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Transport currents in Bi-2223/Ag tapes made using the tape-in-rectangular tube process, current distribution and I_c stress degradation

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Abstract
Using the tape-in-rectangular tube (TIRT) process, we have made multi-core Bi-2223/Ag tapes with various numbers of filaments (10–162), and with different filament architectures and orientations. We have measured the angular dependence of the transport current of the tape samples with ‘parallel’ and ‘perpendicular’ filaments. The transversal I_c distribution obtained by spatially resolved transport measurements (‘magnetic knife’) illustrates that the filament quality of the TIRT tapes is better at the tape edges than in the centre. The tapes were stressed by two types of tensioning set-up (a short straight sample and a U-shaped spring) and by bending at 77 K. The I_c degradation shows different behaviour for parallel and perpendicular filaments, which is attributed to the difference in filament density and crack propagation.

1. Introduction

The most common manufacturing procedure for BSCCO/Ag composite tapes is cold drawing followed by flat rolling [1]. This procedure results in a limited fill factor [2], a non-uniform filament density depending on filament position [3] and crack generation [4], especially during the final deformation steps where a relatively high tape widening is needed to reach a sufficiently high transport current. The tape-in-rectangular tube (TIRT) process has been introduced, aiming to improve filament uniformity and to reduce the final step widening. The TIRT process is based on two-axial rolling (TAR) deformation of BSCCO/Ag composites assembled from pre-deformed single-core tapes inserted in a rectangular Ag (Ag-alloy) tube. It allows the preparation of multifilamentary Bi-2223/Ag tapes with various filament architectures and different filament orientations [5]. Depending on the orientation of the filaments, the TIRT process leads either to filaments with high density and high aspect ratio (for the parallel configuration) or to filaments with low density and small aspect ratio (for the perpendicular arrangement). In an earlier publication we have studied the effect of the filament orientation on transport and magnetic properties [6]. In that paper, we concluded that the filament arrangement influences the distribution of shielding currents and dramatically affects the external susceptibility in the diamagnetic state, and thereby the losses in the perpendicular ac magnetic field [7].

The aim of this paper is to study the I_c anisotropy, I_c distribution and I_c degradation for typical TIRT tapes with parallel and perpendicular filaments.

2. Experimental details

Using the TIRT process, we have made various Bi-2223/Ag tapes with parallel filaments in an arrangement of one or

