Conf-9110181--2

Proceedings of the 2nd Tokai University International Workshop on Superconductivity, Honolulu, Hawaii, October 9-12, 1991.
Journal of Advanced Science (Japan) (in press,1992)

THEORETICAL MODELS OF FLUX PINNING AND FLUX MOTION IN HIGH-T_c SUPERCONDUCTING OXIDES

BNL--47215
DE92 009372

David O. Welch
Department of Applied Science, Brookhaven National Laboratory
Upton, NY 11973 USA
TEL:(516) 282-3517 FAX: (516) 282-4071

ABSTRACT

Various issues involved in the development of phenomenological models of flux pinning and motion in high-T_c oxides are discussed. A simplified model is presented for the critical current density and is used to examine the question of whether flux flow results from an instability due to plasticity of the flux-line array or from pin breaking.

Key Words: Flux pinning, critical current densities, high-T_c superconductors

1. INTRODUCTION

In this paper I will discuss some aspects of the development of phenomenological models of flux pinning and flux motion in superconductors, with an eye to the special requirements posed by the character of the high-T_c oxide superconductors (HTSCs). We need such models to correlate and interpret experimental data on such properties as critical current densities, flux creep rates, and the temperature and magnetic field dependence of current-voltage characteristics; such interpretations would then lead us to characterize these data in terms of derived quantities such as flux pinning energies and elementary pinning strengths for various types of pinning centers. This would ideally lead to an understanding of what kind of lattice defects could lead to improved critical current densities, reduced creep rates, and to raising the limits on operating temperature and magnetic field imposed by the irreversibility line for HTSCs such as the Bi cuprates. [Indeed, the same need for adequate phenomenological theories of magnetic flux behavior still exists for low-T_c superconductors (LTSCs) as well as for HTSCs.]

The development of phenomenological models of magnetic flux behavior can be broken down into several aspects: (1) the strength of pinning forces and energies; (2) "stability problems" (e.g., the nature of the critical state and the value of the critical current density J_c); (3) "kinetic problems" (e.g., the nature of the irreversibility line, flux-flow resistivity in the mixed state, flux creep kinetics); and (4) aspects of magnetic flux behavior that are unique to HTSCs. Items (2) and (3) together make up what is sometimes called "the summation problem" in the theory of flux pinning: for a given set of pinning centers of specified strength and a given density of flux lines, what is the flux flow rate for a specified magnetic field, temperature, and current density? Space limitations preclude more than a cursory examination of any of these aspects here, and, in fact, I will only give a very brief discussion in Section 2 below of some of the particular problems of current interest in items (1), (3), and (4) while expanding a little more in Section 3 on item (2) the "stability problem," in particular what characteristics of the strength, concentration, and distribution of flux pinning centers are most significant in determining the critical current density J_c.

2. SOME UNSOLVED PROBLEMS RELEVANT TO MODELS OF FLUX PINNING AND FLUX MOTION

Very little is actually known about the defects which pin magnetic flux in HTSCs, although dislocations, twin boundaries, radiation damage tracks, and small precipitates have all been suggested as pinning centers. However, because of the small values of the superconducting coherence length in these materials, point defects and small point-defect aggregates can make an appreciable contribution to flux pinning in HTSCs, unlike the case of LTSCs. Unfortunately, such point-defects are not visible by transmission electron microscopy, thus making the systematic study of flux pinning by defects in HTSCs particularly difficult. Most of the experimental evidence regarding the strength of pinning in HTSCs has been derived from flux creep kinetics. However, the deduction of pinning energies from such experiments is somewhat problematic.[1,2] Much work, both theoretical and experimental, on the structure, energetics, and effect on superconducting properties of defects in HTSCs remains to be done.

Also somewhat uncertain is the nature of magnetic flux lines in layered, anisotropic HTSCs. Under some circumstances, the flux "lines" may behave more like a weakly coupled stack of disks in the essentially two-dimensional superconducting CuO_2 planes, as in the "pancake model" of J. Clem.[3] Furthermore, the spatial arrangement of the flux "lines" is very likely to depart significantly from the distorted Abrikosov lattice appropriate to LTSCs. For example, glassy structures[4] and entangled-polymer-like structures[5] have recently been proposed to explain various aspects of flux-line behavior in HTSCs. The nature of the flux line structure is the subject of active debate. [For a sampling of recent views on this topic, see the proceedings of the recent Cambridge conference on critical currents.[1]] Unfortunately, the experimental methods used to infer the structure have either been restricted in their range of applicability, such as flux-line decoration techniques[6], or indirect in nature, such as measurements of flux-flow contributions to resistivity. [Recently the latter technique has been used to infer the presence or the absence of a vortex glass transition in HTSC[7] and LTSC[8] films, respectively.] In addition to these questions about flux-line nature and the structure of the flux-line arrays, the layered nature of HTSCs (leading to quasi 2-dimensional behavior), the short coherence lengths, and the high temperatures may result in important effects on flux line behavior caused by normal-state fluctuations.

