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A model to describe the angular dependence of the critical current in a Bi-2223/Ag superconducting tape

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Abstract

A model to describe the angular dependence of the critical current of a superconducting Bi-2223/Ag tape is developed. The model is based on a Gaussian distribution of the misalignment angles of the grains. With this model it is possible to calculate the standard deviation of the misalignment angle of the grains from critical current measurements in a magnetic field oriented perpendicular and parallel to the tape plane. This enables us to determine the critical current behaviour for all orientations of the magnetic field. The theory is confirmed in an experimental way. The angular dependence of the critical current of the measured tape can be described at 77 K in the region between 0 and 200 mT within 3% by using a standard deviation of 7.8° in the misalignment angle. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The field dependence of the critical current (I_c) is an important parameter of superconducting $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223)/Ag tapes. Because the Bi-2223 compound is a highly anisotropic material, the critical current in a Bi-2223 tape does not only depend on the magnitude of an applied magnetic field (B), but also on the orientation of this field. Due to the rolling steps in the production process of the tapes most grains are aligned in the tape plane, but not all the grains are aligned perfectly in this plane. If the magnetic field is applied perpendicular to the wide face of the tape conductor, it is applied mainly parallel to the c-axis of the grains. This results in a much larger decrease in critical current than in the case where the magnetic field is applied parallel to the tape surface (mainly parallel to the ab-plane of the grains). In this paper a method is presented to calculate the critical current as a function of the applied magnetic field for any orientation of the magnetic field, if the $I_c(B)$ relations are known for perpendicular and parallel applied magnetic field. The $I_c(B)$ relations for angles in between can be calculated from the model.

2. Theory

The critical current of a superconducting Bi-2223/Ag tape does not only depend on the

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magnitude of an externally applied magnetic field, but also on the orientation of that field. However, in small crystals of Bi-2212 it is observed that the critical current does not depend on a magnetic field applied parallel to the *ab*-plane [1]. In a Bi-2223 tape, the *ab*-planes of the grains have a certain misalignment with respect to the tape plane [2,3]. This means that if the magnetic field is applied parallel to the tape surface these misaligned grains see a fraction of this field perpendicular to their *ab*-plane. To describe the magnetic field dependence of a Bi-2223/Ag tape it is assumed that the critical current of such a tape only depends on the component of the magnetic field that is applied perpendicular to the *ab*-plane of the grains.

Every grain in the tape has a certain misalignment angle φ, see Fig. 1. Only misalignment in the plane perpendicular to the current direction is taken into account. X-ray measurements have shown that the grains are misaligned with a certain distribution that is symmetrical around the tape plane [2]. In X-ray measurements only grains close to the surface are seen, while the critical current depends on all the current-carrying grains (not all the grains can carry a supercurrent). In the analysis the angular distribution is described by a Gaussian function (as proposed in Ref. [4]) with an average misalignment of 0° and a standard deviation σ:

$$G(\varphi) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{-(\varphi^2/2\sigma^2)}, \quad -90^\circ \leqslant \varphi < 90^\circ, \qquad (1)$$

where $G(\varphi)$ is the fraction of grains that have a misalignment angle φ.

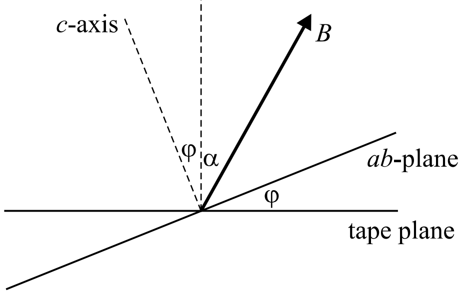

Fig. 1. Definitions of the field angle α and the misalignment angle φ.