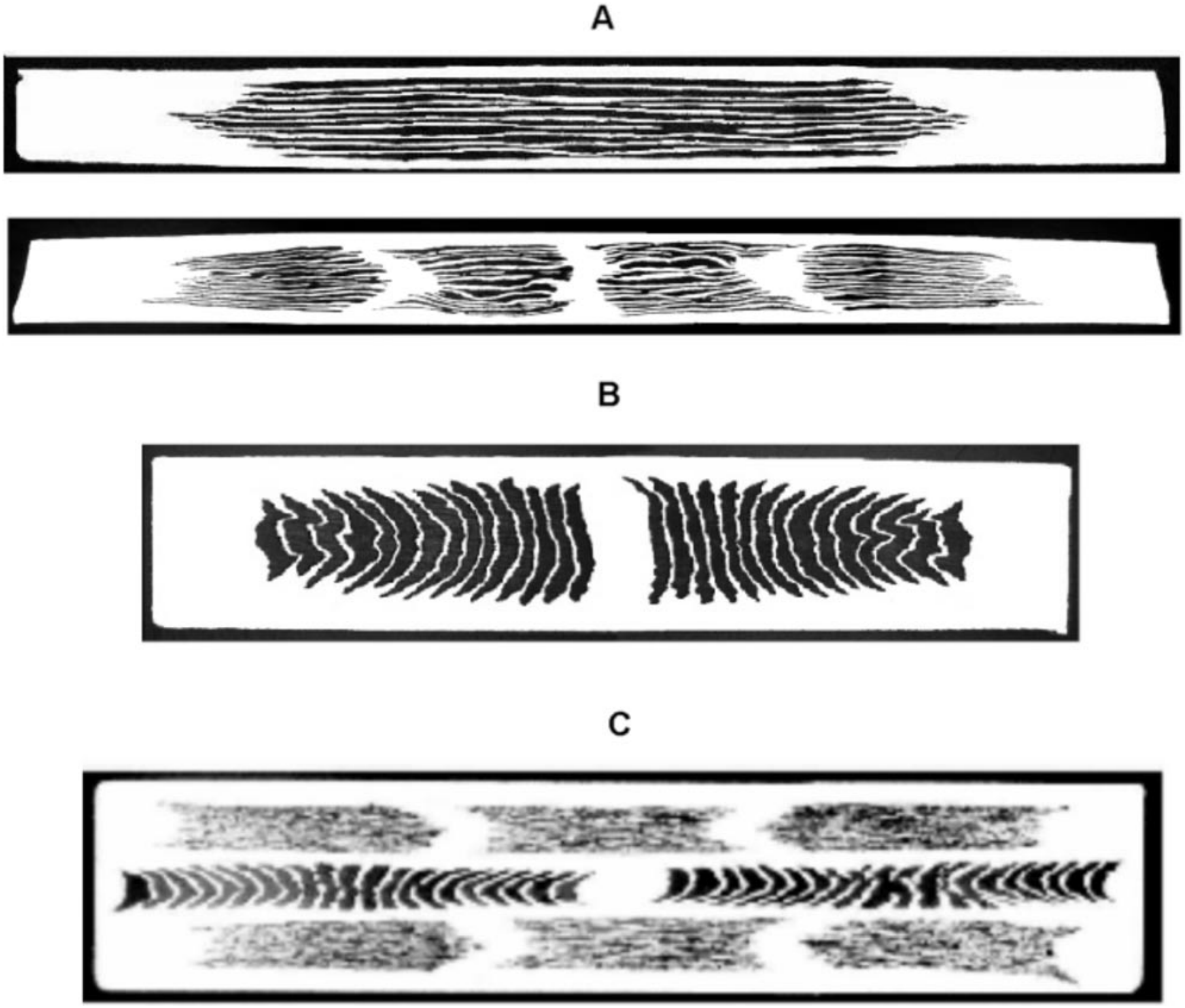


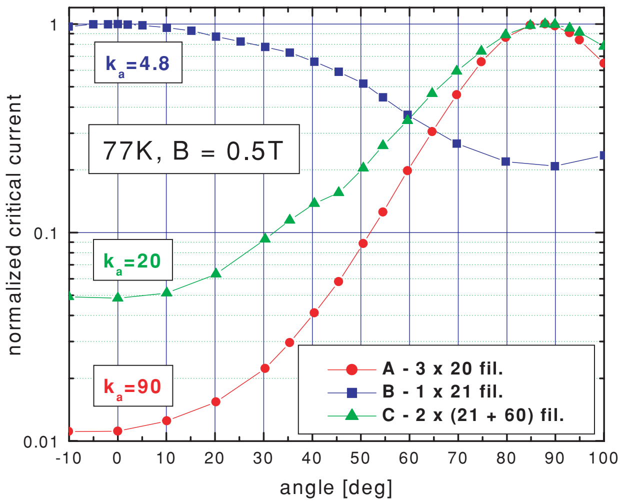
Figure 1. The cross sections of typical Bi-2223/Ag tapes made by the TIRT process with (*a*) parallel filaments, (*b*) perpendicular filaments and (*c*) combined filaments.

several columns (type A), with perpendicularly oriented filaments (type B), and with a combination of these two orientations (type C). The typical cross sections are shown in figure 1.

