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Role of Flux Pinning in High Temperature Superconductors*

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Abstract

The critical state model with a pinning force independent of flux density is employed to interpret the measured ac magnetic flux response and the weak critical current density of ceramic Y-Ba-Cu-O material. The intergranular (Josephson) vortex pinning is found to be about 10^8 times weaker than that in conventional type II superconductors.

1. Introduction

It has been shown by many different measurements that bulk ceramic copper-oxide-based high-temperature superconductors are agglomerates of anisotropic grains separated by nonstoichiometric interface material (see e.g. Camps *et al.* 1987). The critical current density in these ceramic superconductors has been found to be at least two orders of magnitude too low for practical large-scale applications (Geballe and Hulm 1988). As these materials show type II superconducting behaviour, critical current and magnetic properties are expected to be strongly dependent on pinning forces acting on intergranular and intragranular vortices. In this report we demonstrate that the low magnetic field properties of $YBa_2Cu_3O_{7-x}$ can be described quantitatively by employing a critical state model, where the pinning force density for vortices, threading Josephson weak links, is flux density independent and small compared to pinning forces acting on vortices inside superconducting grains (Müller *et al.* 1989*a*). This weak Josephson vortex pinning force is responsible for the weak shielding and low critical current density observed in bulk high-T_c materials.

2. Theoretical Model

The high-T_c bulk superconducting material consists of superconducting grains connected by Josephson weak links. For an applied magnetic field less than the Josephson critical field, H_{c1J} (~0.1 Oe at 77 K), the weak link region restricts field penetration to a depth, λ_J, which depends on the critical Josephson current. For fields greater than H_{c1J}, it is energetically favourable for Josephson vortices to form at grain boundaries and then enter the intergranular region where they encounter an intergranular pinning force density, α (Clem

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1988). A quasi-equilibrium (critical state) is established (Bean 1962) where the pinning force density is equal to the gradient of the local magnetic flux pressure such that at each point in the material (Kim *et al.* 1962)

$$\left| \frac{1}{4\pi}(\mathrm{curl}\boldsymbol{H}) \times \mu \boldsymbol{H} \right| = \alpha(\boldsymbol{H}). \tag{1}$$

Here, $\boldsymbol{H}(\boldsymbol{r})$ is the local magnetic field obtained by averaging the meandering vortex lines over a volume containing a large number of grains, and μ is the effective permeability of the medium due to the diamagnetism of the grains, representing the fraction of the sample which is in a non-Meissner state (Raboutou *et al.* 1980).

3. Results and Discussion

We have solved equation (1) for a cylindrical rod where an ac magnetic field, $H_a = H_a^m \cos(2\pi\nu_o t)$, is applied parallel to the rod axis. Fig. 1 shows a local magnetic field, $H(r)$, inside the cylinder of radius R versus the radial coordinate r during half an ac cycle, where H_a^* is the applied magnetic field which causes vortex penetration deep enough to reach the cylinder axis. The Josephson vortices which sweep into and out of the rod during each ac cycle induce a voltage, U_{ind}, across a pick-up coil of N turns, wound around the rod:

$$U_{ind}(t) = -\frac{2\pi}{c} N\mu \frac{d}{dt} \int_0^R H(r, H_a(t)) r dr \tag{2}$$

An ac magnetic field was applied at 77 K to a cylindrical rod of $YBa_2Cu_3O_{7-x}$ (R = 1.6 mm, $\rho = 5.5$ g/cm^3). As shown in Fig. 2, the critical state model (equations 1 and 2) predicts the induced voltage, U_{ind}, extremely well. The ac frequency is ν_o = 130 Hz. No frequency dependence was found up to the maximum applied frequency of 50 kHz in agreement with the model. The spike structure in Fig. 2 is related to the fast field change inside the rod when the applied field passes through zero (see Fig. 1). The inflections marked by arrows are caused by the circulating critical current which changes direction near the rod surface when the applied ac field passes a maximum or minimum. The pinning force density used for our sample was 116 T A m^{-2} which is extremely small compared to conventional type II superconductors [e.g. in Nb_3Sn pinning is about 10^8 times stronger (Williams 1970)]. For ac field amplitudes, H_a^m, greater than about 70 Oe, the critical state model with a constant pinning force density failed to predict accurately the induced voltage of our sample. This is due to the formation of intragranular vortices as in this case the field between grains exceeds the lower critical field of the grains, H_{c1g} (Umezawa *et al.* 1988). For $H(r) \geq H_{c1g}$, neglecting the crystalline anisotropy, the pinning force density is expected to be field dependent.

In addition, we have investigated the effect of a steady magnetic field, H_a^{dc}, superimposed on an applied ac field (Müller *et al.* 1989*b*). The dc field breaks the inversion symmetry seen in Fig. 2 and causes even harmonics to appear in the Fourier spectrum of U_{ind}. Fig. 3 shows the pick-up coil voltage for a full ac cycle where the applied field is $H_a(t) = H_a^m \cos(2\pi\nu_o t) + H_a^{dc}$. Again, we found that the prediction of the above critical state model is in excellent agreement with the experimental data.

