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PHYSICA C

Physica C 226 (1994) 12–16

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Received 13 December 1993; revised manuscript received 22 March 1994

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PHYSICA A, PHYSICA B, PHYSICA C and PHYSICA D are published by North-Holland (Elsevier Science B.V.), Amsterdam.

Subscription data

Physica A (ISSN 0378-4371). For 1994, volumes 201–211 are scheduled for publication. Physica A is published semimonthly.
Physica B (ISSN 0921-4526). For 1994, volumes 192–202 are scheduled for publication. Physica B is published monthly.
Physica C (ISSN 0921-4534). For 1994, volumes 219–236 are scheduled for publication. Physica C is published two to three times per month.
Physica D (ISSN 0167-2789). For 1994, volumes 70–78 are scheduled for publication. Physica D is published semimonthly.
Subscription prices are available upon request from the publisher. A combined subscription to Physica A, Physica B, Physica C and Physica D is available at a reduced rate.

Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, China, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request.
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US mailing notice – Physica C (ISSN 0921–4534) is published three times per month except semi-monthly in January, August, October and December (total 32 issues) by Elsevier Science B.V., Molenwerf 1, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Annual subscription price in the USA is US $7578 (valid in North, Central and South America only), including air speed delivery. Second class postage paid at Jamaica, NY 11431.
USA POSTMASTERS: Send address changes to Physica C, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.
Airfreight and mailing in the USA by Publications Expediting.

Printed in The Netherlands

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Abstract

The hysteretic behavior in the $J_c(B_a)$ dependence for $(Bi_{1.64}Pb_{0.36})Sr_2Ca_2Cu_3O_y$ polycrystalline samples at low magnetic fields ($B_a < 30$ mT) has been studied in detail. The standard four-probe technique was used to measure the critical current density. It was shown that the samples exhibit values of J_c (77 K) ranging from 100 to 400 A/cm^2. In all the cases, a special behavior of the $J_c(B_a)$ dependence in decreasing magnetic fields was observed as compared with the Y–Ba–Cu–O system. An alternative explanation is given using models based on intragranular flux trapping.

1. Introduction

The study of the $J_c(B_a)$ dependence of sintered superconductors has played a central role in the understanding of the mechanism responsible for the superconducting transport current in these materials.

Peterson and Ekin [1] and later Evetts and Glowacki [2] showed the theoretical basis for its explanation. After them, many workers have observed the hysteretic behavior of the $J_c(B_a)$ dependence in Y–Ba–Cu–O polycrystalline superconductors. Altshuler et al. [3] suggested a model to explain the hysteresis in samples where the first critical field is neglectable. Müller and Matthews [4] generalized the model for any value of the first critical field both for field cooling (FC) and zero field cooling (ZFC) conditions.

We have investigated in detail the hysteresis in the $J_c(B_a)$ dependence of a sample with normal starting composition $Bi_{1.64}Pb_{0.36}Sr_2Ca_2Cu_3O_y$, which constitutes, as far as we know, the first report on the subject.

As is well known in the case of Y–Ba–Cu–O polycrystalline superconductors, the maximum of the $J_c(B_a)$ dependence in decreasing applied magnetic field is obtained when $B_a = B_p$ where $B_p > 0$ for every value of $H_{am} > H_{c1g}$ (here H_{am} is the maximum applied field and H_{c1g} the first critical field of the superconducting grains); and B_p increases when B_{am} is increasing.

In our samples, we have observed a behavior quite different from the one usually observed for Y–Ba–Cu–O ceramics, i.e., $B_p = 0$ for every value of B_{am}. In this paper, we give a possible explanation essentially based on the model described in Ref. [4].

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SSDI 0921-4534(94)00180-N

2. Experimental

Pb doped Bi–Sr–Ca–Cu–O oxide samples were prepared by a solid-state reaction of Bi_2O_3, PbO_2, $SrCO_3$, $CaCO_3$ and CuO powders [5]. The ratio of Bi:Pb:Sr:Ca:Cu in the starting material was 1.64:0.36:2:2:3. Appropriate amounts of the different components were weighed, manually mixed with an agate mortar using alcohol to homogenize the mixture which was then calcined at 800–820°C for 45 h in air and cooled in the furnace. This powder was again dry ball-milled for 24 h and heated at 845°C for 24 h. The powders were then ground manually using an agate mortar and pressed into 1 mm thickness pellets at (200–300) MPa. The pellets were sintered at 845°C for 40 h. Thin slabs of Bi ceramic were cut from the samples prepared as described above with dimensions of typically $d=0.2$ mm (thickness), $w=2$ mm (width) and $l=10$ mm (length).