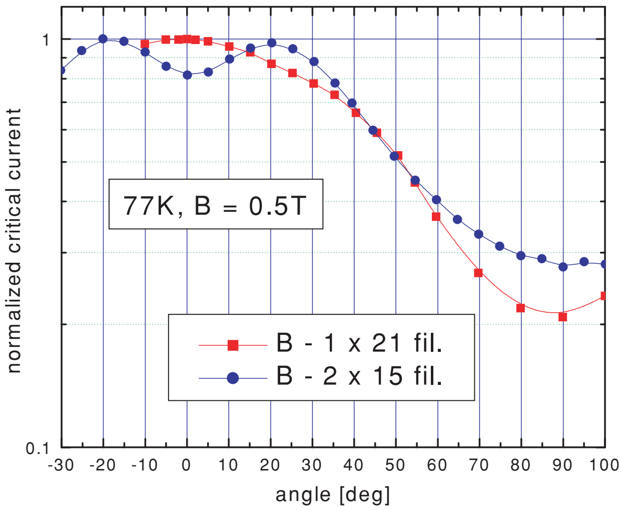
Using a four point probe method, at 77 K, we have measured the transport critical currents in an external magnetic field of magnitude $B = 0$ to 1 T and orientations between parallel and perpendicular at a constant field ($B = 0.5$ T) [5].

The magnetic profiling method ('magnetic knife'), based on the movement of the Bi-2223/Ag sample through a sharp perpendicular field gradient (from +0.2 T to −0.2 T) and subsequent $V(I)$ curve measurement at each position, has been used to determine the current distribution inside the tapes [8]. The current $I_c(x_0)$, which is measured when the tape is at a certain position x_0 with respect to the position of zero magnetic field, is made up of contributions of both low and high field regions inside the tape, as can be mathematically described by a convolution integral, as discussed in detail in [8]. By deconvolving the measured current profile $I_c(x_0)$ with respect to the resolution function of the magnetic knife, we obtain $J_{c0}(x) \cdot t(x)$, i.e. the product of the local current density $J_{c0}(x)$ and the local thickness $t(x)$. The transversal filament area variation $t(x)$ was estimated by optical microscopy from the cross section of the measured tape, so that $J_{c0}(x)$ could be determined.

Stress measurements were performed with two types of tensioning set-up: a short straight sample (SS) and a U-shaped spring (US) [9]. The SS system is a simple instrument in which one end of the sample is fixed in the lower arm and tension is applied through the upper arm, which is directly connected to a force loading cell by a steel spring. The axial strain is measured by a strain gauge (≈5 mm active length area) glued in the middle of ≈50 mm long Bi(2223)/Ag tape sample just between two potential taps which are ≈10 mm apart. We measure $\sigma(\varepsilon)$ and $I_c(\varepsilon)$ while the sample is elongated. The US set-up [10] is a device, which allows us to study both the tensile and the compressive strain. In this set-up the Bi(2223)/Ag tapes are mounted with conventional tin–lead solder to a U-shaped spring made of brass.



(*a*)



(*b*)

Figure 2. The angular dependences of critical current for TIRT tapes (*a*) of various filament orientations (A, parallel filaments; B, perpendicular filaments; C, combined filaments) and (*b*) for differently deformed perpendicular filaments.

For bending experiments, the tested tapes were heat-treated on a ceramic former with a diameter of 40 mm. During the stressing, the bending diameter was decreased from 40 mm to 15 mm, and then back to 40 mm at 77 K [11].

