Small and Repetitive Axial Strain Reducing the Critical Current in BSCCO/Ag Superconductors

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Abstract — **The critical current in two types of axially deformed BSCCO/Ag tape conductors is investigated. An I_c reduction is observed for small axial strains (ranging from 0 to 0.3%) with a characteristic slope $di_c/d\varepsilon = -5\pm1$ (relative i_c change per relative change in length). In the case of an axial compression there is a more pronounced I_c reduction. For small axial strains (<0.3%) a certain reversible change in I_c is observed. This reversible behaviour occurs in combination with an irreversible reduction that increases when the number of strain cycles is increased. The reversible part of the I_c change remains for a large number of strain cycles (>10000) and has a similar negative slope for both compressive and tensile strains. It is proposed that the reversible I_c change is correlated to a non-hydrostatic lattice deformation. The I_c versus strain behaviour is in good agreement with an earlier proposed model.**

I. INTRODUCTION

The critical current of poly-crystalline BSCCO can be reduced significantly due to a certain deformation. This is observed in deformed BSCCO/Ag superconductors. Experiments on Bi-2212 and 2223 conductors showed an irreversible I_c reduction for an axial tension and compression and after a transverse compression [1],[2]. The irreversible nature of the I_c reductions and the absence of a temperature or field dependence forces to conclude that the I_c change is attributed to (micro-)cracks in the poly-crystalline structure.

In this paper a detailed study is presented on the I_c in BSCCO/Ag superconductors, when deformed in the strain range from -0.3 to 0.3%. The influence of repetitive tensile and compressive axial strains, with a peak value around 0.2%, is investigated. Special attention is paid to the reversibility of the I_c change after multiple strain variations. The results are evaluated in relation to the descriptive model that is presented earlier [2].

II. SAMPLE MATERIAL

The deformation experiments are made with two prototype superconductors recently obtained from different manufacturers. Both tapes are produced with the "powder-in-tube" process. The relevant characteristics are summarised in Table 1. These conductors have a good J_c, but the highest current density is measured in conductor-B. This higher J_c correlates to a higher degree of compaction of the filaments. An optical analysis of the tape cross-section shows that the filaments in conductor-A contain significantly more voids (about 30%) than those in conductor-B (10-20%).

Manuscript received August 24, 1996

TABLE I
THE TWO BI-2223/AG TAPES FROM DIFFERENT MANUFACTURERS

Conductor	A	B
Size [mm×mm]	3.4 × 0.25	4.1 × 0.30
No. filaments	49	85
Ag : S.C.	4 : 1	3 : 1
J_c(non-Ag @ 77 K) [A/mm^2]	75	130

III. STATIC AXIAL STRAIN

The characterisation of the critical current as a function of the axial strain is made with a "bending-spring", where the conductor is tightly connected to a thick substrate [3]. This set-up enables the determination of I_c in a strain range from -1% to +1% uni-axial strain. Consequently it requires at least two pieces of sample material in order to investigate both the compressive and tensile strain regime. A second feature is that the thermal compression in the last part of the cooling phase, from soldering at 500 K down to 77 K, is fixed and mainly determined by the thermal contraction of the bending spring (brass).

A. Tensile Strain

The reduction of the I_c due to tensile strain is similar to that observed in many other BSCCO/Ag conductors. The results for the two conductors are presented in figure 1. The strain state after cooling to 77 K is defined as zero.

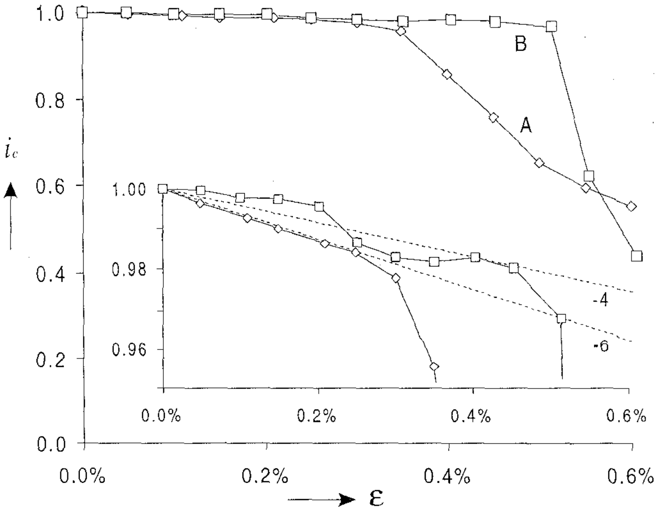

Fig. 1. The reduction of the normalised critical current $i_c = I_c(\varepsilon)/I_c(0)$ as a function of the tensile strain (including a magnified part of the curve).

