FLUX PINNING AND FLUX FLOW STUDIES IN SUPERCONDUCTORS
USING FLUX FLOW NOISE TECHNIQUES

MASTER

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Abstract

We have developed a model for the flux flow state in type II superconductors in which flux motion is interrupted by local interactions between pinning centers and moving fluxoids. This model allows us to predict the functional forms for the flux flow noise power spectrum and for the dc voltage-current characteristics. Our experimental results conform quite closely to the predictions of this model. We have used measurements of noise spectra, voltage-current characteristics, and volume pinning force curves to study flux flow and local pinning interactions in situations in which pinning is dominated by: (1) normal metal precipitates, (2) grain boundaries, and (3) a combination of dislocations and grain boundaries. In each case, the metallurgical state of the sample controls the measured results. We continue to emphasize the greater sensitivity of noise spectra as compared to bulk critical current measurements in obtaining a detailed picture of flux flow.

I. A Model of Fluxoid Motion Interrupted by Local Pinning Interactions and the Noise Power Spectrum

During the initial phases of the work sponsored by this grant, we attempted to understand the basic mechanisms responsible for noise generation in the flux flow state of type II superconductors. Our initial experimental investigations revealed that measured flux flow noise power spectra did not fit the functional form previously predicted for our sample geometry. Moreover, the noise power remained large at frequencies which were much higher than those associated with the average flux transit time, calculated from the average flux flow velocity, $\bar{v} = \frac{E}{B}$, and the sample width, L .

Although noise persisting to these higher frequencies was observed by van Gorp in his original experiments, and was attributed to a fraction of the fluxoids being pinned, thus increasing the velocity of moving fluxoids above that of the velocity averaged over all fluxoids, a more natural explanation to us seemed to be that flux transit was interrupted by local interactions with pinning centers. We therefore developed a model based on this idea, and a paper describing this model and discussing its implications was published this year. A copy of this publication appears as Appendix A of this report, and so will not be described further in this summary.

Experimental spectra fit very well to the predictions of this model, as can be seen in Appendix A. Moreover, shifts in the distribution of subpulse times, i.e. the times for fluxoids to travel between pinning interactions, can be extracted from the noise spectra, and these shifts correspond to changes in the metallurgical condition of the sample.

A considerable experimental effort has been made to obtain data on $\text{Pb}_{80}\text{In}_{20}$ samples which have different metallurgical histories. Although these experiments are presently continuing, and we are analyzing our early results, certain preliminary conclusions can be drawn. These are discussed in the next section.

II. Flux Flow Noise Characteristics and Pinning Force Curves in Severely Deformed

Pb₈₀In₂₀ Samples and Changes with Annealing

When Pb₈₀In₂₀ is severely cold worked, grains cannot be observed in this early stage by usual optical microscopy or by using the scanning electron microscope. This is either because of the high dislocation density or because grains are too small to resolve. After annealing for perhaps one half hour at room temperature, very small grains can be observed. Further room temperature annealing produces grain growth. Etching deformed samples before annealing produces surface etch pits, but such etch pits are uncommon in samples undergoing a several hour anneal. It therefore appears that room temperature annealing reduces the dislocation density within the grains, and produces some grain growth.

Accompanying these metallurgical changes are changes in the pinning and the flux flow noise. The initially deformed sample exhibits two volume pinning force peaks as a function of magnetic field. One peak is rather narrow and exists at fields close to H_{c2} , while the second peak is broader and exists at lower fields. See Fig. 1. A noise peak exists in the valley between the two force peaks. As room temperature annealing progresses, there is a gradual change in the shape of the pinning force curve. The high field force peak decreases, and eventually disappears. We associate the disappearance of this peak with the annealing out of dislocations. After approximately one day of room temperature annealing, the pinning force curve undergoes further changes only very slowly with time, and we associate the curve at this stage with pinning at grain boundaries. The noise peak observed in the initially deformed condition disappears in the early stages of annealing, and the general noise level is reduced by approximately two orders of magnitude during the initial 24 hour annealing period. For longer times, the noise level remains reasonably stable, although it increases again as grains become larger.

The sensitivity of the magnitude of the noise (2 orders of magnitude) to the changes in metallurgical structure is much greater than the sensitivity of the volume pinning force, which typically may change by 20%. A preliminary discussion of effects of annealing on the flux flow noise has been published, and a copy of this publication appears as Appendix B.