3. Results and discussion

Figure 2(*a*) shows the angular dependences of critical current ($I_c(\alpha)$ curves) measured at 77 K and $B = 0.5$ T for tapes A (3 × 20 filaments), B (21 filaments) and C (2 × 60 + 2 × 21 filaments). As shown in figure 2(*a*), the maximum current of tape B is measured when the external field is perpendicular to the tape surface ($\alpha = 0°$) and the minimum for parallel field, $\alpha = 90°$ (in contrast to the usual $I_c(\alpha)$, e.g. tape A). The $I_c(\alpha)$ curve of tape C illustrates how the angular dependence and the total anisotropy ratio can be influenced by a combined filament orientation. As shown in figure 1, the filaments of tapes B are not fully perpendicular to the tape surface, but are partially bent depending also on their position, which consequently leads to a disorientation of the Bi-2223 grains with respect to the tape surface. Figure 2(*b*) shows a comparison of the angular dependence for two tapes with perpendicular filaments. The orientation of the filaments (which is strongly influenced by the deformation) is directly reflected in $I_c(\alpha)$. In the case of the tape with 30 filaments (see figure 1(*b*)) the maximum of the $I_c(\alpha)$ curve is measured at 20° and a local I_c minimum occurs at 0°. This means that the majority of well-connected grains are not oriented perpendicularly to the tape surface but inclined by 20° with respect to the normal of the tape surface. This is caused by an inhomogeneous stress–strain pattern during two-axial rolling deformation [12] and unequal reductions for rolling axes. Grasso *et al* [13] have presented results for a Bi-2223/Ag tape with filaments originally inclined from the perpendicular direction by 15°. The final inclination angle estimated from $I_c(\alpha)$ was at 35–55° due to the aspect ratio of the changed tape.

An apparent decrease of the I_c anisotropy ($I_{c\text{-max}}/I_{c\text{-min}}$) and a reversed angular dependence has been reached for perpendicular filaments. However, due to a lower density, a lesser degree of texture and a relatively small aspect ratio of the filaments [14], J_c was much lower in comparison to the thin, dense and well-textured filaments in the parallel configuration. Su *et al* [15] have concluded that the reason that square wires have a lower value of J_c is due to a lower degree of texture in the filaments. Although the absolute value of the engineering current density J_{eB} for tape B, which has perpendicular filaments, is lower than for tape A, it has a cross-over with the J_{eA} curves at external fields 0.23 T for B//c and 0.35 T for B//ab [5]. This means that it is possible to use the tape with perpendicular filaments for the outer part of a superconducting coil in order to reduce the effect of the radial field component.

Figure 3 shows the typical spatial transport current distributions for Bi-2223/Ag tapes with ten parallel filaments arranged in one column. The transport current distribution and the filament area variation are plotted in figure 3(*a*). It can be seen that in the central area of the tape (approximately 1 mm wide) the transport current is apparently lower than at the edge sites, although the filament area is smaller there. This non-uniformity is related to differences in the connectivity of the Bi-2223 grains along the filament width. The central part of the filament area has the highest density due to maximal rolling pressure there [14], but there is not such a large rate of widening (especially during the final eccentric rolling steps) as at the filaments edges, which are free to move into both sides.

However, the diffusion of oxygen into filaments in the centre of the tape is much worse than into filaments at the outer parts because the diffusion coefficient for oxygen through silver is two orders of magnitude smaller than through BSCCO [16]. The effect of the total tape widening $w_t = [(b_f - b_0)/b_0] \times 100$, where b_f is the final tape width and b_0 is the initial wire dimension, on the current distribution is shown in figure 3(*b*) for w_t ranging from 65% to 77%. The application of low tape widening $w_t = 65\%$ leads to a relatively uniform current distribution along the width of the tape, but the final value of J_c is only 8500 A cm^{-2}. A larger widening results in a higher value of J_c but causes a less homogeneous current distribution.

While for the usual multifilamentary Bi-2223/Ag tape deformed by drawing and flat rolling the highest currents are

