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Bending and axial strain dependence of the critical current in superconducting BSCCO tapes

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Abstract
A comparison is made between the critical current (I_c) versus bending strain and axial strain of superconducting multi-filamentary $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) AgMg sheathed tapes. For the bending strain measurement the tape is sandwiched between a curved base and cover plate. Six sets of bending plates introduce bending strains ranging from 0% to 1.0%. The measurements show a slight decrease in I_c after the first bending step after which the degradation becomes more pronounced. The I_c in a bent conductor is calculated assuming a linear axial strain profile inside the conductor. For this calculation the I_c degradation determined in an axial compression and elongation experiment is used. The model predicts an immediate decrease of I_c, caused by the compressive strain dependence. There is a good agreement (within 5%) between the measured data and the calculated values. Based on this good agreement it can be concluded that a possible shift in the neutral line or the formation of additional cracks due to bending has no significant influence on the I_c degradation. It is concluded that the influence of thermal contraction is crucial for a good calculation.

1. Introduction

Bismuth-based oxide high-temperature superconducting tapes are used in various applications. The conductors then undergo mechanical deformations, for example, conductor winding, that can significantly degrade the critical current (I_c). In order to make optimal use of the conductor it is necessary to be able to predict the transport properties under operating conditions. Critical current versus bending measurements performed on $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) AgMg sheathed tapes are presented. The irreversible reduction of the critical current due to bending is calculated, assuming a linear axial strain profile in the tape. For this calculation the results from an axial compression and elongation experiment are used.

2. Experimental details

The test sample is sandwiched between a curved base plate and a curved cover plate as shown in figure 1. The sample is mounted at room temperature and subsequently cooled to liquid nitrogen temperature. The plates are made from epoxy reinforced glass fibre (G10) to match the thermal contraction of the sample. After determination of I_c the sample is brought to room temperature. At this temperature the sample is further deformed using a different set of bending plates. Six sets of bending plates are used, which introduce a maximum strain at the matrix surface of 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0% for a 0.27 mm thick conductor. The total length of the sample is 80 mm and the distance between the voltage taps is 30 mm. The I_c is defined, with a four-point measurement method, at an electric field criterion of 10^{-4} V m^{-1}. For the axial compression and elongation measurement, two tapes of the same batch are investigated. One piece is used in the compressive strain regime and the other in the tensile strain regime. The sample is soldered to a brass U-shaped sample holder. After cooling to liquid nitrogen temperature, strain is applied to the sample by a force that acts on the legs of the U-shaped sample holder. The strain can be varied in the range

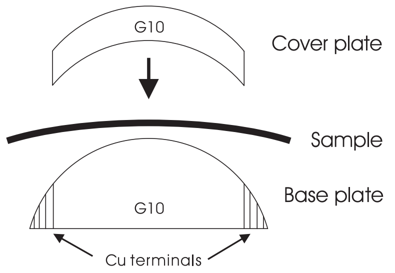

Figure 1. The sample is sandwiched between a curved base and cover plate.

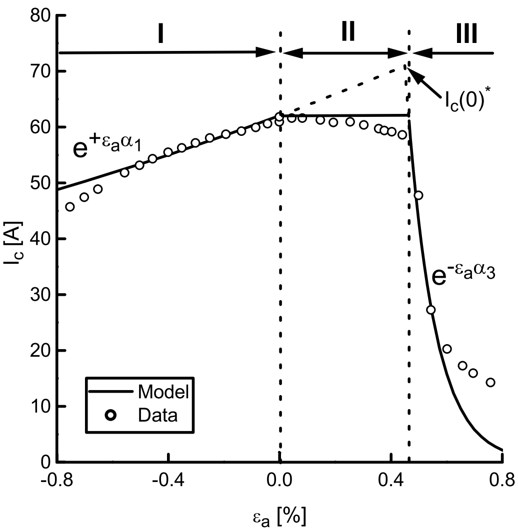

Figure 2. Axial strain dependence of the critical current of sample A as measured on a brass bending spring at 77 K (data) and the description (model).

from −1% to +1%. A detailed description of this measurement method is given elsewhere [1].