III. Flux Flow Noise Characteristics in Pb In Samples After Room Temperature Annealing 80 20

Studies of flux flow noise power spectra at this stage are still underway, and as our analysis and experimental work is completed, these results will be prepared for publication. We list here without a detailed description what appear to be our most important results. We emphasize that several of these results are tentative, and further work and analysis is still underway. These results include:

- a) The generalized flux bundle size, i.e. the noise magnitude at $f = 0$, appears to fall off rapidly at fields in the vicinity of the pinning force peak. This seems to confirm Kramer's notion of a transition in the initiation of flux flow from "pin breaking" to plastic shear in this field region.
- b) The distribution of subpulse times (as a fraction of the average transit time) does not appear to be affected by the d-c voltage level. As the d-c voltage increases, the average velocity of fluxoid motion increases, as does the Lorentz force which drives the fluxoid motion. This produces the unexpected result that if at low velocity and forces pinning centers are present and are interrupting fluxoid motion, these pinning interactions become no less effective as the force or velocity increases. Although the average fluxoid velocity increases with $\frac{1}{B}$, the situation as to whether shifts in the distribution of subpulse times occur with shifts in magnetic field is not so clear, because of increased scatter in the data when the field is changed. One of our present priorities is to clarify this point.
- c) Certain structures, or orientation of structures relative to the direction of fluxoid motion, can create unusually large flux bundle sizes (high noise levels). Accompanying these large flux bundles is the

apparent absence of very short subpulse times. We can think of no physical reason for this apparent relationship.

- d) Surface pinning plays an important, but as yet poorly understood role, in determining the total pinning force. Etching the sample surface, for example, can greatly reduce the total pinning force without shifting the magnetic field at which a force peak is observed. In certain field ranges etching reduces the noise; at other fields etching enhances the noise.
- e) As we have noted, annealing, particularly at temperatures close to the melting point, increases grain sizes. Accompanying the increase in grain size is a shift of the subpulse times to longer times, and an increase in the noise magnitude. Both results are consistent with our model (Appendix A).

IV. Voltage-Current Characteristics

Our model of flux motion interrupted by interactions with pinning centers also leads to an expression for the flux flow voltage-current characteristics. (See eqn. 22 of Appendix A.) When this expression is fit to measured characteristics, excellent fits are obtained.

Three parameters completely specify the voltage-current curve. These are: (1) the slope of the curve, ρ , in the linear flux flow region; (2) the minimum pinning strength associated with the critical current, I_c , at which flux motion begins; and (3) the spread in pinning strengths, characterized by the current I_0 . The ratio of I_0/I_c is thus a measure of the relative spread in pinning strengths existing within a sample. From fits to the V-I characteristics at different fields, the field dependence of the ratio I_0/I_c may be obtained. Although some structure exists in this ratio at low fields, its value remains small (approximately 0.5) at low field, but there is a sudden increase in this ratio at fields in the vicinity of the pinning force peak, and the ratio can often reach 10.0 at H_{c2} . Again, this result gives support to Kramer's ideas about a transition at the force peak from "pin breaking" to plastic shear as the mechanism for initiating flux flow.

A report on this result is scheduled for publication this month, and a copy of a preprint is included as Appendix C.

V. Flux Flow and Noise Measurements in a Sample Containing a Laminar Normal Metal Precipitate

Lead-tin alloys can be quenched from high temperatures to produce single phase samples with nearly ideal type II behavior. However, at high tin concentrations, tin will precipitate from solution at room temperature. The precipitation is laminar in shape, and although it begins in the region of the grain boundaries, it eventually pervades the grains.

As the precipitation of the tin progresses, a reduction in the flux flow noise results, and very unusual hysteresis effects develop in the flux flow properties. Although hysteresis in magnetization curves is well known, history dependent effects in the flux flow properties of the magnitude, variety, and nature of those which we observe in this system have not previously been reported in the literature. A detailed manuscript describing these effects, and offering what we believe is a reasonable explanation of their origin has been submitted for publication. A copy of this manuscript is included as Appendix D.

VI. Pinning Forces and Flux Flow Characteristics in Low Kappa Materials

Several years ago we were interested in the magnetic field and temperature dependence of the flux flow resistance. We thus had in our possession a number of flux flow curves taken on PbTl alloys characterized by low critical currents. Although the data is not ideal for our present purposes, we reanalyzed these curves in terms of the voltage-current characteristic predicted by our model. Two very interesting results emerge. For low kappa, $\text{Pb}_{95}\text{Tl}_{05}$ samples, no peak is observed in the pinning force curves to very low fields. In fact, it appears that the pinning force increases more rapidly as the field is decreased in the low field region. Moreover, the ratio of I_0/I_c remains small until fields very close to H_{c2} , at which point it begins to increase. It does not, however, reach the magnitude obtained in samples exhibiting a peak effect.

As noted, our existing data was not ideal for this purpose. Moreover, this analysis was not central to the main thrust of our previous work. Nevertheless, we do think that this result, which we believe is the first situation reported in which the pinning force curve does not exhibit a peak, warrants further investigations of low kappa alloys.

A short report has been given on this investigation and is included as Appendix E.

Figure Caption

Fig. 1. Changes in volume pinning force curve with annealing for $\text{Pb}_{80}\text{In}_{20}$ alloy. 11T, cold worked plus ten minutes at room temperature; 11T β , 5 hours at room temperature; 11T δ , 15 hours at room temperature; 11T η , 22.5 hours at room temperature; 11T λ , 46.5 hours at room temperature.