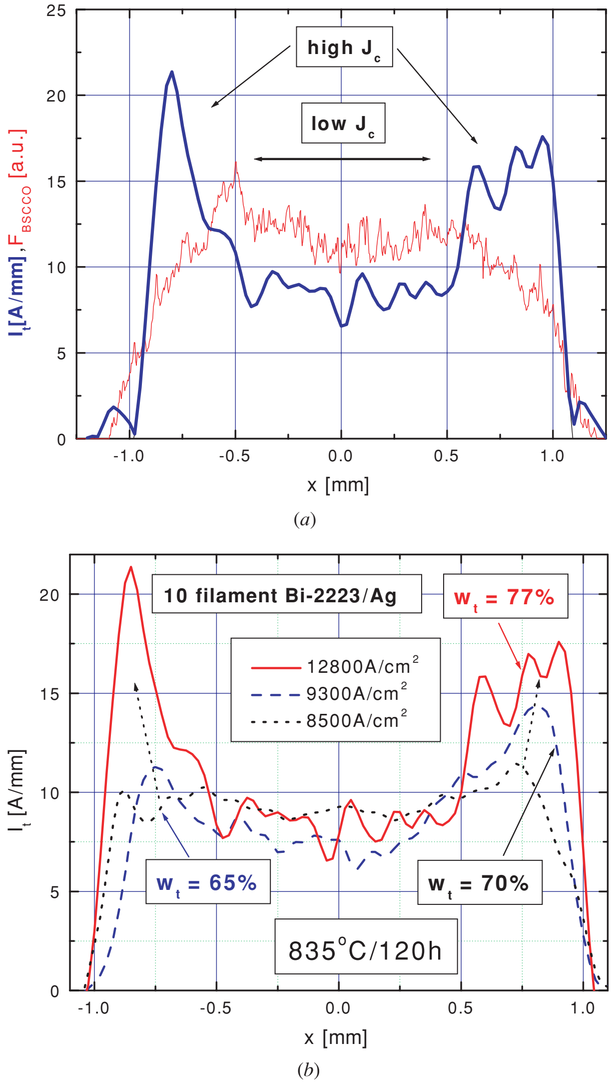


Figure 3. (*a*) Spatial distribution of transport current (thick curve) obtained by the magnetic profiling method in the ten filament tape compared to the distribution of filament area (thin curve).
(*b*) Current distributions in the ten filament tapes with various deformations (total tape widening $w_t = 65$–77%).

transported by the central filaments [3, 8], the TIRT tapes behave similarly as single core tapes [17, 18] with the highest current densities at the tape edges and the lowest at its centre. TIRT tape deformation is very similar to a single core tape (especially for a one-column arrangement) and therefore a corresponding I_c distribution is measured.

On the basis of the reasons presented above for a non-uniform current distribution for TIRT tapes with a one-column arrangement, the filaments have been arranged into more than one column. Figure 4(*a*) shows the local transport current (I_t) versus position (x) for tapes A with one and two columns, which have comparable rolling deformations. The $I_t(x)$ curve of the tape with two columns is roughly symmetrical and has a very low current near the centre of the tape ($x = 0$), where there are no Bi-2223 filaments. The non-zero current in the centre of the tape can be attributed to the non-ideal deconvolution of the measured current profile $I_c(x_0)$ with respect to the