If a magnetic field B with orientation α, see Fig. 1, is applied to the tape (the magnetic field is always perpendicular to the current direction), a misaligned grain will see a magnetic field component of $B|\cos(\alpha+\varphi)|$ perpendicular to its *ab*-plane. The effective perpendicular component of the magnetic field on all the grains can be calculated by

$$B_{\perp,\mathrm{eff}}(\alpha) = B \int_{\varphi=-90^\circ}^{90^\circ} G(\varphi)|\cos(\alpha+\varphi)|\,\mathrm{d}\varphi, \qquad (2)$$

which is equal to $B_{\perp,\mathrm{eff}}(\alpha) = B\cos(\alpha)$ if all grains are perfectly aligned ($\sigma = 0^\circ$). Now a function $f(\alpha)$, introduced in Ref. [5], can be defined by normalising $B_{\perp,\mathrm{eff}}(\alpha)$ with respect to the $B_{\perp,\mathrm{eff}}$ value for the case that the magnetic field is applied perpendicular to the tape surface:

$$f(\alpha) = \frac{B_{\perp,\mathrm{eff}}(\alpha)}{B_{\perp,\mathrm{eff}}(0^\circ)} = \frac{\int_{\varphi=-90^\circ}^{90^\circ} G(\varphi)|\cos(\alpha+\varphi)|\,\mathrm{d}\varphi}{\int_{\varphi=-90^\circ}^{90^\circ} G(\varphi)|\cos(\varphi)|\,\mathrm{d}\varphi}. \qquad (3)$$

The function $f(\alpha)$ is a scaling function, independent of the magnitude of the magnetic field. The effective perpendicular field component $B_{\perp,\mathrm{eff}}$ is the same for an applied magnetic with magnitude B and orientation α as for a field with magnitude $B \times f(\alpha)$ that is applied perpendicular to the tape surface. From the assumption that the critical current density only depends on the field components applied perpendicular to the *ab*-planes of the grains, it follows directly that $I_\mathrm{c}(B,\alpha) = I_\mathrm{c}(B \times f(\alpha), 0^\circ) \equiv I_\mathrm{c}(B^*, 0^\circ)$, where B^* is the scaled field amplitude.

Fig. 2 shows the behaviour of $f(\alpha)$ for several values of the standard deviation σ. For $\alpha < 70^\circ$ the function $f(\alpha)$ is almost equal to $\cos(\alpha)$ (the line with $\sigma = 0^\circ$). A tail appears for $\alpha > 70^\circ$, if $\sigma > 0^\circ$. Due to the larger misalignment of the grains ($B_{\perp,\mathrm{eff}}$ is larger), the deviation with the line $\cos(\alpha)$ increases for larger σ. The averaging effect of the misalignment distribution leads also to the fact that the function $f(\alpha)$ is almost constant between $\alpha \approx 87^\circ$ and $\alpha = 90^\circ$. This effect is more pronounced for high values of σ.

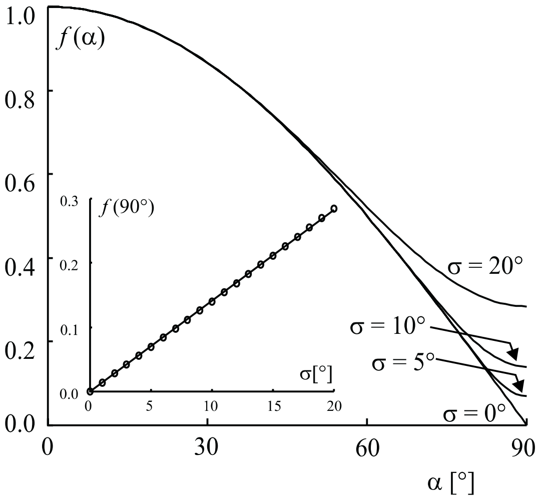

Fig. 2. The function $f(\alpha)$ for several values of the standard deviation in the misalignment angle. Also the relation between σ and $f(90°)$ is shown. The points are calculated data, the line is a linear description of these data.

The shape of the $f(\alpha)$ function does not depend significantly on the distribution function for the grain misalignment in Eq. (1): a rectangular or a triangular distribution function gives similar results for $f(\alpha)$.

In Fig. 2 the relation between $f(90°)$ and σ is also shown. The points are calculated data and can be described within 1% by the function

$$f(90°) = 0.0141\sigma \Longleftrightarrow \sigma = 70.9 f(90°), \qquad (4)$$

for σ between 0° and 20°. This means that if $f(90°)$ is known, σ is known and thus $f(\alpha)$ can be calculated for any α.

3. Experimental

The DC voltage–current characteristics of a short sample superconducting tape (about 8 cm) were measured at liquid nitrogen temperature (77 K) using a four-point measurement, with a voltage tap distance of about 2 cm. A dipole magnet was used to apply DC magnetic fields up to 200 mT with various orientations to the tape surface. The voltage criterion to determine the critical currents was 10^{-4} V/m.