As this brief discussion indicates, neither the nature of flux pinning centers and their strengths nor the nature of flux lines and their spatial organization in HTSCs is known with any degree of certainty. This makes the construction of theoretical models either a risky proposition or an opportunity for imaginative models without too many inconvenient experimental constraints, depending on one's point-of-view.

3. FLUX LINE PLASTICITY OR PIN BREAKING: WHICH DETERMINES J_c?

As the discussion above suggests, we known with confidence neither what defects are actually pinning flux in HTSCs nor how strongly these defects pin magnetic flux lines. Our lack of knowledge of flux line structures and properties for these materials means our discussion of critical current densities and how they might be changed by suitable treatments must be somewhat general and over simplified. We will discuss here such a primitive model for the critical current density J_c.

If we add more defects or make the defects more strongly pinning, by radiation damage[9] or adding a suitable precipitate[10], experiment indicates that the critical current density (assuming no weak-link effects) will rise. Why this is so may not be simply that the pinning strength has increased, as one initially and naively might guess, but may be more indirect, such as effects on the plasticity of the flux-line "lattice." The following simple model illustrates the issues involved in the interpretation of such experiments.

When a sufficiently small current J passes through (perpendicular to) an array of flux lines at some magnetic induction B, the Lorentz-force JB is resisted by the force of the pinning centers until the current density reaches the critical value J_c, at which point an instability sets in and flux flow begins. This instability can arise from two limiting causes: either the pinned flux lines pull away from their pinning centers (pin breaking) or the flux line array begins to deform plastically. The observed dependence of the so-called pinning force density J_cB on the value of the magnetic field is used to ascertain whether pin breaking or plastic flow is the limiting factor. For fields near either the upper critical field or the irreversibility line, denoted by B_o, J_cB is found to be proportional to $(B_o-B)^n$: for pin breaking the exponent n is near unity whereas for plasticity, n is approximately two.[11] Recent experiments show that the exponent n is near two for both $YBa_2Cu_3O_7$ films[12] and $(La,Sr)_2CuO_4$ single crystals[13], implying the importance of flux-line plasticity as the factor limiting J_c in these HTSCs. What then is the role of the pinning centers and what will be the effect of increasing their strength in such cases? The following simple model gives more indication.

Real materials need shear stresses to flow plastically, and this is also the case for an array of flux lines. For such shear stresses to arise, the forces acting on the flux lines by the pinning centers must be non-uniformly distributed spatially. If the pinning centers are of uniform strength and distribution, the only way that the flux lines can move is by breaking free of the pins. In the non-uniform case, the Lorentz force may exceed the strength of the pins in some locations while being resisted by stronger pins in other regions, provided that the rigidity of the flux-line array can withstand the shear stresses generated by the non-uniform distribution of forces. When the shear strength of the array is exceeded, the array deforms plastically, and thus flux flow occurs. A very idealized model illustrates this behavior: we will approximate the spatial variation of pinning strength by a square-wave of wavelength L. In a fraction α of the wavelength the pinning is weak, whereas in the remaining fraction $(1-\alpha)$ the pinning is strong. For current densities below J_c, the net force on the flux-line array in each of the two regions must be zero. In the square-wave and direct-summation-of-pinning-forces approximations these net forces F are:

$$F_S = JBL(1-\alpha) - L(1-\alpha)(B/\phi_o)g_s f_{ps} + 2\tau \quad (1a)$$

$$F_W = JBL\alpha - L\alpha(B/\phi_o)g_w f_{pw} - 2\tau \quad (1b)$$

where ϕ_o is the flux quantum, g is the probability that any given flux line in the region is pinned by a center with pinning force per unit length, f_p; the subscript s and w denote the strong and weak regions, respectively. τ is the shear stress acting at the boundary between the strong and weak regions. For current densities below J_c, F_S and F_W are zero, thus one finds the shear stress on the flux lattice array to be:

$$\tau = \frac{1}{2}\alpha(1-\alpha)(B/\phi_o)L[g_s f_{ps} - g_w f_{pw}] \qquad (2)$$

Note that the shear stress depends on the difference in pinning force densities between the strong and weak regions, *i.e.* on the spatial non-uniformity of the pinning center strength and/or concentration.

We see that when the current density becomes large enough, one of two possible instabilities occurs: either the shear stress needed for static equilibrium exceeds the plastic flow stress of the lattice τ^* before the strongest pins are broken or the strongest pins break before the plastic flow stress τ^* is exceeded. If a plastic flow instability occurs, the critical current density will be given by:

$$J_c B = \frac{\tau^*}{L\alpha} + g_w f_{pw,max} \qquad (3)$$

where $f_{pw,max}$ is the maximum value of the pinning force (per defect) in the weak region. $L\alpha$ is the width of the weak region, i.e. the channel width in which plastic flow occurs. [When the second term of Eq. (2) is neglected, one obtains the expression originally derived by Pruymboom et al.[14]] If the plastic flow stress is large relative to the pinning strength and a pin breaking instability occurs, then the critical current density will be given by:

$$J_c B = (B/\phi_o)\ \langle g f_{p,max} \rangle \qquad (4)$$

where $\langle g f_{p,max} \rangle$ is the value of the product of the maximum pinning force and pin probability averaged over both the weak and strong regions. The criterion for the occurrence of a plastic flow instability is:

$$\tau^* < \frac{1}{2}\alpha(1-\alpha)L(B/\phi_o)[g_s f_{ps,max} - g_w f_{pw,max}] \qquad (5)$$

which depends on the plastic flow stress τ^* relative to the difference in maximum pinning strengths between the weak and strong pinning regions.

