# Flux Pinning by Phase Boundaries in Type-II Superconductors*

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Measurements have been made, from magnetization curves, of the surface hysteresis in PbTl in low fields. The surface was plated with Tl and diffused for various periods so that the distance in which the specimen changed from normal to superconducting varied from a few atomic diameters to several times the penetration depth. It was found that plating had little effect, but that the hysteresis dropped markedly on diffusing over a distance $\lambda$. The results indicate that magnetic pinning to the surface is the predominant factor, rather than surface "sheath" currents.

A major contribution to hysteresis in type-II superconductors comes from the pinning of flux vortices at interior phase boundaries and at the surface interface.[1,2] For pinning to occur there must be a sharp change in superconducting properties across the boundary. The experiments reported here show how sharp this change must be.

Pure reversible specimens of[3] Pb–36% Tl were prepared in cylindrical form; the total bulk hysteresis was an order of magnitude less than the hysteresis arising from flux pinning at the specimen surface. The specimens were then chemically polished and plated with a 10-$\mu$m layer of thallium. A sensitive ballistic magnetometer ($\pm 0.2$ G) was used to measure the specimen hysteresis, first in the as-plated condition and then at intervals during the aging of the specimen at a carefully controlled temperature. The initially sharp boundary between the plated layer of thallium and the specimen was progressively smeared out by interdiffusion. The hysteresis was observed to fall gradually to a low level representing the residual bulk hysteresis. In a separate experiment using an ac technique it was established that for a highly interdiffused boundary the surface contribution to the hysteresis fell to less than $\frac{1}{500}$th of its initial value.[4]

The Pb-Tl system is suitable for an interdiffusion experiment for a variety of reasons. The superconducting phase extends continuously from pure lead to Pb–87% Tl[4] and its superconducting properties have been extensively studied.[5] As the phase becomes richer in thallium, $T_c$ falls reaching 4.2 °K at 71% Tl, still well within the single-phase region. For Pb–36% Tl at 4.2 °K the penetration depth $\lambda = 190$ nm, the coherence length $\xi = 33$ nm, and the upper and lower critical fields are $H_{c2} = 2880$ Oe and $H_{c1} = 92$ Oe. Very extensive data on the self-diffusion coefficients of Pb and Tl across the system for a wide range of temperatures[6] make it possible to calculate the diffusion profile accurately. The self-diffusion coefficients vary by a factor of 5 with composition, however, the over-all diffusivity, calculated using the Darken equation and values of the thermodynamic factor,[7] only varies by a factor of about 2. The diffusion profile obtained using the Matano method differs by less than 5% from the error function curve for a diffusivity of $3.5 \times 10^{-10}$ mm$^2$ sec$^{-1}$ at 206.5 °C, the aging temperature most frequently used. At 4.2 °K for a Tl|Pb–36% Tl diffusion couple the composition Pb–71% Tl for which $T = T_c$ remains almost stationary at the position of the original plated interface. From there the Tl content falls half-way towards Pb–36% Tl in a distance $(Dt)^{1/2}$ and four-fifths of the way in $2(Dt)^{1/2}$, where $D$ is the diffusivity and $t$ is the time. The superconducting diffused area will be particularly clean because any dirt or porosity at the plated interface will be moved rapidly off into the normal Tl-rich region by the considerable Kirkendall effect.

The preliminary results for three separate specimens are displayed in Fig. 1. For a given hysteresis loop the hysteresis is displayed as a fraction of the maximum hysteresis before diffusion $(\Delta M)/(\Delta M)_0$. This was done at two fields, 154 and 220 Oe; at present the sensitivity of the magnetometer is not sufficient to give good results at much greater fields; at lower fields small irreproducible anomalies due to the proximity of $H_{c1}$ begin to appear. The values of $(\Delta M)/(\Delta M)_0$ at the two fields did not show significantly different trends so that the mean of the two values is plotted as a single point in Fig. 1. The scatter in the low hysteresis region arises mainly because the residual bulk hysteresis value differs for each specimen. Bending and straightening a specimen in the course of an experiment is sufficient to step the curve by a noticeable amount. Values of the hysteresis of the as-plated specimens, as a fraction of the reversible magnetization $M_0$, were 0.13 and 0.10 at the fields 154 and 220 Oe, respectively (when surface hysteresis predominated).

The results indicate that the surface hysteresis at a normal-metal–type-II-superconductor interface is related to an interaction with range much

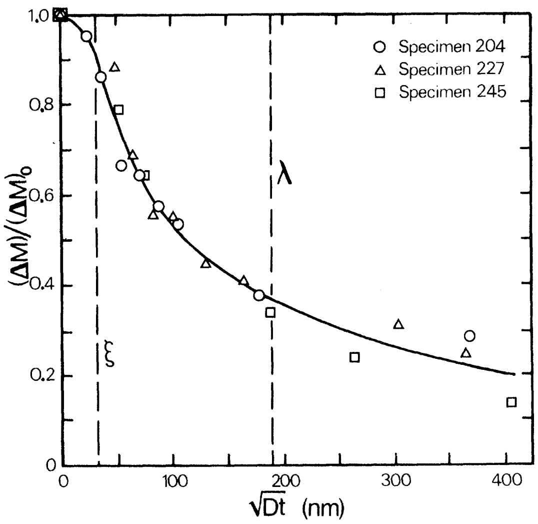


FIG. 1. Specimen hysteresis plotted as a function of the diffusion profile for three separate specimens. The hysteresis is expressed as a fraction of the total hysteresis for the as-plated specimen before diffusion. The normal to superconducting diffusion profile has a half-width of $(Dt)^{1/2}$ as described in the text.

greater than $\xi$. The superconducting properties can be smoothed over distances greater than $\xi$ without appreciably affecting the hysteresis. The surface hysteresis does not therefore contain a component arising from a "surface-sheath" current.[8] The initial plating of the specimen increases the surface hysteresis slightly, so one can deduce that there is unlikely to be a significant surface-sheath contribution at a vacuum interface for this material at these fields.

The hysteresis falls to half for $(Dt)^{1/2} \simeq \frac{1}{2}\lambda$; the effective width of the diffused junction ($\frac{4}{5}$ of final value) is then about $\lambda$. This is strong evidence for the Bean-Livingston "surface-barrier" type mechanism for flux pinning at phase boundaries.[1,2] It is not possible at this stage to determine whether the important distance is $\lambda$ or the flux line spacing $d$, since at 154 Oe, $d = 2.6\lambda$, and at 220 Oe, $d = 2\lambda$. In order to make this discrimination the measurements must be extended to higher fields; this is now being attempted using a low-frequency ac technique with much more sensitivity than the ballistic magnetometer.[9]

The theory given by Campbell, Evetts, and Dew-Hughes[2] predicts that the hysteresis will decrease as the diffusion width approaches the flux line spacing even though the magnitude of the hysteresis is itself inversely proportional to $\lambda$.

For short diffusion distances around $(Dt)^{1/2} = 4$ nm the hysteresis was observed to rise anomalously by as much as 20%. This effect requires further investigation; it may be simply related to porosity and dirt at the interface before it is swept away by the Kirkendall effect.

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