A Bi-2223 tape (with a pure silver matrix and sheath) has been used in the experiment. The tape has been fabricated with the powder-in-tube (PIT) method. It has 37 non-twisted filaments, a width of 3.4 mm and a thickness of 0.20 mm. The filling factor is about 25% and the critical current at 77 K in self-field is 28 A.

4. Results

In Fig. 3 the magnetic field dependence of the critical current of the tape is shown for several orientations of the magnetic field. From the measurements for perpendicular ($\alpha = 0°$) and parallel ($\alpha = 90°$) magnetic field, the value of $f(90°)$ can be determined as described in Section 2. From the measurements a value of 0.11 is found for $f(90°)$. According to Eq. (4), the standard deviation for the misalignment is now $\sigma = 7.8°$.

In Fig. 4 the measurement results from Fig. 3 are plotted as a function of the scaling field $B^* = B \times f(\alpha)$. The function $f(\alpha)$ is calculated using Eq. (3) with a standard deviation for the misalignment angle of $\sigma = 7.8°$. All data fit within less than 3% on the data measured for the field applied perpendicular to the tape surface. The results of this

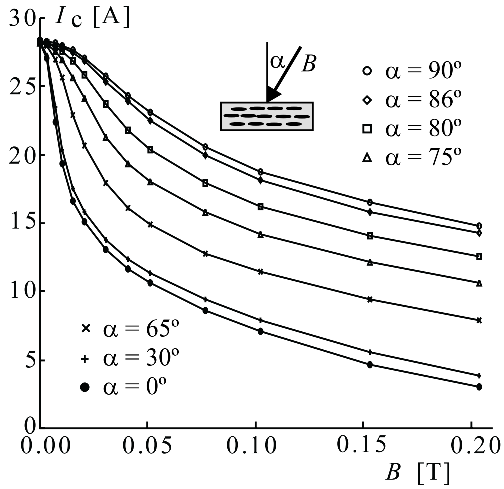

Fig. 3. Magnetic field dependence of the critical current for several orientations of the applied magnetic field. Symbols are measured data, lines are a guide to the eye ($T = 77$ K).

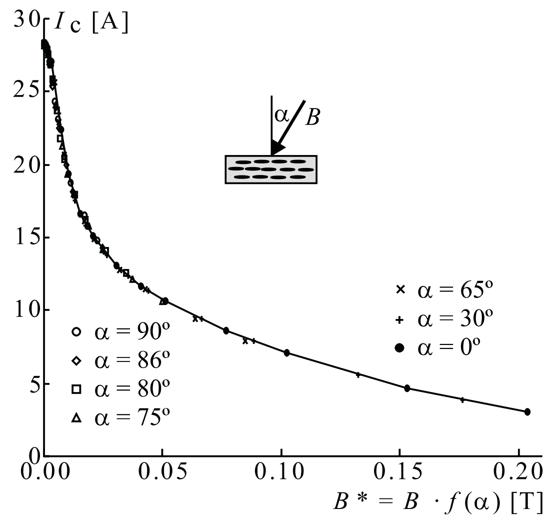

Fig. 4. The critical current as a function of the scaled magnetic field $B^* = B \times f(\alpha)$. Symbols are measured data, the line is a guide to the eye ($T = 77$ K).

tape are similar to results obtained from other tapes [5,6].

5. Conclusions

The angular dependence of the critical current of a Bi-2223/Ag tape is investigated at liquid nitrogen temperature. A scaling function $f(\alpha)$ can be calculated by assuming that the grains in the tape are aligned with a Gaussian distribution. The standard deviation σ of the misalignment angle is the only free parameter in the model. The value of $f(90°)$ can be determined from the $I_c(B)$ measurements for perpendicular and parallel applied magnetic field.

From this value σ can be determined and thus $f(\alpha)$ can be calculated for any orientation of the magnetic field. The validity of the model has been confirmed by measured data. Using a value of 7.8° for σ, the field dependence of the tape can be described accurately by $I_c(B, \alpha) = I_c(B \times f(\alpha), 0°) = I_c(B^*, 0°)$ within the field range between 0 and 200 mT at 77 K.

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