Pinning force F_p versus h for different stages of annealing.

Legend: 11T; 11Tβ; 11Tδ 11Tη and 11Tλ.

Contract Compliance

Work in the reporting period has progressed in compliance with terms specified in the contract.

Percent Effort of Principal Investigator

The Principal Investigator has devoted 10% of his effort to the project during the academic year, and 50% of his effort during 12 weeks of academic recess. During the remainder of the current term he will devote 10% of his effort, all during the academic year, to the project

Papers and Reports

"Correlation between changes in pinning strength and flux flow noise due to annealing in a type II superconductor," F. Habbal and W.C.H. Joiner, Physics Letters 60A, 434 (1977).

"Flux flow noise power spectra in the presence of local pinning interactions," F. Habbal and W.C.H. Joiner, Journal of Low Temperature Physics Vol. 28, Nos. 1/2, 83-93 (1977).

Flux flow current-voltage characteristics and their magnetic field dependence in a type II superconductor," to be published in Physics Letters A (1977).

"History dependent flux flow characteristics and flux flow noise in type II PbSn alloys containing Sn precipitates," submitted for publication.

"Changes in the flux flow noise spectra of heavily deformed type II superconductors with annealing," F. Habbal, W.C.H. Joiner, and J. D. Thompson, Bulletin of the American Physical Society 21, (1976).

"History dependence of flux flow voltage-current characteristics in type II superconductors containing precipitates," R. Rehemann, F. Habbal, and W. C. H. Joiner, Bulletin of the American Physical Society 22, 209 (1977).

"On the flux flow properties of type II superconductors containing precipitates," F. Habbal, R. G. Pirich, and W.C.H. Joiner, Bulletin of the American Physical Society 22, 53 (1977).

"Flux flow power spectra measurements as a means of studying flux flow in type II superconductors," W.C.H. Joiner, F. Habbal, and R. G. Pirich, Bulletin of the American Physical Society 22, 425 (1977).

"Evidence of shear in the fluxoid lattice from voltage-current curves of type II superconductors," W.C.H. Joiner, Bulletin of the American Physical Society (Miami Meeting, October 21-22, 1977).

APPENDIX A

Abstract Submitted
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Superconductivity

Flux Flow Power Spectra Measurements as a Means
of Studying Flux Flow in Type II Superconductors*.
W.C.H. JOINER, F. HABBAL, and R. G. PIRICH, University
of Cincinnati.--Flux flow power spectra, pinning forces,
and current-voltage characteristics have been studied
in samples in which different pinning mechanisms domi-
nate. Pinning mechanisms studied include: grain bound-
aries, normal metal precipitates, grooves impressed in
the sample surface, and extreme cold work (which pro-
duces a peak effect). Our results suggest that the
characteristics of the flux flow noise are determined
by local interactions between flux pinning centers and
moving fluxoids. Data covering each of these pinning
situations will be discussed.

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Flux Flow Noise Power Spectra in the Presence of Local Pinning Interactions*

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We derive expressions for the dc flux flow voltage and for the flux flow noise power spectrum in type II superconductors using a model in which flux bundles travel a distance l less than the sample width L before being stopped for finite times by local pinning interactions. The frequency dependence of the power spectrum is shown to be identical to our earlier derivation, where we assumed that pinning and release of flux bundles occurred in zero times, an assumption we now show to be incorrect. This frequency dependence has been shown to lead to good agreement for experimentally measured transit times, which have repeatedly been shown to be too short when obtained from models of uninterrupted flux transit across the sample width. The concept of a pinned fraction arises naturally in our model, and occurs because of two factors; first, in certain regions the Lorentz force is not sufficient to overcome pinning, and second, in regions where flux flow occurs, fluxoids will be held up for brief periods because of interaction with local pinning centers. The expressions for the noise power at zero frequency and the dc voltage are modified by factors that depend on averages of l .

1. INTRODUCTION

Several studies of the flux flow state in type II superconductors have been made using measurements of the noise power spectra as an investigative technique.¹⁻⁵ These spectra arise because fluxoids traversing a sample, either singly or in bundles, give rise to individual voltage pulses with a height proportional to the product of the flux bundle size and the velocity of the bundle, and a duration equal to the transit time of the bundle across the sample width. Clem has predicted that these spectra should depend on the geometry of the sample and the arrangement of the measuring circuit.^{6,7} For a foil sample with width L much less than the probe separation d , the pulse

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shape as observed by the measuring circuit can be approximated to be rectangular in shape. For such a pulse the power spectrum would be of the form

$$W(f) df = 2\Phi V_{av} \left(\frac{\sin \pi f \tau_c}{\pi f \tau_c} \right)^2 df \quad (1)$$

where Φ is the magnitude of the moving flux entities, V_{av} is the dc voltage, df is the measuring bandwidth, and τ_c is the transit time of fluxoids across the sample width. The noise spectra should thus yield a critical frequency $f_c = 1/\tau_c = v/L$, where v is the fluxoid velocity. The fluxoid velocity, however, can be calculated directly from the dc voltage V_{av} and the magnetic field B :

$$v = \frac{V_{av}}{Bd} \quad (2)$$

Critical frequencies obtained from the noise spectra and from the velocities should therefore be comparable.