The standard four-probe technique was used to measure the $J_c(B_a)$ dependence in ZFC conditions in increasing applied field ("virgin curve") and in decreasing applied field ("returning curve"), the latter for different values of B_{am}. The magnetic field was applied perpendicular to the current which was injected along the major axis of the sample.

The results of X-ray diffraction analysis have shown that our samples contained about 85% of the high-T_c phase and the rest basically composed by the low-T_c one. The optical microscopy revealed that the average grain size was approximately 5 μm.

3. Results and discussion

We show in Fig. 1 the normalized critical current density versus increasing applied field curve for ZFC conditions. Good agreement of the experimental data was found as compared to the formula

$$J_c(B_a) = \frac{1}{1+\left(\frac{B_a}{B_0}\right)^{1.5}} \qquad (1)$$

according to Müller et al. [6], which assumes Airy patterns for the intergrain junctions [7], where B_0 is a parameter connected somehow to the size of the weak links; J_c is the normalized critical current density and B_a the flux density of the applied magnetic field. The sensitivity of J_c on magnetic field reflects that there is a large amount of weak-link junctions.

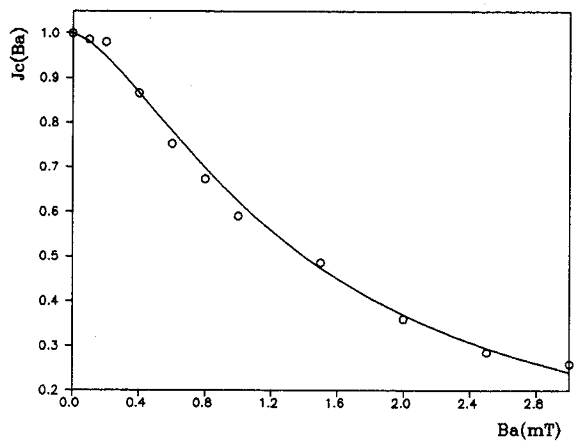

Fig. 1. Variation of the normalized critical current density with flux density of applied magnetic field at 77 K: (○) experimental data, (–) $J_c(B_a)$ fitting according to Eq. (1), with $B_0=14$ mT.

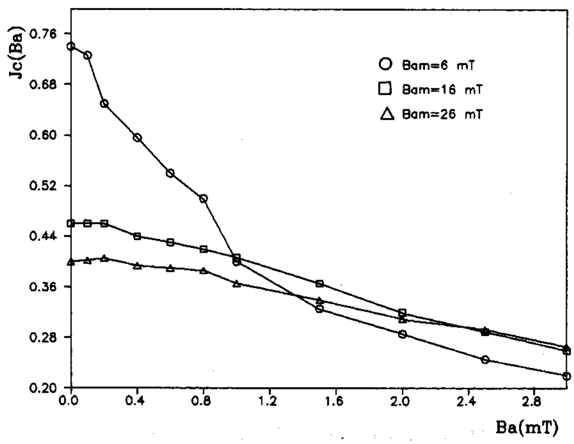

Fig. 2. Experimental $J_c(B_a)$ characteristics when the external field decreases from (1) $B_{am}=6$ mT; (2) $B_{am}=16$ mT and (3) $B_{am}=26$ mT after ZFC.

Fig. 2 shows the $J_c(B_a)$ dependence in decreasing magnetic field for different values of B_{am} the maximum values of which are situated for all cases at $B_a=0$. Finally we obtained the "flux trapping" curve [8] which is shown in Fig. 3. It saturates at about 26 mT and $J_c(0, B_{am})$ decreases from its maximum value at about 2.5 mT.

The explanation of the hysteretic behavior (exposed in Refs. [3] and [4]) rests on two insights: (1) the sintered bulk superconductor consists of a

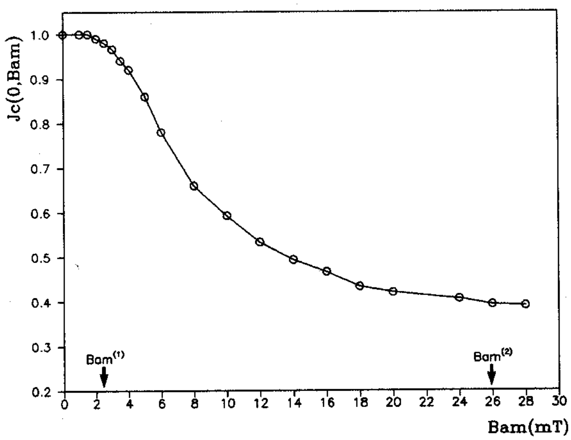

Fig. 3. $J_c(0, B_{am})$ vs. B_{am} characteristic. In the figure, $B^1_{am} = \mu_0 H_{c1g}$ and $B_{am}{}^2 = \mu_0(H_{c1g} + 2H^*)$ [8].