3. Uniaxial strain

The measured axial strain (ε_a) dependence of tape A is plotted in figure 2. The I_c curve can be defined by three different exponents for the different strain regimes [2]:

$$\begin{array}{lll} \text{I}: & \varepsilon_a < 0 & I_c \propto e^{\varepsilon_a \alpha_1}, \\ \text{II}: & 0 < \varepsilon_a < \varepsilon_{irr} & dI_c/d\varepsilon_a = 0, \\ \text{III}: & \varepsilon_a > \varepsilon_{irr} & I_c \propto e^{-\varepsilon_a \alpha_3}. \end{array}$$

The compressive regime (I) shows a relatively slow degrading of I_c, starting immediately from $\varepsilon_a = 0$. In the limit for small compressive strains the I_c degradation can be approximated by a linear dependence ($I_c \propto 1 - \alpha_1 \varepsilon_a$). This behaviour has been reported earlier on several BSCCO conductors [3]. The mechanism behind this irreversible reduction still remains unclear. Other authors even reported a strain insensitive plateau in their data, using a different measurement method [4]. The tensile strain behaviour has been described by various authors [5–7]. The I_c in the second strain regime (II) shows a very small decrease and is often considered to be constant up to an irreversible strain level (ε_{irr}). Beyond this strain level the I_c falls abruptly (III). This strong reduction is commonly attributed to crack formation and propagation. The value of ε_{irr} depends on the pre-compression on the superconducting filaments after cool down. The pre-strain of the filaments in a bare tape at a certain temperature depends on the matrix material, the superconductor to matrix ratio and the reaction temperature. This pre-strain can be estimated if the mechanical properties of the matrix and the filaments are known. A detailed analysis of this problem is made by Passerini [7]. After soldering the tape to the brass sample holder, the thermal contraction is determined by the holder. The amount of pre-strain of the filaments (ε^{fil}) can then be calculated with

$$\varepsilon^{fil}(T) = \varepsilon^{fil}(T_{solder}) + \int_{T_{solder}}^{T} (\alpha^{brass} - \alpha^{fil})\, dT, \qquad (1)$$

where α is the thermal contraction coefficient.

4. Bending strain

The bend strain is defined as the maximum axial strain on the matrix surface: $\varepsilon_b = \varepsilon_{max} = D/2R_b$ where D is the thickness of the sample and R_b is the curvature radius. In the case of a tape conductor with elastic properties, there will be a linear axial strain profile from $-\varepsilon_{max}$ to $+\varepsilon_{max}$ along the height of the conductor. Together with the description for the three axial strain regimes the critical current density (J_c) becomes a function of the height ($-D/2 < x < +D/2$) along the conductor cross-section. Assuming a homogeneous Bi-2223 distribution, the I_c of the conductor can be calculated by direct integration of J_c over the entire cross-section.

In the case of small strains ($\varepsilon_{max} < \varepsilon_{irr}$, i.e. large bending radius), the third strain regime (III) will not occur inside the tape. Therefore, a simple dependence for the normalized critical current (i_c) of a bent tape can be derived for a rectangular cross-section (using the linear approximation for the compressive regime):

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

If the maximum value of the axial strain becomes too large ($\varepsilon_{max} > \varepsilon_{irr}$, i.e. small bending radius) then the third strain regime has to be considered. This leads to a different i_c dependence for a rectangular cross-section (using the linear approximation for the compressive regime):

$$i_c = 1 - \frac{\alpha_1}{4} \frac{D}{2R_b} + \frac{R_b}{D} \left(\frac{1}{\alpha_3}(1 - e^{-\alpha_3 x}) - x \right), \qquad (3)$$

where

$$x = \frac{D}{2R_b} - \varepsilon_{irr}. \qquad (4)$$

With (2) and (3) the bending strain dependence can be predicted using the uniaxial strain data.