Measurements made on polycrystal foil samples that do not have low defect densities have repeatedly led to noise spectra characterized by critical frequencies higher than predicted by Eq. (2). To overcome this difficulty, van Gorp¹ and Jarvis and Park⁴ have used the concept of a pinned fraction of vortices p such that the velocity of the unpinned vortices is enhanced:

$$v = \frac{V_{av}}{Bd(1-p)} \quad (3)$$

We have previously presented results in which we also observed noise spectra yielding higher critical frequencies than predicted by Eq. (2), although these critical frequencies increased linearly with V_{av}/B as required by Eq. (2).⁸ Our noise spectra also fell off at high frequencies as $1/f$ rather than the more rapid decrease predicted by Eq. (1). To overcome these difficulties, we applied a suggestion originally made by van Gorp⁹ with respect to flux motion in type I superconductors. Thus we assumed that the flux did not directly transit the sample producing a pulse of length τ_c . Instead, we assumed that the fluxoid motion is interrupted momentarily as fluxoids are temporarily held up at pinning centers. The fluxoid motion thus gives rise to subpulses, each of duration τ_i , and the total spectrum represents the total contribution from the various subpulses:

$$W(f) = \int_0^{\tau_c} g(\tau_i) W(f\tau_i) d\tau_i \quad (4)$$

where

$$W(f, \tau_i) = 2\Phi V_{av} \left(\frac{\sin \pi f \tau_i}{\pi f \tau_i} \right)^2 \quad (5)$$

$g(\tau_i)$ is a distribution function for the τ_i and the limits of integration on the subpulse duration are expressed in terms of the unimpeded transit time τ_c . Our assumption, following van Gorp, was that the fluxoids were held up for sufficiently short times at pinning centers so that the average transit time τ_c was not altered. By using as a distribution function

$$g(\tau_i) = 1/(\alpha - \beta)\tau_c, \quad \alpha\tau_c > \tau_i > \beta\tau_c$$

we fit the experimental data very well by using α and β as adjustable parameters. In general, best fits are obtained for $\beta = 0$, whereas $\alpha = 1$ for well-annealed samples, but decreases as grain sizes are reduced, thus producing shorter average subpulse times. See Fig. 1.

Fig. 1. Noise power spectra for $\text{Pb}_{90}\text{In}_{10}$ foil. Measurements are taken at $H = 1600$ Oe, $V = 500 \mu\text{V}$, and $T = 2.15$ K. Sample dimensions are: width $L = 0.41$ cm; probe separation $d = 2.3$ cm; thickness 0.024 cm. Open points were taken before sample was annealed, and solid points after annealing eight days at 260°C . The solid curves represent best fits and yield $\alpha = 0.40$ (unannealed) and $\alpha = 1.00$ (annealed). β is approximately zero in both cases.

Although the model has been successful in helping us interpret noise spectra, we now understand that it has been derived assuming an incorrect value for the height of the subpulses. Further, the idea of fluxoids held up for vanishingly small times at pinning centers is incorrect. The purpose of this paper is to present a more comprehensive model for fluxoid motion interrupted by pinning. The principal result of this model is that the form for the frequency dependence of the noise spectrum is as given by Eqs. (4) and (5), although the value of the spectrum at zero frequency $W(0)$ is altered. We are led to an explicit expression for the pinned fraction, although our interpretation of this concept is somewhat altered. An expression for the dc voltage as a function of current is also obtained which yields a nonlinear region at low currents as previously derived by Baixeras and Fournet.¹⁰

2. DIFFICULTIES WITH PREVIOUS MODEL

As noted, the model of fluxoids being held at pinning centers for vanishingly small times is incorrect. This is because in the limit of zero stopping time, the end of one subpulse is exactly correlated with the beginning of the succeeding subpulse. The subpulses are therefore not statistically independent and interference terms would appear in the correlation function from which the noise spectrum is derived. Since the subpulses are not independent, the summation of their individual power spectra cannot be carried out as is done in Eq. (4).

