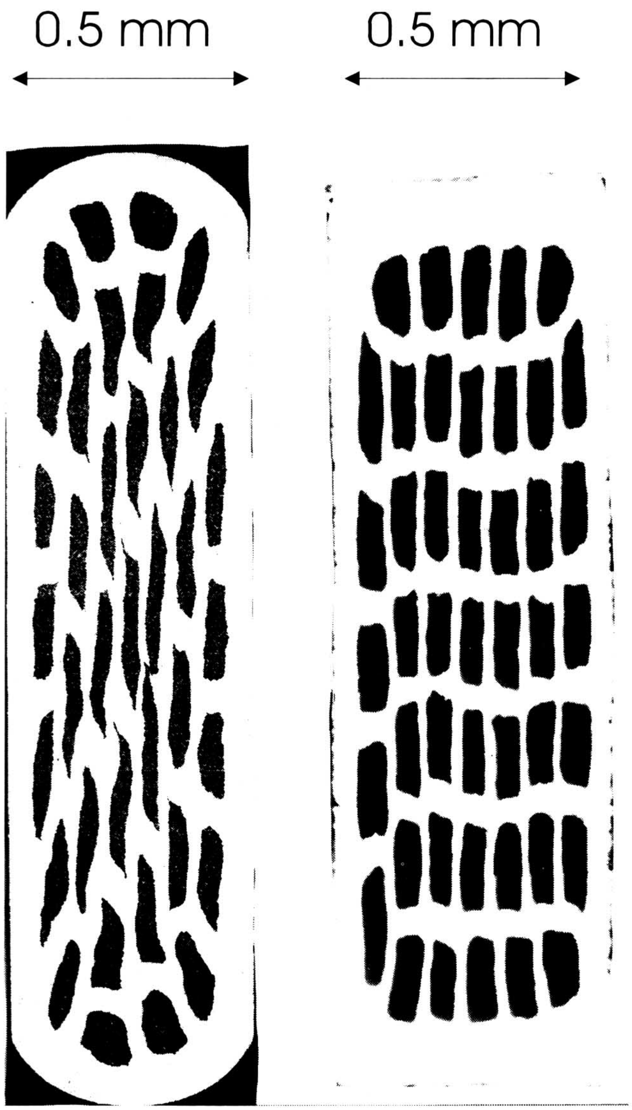

Fig. 2. Transverse cross-sections of a standard PIT processed tape (upper) and of a four-rolled tape (lower). The tape thickness is 0.5 mm in both cases.

Table I. Critical Current Density Values of Four-Rolled Tapes with Number of Filaments up to 100

Number of filaments	Superconductor fraction (%)	Tape size (mm^2)	Heat treatment process at 837°C	j_c (kA/cm^2)
18	20	3 × 0.20	50 h + 100 h	25
34	25	3 × 0.20	40 h + 100 h	26
34	25	3 × 0.30	50 h + 100 h	26
45	35	3 × 0.20	40 h + 100 h	23
45	35	3 × 0.30	50 h + 100 h	23
45	35	3 × 0.40	50 h + 100 h	21
100	20	3 × 0.20	35 h + 80 h	15

with respect to those of the standard PIT processed tapes, without any additional formation of cracks over long lengths (>10 m). Tapes with as high as 45% of superconducting fraction have been reproducibly prepared with such a process.

An optimal tape cross-section configuration was still achieved by four-rolling even with a large number of filaments. In Fig. 3, a typical transverse cross-section of a 100-filament tape of about 250 μm in thickness is presented. The 100 filaments have been stacked with a 10×10 configuration, and each of them showed an average thickness of about 10 μm.

The critical current density values we achieved at present on four-roll deformed tapes are summarized in Table I for different numbers of filaments and overall tape dimension. Critical current density values above 20 kA/cm^2 have been reproducibly achieved on tapes with up to 45 filaments, for a tape thickness up to 0.4 mm. Only the 100-filament tapes presented lower values, probably due to the appearance of sausaging as the filament thickness reaches 10 μm or less. Further optimization of the deformation process is therefore required for four-rolled tapes with a high number of filaments. Nevertheless, engineering critical current densities of 8 kA/cm^2 have been reproducibly achieved on the four-rolled tapes.