Up to a certain limit of strain (0.45% for A and 0.30% for B) the I_c remains almost constant. For a larger strain the current reduces drastically to below 0.6 of its original value at 0.6% strain. The I_c reduction, where the current reduction is small, is presented also in figure 1. The I_c reduction in this regime can satisfactory be described with a constant slope in the normalised critical current of $di_c/d\varepsilon = -5\pm1$. This strain performance of the two tapes is in good agreement with earlier results on other Bi-2223/Ag tapes [2].

B. Compressive Strain

The I_c reduction in axially compressed conductors can be investigated very well with the bending spring. The results are depicted in figure 2. A regular I_c reduction is observed that can be described with a constant relative change of $di_c/d\varepsilon = 20\pm2$. Again, this is in good agreement with the lowest values of earlier results on axially compressed Bi-2223/Ag tape [2].

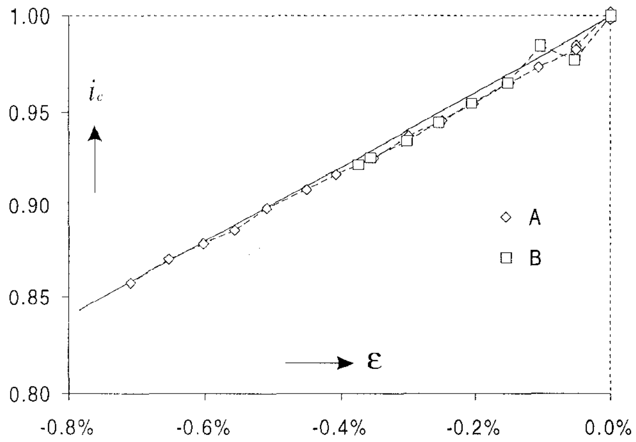

Fig. 2. The critical current reduction due to a compressive axial strain in conductors A and B.

C. Comparison with the I_c - strain model

The observed I_c versus strain relation in combination with the irreversible nature of the I_c reduction, lead to the proposal of a descriptive model [1]. This model assumes an I_c in the strain-free state that is slightly above the I_c measured at the beginning of the strain experiment, as depicted in figure 3.

Due to the thermal compression of the BSCCO, the critical current is already reduced by a certain factor at the beginning of the strain experiment. In fact the strain history already starts at about 830 °C just after the solidification of the BSCCO. When the conductor is then compressed the I_c decreases further, but when a tension is applied the I_c deviates from its original line. The irreversible nature of the I_c reduction limits the I_c to the value present in this strain state. Finally for a larger tension, when the tensile strain counteracts the thermal compression, a strong I_c reduction occurs.

The differences in the I_c values between the different manufacturers and the variations within a single production batch make it at present not possible to compare the I_c between conductor samples with a different thermal contraction, either by comparing the I_c between different types of conductors or by investigating the influence of different sample-holder materials.

As mentioned before, the results found with these two conductors are in good agreement with earlier results on Bi-2223/Ag and Bi-2212/Ag conductors and the model that is proposed to describe the behaviour. The back-bone of this description for the strain induced I_c reduction is the irreversible nature of the I_c reductions. To verify this the reversibility of the I_c changes is studied in detail. Cyclic strains are applied in the strain range around the strain state after cooling down to 77 K.

IV. THE REVERSIBILITY OF I_C FOR SMALL STRAINS

The cyclic strain experiments are made on a slightly modified bending spring. The tape is soldered with Indium at 500 K on a brass substrate, 3 mm thick and 15 mm wide. The tape and the substrate are bend over a 25 mm long section. Outside the deformed section is a 5 mm zone at each side where the substrate is 5 mm thick and the deformation is much smaller. The strain in the sample is determined by measuring the deformation of the substrate adjacent to the tape. The I_c is determined at a level of 10^{-4} V/m with a reproducibility of about 0.3%.