Since our observed spectra follow quite closely the functional form obtained with Eq. (4), we assume that the summation process is correct, but that the assumption of zero stopping time is incorrect. We therefore modify this assumption by associating two times with a given subpulse. For the i th pulse we let τ_i be the actual time the flux is in motion and θ_i be the time between the initiation of flux motion giving rise to the i th pulse and the initiation of the $(i+1)$ th pulse. Assuming that the fluxoids are held for random times upon pinning is equivalent to assuming that the pulses are statistically independent, or that the distribution function for the θ 's can be written

$$u(\theta) = (1/\theta_0) \exp(-\theta/\theta_0) \quad (6)$$

A second problem in the van Gorp model was that in the case of a flux bundle transiting the distance l , between pinning centers, the expression for the voltage pulse for a flux bundle whose motion is uninterrupted was simply altered by replacing τ_c by τ , (i.e., it was assumed $V_i = \Phi/\tau_i$). This is inappropriate because τ is determined both by the velocity of the moving fluxoids and by the distance between pinning centers. The proper form for

the voltage generated by the i th pulse is therefore

$$V_i = \Phi l_i / L \tau_i \quad \text{for} \quad \sum_{j=1}^i \theta_{j-1} \leq t \leq \sum_{j=1}^i \theta_{j-1} + \tau_i \quad (7)$$

We note that this expression for V_i satisfies the necessary condition

$$\sum V_i \tau_i = \Phi$$

3. CALCULATION OF THE PINNED FRACTION

We have characterized a given subpulse associated with the motion of a group of fluxoids between two pinning centers by the parameters θ_i , τ_i , and l_i . We are assuming that l_i and τ_i are independent variables, l_i being determined by the physical distribution of pinning centers in the material, whereas for a given l_i , the value of τ_i will be determined by the driving force on the flux. For generality we should also assume that the size of the flux bundle Φ , can vary from one subpulse to the next.

We note that the concept of a time of motion τ_i and a stopping time $\theta_i - \tau_i$ allows us to define two velocities for each subpulse. While the flux is in motion the velocity is given by

$$v_i = l_i / \tau_i = \Phi J / \eta \quad (8)$$

where η is the viscosity coefficient and J is the transport current density. One can also obtain the average velocity over the entire time associated with the i th subpulse:

$$\bar{v}_i = l_i / \theta_i = \Phi_i (J - J_c) / \eta \quad (9)$$

J_c represents a critical current density for the i th pinning event, which Yamafuji and Irie¹¹ have related to the relationship between v_i and $\bar{v}_i$. The distribution in times θ_i for a given applied current is therefore related to a distribution in l_i , Φ_i , and J_c . For the distribution function of J_c we use the form

$$f(J_c) = (1/J_0) \exp[-(J_c - J_c)/J_0], \quad J_c \geq J_c$$

$$= 0 \quad J_c < J_c$$

used by Baixeras and Fournet¹⁰ in deriving the shape of the flux flow current-voltage characteristic. J_c is the minimum value of the critical current density required to produce flux motion, and J_0 determines the spread in values of J_c .

One can, at this point, introduce the concept of a pinned fraction. For the combination of parameters giving rise to the i th type of subpulse, and for a current in excess of J_c , the pinned fraction will be the fraction of the time

Fig 2 Curves showing pinned fraction p from Eq (11) as a function of the normalized current J/J_c . The parameter J_0 , which gives rise to the difference between the curves, represents the spread in local pinning strengths from the minimum value J_c .

which such pulses on the average spend pinned. Thus, using Eqs (8) and (9),

$$p_i = (\theta_i - \tau_i)/\theta_i = J_i/J, \quad J \geq J_c \quad (10a)$$

$$= 1, \quad J < J_c \quad (10b)$$

For the sample as a whole, the pinned fraction will be, for a given driving current J , determined by the fraction of time each group spends pinned, as well as on the distribution of the J_i . Thus for $J \geq J_c$, $p = \int_{J_c}^{\infty} p_i f(J_i) dJ_i$, and

$$p = \int_{J_c}^J \frac{J_i}{JJ_0} \exp\left(-\frac{J_i - J_c}{J_0}\right) dJ_i + \int_J^{\infty} \frac{1}{J_0} \exp\left(-\frac{J_i - J_c}{J_0}\right) dJ_i$$

$$p = \frac{J_c + J_0[1 - \exp\{-(J - J_c)/J_0\}]}{J} \quad (11)$$

Although we have used the distribution function for $f(J_i)$ as used by Baixeras and Fournet, the pinned fraction we obtain at a given J is much larger than that which they find (see Fig. 2). The physical reason for this difference is their assumption that if $J > J_c$, the i th group of fluxoids will definitely be in motion. In our model, such fluxoids will spend part of their time in motion and part of their time pinned. As a result, even in the linear flux flow region, we find that for a sample with J_0 comparable to J_c a sizable fraction of the total flux is at any given time not in motion.

4. CALCULATION OF THE DC VOLTAGE AND THE NOISE SPECTRUM

For identical pulses occurring at a rate n , the noise spectrum can be calculated (Carson's theorem)¹² from

$$W(f) = 2n|F(f)|^2 \quad (12)$$

where

$$|F(f)|^2 = \left| \int_{-\infty}^{\infty} y(t) \exp(-2\pi i f t) dt \right|^2 \quad (13)$$

If we use for $y(t)$ the voltage subpulses given by Eq. (7), then for a given type of subpulse characterized by specific values for the variables θ_i , τ_i , l_i , and Φ_i ,

$$|F_i(f)|^2 = \frac{\Phi_i^2 l_i^2}{L^2} \left(\frac{\sin \pi f \tau_i}{\pi f \tau_i} \right)^2 \quad (14)$$

and the associated power spectrum will be

$$W_i(f) = 2n_i \frac{\Phi_i^2 l_i^2}{L^2} \left(\frac{\sin \pi f \tau_i}{\pi f \tau_i} \right)^2 \quad (15)$$

