Surface Dependence of the Critical Pinning Current Density in Type-II Superconducting Foils*

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Measurement of flux-flow curves in cold-worked Pb-Bi type-II superconducting foils indicates that for samples otherwise prepared in the same way, J_P, the critical current density required to initiate flow, is linear in the surface-to-volume ratio of the samples. This and other surface effects suggest that, for these samples, pinning is almost entirely at the surface. Surface irregularities as well as mechanical defects act as sources of surface pinning. Changes in these pinning sources, achieved either through modifying the method of sample preparation or by annealing the samples, change the slope of the curve of J_P versus surface-to-volume ratio. The results are discussed in terms of Pearl's theoretical model, in which the electromagnetic region of a fluxoid spreads at the sample surface.

THE problem of critical current densities in type-II superconductors has received considerable experimental attention.[1–8] However, there is still not a very clear picture of the dependence of the critical current density on field, temperature, surface-energy parameter κ, or on the scale or type of inhomogeneities in a sample.

That inhomogeneities play a role in determining the critical current density has been illustrated repeatedly. Kamper,[6] in fact, suggests that a perfectly homogeneous superconductor in the mixed state cannot support a transport current.

If measurements are made on foils with the magnetic field perpendicular to the surface of the foil and to the transport current, then for a constant field and temperature one can obtain linear current-voltage characteristics at sufficiently high currents.[1,9] In order to understand these characteristics, Kim[10] has suggested that the Lorentz force F_L between the magnetic fluxoids of the mixed state and the transport current produces a viscous motion of the fluxoids across the foil. The equation of motion is given by

$$F_L - F_P = \eta V_L, \tag{1}$$

where F_L is the Lorentz force per unit length $J\Phi_0/c$, η is a viscosity parameter, and V_L is the velocity of fluxoid motion. J is the transport current density and Φ_0 is the unit flux quantum. F_P is the pinning force and may be written in the form

$$F_P = J_P\Phi_0/c. \tag{2}$$

If there are N fluxoids per unit area, so that $N\Phi_0 = B \sim H$, the total power dissipated per unit volume in the flux motion is $NF_L \times V_L$. An electric field E is developed across the sample so that the power is also equal to the Joule heat EJ. Equating these expressions and using (1) and (2), we obtain

$$E = (\Phi_0 H/c^2)[J - J_P]. \tag{3}$$

Equations (2) and (3) define a critical current density J_P required to initiate flux flow. Thus defined, J_P is obtained by extrapolating the linear current-voltage characteristics to zero voltage.

It should be noted that previous workers have defined critical current densities in terms of the onset of a minimum voltage, which usually lies on the nonlinear portion of the flux-flow curves and also depends on other factors, such as geometry and normal-state resistivity. Results based on such a criterion are therefore not directly comparable from experiment to experiment. The present criterion, based on the gross flux-flow properties of the superconductor, defines the critical current density uniquely, and provides results which can be compared from sample to sample.

We have measured the flux-flow characteristics of a number of foils of several lead-bismuth alloys. The alloys were prepared by melting the high-purity constituents in glass under a vacuum of 10^{-6} Torr, stirring and outgassing for several days, and then air quenching. Foils were prepared by compressing the ingot in a hydraulic press to a plate about 100 mils in thickness, and then rolling to the desired foil thickness by making several passes through a rolling mill. The orientation of the foil was not maintained the same in each pass, so that no single direction of cold working should predominate. The foils were cut into rectangular samples, approximately 1.5 in. long and 0.15 in. wide, their edges were smoothed, and they were mounted in a four-probe measuring rig and annealed for 24 h at 110°C, a temperature which we have shown removes little of the cold

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[1] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 131, 2486 (1963).
[2] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Rev. Mod. Phys. 36, 43 (1964).
[3] L. J. Barnes and H. J. Fink, Phys. Rev. 149, 186 (1966).
[4] P. S. Swartz and H. R. Hart, Phys. Rev. 137, A818 (1965).
[5] J. W. Heaton and A. C. Rose Innes, Phys. Letters 9, 112 (1964).
[6] R. A. Kamper, Phys. Letters 5, 9 (1963).
[7] G. D. Cody, G. W. Cullen, and J. P. McEvoy, Rev. Mod. Phys. 36, 95 (1964).
[8] S. R. Sekula, R. W. Boom, and C. J. Bergeron, J. Appl. Phys. Letters 2, 102 (1963).
[9] B. S. Chandrasekhar, I. J. Dinewitz, and D. E. Farrell, Phys. Letters 20, 321 (1966).
[10] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 139, A1163 (1965).

work. One alloy, 9.3 at.% Bi+90.7 at.% Pb, was cast in two ingots. Ingot No. 1 received the usual treatment, while ingot No. 2 received a prolonged high-temperature anneal after compressing but before rolling.