5. Results

The constants $I_c(0)^*$, α_1, α_3 and ε_{irr} are determined from the $I_c(\varepsilon_a)$ data shown in figure 2. $I_c(0)^*$ is a fictional current predicted by the I_c description in the strain-free case. Due to differences in the measurement method between

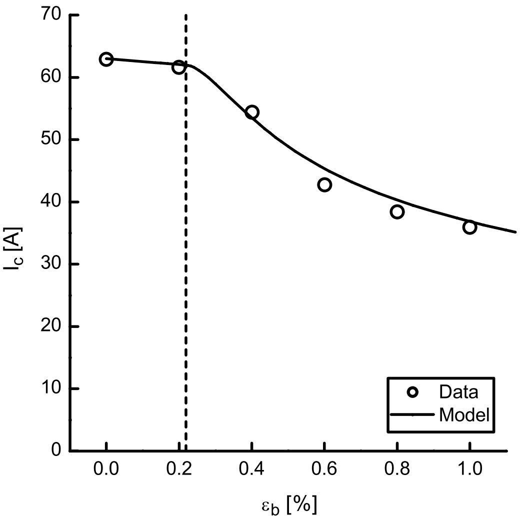

Figure 3. Critical current reduction as a function of bending strain of sample A, measurement (data) and calculation (model). The dashed line represents the value of ε_{irr}.

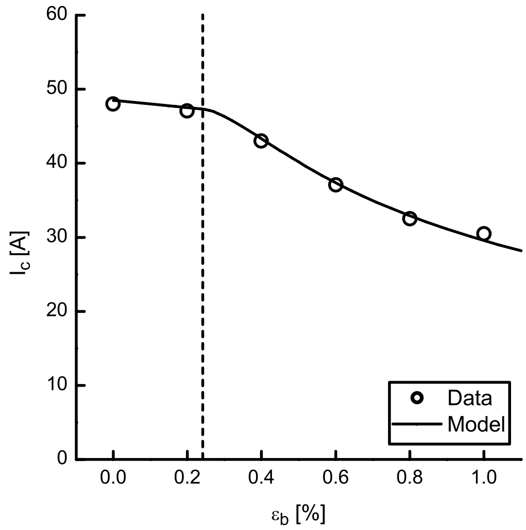

Figure 4. Critical current reduction as a function of bending strain of sample B, measurement (data) and calculation (model). The dashed line represents the value of ε_{irr}.

Table 1. Sample properties.

	Sample A	Sample B
$I_c(0)^*$ (A)	71	61
α_1	30	40
α_3	1000	550
ε_{irr} (%)	0.22	0.24
	$(0.45 - 0.23)$	$(0.47 - 0.23)$
Number of filaments	55	57

the bending and the axial strain measurements, the pre-compression of the filaments will be different in both cases. In the bending experiment, the strain is introduced at room temperature. However, the axial strain measurement is performed at liquid nitrogen temperature. In order to compare these measurements ε_{irr} has to be altered by the difference in pre-strain. This difference can be calculated by comparing the thermal contraction of the sample holder with respect to the filaments, hereby neglecting the initial difference in pre-compression between solder and room temperature (≈0.01%). With an estimated contraction of $\Delta\varepsilon = 0.65\%$ for the brass sample holder and $\Delta\varepsilon = 0.42\%$ for the ceramic filaments, the difference is 0.23%. Table 1 shows the fitted values of $I_c(0)^*$, α_1, α_3 and ε_{irr} for the two different conductors.

The results of the measurement and calculation of I_c as a function of the bending strain are shown in figures 3 and 4. The first part of the curve, where $0 < \varepsilon_{max} < \varepsilon_{irr}$, is determined by the compressive strain dependence. The calculated slope of approximately 1% per percent strain is supported by the measurement. The second part, $\varepsilon_{max} > \varepsilon_{irr}$, is mainly determined by the tensile strain dependence. The strong I_c reduction above ε_{irr} results in a more pronounced decrease. Overall there is a good agreement (within 5%) between the measured data and the calculated values. This good agreement implies that an eventual shift in the neutral line, as can be induced by non-elastic deformations, or the formation of additional cracks due to bending has no significant influence.

6. Conclusions

- The proposed model can be used to approximate the bending strain dependence of I_c using the measured axial strain dependence of I_c.
- The model predicts an immediate decrease of I_c, even in the case of a large bending radius, caused by the compressive strain dependence. No strain-insensitive regime exists in the case of bending.
- Because of the good agreement between the measured and calculated data no shift in neutral line or formation of additional cracks due to bending the conductor is expected to influence I_c.
- The influence of thermal contraction is crucial for a good calculation of the bending strain dependence.

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