With the assumption that the events are random, which is equivalent to assuming that the times θ_i are statistically independent, we have for the total spectrum containing all subpulses

$$W(f) = \sum_i W_i(f) \quad (16)$$

Assuming that values of θ_i , τ_i , l_i , and Φ_i are continuously distributed, the summation can be converted to an integral by using a distribution function $\gamma(\theta_i, \tau_i, l_i, \Phi_i)$ such that

$$\sum n_i = \iiint \gamma(\theta_i, \tau_i, l_i, \Phi_i) d\theta_i d\tau_i dl_i d\Phi_i = N \quad (17)$$

where N is the total repetition rate for all subpulses. Assuming further that there is no coupling between θ , τ , l , and Φ ,

$$\gamma(\theta, \tau, l, \Phi) = Ng(\tau)h(l)k(\Phi)u(\theta) \quad (18)$$

where $u(\theta) = (1/\theta_0) \exp(-\theta/\theta_0)$ is required for statistical independence and the distribution functions $g(\tau)$, $h(l)$, and $k(\Phi)$ are separately normalized to unity, i.e.,

$$\int_{\beta\tau_c}^{\alpha\tau_c} g(\tau) d\tau = 1$$

where here the limits of integration have been expressed in terms of the transit time calculated from Eq. (2), $\tau_c = B dL/V_{av}$. Using the fact that the integration over θ yields unity, we obtain for the power spectrum

$$\begin{aligned} W(f) &= \frac{2N}{L^2} \int_{\Phi_{min}}^{\Phi_{max}} \Phi^2 k(\Phi) d\Phi \int_{l_{min}}^{l_{max}} l^2 h(l) dl \\ &\quad \times \int_{\beta\tau_c}^{\alpha\tau_c} g(\tau) \left(\frac{\sin \pi f \tau}{\pi f \tau} \right)^2 d\tau \\ W(f) &= \frac{2N}{L^2} \langle \Phi^2 \rangle \langle l^2 \rangle \int_{\beta\tau_c}^{\alpha\tau_c} g(\tau) \left(\frac{\sin \pi f \tau}{\pi f \tau} \right)^2 d\tau \end{aligned} \quad (19)$$

where N is the total pulse rate for all events

The average voltage, on the other hand, is

$$\begin{aligned} V_{av} &= \sum_i n_i V_i \tau_i \\ &= (N/L) \iiint \Phi l g(\tau) h(l) k(\Phi) u(\theta) d\tau dl d\Phi d\theta \\ &= N \langle \Phi \rangle \langle l \rangle / L \end{aligned} \quad (20)$$

The total pulse rate N is given by the product of the total number of flux bundles that exist within the sample M and $(1/\theta_0)$. Using Eq. (9) for θ ,

$$\begin{aligned} \left\langle \frac{1}{\theta} \right\rangle &= \frac{\langle \Phi \rangle}{\langle l \rangle \eta} \int_{J_c}^J (J - J_c) f(J_c) dJ_c \\ \left\langle \frac{1}{\theta} \right\rangle &= \frac{\langle \Phi \rangle}{\langle l \rangle \eta} \left\{ J - J_c - J_0 \left[1 - \exp \left(-\frac{J - J_c}{J_0} \right) \right] \right\} \end{aligned}$$

and

$$V_{av} = \frac{M\langle\Phi\rangle^2}{\eta L} \left\{ I - J_c - J_0 \left[1 - \exp\left(-\frac{I - J_c}{J_0}\right) \right] \right\} \quad (21)$$

or

$$V_{av} = \frac{B\langle\Phi\rangle R_n \sigma_n}{\eta} \left\{ I - I_c - I_0 \left[1 - \exp\left(-\frac{I - I_c}{I_0}\right) \right] \right\} \quad (22)$$

where R_n and σ_n are the normal-state resistance and conductivity. This is the same expression obtained by Baixeras and Fournet, even though, as we have noted, we have a different interpretation and a higher value for the pinned fraction than that which they calculate. Representative V - I curves are shown in Fig. 3.

