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Physica C 386 (2003) 575–577
PHYSICA C
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Critical current density anisotropy of aligned MgB_2 crystallites

O.F. de Lima [a,*], C.A. Cardoso [b]

[a] Instituto de Física Gleb Wataghin, UNICAMP, C.P. 6165, 13083-970 Campinas, SP, Brazil
[b] Depto. de Física, UFSCar, C.P. 676, 13565-905, São Carlos, SP, Brazil

Abstract

We have obtained the induced critical current density, $J_c \propto \Delta M$, with ΔM taken from hysteretic magnetization loops measured for temperatures between 5 and 35 K, in a sample of aligned MgB_2 crystallites. We found an almost temperature independent ratio $J_c^{ab}/J_c^c \sim 1.5$, between the critical current density parallel and perpendicular to the *ab* planes. This latter result follows closely the expected dependence of $J_c^{ab}/J_c^c \approx \xi_{ab}/\xi_c \sim 1.7$, where ξ_{ab} and ξ_c are the corresponding coherence length values. Uncertainties related to the evaluation of geometric factors and subtraction of a magnetic background are also discussed.

PACS: 74.25.Ha; 74.60.Ec; 74.60.Jg; 74.70.Ad
Keywords: MgB_2 anisotropy; MgB_2 crystallites; Magnesium diboride; Critical current anisotropy

1. Introduction

The strongly anisotropic crystalline structure of MgB_2 has been known [1,2] for almost 50 years before the recent discovery of superconductivity in this binary compound [3]. Then, it was not a surprise when specific heat studies done in polycrystalline samples [4] as well as band structure calculations [5] pointed to a possible anisotropic nature of the electronic and magnetic properties of MgB_2. The first direct measurement of an anisotropic superconducting property was achieved for the bulk nucleation field H_{c2}, in samples of aligned MgB_2 crystallites [6]. A ratio $\gamma = H_{c2}^{ab}/H_{c2}^{c} \approx 1.7$ between the critical field parallel to the *ab* plane and parallel to the *c*-axis direction was found. Since then, different groups have found values of γ between 1.1 and 6, using different types of samples and different techniques to characterize the normal–superconducting transition [7]. In our view the large scattering of reported γ values could be ascribed mainly to three factors [8]: (1) the sample purity, since it affects directly the energy gap anisotropy at the microscopic level; (2) the experimental criterion used to define a reliable superconducting bulk transition; (3) the temperature dependence of γ that could be originated from a temperature dependent gap anisotropy. Indeed, recent reports [9,10] have shown that γ goes from $\sim$2 to $\sim$6 when T varies between $\sim$39 and $\sim$15 K.

Although no experimental results of J_c anisotropy in MgB_2 has been reported yet, it was anticipated [8] that the in-plane critical current density values, J_c^{ab} (for $H \| c$), should be at least about 60% higher than the values along the *c*-axis direction, J_c^c (for $H \| ab$). This outcome is expected

* Corresponding author. Fax: +55-19-3289-3137.
E-mail address: delima@ifi.unicamp.br (O.F. de Lima).

0921-4534/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0921-4534(02)02190-1

because J_c is proportional to ξ^2, where ξ is the anisotropic coherence length, therefore [11] $J_c^{ab}/J_c^c \approx \xi_{ab}/\xi_c \approx H_{c2}^{ab}/H_{c2}^c$. In this paper we present results which are consistent with this latter statement. We use the Bean's model [12] to analyze a series of hysteresis loops $M \times H$, taken between 5 and 35 K, in a sample of aligned MgB_2 crystallites.

2. Results and discussion

We measured a sample of well-aligned MgB_2 crystallites whose preparation details have been described elsewhere [6]. Briefly, a MgB_2 powder of almost 100% crystallites, was obtained from a weakly sintered material reacted at $T = 1200$ °C, much higher than the currently reported temperatures below 900 °C. By spreading this powder on both sides of a piece of paper we aligned the crystallites with their *ab* planes sitting on the paper surface. Several samples were then mounted consisting of a pile of five squares of 3×3 mm^2, cut from the crystallite-painted paper and glued with epoxy resin.

Measurements of the magnetic moment as a function of the applied magnetic field, for several temperatures below $T_c = 39$ K, were performed with a SQUID magnetometer (model MPMS-5), made by Quantum Design. The average crystallites dimensions were $10 \times 10 \times 2$ μm^3, determined by visual inspection of several of them. An estimate of the total volume of crystallites in the sample gives 0.06 mm^3, in agreement with a value that produces a slope $\Delta M/\Delta H = -1/4\pi$ for the region of diamagnetic shielding at $H \approx 0$. In order to subtract the magnetic background present in all measurements [6] the same type of measurements were repeated at temperatures above T_c (not shown here). No significant temperature dependence was observed for the hysteresis loops measured at several temperatures from 45 to 80 K, in the low field region. Thus, the loop obtained at $T = 45$ K was taken as a good approximation for the magnetic background, in the entire temperature range going from 5 to 35 K. The fully corrected magnetization curves are presented in Fig. 1, for (a) $H \| c$ and (b) $H \| ab$. The remanent magnetization values, in both field directions, can be seen in the insets of Fig. 1. To avoid complications associated with demagnetizing effects we will restrict the present analysis only to the case of $H = 0$.

