Turk J Phys
29 (2005) , 9 – 15.

Investigation of the Intergrain Junctions of Polycrystalline HTSC in Rotating Weak ac Magnetic Fields

Ioseb METSKHVARISHVILI, Magda METSKHVARISHVILI, Luiza KHORBALADZE, Mikheil ELIZBARASHVILI, Zaur MIMINOSHVILI, Larisa NEKRASOVA
Iv. Javakhishvili Tbilisi State University, Physics Faculty, 0128 Tbilisi, Chavchavadze ave.3, Georgia
e-mail: ioseb@ictsu.tsu.edu.ge

Received 29.04.2004

Abstract

$YBa_2Cu_3O_y$ polycrystalline superconductor has been studied in weak rotating ac magnetic fields with existence of constant *dc* field. Measurements were carried out in various temperature intervals, and in various variable and constant fields. Results of our experiments are in good agreement with the isotropic model.

Key Words: Josephson junctions, rotating weak ac magnetic field, even and odd harmonics.

1. Introduction

Polycrystalline superconductors are associated as a collection of superconducting particles weakly connected to their neighbors by Josephson junctions. Such systems typically show a two-peak transition to superconductivity upon cooling in a magnetic field; the first peak shows flux shielding from grains, and the second between the grains [1–2]. In polycrystalline superconductors the penetration depth into weak links for weak magnetic fields can be estimated by the relation [3–4]

$$\lambda = \left(\frac{c\Phi_0}{16\pi^2 a \mu_{eff} j_c} \right)^{1/2}. \qquad (1)$$

Here, a is the average characteristic size of granules; Φ_0 is the magnetic flux quantum; μ_{eff} is the effective permeability of the ceramic material, taking into account the fact that the field does not penetrate into granules; and j_c is the junction critical current density.

When $\lambda >> a$, a granular superconductor behaves as a classical type II superconductor, in which the field penetrates in the form of vortices, and anisotropy induced by the field becomes an important factor.

The present approach is directly connected with a very important though sparsely studied problem of longitudinal currents in hard type II superconductors. The essence of the problem can be briefly formulated as follows. It is well known [5] that, in the presence of uncut vortices and pinning, the critical current $j_{c_{II}}$, which is longitudinal relative to the magnetic field, is equal to infinity, while the longitudinal electric field E_{II} is always equal to zero. However, experiments [6–11] show that $j_{c_{II}}$ and $j_{c_\perp}$ are of the same order of magnitude, and E_{II} differ from zero. In order to explain these phenomena, a model involving flux-line cutting (FLC) was proposed [12–15]. According to this model, nonparallel external magnetic fields penetrate into a superconductor through mutual cutting of the flux lines formed by these fields, followed by their cross restoration. As a result, finite $j_{c_{II}}$ and E_{II} are formed. In such a case, the local current-voltage characteristic (CVC) connecting the electric field $\vec{E}$ and the current density $\vec{j}$ is strongly anisotropic relative to the magnetic induction vector $\vec{B}$.

When $\lambda << a$, the local CVC does not depend on the angle between the current and the magnetic field and is isotropic. Such behavior was predicted by other theoretical approaches [16–18].

2. Rotating ac Magnetic Field

We consider an infinitely large slab in the yz-plane, having a thickness d along the x-axis and the penetration of rotating alternating current (ac) fields of amplitude h in the presence of a direct current (dc) constant field H for the anisotropic and isotropic models. In all cases, we assume that the dc field is directed strictly along the z-axis, while the ac field $h(t) = h\cos\omega t$ lies in the zy-plane at an angle γ to H.

In the case of the rotating ac magnetic field, the dependencies of the z and y components of the odd and even harmonics on the inclination γ angle of the variable magnetic field with regard of the constant magnetic fields are different in the anisotropic and isotropic theoretical models [18] which are presented in subsections 2.1 and 2.2.