Finally we can write

$$W(f) = \frac{2}{L} V_{av} \frac{\langle\Phi^2\rangle\langle I^2\rangle}{\langle\Phi\rangle\langle I\rangle} \int_{0}^{\pi\tau_c} \left(\frac{\sin \pi f \tau_i}{\pi f \tau_i} \right)^2 g(\tau_i) d\tau_i \quad (23)$$

Fig. 3. Normalized flux flow voltage-current characteristics as calculated from Eq. (22). The three curves differ because of the difference in the value of J_0 . Comparison with Fig. 2 shows that the value for the fraction of flux not in motion at any instant can be significant even well into the linear flux flow region.

$$W(f) = \frac{2BR_n\sigma_n}{L\eta} \frac{\langle \Phi^2 \rangle \langle l^2 \rangle}{\langle \Phi \rangle \langle l \rangle} \left\{ 1 - I_0 - I_0 \left[1 - \exp \left(-\frac{l - l_0}{l_0} \right) \right] \right\} \\ \times \int_{0}^{\infty} \left(\frac{\sin \pi f \tau_1}{\pi f \tau_1} \right)^2 g(\tau_1) d\tau_1 \quad (24)$$

5. DISCUSSION

The model we have presented of the flux flow state in which flux bundles transit a sample with their motion interrupted by pinning interactions is physically realistic. Although we have no specific a priori justification for assuming the subpulses are statistically independent, interference terms would appear between subpulses if this assumption were not correct. Our further assumption of an absence of coupling between τ_n , l_n , and Φ_n for subpulses also has no prior justification. Experimentally, the noise spectrum as expressed by Eq. (23) could not be used to determine whether coupling between Φ_n and l_n exists. However, the good fit we obtain to the experimental data for the frequency dependence of the spectra would seem to indicate that τ_n is not coupled to l_n and Φ_n .

The magnitude of the noise spectrum extrapolated to zero frequency is no longer simply proportional to the average flux bundle size; thus in some sense the noise spectra are reduced in their usefulness for determining this quantity. On the other hand, there is now a dependence on the distribution of distances that flux bundles travel before becoming pinned. The magnitude of the spectrum is in fact reduced by the factor $\langle l^2 \rangle / L \langle l \rangle$ from previous models. Therefore, there exists the possibility of extracting information about the distribution of distances flux bundles travel before becoming pinned. We note in this regard that preliminary measurements in a sample of PbSn in which the tin has precipitated so as to form a finely divided microstructure indicate that the noise level is very low so that $l \ll L$, thus verifying the noise reduction with short l which we predict.

Recent neutron diffraction measurements in NbTa samples,¹³ which show little change from the static flux lattice when the fluxoids are far into the linear flux flow state, might seem to contradict our assumption of the flux motion being interrupted by pinning interactions. However, the NbTa sample studied shows very weak pinning, and the pinning interactions may be less effective than in the PbIn samples for which we have presented data. Moreover, as we will discuss in a separate paper in which our experimental results are presented in more detail, we envision the identity of a flux grouping as a "bundle" which exists only at the time of a pinning interaction.

For samples of macroscopic grain size in which grain boundaries provide the principal pinning mechanism, there is undoubtedly long-range correlation while fluxoids are moving within the grains and thus a nearly perfect lattice would exist for the large majority of the fluxoids. We note in this regard that the role of such long-range correlation in reducing the noise has not been included in our model.

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APPENDIX B

CORRELATION BETWEEN CHANGES IN PINNING STRENGTH AND FLUX FLOW NOISE DUE TO ANNEALING IN A TYPE II SUPERCONDUCTOR*

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Correlations are observed between reductions in the critical current and the superconducting flux flow noise power as a deformed $Pb_{80}In_{20}$ foil undergoes room temperature annealing, thus providing evidence that the noise originates from local interactions between moving fluxoids and pinning centers.

Van Gorp [1] suggested that measurements of the flux flow noise spectra could be used as a method of studying the dynamics of flux flow motion in type II superconductors. The noise was regarded as being due to the direct and uninterrupted transit of randomly distributed flux bundles across the sample. Theoretical power spectra for such a case were calculated by Burgess [2] and by Clem [3] who also pointed out that the measured power spectra are dependent on the spatial configuration of the measuring circuit. Similar results were derived by Choe and Van der Ziel [4].

However, other investigations have raised some question about the origin of the noise. For example, Heiden and Kohak [5] have shown in niobium that flux flow in the vicinity of a grain boundary leads to a high level of noise, while within a grain the noise level is low. This suggests that noise results because of local interactions between moving fluxoids and pinning centers. We [6-8] have found similar results in multigrain Pb-In samples where the measured frequency dependence of the noise power spectra and flux bundle sizes can be understood by assuming that the fluxoid motion is interrupted by local interactions between fluxoids and grain boundaries. On the other hand, Heiden [9] has also suggested that the edges of the sample at which fluxoids are created and destroyed may play the major role in the noise generation. Similar conclusions have also been drawn by Jarvis and Park [10].

We present here evidence that changes in the noise level are well correlated with changes in the critical current, thus indicating that the noise does depend strongly

on local interactions between the fluxoids and the pinning centers.

A $Pb_{80}In_{20}$ foil sample was prepared by quenching an ingot from the melt, and immediately compressing the metal slug into a foil. This treatment produces a high density of effective pinning centers as demonstrated by the relatively high critical current which is observed. However, if the sample is left at room temperature, recovery takes place, and the critical current decreases. Our experiment therefore consists of measuring both the critical currents and the noise spectra as a function of annealing time at room temperature. Both the sample edges and the sample surface are left unaltered from run to run during the annealing process, and therefore the resulting changes in the measured properties can be attributed solely to the changes in the local pinning centers. When the sample was not being annealed at room temperature, it was stored in vacuum at liquid nitrogen temperature, and we determined that its properties did not change measurably over a three week period when so preserved.