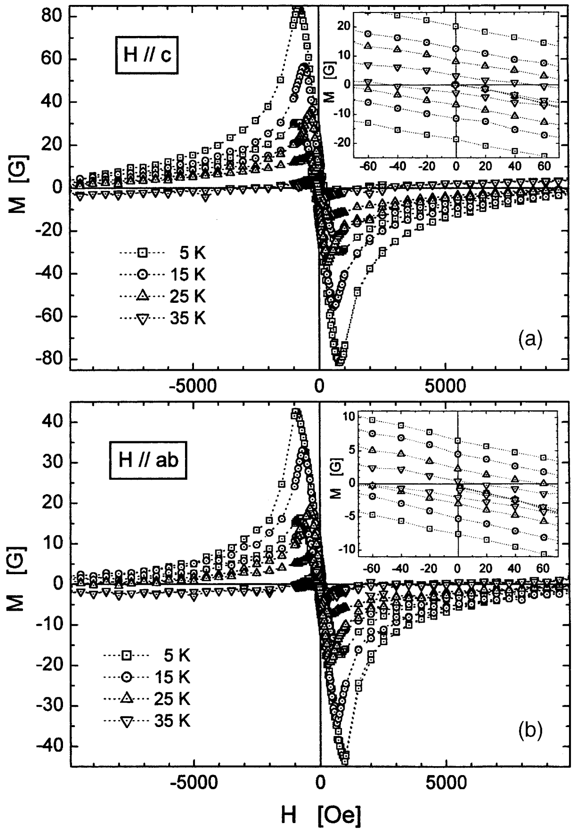

Fig. 1. Magnetization loops for applied fields H (a) perpendicular and (b) parallel to the crystallites planes after subtracting the magnetic background measured at $T = 45$ K. The insets are enlarged views near $H = 0$, showing the remanent magnetization in each temperature.

The critical current density can be estimated from the corrected magnetization curves of Fig. 1, if one assumes the occurrence of uniform gradients in the flux density distribution inside the crystallites. According to the Bean's critical state model [12] J_c is proportional to the width of the hysteresis loop and for a slab geometry reads

$$J_c = \frac{40|\Delta M|}{t(1 - t/3w)} \tag{1}$$

where $t < w$ are the sample dimensions perpendicular to the applied field and $|\Delta M|$ is the mag-

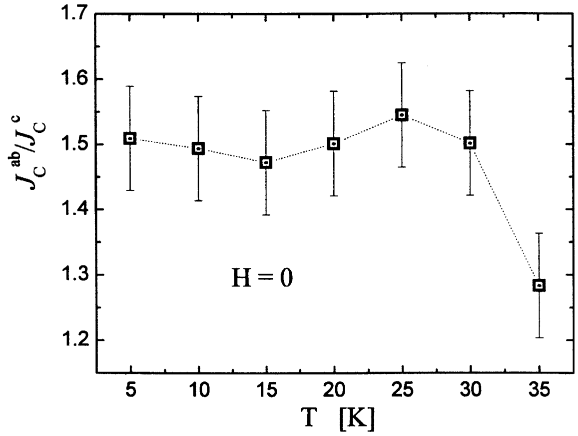

Fig. 2. Critical current density anisotropy (ratio between in-plane and out-of-plane values) evaluated from the remanent magnetization at zero applied magnetic field.

netization loop width. Notice that the sample used in this work is formed by a collection of isolated crystallites, so t and w appearing in Eq. (1) refer to the crystallites dimensions, instead of to the whole sample dimensions.

The ratio J_c^{ab}/J_c^c was determined by evaluating $|\Delta M|$ at $H = 0$, followed by the use of Eq. (1) to both field orientations. Fig. 2 shows that $J_c^{ab}/J_c^c = 1.5 \pm 0.1$, between 5 and 30 K and drops suddenly at $T = 35$ K. The large error bars shown in Fig. 2 reflect essentially the uncertainty in the crystallites sizes, taken to be $a = b = 10 \pm 4$ μm and $c = 2 \pm 1$ μm. Based on this evaluation it is safe to conclude that we found an anisotropy ratio J_c^{ab}/J_c^c of the same order of the H_{c2} anisotropy measured in the same sample [6]. A confirmation of this outcome through measurements taken on larger single crystals, or well-textured samples, is highly desirable. In this case, we expect also a large scattering of J_c^{ab}/J_c^c values coming from different works. Perhaps this will be even larger than what has been observed for H_{c2}^{ab}/H_{c2}^c [7], since the critical current density is a much complex variable that depends also on pinning of vortices and hence depends more strongly on sample quality.

3. Conclusions

Measurements of the critical current density anisotropy in MgB_2 have not been reported yet, although this has been an expected result [6,8,13]. Here we presented an experimental evaluation that gives an almost temperature independent ratio $J_c^{ab}/J_c^c = 1.5 \pm 0.1$, between the critical current density parallel and perpendicular to the *ab* planes of a sample formed by aligned MgB_2 crystallites. This result is consistent with the anisotropy value of H_{c2} ($\gamma \approx 1.7$) measured previously [6] in the same sample. Therefore, we conclude that in order to optimize J_c in MgB_2 wires or other polycrystalline components some texturization technique will be useful.

Acknowledgements

The authors acknowledge the financial support from the Brazilian Science Agencies FAPESP and CNPq.

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