Descriptive Model for the Critical Current as a Function of Axial Strain in Bi-2212/Ag Wires

Bennie ten Haken, Arno Godeke, Henk-Jan Schuver and Herman H. J. ten Kate.

Low Temperatures Division, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

Abstract—A descriptive model is presented for the critical current of a Bi-2212 conductor that is axially deformed. This model is based on previously published critical current measurements on axially compressed and elongated Bi-2212 wires. The validity of the model is investigated by applying an additional pre-strain at room temperature. The experimental results on the pre-strained wires are in reasonable agreement with the prediction. The description for the critical-current reduction in Bi-2212 is applied in a model for a bend conductor. This model predicts the critical current as a function of the bending radius in a wire and a tape conductor.

I. INTRODUCTION

The critical current of the present generation of Bi-2212/Ag wires is relatively sensitive for mechanical deformations. Considerable reductions (> 10%) are observed when a wire is axially elongated above a certain typical strain value in the order of 0.4% strain. Axial compressive strains can also cause a large reduction in the critical current, but this reduction is more gradual [1]. An important feature observed in all the deformation experiments on BSCCO-2212 and 2223 conductors is, that all the observed critical current reductions are completely irreversible.

It is generally accepted that the critical current in polycrystalline bulk of BSCCO superconductors is restricted by the grain boundaries of the structure. The irreversible nature of the critical-current reduction after any mechanical deformation, is a strong indication that this reduction is also determined by the grain boundaries. If the deformation of the lattice would cause the changes in the critical current (I_c) then this would result in a reversible change over at least a certain deformation range.

In this paper a descriptive model is proposed for the irreversible reduction of the critical current of Bi-2212/Ag wires, due to axial deformations. The analysis is based on the previously published results [1]. First the validity of the description is compared with the experimental results on wires that are pre-strained at room temperature. The proposed I_c versus axial strain dependence is finally applied in a model for a conductor that is bend with a certain radius.

II. AXIAL STRAIN IN BI-2212/AG WIRES

The results of combined tensile and compressive axial strain (ϵ_a) experiments on Bi-2212/Ag wires, leads to a subdivision of the $I_c(\epsilon_a)$ relation for three strain ranges:

- I: $\epsilon_a < 0$ Compressive strain
- II: $0 < \epsilon_a < \epsilon_{2\%}$ First tensile regime (I_c reduction < 2%)
- III: $\epsilon_a > \epsilon_{2\%}$ Second tensile regime (I_c reduction > 2%)

This subdivision, that is also presented in figure 1, defines the characteristic strain parameter ($\epsilon_{2\%}$), as the point where a 2% reduction in the I_c is observed. Sometimes an irreversible strain level (ϵ_{irr}) is defined instead of the $\epsilon_{2\%}$ that is preferred here.

Fig. 1. The normalised critical current as a function of the axial strain. Measured on different samples for compressive and tensile strains (measured at 4.2 K and 8 or 16 T).

The compressive strain regime (I) is investigated with a very large number of wires and in all these samples a similar, almost linear, reduction is measured as a function of the compression. The slope of this reduction is typically 30, (percent reduction in I_c per percent strain). For large strains, this leads to an exponential reduction of the critical current, but in most cases ($\epsilon_a < 1\%$) a linear function is accurately enough.

The critical current in the first tensile regime (II) is often considered to be constant. But a detailed analysis on Bi-2212 wires shows a small, but significantly irreversible, I_c reduction with a constant slope of approximately 4. In the second tensile regime (III) a strong reduction in the I_c is observed. The maximum slope in this strain regime ranges from 100 to 500 for the various types of conductor.

III. A DESCRIPTIVE MODEL

The backbone of the description presented here is the irreversible nature of all the I_c reductions measured in the various strain experiments. A second point is formed by the two

Manuscript received June 12, 1995

discontinuities in the $I_c(\epsilon_a)$ relation at $\epsilon_a = 0$ and $\epsilon_a = \epsilon_{2\%}$. Finally an estimation of the thermally induced strain in the Bi-2212 filaments gives a value in the order of $-\epsilon_{2\%}$ [2]. This implies that the discontinuity at $\epsilon_{2\%}$ occurs close to the position where the axial strain compensates the thermal contraction.