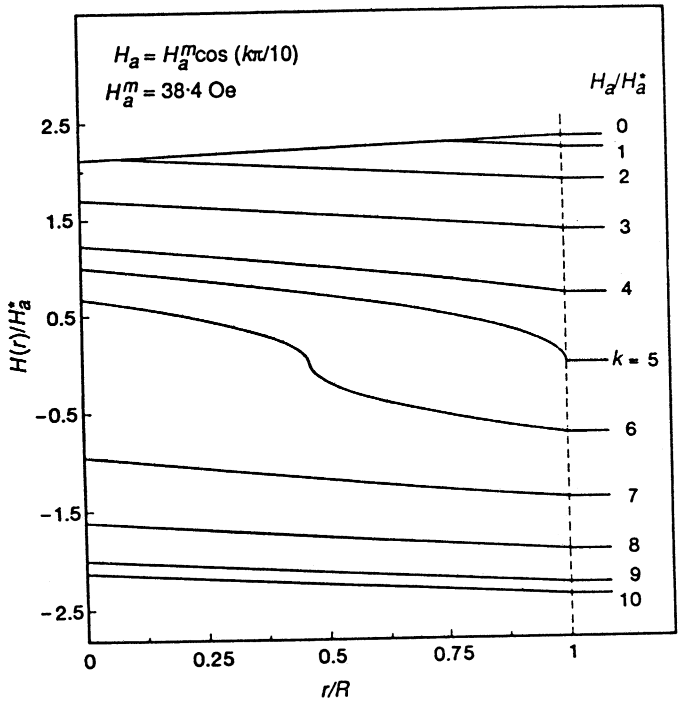

Fig. 1. Magnetic field inside a cylindrical rod versus the radial coordinate, r, at different times during half an ac cycle.

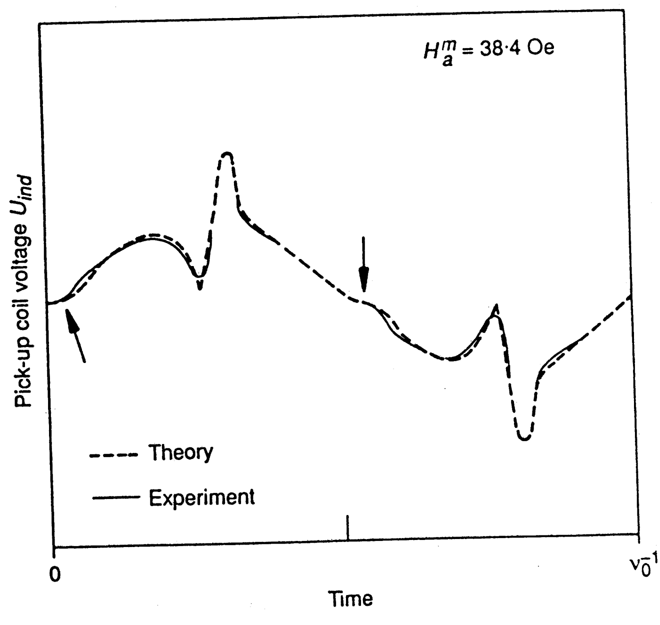

Fig. 2. Pick-up coil voltage, U_{ind}, during a full ac cycle at frequency 130 Hz and temperature 77 K.

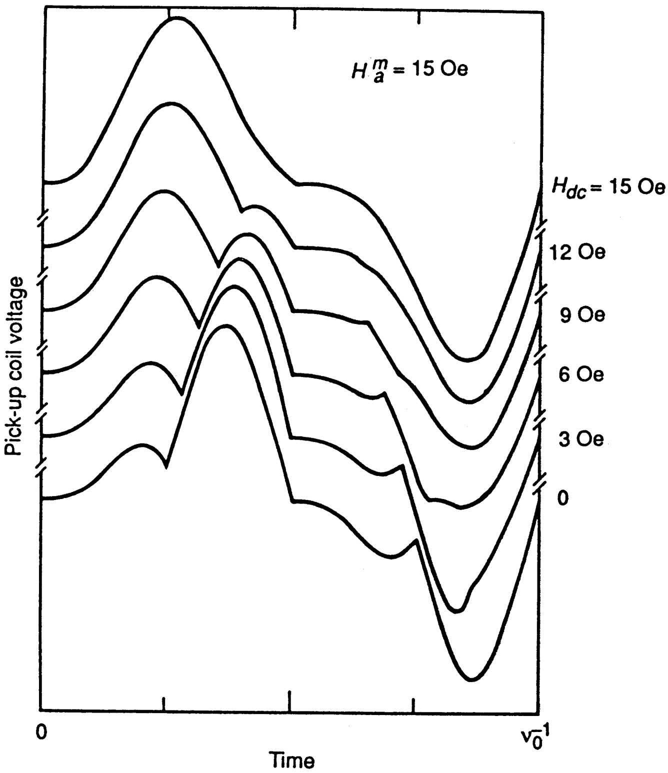

Fig. 3. Pick-up coil voltage, U_{ind}, during a full ac cycle for different dc fields H_a^{dc}.