In order to obtain an explicit expression for the critical current density it is necessary to give a description of the length scale L describing the weak and strong regions of pinning together with the pinning probability g_w and g_s in terms of the defect structure of the material, as well as an explicit expression for the plastic flow stress τ^* as a function of the temperature, magnetic field, and the structure of the flux line array itself. If the latter can be approximated as a distorted Abrikosov lattice containing dislocations, then the theory of plastic flow in crystals[15] suggests that

$$\tau^* \equiv \frac{C_{66} a}{\ell} \qquad (6)$$

where C_{66} is the shear modulus of the flux-line lattice, a is the inter-flux-line spacing, *i.e.* $(\phi_o/B)^{1/2}$, and ℓ is the characteristic length scale of the dislocation structure of the flux-line lattice. [If the flux-line array in HTSCs is more accurately described as a glass or an entangled polymer, then it is not so clear what to use for the plastic flow stress, but something of the form of Eq. (6) will probably suffice but with different values of C_{66} and ℓ.] If we neglect the second term of Eq. (3) and adopt a shear modulus similar to that used by Wördenweber and Abd-El-Hamed[12] in their discussion of

$YBa_2Cu_3O_7$ films, then we find a critical current density given by:

$$J_c B \propto \frac{C_{66} a}{L\ell} \propto \left(\frac{B_c^2}{2\mu_o}\right) \frac{b(1-b)^2(\phi_o / B)^{1/2}}{L\ell} \qquad (7)$$

where $(B_c^2/2\mu_o)$ is the superconducting condensation energy density, b is the reduced magnetic induction (i.e., B divided by an appropriate irreversibility field), L is a length scale characteristic of the superconductor microstructure and ℓ is a length scale characteristic of the flux-line array microstructure. The latter length scale is not directly accessible experimentally, and a reliable detailed theoretical description of the flux-line array is still not available for HTSCs, but in general ℓ is expected to decrease as the array becomes more disordered, by strong pinning centers for example, as b increases toward unity.

4. DISCUSSION AND CONCLUSIONS

As the discussion above indicates, there are many serious questions remaining before plausible models of flux pinning and motion in high-T_c superconductors can be developed. Among these are the nature and properties of the lattice defects which pin the flux and the nature of flux lines themselves, as well as their spatial organization, and the possible effects of normal-state fluctuations. The simplified discussion in Section 3 of the competing roles of flux-line array plasticity and pin breaking in determining the critical current density points up the need for more understanding of the scale and magnitude of spatial fluctuations in the densities and strengths of pinning centers and the need for more investigation of the plasticity and defect structure of flux-line arrays themselves (lattices, glasses, entangled polymers?) in HTSCs. Considerable work, both experimental and theoretical, remains to be done before we can be confident of theoretical models of flux pinning and flux motion in HTSCs.

5. ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy, Division of Materials Sciences, Office of Basic Energy Sciences under Contract No. DE-AC02-76CH00016.

REFERENCES

[1]Proc. 6th Intern. Critical Current Workshop, Cambridge, England, July, 1991. Superconductor Sci. and Technol. (in press).

[2]D. O. Welch, in Ref. 1.

[3]J. R. Clem, Phys. Rev. B. 43, 7837(1991).

[4]D. S. Fisher et al., Phys. Rev. B 43, 130(1991).

[5]S.P. Obukhov and M. Rubinstein, Phys. Rev. Lett. 65, 1279(1990).

[6]C. A. Murray et al., Phys. Rev. Lett. 64, 2312(1990).

[7]R. H. Koch et al., Phys. Rev. Lett. 63, 1511(1989); 64, 2585(1989).

[8]R. C. Budhani et. al., Solid State Commun. 81, 179(1992).

[9]L. Civale et al., Phys. Rev. Lett. 67, 648(1991).

[10]M. Murakami et al., *Advances in Superconductivity II*, edited by T. Ishiguro and K. Kajimura (Springer-Verlag, 1990), pp. 659-663.

[11]E. J. Kramer, J. Appl. Phys. 44, 1360(1976).

[12]R. Wördenweber and M. O. Abd-El-Hamed, J. Appl. Phys. 71, 808(1992).

[13]K. Kishio et al., Proc. Intern. Conf. on Materials and Mechanisms of Superconductivity (M^2S-HTSC III), July 1991, Kanazawa, Japan, Physica C (in press).

[14]A. Pruymboom et al., Appl. Phys. Lett. 52, 662(1988); Phys. Rev. Lett. 60, 662(1988).

[15]A. H. Cottrell, *Dislocations and Plastic Flow in Crystals* (Oxford at the Clarendon Press, 1953).

END

DATE FILMED

4 / 29 / 92