2.1. Anisotropic model

Since the FLC model describes the cases of rotating ac field in the presence of a dc field in a very similar way, we consider them here in parallel, beginning with the following characteristic equations:

$$\vec{h}(t) = h_z(t)\,\vec{e}_z + h_y(t)\,\vec{e}_y,$$

$$h_z(t) = \sum_k a_{kz}\cos(k\omega t) + b_{kz}\sin(k\omega t),$$

$$h_y(t) = \sum_k a_{ky}\cos(k\omega t-\varphi) + b_{ky}\sin(k\omega t-\varphi)\,, \tag{2}$$

$$a_{1z} = \frac{h^2\cos^2\gamma}{4\pi j_{c_\perp}(H)d}, \quad a_{1y} = \frac{h^2\sin^2\gamma}{4\pi j_{c_{ii}}(H)d},$$

$$a_{2k+1,z} = a_{2k+1,y} = 0, \quad k \geq 1$$

$$b_{2k+1,z} = -\frac{h^2\cos^2\gamma}{8\pi^2 j_{c_\perp}(H)\,d\,(k^2-1/4)\,(k+3/2)}, \quad b_{2k+1,y} = -\frac{h^2\sin^2\gamma}{8\pi^2 j_{c_{ii}}(H)\,d\,(k^2-1/4)\,(k+3/2)},$$

$$a_{2z} = \frac{h^3\cos^3\gamma}{32\pi d}\left(\frac{\partial}{\partial H}\frac{1}{j_{c_\perp}(H)}\right),$$

$$a_{2k,z} = 0, \quad , \quad k \geq 2$$

$$b_{2k,z} = -\frac{h^3 \cos^3 \gamma}{16\pi^2 d} \frac{k}{(k^2 - 1/4)(k^2 - 9/4)} \left(\frac{\partial}{\partial H} \frac{1}{j_{c_\perp}(H)} \right), \quad b_{2k,y} = 0,$$

where, a, b denote high harmonics, k is the high harmonics number, h is a variable field, d is thickness of sample, H is the strength of the constant field, and j_c is the junction critical current density. It can be seen from these equations that z and y components oscillate independently with their j_c, and odd harmonics are proportional to $h^2 \cos^2 \gamma$ and $h^2 \sin^2 \gamma$, while even harmonics differ from zero only for the z component and are proportional to $h^3 \cos^3 \gamma$.

2.2. Isotropic model

As in the previous case, we assume that the variable field is directed at an angle γ to the constant field. For the isotropic model, the expressions for the z and y components are given by:

$$a_{1z} = \frac{h^2 \cos \gamma}{4\pi j_c(H) d}, \quad a_{1y} = \frac{h^2 \sin \gamma}{4\pi j_c(H) d},$$

$$a_{2k+1,z} = a_{2k+1,y} = 0; \quad k \geq 1$$

$$b_{2k+1,z} = -\frac{h^2 \cos \gamma}{8\pi^2 j_c(H) d (k^2 - 1/4)(k + 3/2)}, \quad b_{2k+1,y} = -\frac{h^2 \sin \gamma}{8\pi^2 j_c(H) d (k^2 - 1/4)(k + 3/2)},$$

$$a_{2z} = \frac{h^3 \cos \gamma}{32\pi d} \left(\frac{\partial}{\partial H} \frac{1}{j_c(H)} \right), \quad a_{2y} = \frac{h^3 \sin \gamma \cos \gamma}{32\pi d} \left(\frac{\partial}{\partial H} \frac{1}{j_c(H)} \right),$$

$$a_{2k,z} = a_{2k,y} = 0; \quad k \geq 2 \tag{3}$$

$$b_{2k,z} = -\frac{h^3 \cos^2 \gamma}{16\pi^2 d} \frac{k}{(k^2 - 1/4)(k^2 - 9/4)} \left(\frac{\partial}{\partial H} \frac{1}{j_c(H)} \right),$$

$$b_{2k,y} = -\frac{h^3 \sin \gamma \cos \gamma}{16\pi^2 d} \frac{k}{(k^2 - 1/4)(k^2 - 9/4)} \left(\frac{\partial}{\partial H} \frac{1}{j_c(H)} \right).$$

It can be seen that the isotropic model strongly differs from the flux-line cutting model; and odd harmonics are proportional to $h^2 \cos \gamma$ and $h^2 \sin \gamma$, while even harmonics are proportional to $h^3 \cos \gamma$ and $h^3 \sin \gamma \cos \gamma$.