The current-voltage characteristics were taken at 4.2°K in a perpendicular field orientation and will be discussed in detail elsewhere.

The measured field dependence of J_P is qualitatively similar to that found for critical currents variously defined and measured elsewhere.[1,2,4,7] A typical curve obtained for a 9.3 at.% Bi sample is shown in Fig. 1. J_P increases rapidly with decreasing fields both at high fields, $H \gtrsim \frac{3}{4}H_{c_2}$ (region I in Fig. 1), and at low fields, $H \lesssim \frac{1}{4}H_{c_2}$ (region III). At intermediate fields, $\frac{3}{4}H_{c_2} > H > \frac{1}{4}H_{c_2}$ (region II), a plateau develops in which J_P varies only slowly with field.

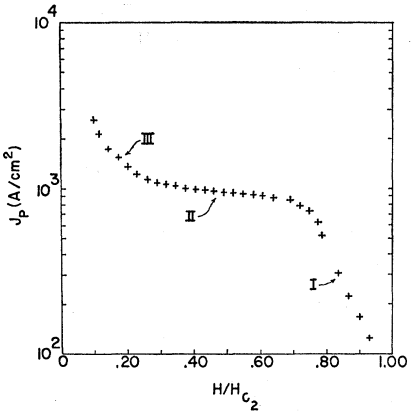

FIG. 1. Typical curve of critical pinning current density J_P as a function of reduced field H/H_{c_2}. Data shown are for a 9.3 at.% Bi+90.7 at.% Pb foil, 9×10^{-3} cm thick.

We concentrate on fields $H \lesssim \frac{3}{4}H_{c_2}$. In this region, J_P increases with decreasing foil thickness *for samples otherwise prepared in the same manner.* This is made clear in Fig. 2, where we plot the value of J_P at $H/H_{c_2}=0.50$ for various samples made from the 15 at.% Bi ingot versus the surface-to-volume ratio of the samples. The surface-to-volume ratio clearly plays a role in determining J_P. Moreover, it would appear that within the limits of the scatter of our data J_P goes to zero, independent of volume defects, as this ratio goes to zero.

We have found such a linear relation between J_P and the surface-to-volume ratio for alloys of five compositions ranging from 3% Bi to 15% Bi. In the case of the two 9.3% Bi ingots, samples from the ingot which received the additional high-temperature anneal showed a slightly lower slope to the J_P versus surface-to-volume-ratio curve than samples prepared from the other ingot.

We are therefore led to the conclusion that the surface is the major determinant in the flux pinning. Other observations support this conclusion. A thick nickel

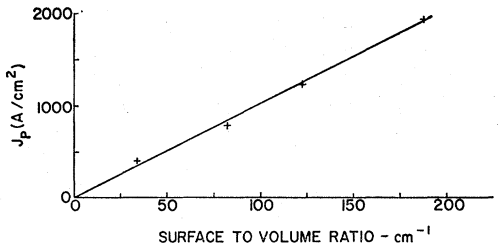

FIG. 2. Critical pinning current density J_P at $H/H_{c_2}=\frac{1}{2}$ as a function of surface-to-volume ratio for rolled foils of 15 at.% Bi+85 at.% Pb. Within the scatter of data, the curve passes through the origin, indicating that the pinning becomes zero when the surface-to-volume ratio is zero.

film evaporated onto both sides of one sample reduced the value of J_P by about 20%. Further annealing (below 200°C) of the 9.3% Bi samples which had already received the additional high-temperature anneal did not reduce J_P, and in one case actually increased it. (Annealing studies were not made on the other samples.)

Etching the samples, which not only removed surface defects but also smoothed the surface, decreased J_P, in some cases by over 50%. Because of this observation several samples were prepared from the 15% Bi ingot by compressing between glass plates, thus producing foils with mirror-smooth surfaces, and markedly reduced J_P values. The increase in J_P with surface-to-volume ratio was again observed (Fig. 3), although the scatter of the data was greater than for the rolled foils. This increased scatter might be expected since the samples now have much reduced pinning forces and will therefore be more sensitive to minor surface variations. Comparing the slopes of the curves for the two methods of sample preparation, we find that the pressed foils have J_P values about 50% lower than for the rolled foils. Surface roughness is therefore shown to be a source of surface pinning. Etching of the pressed samples, which now *increased* the surface irregularity in addition to removing surface defects, sometimes in-