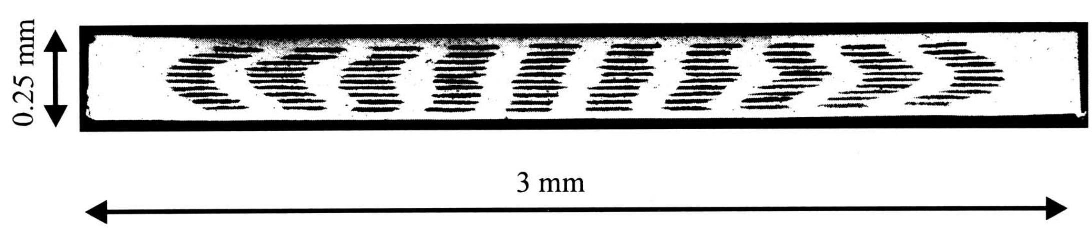

Fig. 3. Typical transverse cross section of a four-rolled 100-filament tape of 250 μm in thickness.

In spite of the improved filament configuration, however, the four-roll tapes reached slightly lower self-field critical current densities than the standard PIT processed tapes. We impute such behavior mainly to a difference in the degree of texture of the Bi(2223) grains. Indeed, by employing a technique derived from the railway-switch model for the calculation of the mean misalignment angle of the grains, already presented in [9], it has been possible to determine the influence of the preparation process and of the number of filaments on the degree of texture of the Bi(2223) phase. The results are shown in Fig. 4.

From this graph it is clear that the degree of texture in standard PIT processed tapes decreases gradually for increasing number of filaments, the mean misalignment angle of 55- and 61-filament tapes being of the order of 5°, that is, 2–3° lower than in monofilamentary tapes. As all the multifilamentary tapes we have studied have similar dimension (~3 × 0.2 mm) and fill factor, the number of filaments should in turn be related to the filament thickness itself.

While the results achieved on the standard deformed tapes would lead to hypothesize a direct correlation between filament thickness and misalignment angle, this does not seem to be applicable to the results concerning the four-roll deformed tapes. In fact, while the 100-filament tape shows an average filament thickness of 10 μm, clearly lower than for all the other tapes, the misalignment angle of the

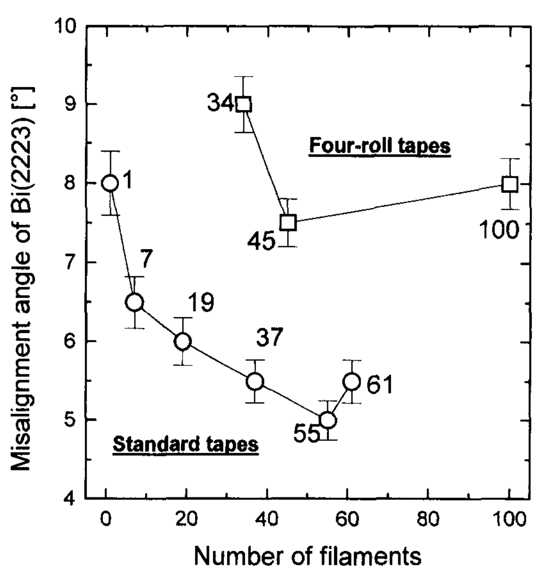

Fig. 4. Transport misalignment angle of the Bi(2223) grains as a function of the number of filaments in standard and four-rolled tapes.

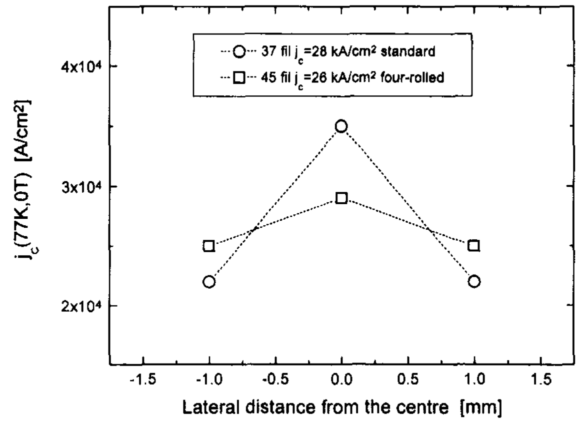

Fig. 5. Lateral distribution of the critical current density in standard and four-rolled tapes.

Bi(2223) grains is still comparable to that of the much thicker single-core tapes. It is therefore clear that the degree of texture of the Bi(2223) grains is not only influenced by the filament thickness and in the *in situ* phase formation and growth, but it is, in general, more affected by the whole deformation process employed for the tape fabrication.