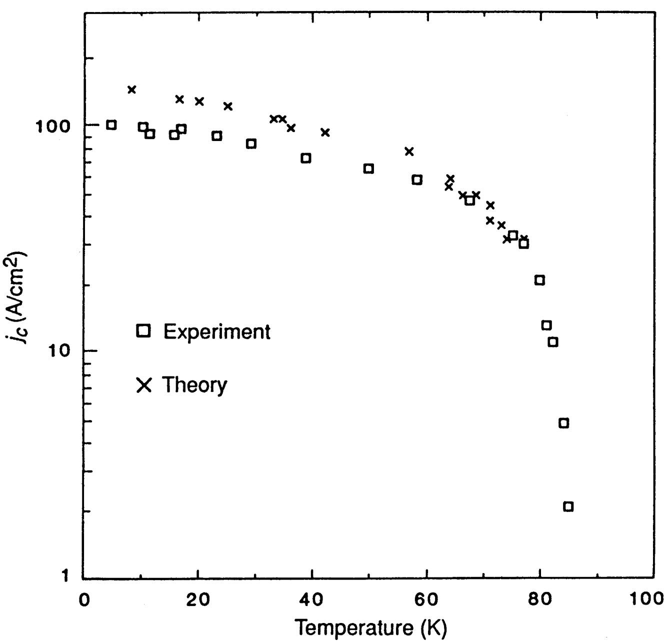

Fig. 4. Critical current density of the cylindrical rod as a function of temperature. The theoretical values are obtained from equations (3) and (4).

We have used a tubular sample to determine the temperature dependence of the intergranular pinning force density α, given by

$$\alpha(T) = \frac{\mu}{8\pi d}\tilde{H}_a^2(T) \tag{3}$$

which results from the solutions of equation (1). Here, $\tilde{H}_a$ is the ac field amplitude ($H_a^{dc} = 0$) at which vortices start to enter the bore through the cylinder wall of thickness d. We have found that the pinning force density increases approximately linearly with decreasing temperature (Müller *et al.* 1989*c*).

The critical current density of a type II superconductor is determined by the pinning force. The critical current density of a long cylindrical rod (wire) can be expressed in terms of the pinning force density, α, and rod radius, R, by employing the critical state model. One obtains

$$j_c = 2\left(\frac{8\pi\alpha}{3\mu R}\right)^{1/2} \tag{4}$$

Fig. 4 shows the critical current density versus temperature, T, resulting from equations (3) and (4) as well as the critical current density directly measured by passing a transport current through our cylindrical rod. A relatively good agreement between the two critical current densities is found.

4. Conclusions

Our investigations have shown that the weak shielding and low critical current density found in bulk high temperature superconductors are related to the weak pinning forces acting on Josephson vortices and are not primarily determined by a low Josephson junction current density. To improve the magnetic and current carrying properties of these materials, methods must be found to enhance the intergranular pinning force. So far only the pinning potential in a square array of identical Josephson junctions has been investigated (Lobb *et al.* 1983).

References

Bean, C. P. (1962). *Phys. Rev. Lett.* **8**, 250.
Camps, R. A., Evetts, J. E., Glowacki, B. A., Newcomb, S. B., Somekh, R. E., and Stobbs, W. M. (1987). *Nature* **329**, 229.
Clem, J. R. (1988). *Physica* C **153**, 50.
Geballe, T. H., and Hulm, J. K. (1988). *Science* **239**, 367.
Kim, Y. B., Hempstead, C. F., and Strnad, A. R. (1962). *Phys. Rev. Lett.* **9**, 306.
Lobb, C. J., Abraham, D. W., and Tinkham, M. (1983). *Phys. Rev.* B **27**, 150.
Müller, K.-H., Macfarlane, J. C., and Driver, R. (1989*a*). *Physica* C **158**, 69.
Müller, K.-H., Macfarlane, J. C., and Driver, R. (1989*b*). *Physica* C **158**, 366.
Müller, K.-H., Ricketts, B. W., and Driver, R. (1989*c*). (in preparation).
Raboutou, A., Rosenblatt, J., and Peyral, P. (1980). *Phys. Rev. Lett.* **45**, 1035.
Umezawa, A., Crabtree, G. W., Liu, J. Z., Moran, T. J., Malik, S. K., Nunez, L. H., Kwok, W. L., and Sowers, C. H. (1988). *Phys. Rev.* B **38**, 2843.
Williams, J. E. C. (1970). 'Superconductivity and its Applications' p.126 (Pion Limited: London).

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