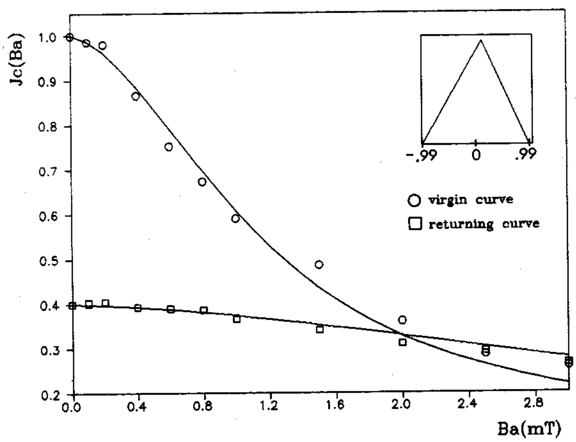

Fig. 4. Calculated and experimental critical current densities as a function of flux density of applied magnetic field, B_a, for the "virgin" and "returning" curves corresponding to $B_{am} = 26$ mT. The inset displays the distribution chosen for the geometric factor G.

random Josephson weak-link network. Such a low value of the field dependence of J_c could be explained by the presence of Josephson-like weak coupling between superconducting grains (see Fig. 1);

(2) at the field H_{am} above H_{c1g}, the demagnetizing effect of grains affects the magnetic field that threads the grain-boundary Josephson junctions. The demagnetization depends on the irreversible magnetization of the grains which in turn causes the critical current density to become hysteretic (see Fig. 4) because

$$H_i = H_a - GM , \tag{2}$$

where H_i, H_a, M and G are intergranular magnetic field, applied magnetic field, magnetization of the grains and a geometric parameter, respectively.

In our materials both insights are experimentally proved through the results of the "virgin" and "flux trapping" curves. That is why we think that the Müller model [4] may be used in this case.

Let us suppose that there is just one Josephson in the case $H_i < H_{c1g}$ and $B_{eq}(H_{im}) > 2\mu_0 H^*$ (Fig. 2, curve 3), where H^* is the full penetration field and B_{eq} is the equilibrium induction of the superconducting grains. In this case

$$H_i = \frac{H_a - G\dfrac{H^*}{2}}{1-G} ; \tag{3}$$

here $H_i = 0$ when $H_a = GH^*/2$ and $H_p = B_p/\mu_0 = 0$ when $G = 0$. In order to calculate the average of $J_c(B_a)$ in a decreasing applied magnetic field we can consider a network of Josephson junctions with statistical distribution of L and G [4]:

$$\langle J_c \rangle = \int\int J_c(G, L)\Omega(G)\delta(L)\mathrm{d}L\mathrm{d}G . \tag{4}$$

Here L is the length of the boundaries, and

$$J_c(G, L) = \frac{\left|\sin\left(\pi\dfrac{\Phi}{\Phi_0}\right)\right|}{\left|\pi\dfrac{\Phi}{\Phi_0}\right|} , \tag{5}$$

where $\Phi = 2\lambda L\mu_0 H_i$ and $\Phi_0 = 2.07 \times 10^{-15}$ Wb. The value of $H_p = B_p/\mu_0$ is reproduced by using a symmetric triangular distribution of G with $G_{peak} = 0$ (see Fig. 4). We have assumed $\lambda = 140$ nm [9], $\mu_0 H^* = 16$ mT and $\langle L \rangle = 3.6$ µm, where λ is the London penetration depth, $\langle L \rangle$ is the mean value of L. The value of H^* is different from the 12 mT obtained using the $J_c(0, B_{am})$ versus B_{am} dependence following the method described in Ref. [8]. The difference could be explained by considering the flux trapping in superconducting loops, which have a different influence in each case [2].

We can explain our experimental results based on two points.