As mentioned before the strain induced I_c reductions in the earlier experiments on the bending spring appeared to be completely irreversible. A recovery of the I_c when the strain is relieved, was never observed so far. The deformation experiments on conductor-A show a certain recovery of the I_c when the strain is relieved. A typical example of this behaviour is presented in figure 4. The first deformation to 0.28% strain results in an I_c reduction to 0.985 of the initial value. When the strain is reduced back to 0% strain, then the I_c recovers (partially) to 0.989 and the next I_c at 0.28% strain is at 0.980. In the following strain cycles this process is repeated, the I_c at 0% remains at an approximately 1% higher value than at 0.28% strain. This process is not perfectly reversible; after 15 cycles the i_c at 0% strain is reduced to 0.980.

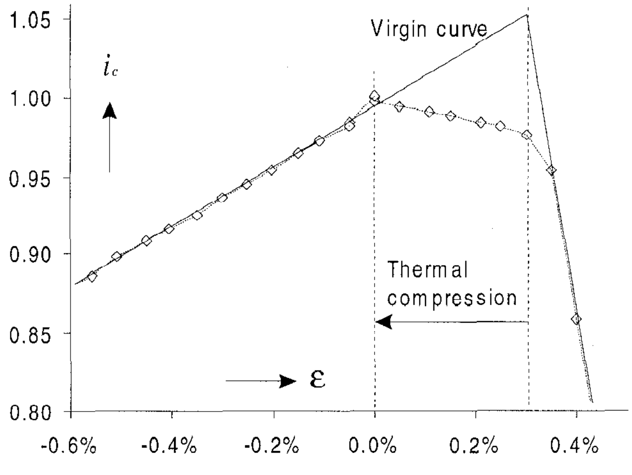

Fig. 3. A comparison between the i_c versus strain in sample A and the descriptive model for the I_c reduction that defines the virgin curve.

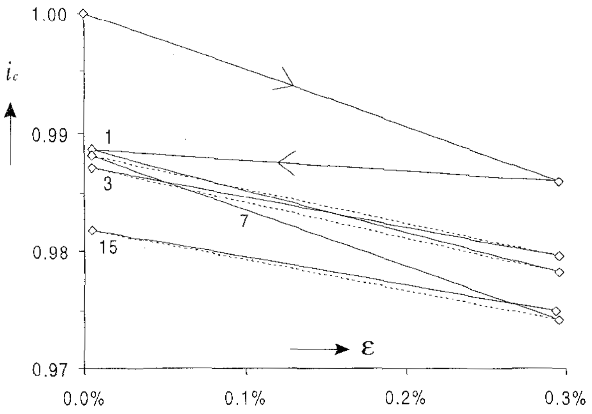

Fig. 4. The I_c versus strain in sample A for a cyclic deformation between 0 and 0.28% axial strain. The solid and dotted lines follow the measuring sequence represented by the numbers too. A solid line indicates two sequential I_c measurements and the dotted line is used when one or more strain cycles are skipped.

A very interesting result is obtained when the effect of cyclic strain is compared between the compressive and tensile strain regimes in figure 5. The first time a compressive strain is applied the i_c reduces with a slope of about $di_c/d\varepsilon = 20$ to a value of 0.938. When the strain is relieved to the initial value then the i_c reduces further to 0.930, with a negative slope similar to $di_c/d\varepsilon = -5$. When the number of cycles is increased this negative slope $di_c/d\varepsilon$ remains, when relieving the strain, similar to what happens after multiple cycles in the tensile regime. When increasing the number of strain cycles the I_c (at constant strain) further reduces step by step, clearly indicating the irreversible behaviour in the I_c reduction.

The I_c reductions shown for conductor-A, also occur in a similar way in conductor-B. This behaviour supports the proposed description for the I_c of axially strained conductors that is discussed in the previous section. The first compression applied to the conductor reduces the critical current immediately and irreversibly. Tensile strains over a very limited strain regime can show a (partially) reversible I_c change with a small slope of typically $di_c/d\varepsilon = -5$.