The general description of the $I_c(\epsilon_a)$ dependence of Bi-2212 is based on the assumption that the first and third strain regime, can be extended into the second strain regime (see figure 2). Thus it is assumed that the critical current of unstrained Bi-2212 lies above the value that is measured in a wire with matrix material that causes a contraction of the superconductor. After cool down, the I_c of the conductor is reduced by a factor that is defined by the thermal contraction and the slope of the $I_c(\epsilon_a)$ relation in the first strain range.

Fig. 2. The proposed description for the $I_c(\epsilon_a)$ dependence of Bi-2212.

The I_c in a compressive strain experiment on a thermally contracted conductor, will follow the line as defined by the exponent α_1 . But the irreversible nature of the I_c reductions does not allow the I_c to follow this line in the first tensile regime. In a tensile strain experiment on a normal wire, the I_c will remain nearly constant close to the strain where the thermal strain is balanced. From this point a sharp reduction occurs with a slope of α_3 . This explains the discontinuity at $\epsilon_a = \epsilon_{2\%}$. The critical current in the intermediate strain regime (II) can be described with an exponent (α_2) which is very small. Hence the entire axial strain dependence can be described with a set of three different constant slopes for the successive strain regimes.

IV. PRE-STRAINED WIRES

According to the description of the strain dependence of Bi-2212/Ag wires as presented above, the thermal strain in the Bi-2212 filaments is approximately -0.4% . This contraction is obtained in two steps. First the wires are cooled down from the temperature during heat-treatment (≈ 1100 K). Then the force balance along the conductor cross-section will determine the compression of the Bi-2212 filaments. The sec-

ond step is defined by the temperature (≈ 400 K) when the sample is tightly connected to the substrate and cooled to 4.2 K. During this second temperature step the strain is determined by the thermal contraction of the (brass) substrate that supports the wire. Within this cooling range room temperature is a suitable intermediate point to adjust the axial strain in the Bi-2212 filaments.

For this investigation three pairs of Bi-2212/Ag wires from a singular batch are mounted in the strain device. A pre-strain is applied at room temperature from -0.2% , 0 to $+0.2\%$ on each pair. After that the I_c reduction is determined subsequently in the compressive and the tensile axial strain regime, one for each wire. The results are presented in figure 3. The strain axis of each sample pair is adjusted according to the applied pre-strain. The critical current is normalised to unity at the zero-point of this shifted strain axis. The dotted lines indicate the initial strain at 4.2 K.

Fig. 3. The normalised critical current as a function of the axial strain measured on three pairs of pre-strained samples (measured at 4.2 K and 16 T).

The strain measurements on the samples, presented in figure 3, roughly follows the predicted dependence. In the compressive strain regime there is always an immediate reduction, even for a very small change of the strain (e.g. 0.05%). The sample that is pre-strained by $+0.2\%$, indeed shows a reduction of the second strain range by 0.2% . On the adjusted strain axis of figure 3, the value of $\epsilon_{2\%}$ remains at a value close to 0.4% strain. Only the elongated sample, with a compressive pre-strain of -0.2% , does not show the full expected extension of the second strain range. The third strain regime, with the stronger I_c reduction, starts already at 0.2% strain.

The experimental results with the pre-strained wires support the proposed description for the $I_c(\epsilon_a)$ relation. The I_c reduction in the compressive strain regime is in good agreement with this model. A deviation occurs in a single sample in the tensile strain regime. Although there is no good explanation for this deviation, it seems reasonable to continue with this description for $I_c(\epsilon_a)$, since all other features are present.

In the following section the I_c of a bend conductor is modelled with the irreversible $I_c(\epsilon_a)$ relation.