3. Experimental Results and Discussion

To study the behavior of the junction critical current density in a rotating low ac magnetic field, we used the method of high harmonics. The harmonic ac susceptibilities were first interpreted by Bean's critical state model. According to Bean [19, 20], amplitudes of each harmonics are inversely proportional to the critical current density $C_n \sim 1/j_c$; therefore it is a very good contactless method for the investigation of the Josephson junction critical current density. As known, as the high harmonic amplitudes decreases with increase of harmonic numbers [1], it will be very useful to use low frequency harmonics. As such, we use only the second and third harmonics.

Our tests were carried out on YBaCuO ceramic pellet samples of 10 mm diameter and 2 mm thickness.

Textolite block of dimensions 18×18×2 mm was made with 10 mm diameter holes, into which the investigated samples were placed (see Figure 1a). For measurements, two multilayer 0.05 mm diameter copper coils were close wound and tightly wrapped perpendicular to each other, as shown in Figure 1 and denoted by coil$_m(y)$ and coil$_m(z)$, respectively. To produce a rotating magnetic field, the textolite forms were wrapped in a single layer of 0.1 mm diameter wire, as schematically shown in Figure 1 as coil$_{ac}(y)$ and coil$_{ac}(z)$. As indicated, the axes of all coils were oriented along the y- and z-axis. A solenoid of constant current around the form created a constant field in the z-axis direction.

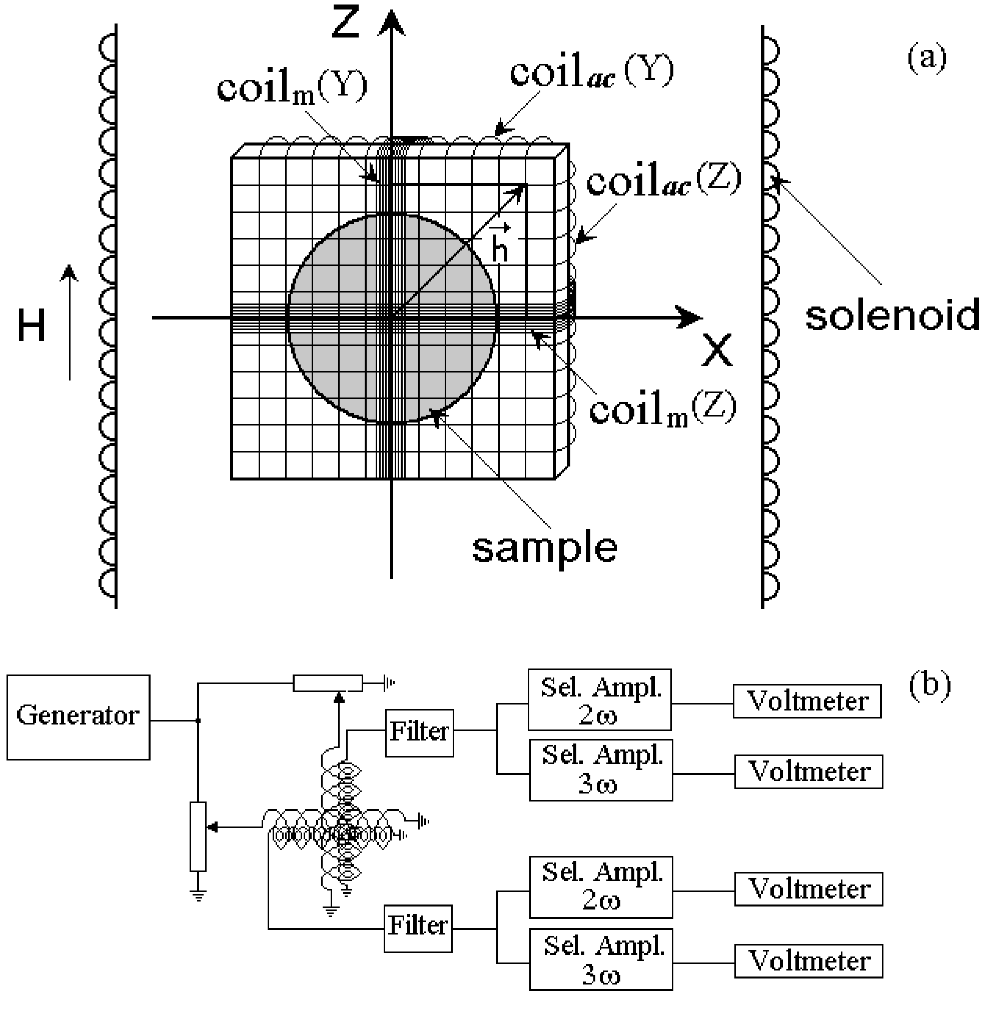

Figure 1. (a) coil$_m$(Y), coil$_m$(Z) are the measurement coils; coil$_{ac}$(Y), coil$_{ac}$(Z) are the coils used to create the rotating ac fields. (b) Schematic diagram of measurement system.