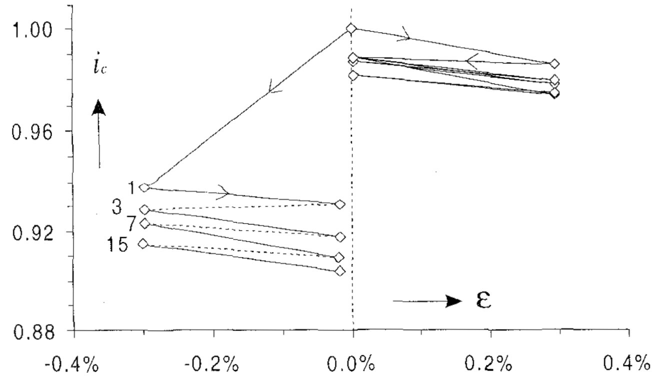

Fig. 5. The I_c versus strain in two samples of conductor A. First a cyclic deformation between 0 and 0.28% axial strain and then between 0 and -0.28% strain. The solid and dotted line follows the measuring sequence. The solid lines indicate two sequential I_c measurements and a dotted line is used when one or more strain cycles are skipped.

V. A LARGE NUMBER OF STRAIN CYCLES

For technical applications it is important to see the effect of a large number of strain cycles. Axial deformations due to the thermal contraction between room and operating temperature may occur a large number of times during the life time of a cryogenic system (typically 10 to 100×). Additional sources of deformation, as Lorentz forces and external forces, may occur much more often (>1000×). The (partially) reversible nature of the I_c reduction, therefor justifies an investigation of cyclic deformed conductors.

The influence of a cyclic strain on the I_c of conductor-A is depicted in figure 6. Basically it shows that the I_c reduces with the number of strain cycles. The difference between the neutral and the elongated state remains constant, within the experimental accuracy, for a large number of cycles of up to at least 10^4. A second observation is that the irreversible part of the I_c reduction decreases faster for a larger strain peak value. This reduction may continue, but a certain saturation of the I_c at a constant level is more likely.

After the first compressive cycle the I_c remains at a higher value than in the tensile strain-state. This shows that the reversible part of the I_c change exists and remains negative, for a very large number of cycles. The first compression to -0.28% can be considered as a starting point in the cyclic strain experiment. The I_c change form this point to a large number of cylces (0.5 to 1000) is about 5%, which is similar to the reduction that is observed after a comparable amount of tensile strain cycles.

The reduction of the critical current in conductor-B after multiple strain cycles is presented in figure 7. Again a compressive cycle is compared with a tensile cycle. The behaviour is similar as in conductor-A. The irreversible part of the I_c reduction saturates after a large number of cycles. The permanent I_c reduction after 10^4 cycles of 0.2% tension is 1%. A compressive strain of -0.21% initially reduces the I_c with nearly 4%, and when this strain is applied multiple times there occurs an additional reduction up to 1%.

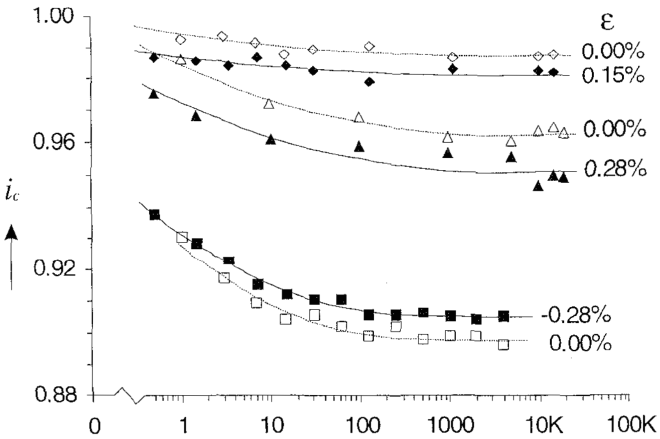

Fig. 6. The I_c versus the number of times strain cycles for three deformation states in conductor-A: 0 to 0.15%, 0 to 0.28% and 0. to -0.28% strain. The solid lines serve as a guide to the eye. The I_c is normalised to the I_c after cooling down to 77 K with a non-deformed bending spring (strain = 0 and cycle = 0). The first tension or compression is numbered as cycle = 0.5.