V. BENDING A CONDUCTOR

An alternative way to investigate the axial strain dependence of superconductors is by bending a conductor over a certain radius (R_b). The maximum axial strain that occurs inside the superconductor is proportional with the thickness of the superconducting section (D): $\epsilon_{max} = D/(2R_b)$. In the case of a symmetric conductor (e.g. a rectangular tape or round wire) with elastic properties, there will be a linear axial strain profile from $-\epsilon_{max}$ to $+\epsilon_{max}$ along the height of the conductor.

A. Definitions

The critical current in the superconductor is defined by three different exponents for the different strain regimes:

$$\begin{aligned} \text{I: } \epsilon_a < 0 & \quad I_c \propto e^{+\epsilon_a \alpha_1} \text{ (in examples } \alpha_1 = 30), \\ \text{II: } 0 < \epsilon_a < \epsilon_{2\%} & \quad dI_c/d\epsilon_a = 0, \\ \text{III: } \epsilon_a > \epsilon_{2\%} & \quad I_c \propto e^{-\epsilon_a \alpha_3} \text{ (in examples } \alpha_3 = 300). \end{aligned} \quad (1)$$

In the case of a bend wire the second exponent can be neglected if it is small compared to α_1 . In the examples a value of 0.4% is applied for $\epsilon_{2\%}$, which is equal to the thermal contraction in the superconducting filaments. Then the critical current becomes a function of the height ($-D/2 < x < +D/2$) along the conductor cross-section. Only the "untwisted" case is considered, which enables a direct integration for determining the total critical current of the conductor. Two different cross-sections are considered: rectangular (tape) and circular (wire).

B. Large bending radii: $R_b > D/(2\epsilon_{2\%})$

In the case of small strains, which is equivalent to a large bending radius, the axial strains are within the range from $-\epsilon_{2\%}$ to $\epsilon_{2\%}$. Hence the second tensile regime is not present in the conductor. Moreover the strain dependence in the limit for small compressive strains can be approximated by a linear dependence. Then a simple dependence for the normalised critical current of a bend tape is derived:

$$i_c = 1 - \frac{\alpha_1}{4} \frac{D}{2R_b}, \quad (2)$$

and for a wire:

$$i_c = 1 - \frac{2\alpha_1}{3\pi} \frac{D}{2R_b}. \quad (3)$$

This relation couples the exponent that is measured in the compressive axial strain regime (α_1) directly with the I_c reduction of a bend wire.

C. Small bending radii: $R_b < D/(2\epsilon_{2\%})$

If the conductor is bent over a smaller radius and the maximum value of the axial strain passes $\epsilon_{2\%}$, then the second tensile regime has to be considered. This slightly complicates the arithmetic necessary to determine the critical current. A reasonable accurate and presentable solution is obtained in case of a tape conductor:

$$i_c = 1 - \frac{\alpha_1}{4} \frac{D}{2R_b} - \frac{D}{4R_b} \left(x + \frac{1}{a_3} (1 - e^{-a_3 x}) \right)$$

with:

$$x = \frac{2R_b}{D} - \epsilon_{2\%}.$$

In this solution for a square conductor, again there is a linear reduction assumed for the compressive strain regime.

D. Overall result

The critical-current reduction, as calculated with the bending model, is presented in figure 4. In this graph the i_c is presented as a function of the inverse bending radius ($D/2R_b$), which is equal to the maximum strain present in the superconductor. The exact solution, when the strain is below $\epsilon_{2\%}$, is also drawn for the circular and rectangular conductors. For larger maximum strains ($>\epsilon_{2\%}$) there is a more pronounced reduction of the critical current.

Fig. 4. Critical current reduction as function of the inverse bending radius. The two descending dotted lines represent the linear slope that is determined by the compressive strain (α_1).

The critical-current reduction for an extended strain range is presented in figure 5. In this graph the x-axis represents normalised bending radius. A tensile strain above $\epsilon_{2\%}$ leads to a drastic reduction of the critical current when the wire is bend over a small radius.