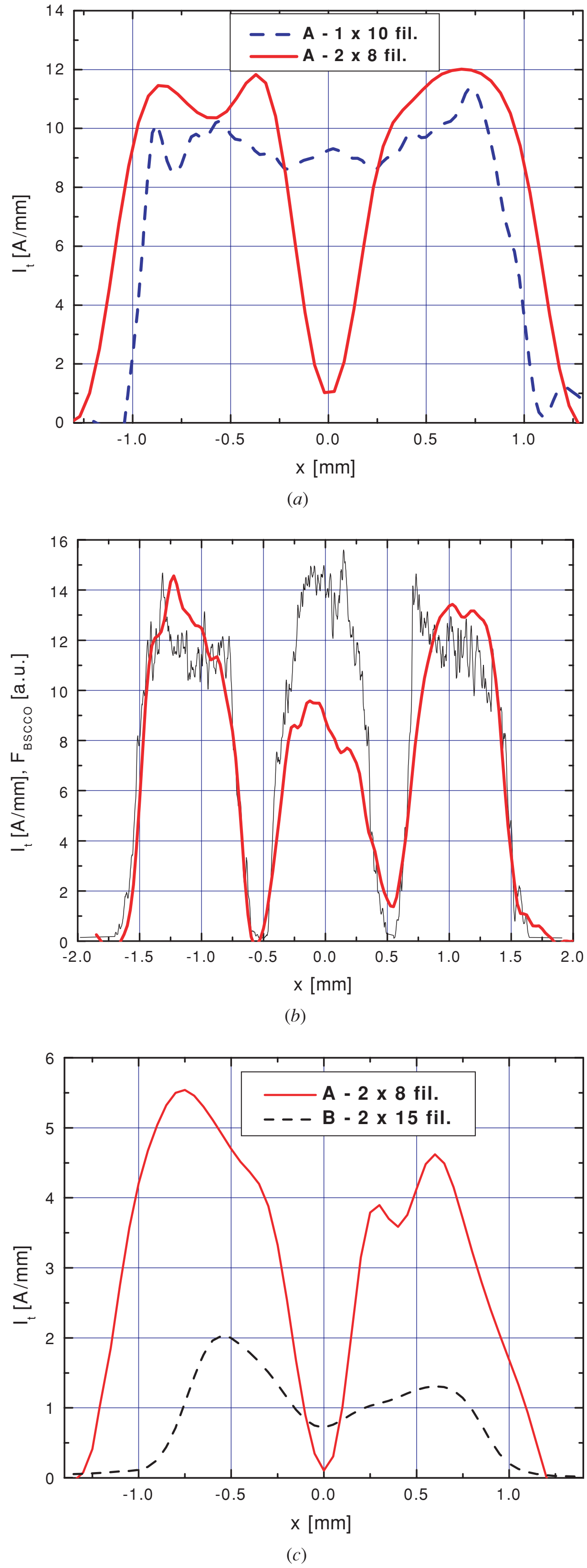


Figure 4. Spatial current distribution (thick curve) in (*a*) one and two filament columns, and (*b*) three-column 60 parallel filaments in an Ag sheath related to filament area (thin curve). (*c*) Comparison of the spatial currents of two tapes with parallel and perpendicular filaments arranged in two columns.

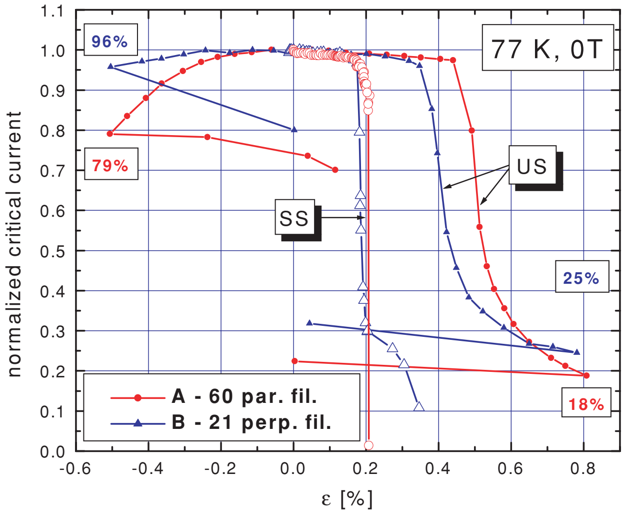
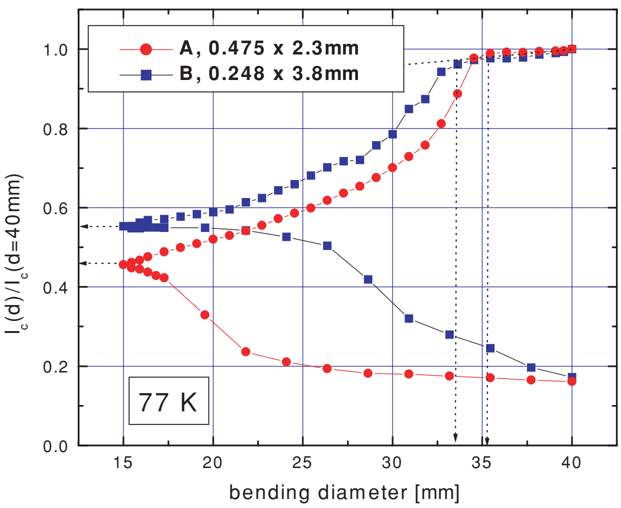