To induce the variable fields via the coils in the y- and z-directions, the coils were driven by sinusoid generators, as shown in Figure 1b. The total amplitude is found via the equation $h = \left(h_z^2 + h_y^2\right)^{1/2}$. Signals from the y and z coils pass through the filters (to dampen the base frequency) then are transmitted to the selective harmonic amplifiers, individually adjusted to the second and third harmonics; the output of the amplifiers were then measure and registered on voltmeters (see Fig. 1b). The amplifiers had a noise level of about 0.1–0.2 μV and the amplitude of the signal measured signal was less than 0.2 μV; the precision of measurement was 2% , but did not exceed 0.5 % at the upper amplitudes.

By placing the sample block within a Permalloy box, the magnetic field due to the Earth about the sample blocks was kept less than 10^{-3} Oe. The measurements were carried out at a frequency of 20 kHz.

The procedure for measurement was as follows. Investigated sample was cooled in zero magnetic field down to the predetermined temperature $T = const$. After establishing equilibrium at temperature T, a constant magnetic field H was established via the solenoid. Then the magnetic field was induced to rotate by appropriately exciting coil$_{ac}(y)$ and coil$_{ac}(z)$. Values of C_{2z} and C_{2y} were measured simultaneously. After measurement, the sample was heated to remove any residual magnetization. The sample was then cooled down in zero magnetic field; the same procedure was carried out for different temperatures, from 78 K to 90 K. Figure 2 shows that the angular dependence of the z-component of the second harmonic is proportional to $\cos^2\gamma$ and the y-component is proportional to $\cos\gamma \sin\gamma$.

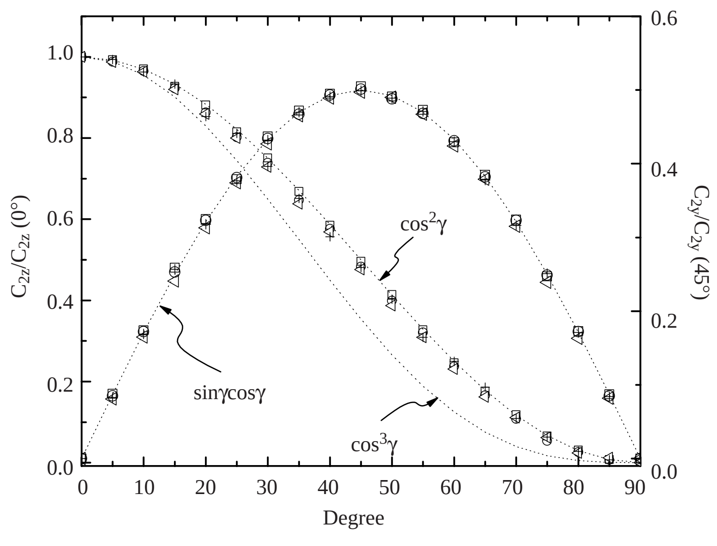

Figure 2. Angular dependences of C_{2z}, C_{2y}: □ show data for the condition $T = 78$ K, $h = 1$ Oe, $H = 8$ Oe; ◯ show data for the condition $T = 82$ K, $h = 0.6$ Oe, $H = 6$ Oe; ◁ show data for the condition $T = 86$ K, $h = 0.3$ Oe, $H = 3$ Oe; and + show data for the condition $T = 88$ K, $h = 0.1$ Oe, H=1 Oe.

The same experiment was carried out for C_{3z} and C_{3y}. Results are presented in Figure 3, which show angular dependence of the z-component of third harmonic corresponds to $\cos\gamma$, and the y-component is proportional to $\sin\gamma$.