The improved homogeneity of the current flow in four-rolled tapes was further verified by estimating the lateral critical current distribution. The lateral j_c distribution in multifilamentary tapes has been preliminary investigated by cutting 3 mm wide, 250 μm thick tapes into three longitudinal slices and measuring their transport properties independently. The experiment has been performed both on standard and four-rolled deformed tapes with 37 and 45 filaments, respectively.

The critical current densities of the different slides are reported in Fig. 5. For the standard tape with average j_c at 77 K of 28 kA/cm^2, the critical current density was clearly higher in the central slice (35 kA/cm^2) than at the sides (22 kA/cm^2), which is an opposite behavior compared to what is usually found in monofilamentary tapes [7]. The amplitude of the local j_c variation is, however, slightly smaller than for monofilamentary tapes. The four-roll deformed tape instead (average j_c value of 26 kA/cm^2) showed a much lower fluctuation of j_c, of the order of 10% of its average value, between the center and the sides.

The innovative four-roll deformation is therefore decisive in homogenizing the current distribution throughout all the filaments, which is clearly not the case for the standard PIT tapes. The explanation of this effect was found in the different compression of

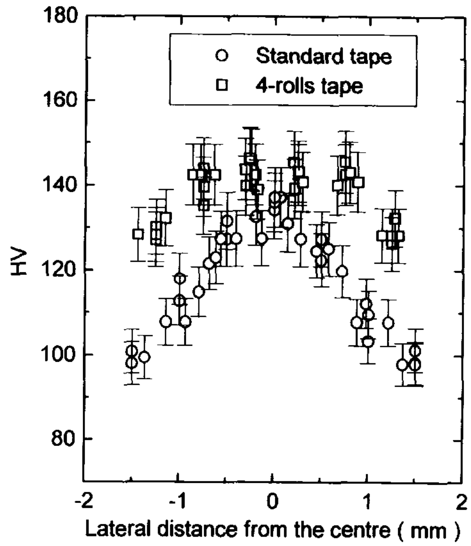

Fig. 6. Vickers microhardness of the single filaments of standard and four-rolled tapes as a function of the lateral position.

the filaments due to the deformation process in the standard and four-roll deformed tapes.

An alternative way to quantify the higher homogeneity of the four-roll deformed tapes was investigated by performing Vickers microhardness measurements on single filaments of both standard and four-roll deformed tapes. These measurements are presented in Fig. 6. The Vickers microhardness of single filaments had been plotted as a function of the lateral distance from the filament center to the tape center. Every filament has been measured at three different places, in order to have a higher accuracy.

For the standard tapes, a significant variation of the microhardness has been observed between the filaments which are near the tape center and those which are near to the sides. Typically, the filaments near to the center present a Vickers microhardness value of about 130–140 Hv, while near to the sides it decreases to about 90 Hv. For the four-roll deformed tapes, the Vickers microhardness is much less position dependent, going from about 145 Hv at the center to 125 Hv near to the tape sides. Finally, the Vickers microhardness of the four-roll deformed tapes is reproducibly higher than that of the standard deformed tape.

The active turks-head machine was also employed for the preparation of rectangular- and square-shaped multifilamentary wires with reduced anisotropy of the transport properties in a magnetic field. The two filament configurations under study at present are shown in Fig. 7. In Fig. 7a, the transverse cross-section of a rectangular wire of about 0.8 mm × 0.5 mm with 20 filaments is shown. The additional pressure exerted by the lateral rolls improves the simultaneous texturing of the Bi(2223) grains inside this wire in orthogonal directions. As