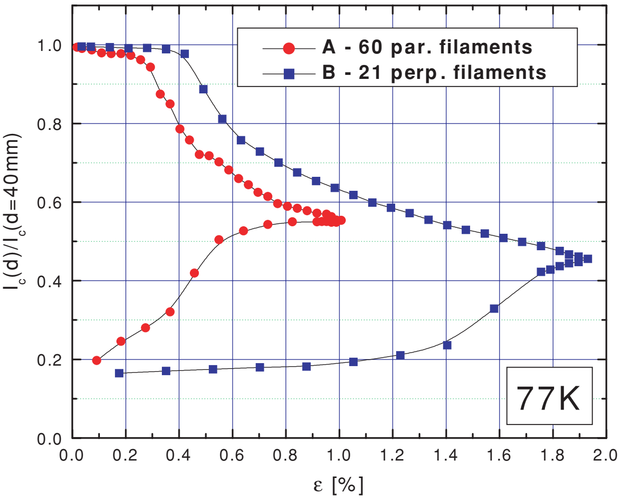
Figure 5. The I_c degradation by tension and pressure stress for the tapes with parallel and perpendicular filaments measured by US spring and SS sample systems at 77 K.

resolution function $g(B(x - x_0)$ [8], especially in the place of the filament edges. Figure 4(*b*) shows a comparison of the current distribution and the transversal filament area variation for 60 filaments placed in three columns (3 × 20). As in figure 3(*a*), the relative intensities of the lines clearly show the higher current densities in the outer columns. The differences in the texturization ratio and Bi-2223 phase content of this tape (3 × 20 filaments in pure Ag) have been studied [19]. It was found that the columns closer to the tape edges ('edge columns') have a better texture than those in the middle of the tape. Also, in the cross section made with optical microscopy (e.g. figure 1(*a*), 4 × 15 filaments), it is visible that the edge filaments are thinner, more uniform and better aligned in comparison to the central filaments. Figure 4(*c*) shows the current distributions for tape B with 30 perpendicular filaments (shown in figure 1(*b*)) and for 16 parallel filaments placed in two columns (tape A). It should be remarked that the intermediate deformation (w_t) of tape A with 16 filaments was not optimal in this case. As mentioned previously, the filaments that are arranged in a perpendicular way have a small aspect ratio, and usually have a much lower value of J_c due to a low density and poor texture. This results in currents a few times lower for perpendicular filaments ($I_{tB\text{-}max} = 2$ A) in comparison to $I_{ctA\text{-}max} = 5.5$ A for parallel filaments. Instead of this, the quality of the Bi-2223 grain connection is different in both filament groups, as shown by the dashed line in figure 4(*c*) where the column on the right side has a much lower critical current. In the case of tape B, the ratio of $I_{t\text{-}max}$ in the left and right filament columns is 1.6, while it is only 1.2 for tape A. Apparently the grain connectivity in perpendicular filaments is more sensitive to TIRT process parameters than in parallel filaments. In figure 1(*b*) it can be observed that the outermost filaments of a tape with perpendicular filaments have the smallest aspect ratios and irregular shapes, which leads to a low current density [14].