In the example, with $\alpha_1 = 30$, the slope of the critical current for a large bending radius is relatively small. At a maxi-

imum strain off $\varepsilon_{2\%} = 0.4\%$, the I_c reduction is only 3% for a rectangular conductor. When the I_c curve is shown as a function of the radius, as in figure 5, the slope of the I_c reduction is small if the bending radius is large. As a consequence it is relatively complicated to determine the value of α_i by a pure bending experiment. For the example an accuracy in the I_c measurement of about 0.1% is required.

The calculated performance presented in figure 4 and 5 summarises the application of the irreversible I_c description in a model for a bend conductor. The validity of this $I_c(R_b)$ model has to be investigated by comparing the I_c of a single type of superconductor in different deformation experiments. The transition from the first to the second tensile regime ($\varepsilon_{2\%}$) can be compared in an axial pull and a bending experiment. The slope of I_c reduction in the compressive strain regime can be determined by a bending experiment if $\varepsilon_{2\%}$ is large and the I_c measurement is very accurate.

Fig. 5. Critical-current reduction as a function of the normalised bending radius, for a circular and rectangular conductor.

VI. THE MICROSCOPIC POINT OF VIEW

The description of the irreversible I_c -strain relation that is considered here assumes two different slopes (α_1 and α_3) for compressive and tensile strains. In the intermediate strain regime the reduction (α_2) is small, but the current will never increase after changing the strain. The strong reduction that is observed for (intrinsic) tensile strains is attributed to cracks in the micro-structure. The I_c reduction will then be a summation of the influence of a certain collection of individual cracks. The precise distribution of these cracks along the conductor cross-section will determine the slope of the I_c reduction.

That a compressive strain leads to a smaller I_c reduction than a tensile strain can be explained. The conductor is considered as a collection of superconducting grains embedded in a metallic matrix. Moreover it is assumed that shear and tensile strains acting on the grain boundaries will mainly

contribute to the micro-cracks. Several types of shear and tensile stresses will act on the grain boundaries, even if the considered structure is uni-axially compressed:

- Shear stresses occur in the grain boundaries in various directions.
- Realignment of grains will lead to tensile forces acting on a certain fraction of the grain boundaries.
- A tensile transverse stress will occur in the polycrystalline structure if the Poisson's ratio of the metallic matrix is larger than the Poisson's ratio of the polycrystalline structure.

All the mechanisms mentioned here can induce cracks between the grains. But the distribution of the cracks, due to a uni-axial compression, will differ entirely from the crack distribution, due to a tensile strain. It is the number of cracks that interrupts the current path that counts for the critical current of the structure. In that case an axial tensile strain cause a larger reduction in the critical current than a compressive strain. The I_c reductions measured in the Bi-2212 wires indicate that these geometrical effects cause a difference of typically a factor of 10 between the I_c reduction due to tensile and compressive strains.

VII. CONCLUSIONS

1 - A model for the strain dependence of the I_c in Bi-2212 conductors is developed, based on axial strain experiments on Bi-2212/Ag wires. Two different degradation rates are assumed in the I_c reduction due to axial compression and elongation. In the intermediate strain range the I_c is almost constant. The transition at $\varepsilon_{2\%}$ from the first to the second tensile strain regime starts when the thermal contraction of the Bi-2212 is counteracted.

2 - The characteristics of the proposed model is investigated further by comparing the strain dependence of various pre-strained Bi-2212 wires. The results confirm the predicted dependence quite well.

3 - The model is applied to predict the behaviour of bent conductors. The I_c of a circular and rectangular conductors is proportional to the inverse bending radius for small strains. The I_c of a rectangular conductor is described with an analytical expression, over an extended strain range.

4 - The observed difference in strain dependence for tensile and compressive strains, may be related to a different distribution of the (micro)cracks in the polycrystalline structure.

REFERENCES

- [1] B. ten Haken, H.H.J. ten Kate and J. Tenbrink, "Compressive and tensile axial strain reduced critical currents in Bi-2212 conductors", IEEE Trans. on Superconductivity (to be published 1995).
- [2] B. Ten Haken, "Strain effects on the critical properties of high-field superconductors", Phd Thesis, University of Twente, Enschede, the Netherlands (1994).