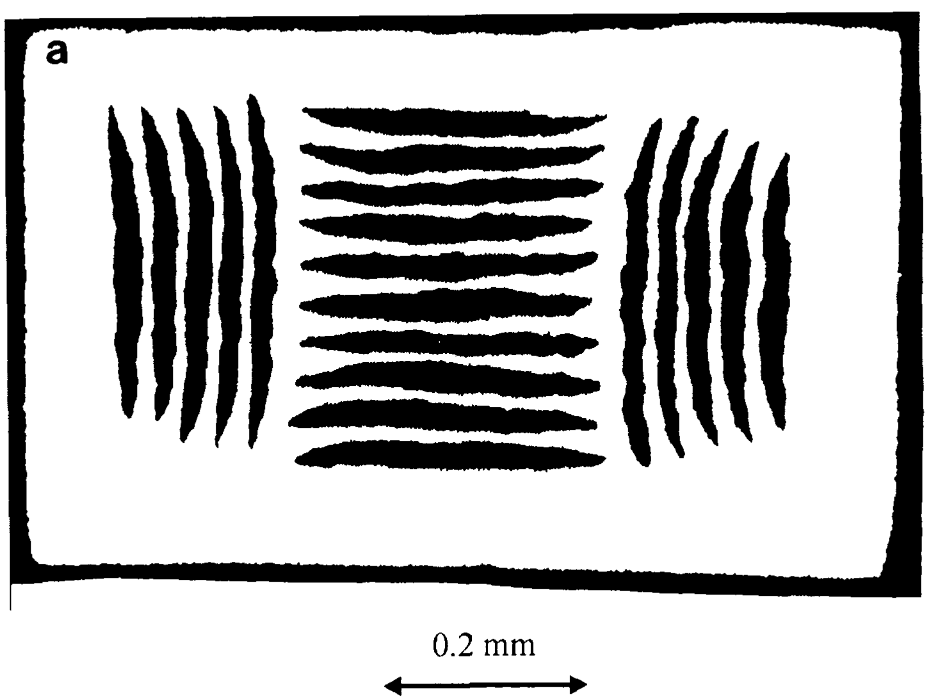

Fig. 7a. Transverse cross section of a rectangular Bi(2223) wire with 20 orthogonal filaments.

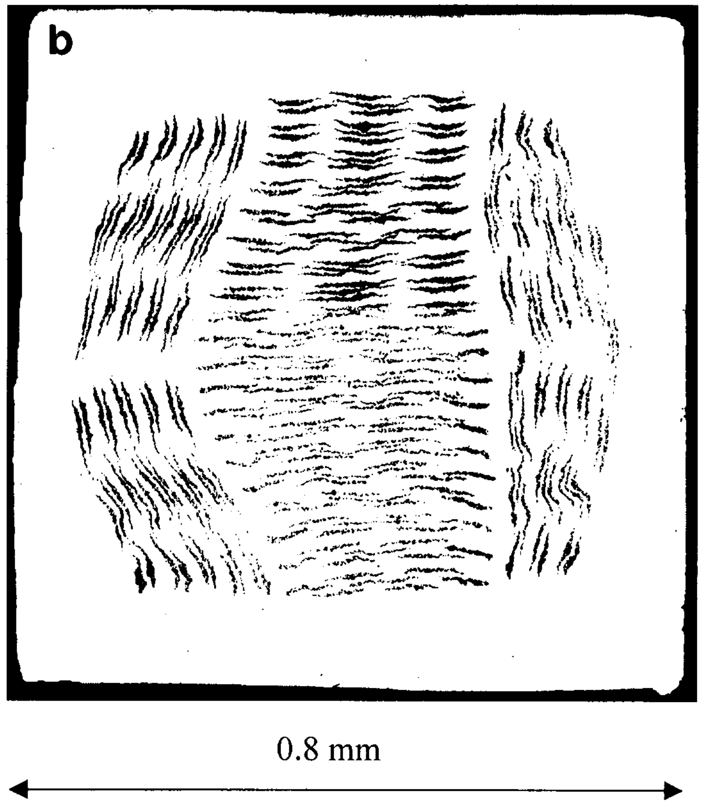

Fig. 7b. Transverse cross section of a square Bi(2223) wire with 203 twisted filaments.

already discussed in [10], the configuration of Fig. 7a leads to a substantial reduction of the anisotropy of j_c, without dramatically affecting its self-field value, which was about 20.5 kA/cm^2 at 77 K.

The more complex configuration of the square-shaped wire of Fig. 7b was developed for the preparation of isotropic Bi(2223) wires. The 203 filaments of this wire were also twisted with a twist pitch length of about 20 mm. Preliminary optimization of the heat treatment process of this wire has led to a self-field j_c value of about 10 kA/cm^2, while its magnetic field dependence was found to be insensitive to the wire orientation.

4. CONCLUSIONS

A prototype active turks-head machine has been employed for the fabrication of high-j_c multifilamentary Bi(2223) tapes, also with innovative filament configuration. These tapes present a higher homogeneity with respect to tapes prepared following the standard deformation route, as confirmed by Vickers microhardness measurements, as well as by local transport measurements. Further work must be done in order to optimize the cold deformation process for these newly developed tapes, in order to improve the Bi(2223) grain texture.

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