(1) When the flux lines enter the polycrystalline superconductor, the intergranular field can be less than, equal to or more than the applied magnetic field for

different regions within the ceramic [10] (see Fig. 5) [11].
(2) For different percolation paths, the influence of the intergranular field must be different (see Fig. 6).

We have assumed that all the situations of H_i in the Josephson junction are considered in the cases A and B represented in Fig. 6, and satisfy Eq. (2) with $G>0$ and $G<0$, respectively.

Taking into account the shape of the statistical distribution of the geometric parameter G, it is reasonable to think that both situations have the same participation in the transport critical current. It is very important to notice that, by considering negative values of G, we can explain not only the "returning curve" and its maximum at $B_a=0$, but the dependence of J_c with the applied field in the virgin curve of the Bi ceramics, which is clearly weaker than the one of Y–Ba–Cu–O as well. We can illustrate this by the following example. First, take one Josephson junction with $B_0=\Phi_0/2\lambda L$. It may be located into the

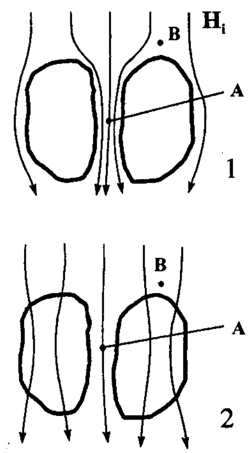

Fig. 5. Schematic drawing of the intergranular magnetic field lines for $H_i<H_{c1g}$, increasing magnetic field (virgin curve) (1), and decreasing magnetic field from $H_i(H_m)>H_{c1g}(2)$ [9]. In (1), $H_i(A)>H_i(B)$ while in (2), the situation is different.

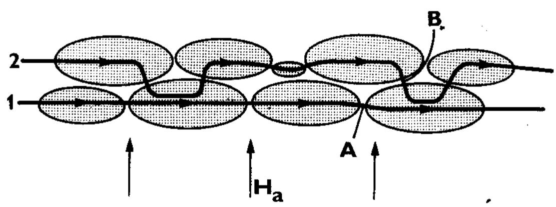

Fig. 6. Model of the granular structure of Bi ceramics showing the possible components of the transport current.

ceramic in one array with either (a) $G=0$, (b) $G>0$ or (c) $G<0$. If we suppose that $H_i<H_{c1g}$, the first minimum of the $J_c(B_a)$ dependence will be determined for the following values of B_a: (a) $B_a^1=B_0$, (b) $B_a^2=(1-G)B_0$ and (c) $B_a^3=(1+|G|)B_0$, respectively. Thus we have a value of B_a which is $(1+|G|)$ times greater than B_0 in case (c) when $G<0$. This indicates that the possible alignment of the grains may be important for the hysteretic behavior of the $J_c(B_a)$ dependence in our Bi ceramic which may be the cause of its different behavior as compared with Y–Ba–Cu–O as we will see. Since Bi based superconductors tend to grow with an almost mica-like morphology lying in the plane perpendicular to the direction of pressing [5], we can consider two components of the transport current in Bi polycrystalline superconductors which are shown in Fig. 6.

The components (1) and (2) flow through Josephson junctions type (A) and (B), respectively, like in the "brick wall model" discussed by Bulaevskii [12], with the difference, that in our ceramic, the c-axes of the grains are not strongly aligned in the direction of pressing like in Bi tapes, but only partially. That is the reason why the component (2) of the transport current is not independent of the applied magnetic field.

4. Conclusions

We have reported measurements of decreasing-field $J_c(B_a)$ curves in Bi based superconductors, which display fundamental differences with the analogous results generally obtained in Y based superconductors although a hysteretic behavior is displayed in both cases. We have also compared these results with decreasing-field $J_c(B_a)$ curves generated from an intragranular flux trapping model in the case of Bi based superconductors. It was possible to fit the $J_c(B_a)$ dependence only when we considered a symmetric statistical distribution of the geometrical parameter G associated to the superconducting grains with a peak at $G=0$. The results in this paper strongly suggest that both situations, $G>0$ and $G<0$, have the same participation in the transport critical current. This might be connected with the shape of the grains in Bi ceramics and the fact that they have a strong tendency

– different from the Y–Ba–Cu–O system – to be aligned parallel to the faces of the pellets.

Acknowledgements

This research was partially supported by the Third World Academy of Sciences grant No. 92-058 RG/PHYS/LA. We also appreciate useful discussions with O. Ares, material support from J. Edelstein and colleagues, and scientific encouragement from D. Wald.

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