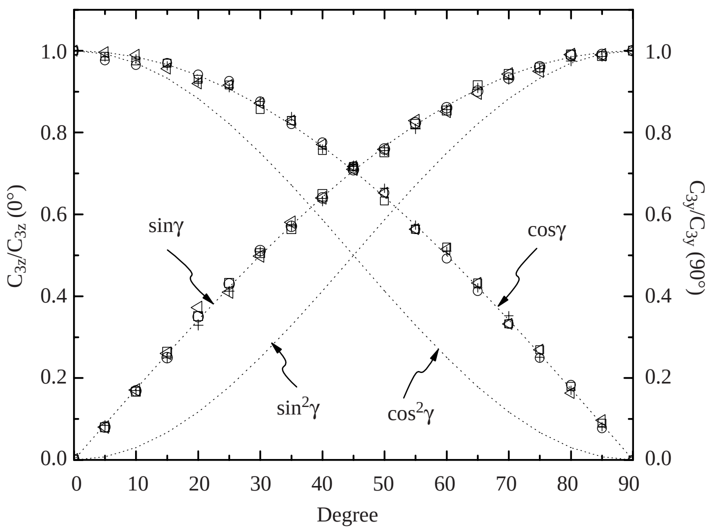

Figure 3. Angular dependences of C_{3z}, C_{3y}: □ show data for the condition T = 78 K, h = 1 Oe, H = 8 Oe; ◯ show data for the condition T = 82 K, h = 0.6 Oe, H = 6 Oe; ◁ show data for the condition T = 86 K, h = 0.3 Oe, H=3 Oe; and + show data for the condition T = 88 K, h = 0.1 Oe, H = 1 Oe.

4. Conclusions

We presented experimental results of measurements in a rotating ac magnetic field, investigating the longitudinal and transverse critical currents of Josephson junction in $YBa_2Cu_3O_y$ polycrystalline superconductor samples, and we find our results concur with the isotropic model.

References

[1] I.R. Metskhvarishvili, N.P. Kekelidze, M.R Metskhvarishvili, *Turkish Journal of Physics*, **26** (2002), 299.

[2] A.I. Malik, S.C. Celebi, S.A. Halim, *Physica C*, **377**, (2002), 421.

[3] K.H. Muller, J.C. MacFarlane, R. Driver, *Physica C*, **158**, (1989), 69.

[4] M. Tachiki, T. Koyama, and S. Takahashi, *Chinese J. of Physics*, **34**, (1996), 340.

[5] A.M. Campbell and J.E. Evets, *Critical Currents in Superconductors*, (Taylor and Francis, London, 1972), p. 243.

[6] R. Boyer and M.A.R. LeBlanc, *Solid State Commun.*, **24** (1977), 261.

[7] G. Fillion, R. Gauthier, and M.A.R. LeBlanc, *Phys. Rev. Lett.*, **43**, (1979), 86.

[8] R. Boyer, G. Fillion, and M.A.R. LeBlanc, *J. Appl. Phys.*, **51**, (1980), 1692.

[9] J. R. Cave and M.A.R. LeBlanc, *J. Appl. Phys.*, **53**, (1982), 1631.

[10] M.A.R. LeBlanc and J.R. Lorrain, *J. Appl. Phys.*, **55**, (1984), 4035.

[11] M.A.R. LeBlanc, D. LeBlanc, A. Golebiowski, and G. Fillion, *Phys. Rev. Lett.*, **66**, (1991), 3309.

[12] E.H. Brandt, J.R. Clem, and D.G. Walmsley, *J. Low Temp. Phys.*, **37**, (1979), 43.

[13] J.R. Clem, *J. Low Temp. Phys.*, **38**, (1980), 353.

[14] E.H. Brandt, *J. Low Temp. Phys.*, **39,** (1980), 41.

[15] J.R. Clem and S. Yeh, *J. Low Temp. Phys.*, **39,** (1980), 173.

[16] S.L. Ginzburg, *JETP*, **79**, (1994), 334.

[17] A. Badia, C. Lopez, *J. of Applied Physics*, **92**, (2002), 10.

[18] S.L. Ginzburg, I.D. Luzyanin, I.R. Metskhvarishvili, É.G. Tarovik, and V.P. Khavronin *JETP*, **92**, (2001), 159.

[19] C.P. Bean, *Phys. Rev. Lett.*, **8**, (1962), 250.

[20] C.P. Bean, *Rev. Mod. Phys.*, **36**, (1964), 31.