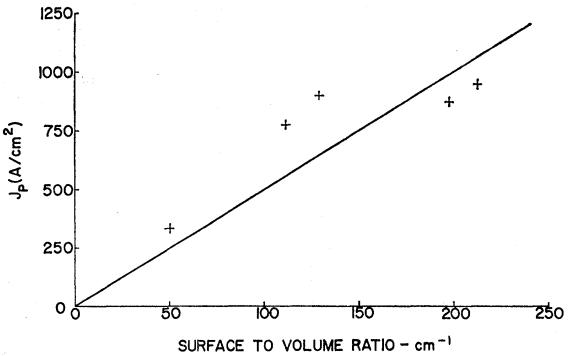

FIG. 3. Critical pinning current density J_P at $H/H_{c_2}=\frac{1}{2}$ as a function of surface-to-volume ratio for pressed foils of 15 at.% Bi+85 at.% Pb. Although the scatter of the data is greater, it is clear that with these smoother surfaces pinning is about half as large as shown for rolled foils in Fig. 2.

creased and sometimes decreased J_P. This would seem to indicate that the net pinning force is determined by both the surface roughness and by mechanical defects, and that depending on the relative effectiveness of the etch in changing the surface condition with respect to either roughness or defects, J_P will increase or decrease.

We have also recently reported that the pinning forces are angle-dependent.[11] We believe this is due to the difference in the way in which fluxoids penetrate the surface when the angle of the field is varied. Thus the interaction of the fluxoids with the surface is again emphasized.

In order to explain the present results we note the calculations of Pearl,[12] which show that the electromagnetic region of a fluxoid spreads as the fluxoid approaches the surface, making fluxoid interactions long-range at the surface. This has the net result of stiffening the fluxoids in the surface layer and requiring that they move in unison. Pinning of fluxoids in this region is therefore enhanced. In order to initiate flux flow one must provide a force to move the fluxoids collectively. If some of the fluxoids are more strongly pinned than others, none of the fluxoids will move until a force equal to this maximum pinning force is provided. Within the volume, however, fluxoids are more flexible and flow can be initiated whenever individual fluxoids see a driving force which exceeds their pinning force. Surface pinning is therefore intrinsically more effective than volume pinning. For a given field and current density, the total driving force on a fluxoid depends on sample thickness [F_L in Eq. (1) is the Lorentz force *per unit length*]. The surface-pinning region, equal to the penetration depth in thickness, remains constant. Thus, for a given current density, the driving force on a fluxoid increases with thickness without a coincident increase in the surface-pinning force. Flux flow can therefore be initiated at a lower current density with a thick sample than with a thinner one, as we observe.

[11] W. C. H. Joiner and G. E. Kuhl, Phys. Rev. (to be published).
[12] Judea Pearl, J. Appl. Phys. 37, 4139 (1966).

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Effect of the Superconducting Energy-Gap Anisotropy on the Thermal Conductivity of Tin*

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Measurements of the normal- and superconducting-state thermal conductivities (K^n and K^s) were made on one pure and eleven cadmium-doped tin single crystals in the temperature range $1°<T<4°$K. Cadmium concentrations ranged from 5×10^{-3} to 0.3 at.%. The crystal orientations are tightly grouped in the near-perpendicular direction (direction of heat flow approximately perpendicular to the tin tetrad axis). The fractional change of the lattice conductivity, K_g^s, in the superconducting state and an effect in the electronic part of the conductivity K_e^s, reflecting the anisotropy of the superconducting energy gap, are studied as a function of impurity concentration. The variation of the size of the anisotropy effect with electron mean free path is found to be in reasonable agreement with the theoretical predictions of Ulbrich *et al.* and the ultrasonic attenuation results of Claiborne and Einspruch. However, the magnitude of the anisotropy effect in tin is found to be approximately twice as large as that predicted by theory. Unsuccessful attempts to bring the theoretical calculations into agreement with experiment by altering the angular features of the energy-gap function are discussed. The variation of α, the temperature coefficient of the electron-phonon scattering term in the thermal resistivity expression, was studied as a function of impurity concentration and found to increase monotonically with concentration. Also the anisotropy of β, the temperature coefficient of the impurity scattering term, is shown to be similar to that of the residual resistivity. From the measured values of the residual resistivity, ρ_0, and β's obtained from the normal-state thermal conductivities, the Lorentz number L_0 was found to be $L_{0\text{exp}}=2.49\pm0.08$ for these samples.

I. INTRODUCTION

THIS paper describes an experimental investigation of the effects of the anisotropy of the superconducting energy gap on the thermal conductivity of single crystals of dilute tin alloys. Tin was selected as the host metal for this work since it exhibits a superconducting energy-gap anisotropy suitable for detection with thermal-conductivity measurements, and single crystals in many of its dilute alloy systems are easily prepared. From recent measurements on Cd-doped tin,[1] we have learned how Cd affects some of the superconducting properties of the host metal, in particular the transition temperature, thus making it convenient to continue with Cd in an attempt to study its effect on thermal conductivity. Previous thermal-conductivity measurements were performed on poly-

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[1] J. E. Gueths, C. A. Reynolds, and M. A. Mitchell, Phys. Rev. 150, 346 (1966).