Figure 5 shows the I_c degradation caused by simple tensile strain on a SS sample and by compressive and tensile strain with a US spring system [9]. Generally, $I_c(\varepsilon)$ curves from SS and US measurements show the same slope of I_c decrease



(*a*)



(*b*)

Figure 6. Sensitivity of parallel and perpendicular filaments to bending stress at 77 K expressed by (*a*) I_c versus bending diameter and (*b*) I_c versus strain at the outer tape surface.

for $0 < \varepsilon < \varepsilon_{irr}$, but different values in ε_{irr} (≈0.2% or ≈0.4%) and in the shape of $I_c(\varepsilon)$ curves at $\varepsilon > \varepsilon_{irr}$. The origin of these differences is explained by different stress patterns for the SS and US methods [9]. Because the Bi-2223/Ag tape is soldered to a massive brass spring for the US measurement, the Bi-2223 filaments are pre-compressed during cool down to 77 K. Kitaguchi *et al* [20] have shown that the strain for the steep degradation of I_c depends on the holder (spring) material. By considering the pre-strain for a given spring material, the $I_c(\varepsilon)$ curve can be corrected. But, the US set-up does not allow the crack propagation as extensively as the SS measurement. For the US set-up, after each plastic elongation of the tape by $\delta\varepsilon$, the tension stress σ_t is decreased [9]. Consequently, the moderate I_c decrease at $\varepsilon > \varepsilon_{irr}$ is measured by the US set-up but there is a very sharp I_c drop for the SS set-up, indicating a strong Bi-2223 filament damage. The I_c falls to the level of a few per cent of its original value at $\varepsilon \approx 0.20\%$ for the SS curves.

Comparing the degradation of parallel and perpendicular filaments in a pure Ag sheath, the dense and high aspect ratio parallel filaments respond more sensitively to tension stress than perpendicular filaments, which is clearly visible in the US measurements (figure 5). The effect seems to be much smaller for the SS measurements. Even more interesting are the differences in $I_c(\varepsilon)$ for both types of tape under compressive strain. The tapes with perpendicular filaments, which have relatively low aspect ratios and low densities, clearly show less degradation by pressure, only by 4% from the original I_c value at $\varepsilon = -0.5\%$ in comparison to 21% degradation for parallel filaments at the same value. This difference can be partly attributed to the lower density of these filaments, which allows some improvement and therefore does not lead to such a rapid I_c decrease.

Figure 6(*a*) shows a plot of the normalized critical current versus bending diameter. Although tape B (perpendicular filaments) is nearly two times thicker than tape A (0.475 mm versus 0.248 mm), only a small $I_c(d)$ difference between these tapes is measured with decreasing bending diameter (40–15 mm). Figure 6(*b*) shows a plot of $I_c(\varepsilon)$ for which ε values at the outer tape surface were estimated from the ratio of the tape thickness to the bending diameter. It is surprising that there is a higher resistance of tape B to the bending strain ($\varepsilon_{irr} \approx 0.4\%$) in contrast to tape A ($\varepsilon_{irr} = 0.21\%$). This can be explained by the previous results shown in figure 5, where a low I_c degradation by compressive strain in perpendicular filaments was demonstrated. During bending, the density of the inner part of the filaments is probably initially increased without apparent I_c degradation, while damage to the connection of the grains occurs for the dense and thin parallel filaments. The superconducting tape is considered as a composite with brittle ceramic filaments, which do not break uniformly. The cracks will start at the point where the highest strain occurs, which is usually at the outer filaments. Therefore, in the case of tape A, a much easier crack formation in the outer filament layer will lead to the beginning of a rapid I_c degradation at $\varepsilon = 0.21\%$.

4. Conclusions

We have measured the main transport properties of Bi-2223/Ag tapes, made using the TIRT process, with parallel and perpendicular filaments. It is shown that the I_c anisotropy can be decreased by the perpendicular filament architecture. This makes it possible to reduce the effect of the radial field component in a superconducting winding. However, perpendicular filaments have a low aspect ratio and a considerably lower value of J_c.

The transport current distribution of TIRT tapes is similar to the current distribution of single core tapes (and unlike the majority of usual multifilamentary Bi-2223/Ag tapes) with the highest current densities at the tape edges and the lowest at its centre.

The parallel filaments are more sensitive to bending stress than perpendicular filaments. This is caused by a different filament density and by a less drastic crack distribution through the perpendicular filaments.

Acknowledgments

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