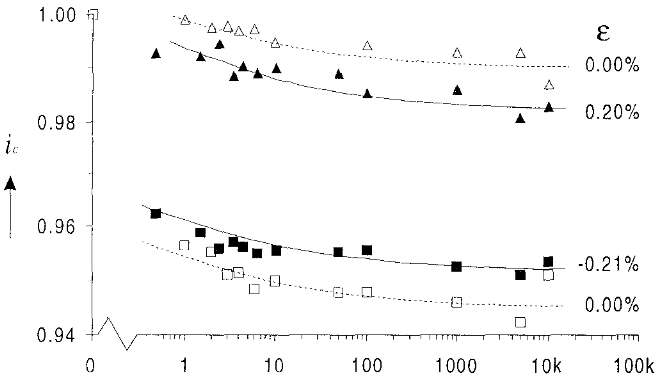

Fig. 7. The I_c versus the number of strain cycles in conductor B, for two strain cycles (0 to 0.2% =tensile and 0 to -0.21% = compressive).

VI. THE MICROSTRUCTURE IN DEFORMED BSCCO

As mentioned above the model for the I_c in axially strained conductors, that is based on an irreversible I_c reduction due to compression, appears to be an adequate description. A new element observed here is the (partially) reversible I_c change for small tensile strains. This behaviour is an indication for a certain intrinsic dependence of the I_c on the strain state of the material. To our knowledge it is also the first experimental evidence for such an intrinsic $J_c(\varepsilon)$ relation in poly-crystalline BSCCO.

The occurrence of reversible lattice deformations in polycrystalline Bi-2212 is recently observed by X-ray diffraction. The lattice deformations are reversible in a very limited strain range of 0.2% [4]. Uni-axial stress and strain experiments on Bi-2212 whiskers show a reduction in T_c when the *a*- or *b*-axis is elongated and the *c*-axis is compressed [5],[6]. Based on the similar $I_c(\varepsilon)$ behaviour it is expected that deformed Bi-2212 and 2223 behave essentially the same. When the observations of the lattice deformation and $I_c(\varepsilon)$ in the reversible regime are combined it seems justified to conclude that a slope of $di_c/d\varepsilon = -5$ in the tensile strain regime is determined by the intrinsic properties $dJ_c/d\varepsilon$ of the grains for the major part.

The irreversible I_c reduction that is observed when a certain deformation is applied for the first time, is expected to correlate with the breaking of grain-boundaries in the polycrystalline system. The observed irreversible I_c reduction is then determined by a statistical distribution in the strain tolerances of the grain boundaries. The mechanism should also determine the difference between the I_c reduction due to an initial tensile or compressive deformation. This process of damaging grain boundaries is also expected to explain the irreversible part of the I_c reduction that occurs when a strain cycle is passed multiple times.

VII. CONCLUSIONS

1 - The static I_c versus axial strain behaviour of two different Bi-2223/Ag multi-filamentary conductors is determined and found to be in good agreement with previous results on Bi-2212 and 2223 conductors. Three different strain regimes are distinguished and described by a model for the strain dependence of I_c in BSCCO/Ag conductors

2 - A partially reversible I_c change is observed when a BSCCO/Ag conductor is subjected to a tensile strain. The reversible part of this I_c change is believed to be an intrinsic property of the poly-crystaline Bi-2223. Assuming a similar mechanical behaviour in Bi-2212 and 2223, it is proposed that the reversible I_c change is correlated to a non-hydrostatic lattice deformation, similar to the T_c reduction that is observed when the *a*- or *b*-axis is elongated in a single crystal of Bi-2212.

3 - The irreversible I_c reduction due to a large number of strain cycles is investigated for tensile and compressive strain cycles. The experimental results suggest a saturation of the i_c after a large number of cycles at a level of 0.99 and 0.95 for strain cycles to 0.15 and 0.28% strain respectively.

4 - The descriptive model for the irreversible I_c reductions in BSCCO/Ag conductors is confirmed by static and cyclic strain experiments performed on the two conductors. An important proof for the model is the I_c change due to multiple strain cycles. The influence of a compressive strain cycle on I_c can be described as a tensile cycle with an enlarged initial compression.

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