All noise measurements are performed at 2.15 K, which is below the helium lambda point, thus eliminating thermal fluctuations as a possible noise source. The magnetic field is applied perpendicular to the broad sample face. The voltage probes are arranged such that the probe separation is much larger than the sample width, and the voltage leads are mounted so that they run perpendicular to the sample surface until they are brought together along a path parallel to, but well above, the surface. The form of the spectra should thus be as we have described previously [6,7].

Typical spectra are shown in fig. 1 for a foil meas-

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Fig. 1. Noise power, $W(f)df$, plotted as a function of frequency, f , as $Pb_{80}In_{20}$ undergoes room temperature annealing for different times as shown. Data are taken at 2.15 K, with $H = 3200$ oersted, and $V = 1500$ microvolts. After 22 hours at room temperature the power spectrum remains constant as shown in the solid curve obtained after 865 hours.

Fig. 2. $W(0)$, the noise power per unit bandwidth ($df = 3$ cycles) at zero frequency, as $Pb_{80}In_{20}$ sample undergoes room temperature annealing for the time, t . Measuring conditions are as in fig. 1.

ured with a dc voltage, $V_{dc} = 1500 \mu V$ and $H = 3200$ Oe, after it has undergone various periods of annealing at room temperature. It can be seen that the noise level decreases, and the shape of the high frequency portion of the curve changes, as the sample anneals. The curve representing the highest noise level was taken immediately after the sample was mounted and cooled to low temperature, which was approximately 20 minutes after the compression of the foil.

In fig. 2 we show after various annealing times the noise power at zero frequency obtained, using procedures described previously [7], for $H = 3200$ Oe and a dc voltage along the sample of $1500 \mu V$. The noise level at zero frequency has been interpreted [1,3] as being proportional to the average flux bundle size. We have recently suggested certain modifications to this interpretation which we shall discuss in detail elsewhere [8]. For our present purposes, however, we may simply consider fig. 2 to represent a reduction in bundle size as the sample anneals.

In fig. 3 we plot the critical current (using a $3 \mu V$ criteria), measured at the same field and temperature at which the noise data were obtained, as a function of annealing time at room temperature. By comparing figs. 2 and 3, it is quite clear that the annealing which reduces pinning, as determined by the critical current, also reduces the noise. After 22 hours at room temperature both the critical current and the flux bundle size stabilize, the critical current having decreased by about 20% and the flux bundle size by about two orders of magnitude from their initial values (obtained after

Fig. 3. Variation of critical current, I_c , as $Pb_{80}In_{20}$ sample undergoes room temperature annealing for the time, t . $T = 2.15$ K, $H = 3200$ Oe, $V = 3$ microvolts.

20 minutes at room temperature). The large relative change observed in the noise as against the smaller changes in the critical current confirms our earlier conclusions [7] that noise power spectra are extremely sensitive probes of changes in pinning.

We note that the decrease in flux bundle size with room temperature annealing is a result opposite to that which we have observed [7] in samples which are annealed at temperatures near the melting point, after the initial stage of recovery is complete. In the case of the higher temperature annealing it was found that the flux bundle size increases in proportion to the average grain size, and the grain boundary is the principle pinning defect which interrupts the motion of the fluxoids. In both instances, therefore, our measurements demonstrate that the characteristics of the noise are determined by the local interactions of the moving fluxoids and the pinning centers, and that information about

these interactions can be extracted from noise measurements.

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APPENDIX C

Flux Flow Current-Voltage Characteristics and Their
Magnetic Field Dependence in a Type II Superconductor*

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Abstract

Experimental flux flow V-I characteristics are compared with our previous model which assumes flux motion is interrupted by local pinning interactions. Quantitative changes in these characteristics occur at the field at which the peak in the pinning force occurs.

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The nonlinearity of the flux flow voltage-current characteristic has been a subject of interest ever since these characteristics were first observed. There have been a number of attempts to explain this non-linear behavior or to obtain a general mathematical expression fitting the data at all fields and in all samples [1-3]. These attempts have generally met with experimental demonstrations that the proposed generalizations were inadequate for other samples or sample conditions [4-5].

Until recently the clearest experimental insight into factors influencing the nonlinear region was obtained by Jones et al [6], who demonstrated that variation in pinning strengths along the sample gives rise to nonlinearities. However, no clear indication was obtained as to the scale over which such variations typically take place. Baixeras and Fournet [7] built upon this idea and derived a particular form for the distribution of pinning strengths. Their prediction for the shape of the voltage-current characteristics fitted very well their experimental results for a Nb foil.

Renewed interest in the significance of the nonlinear region has occurred recently based on the experimental work of Goncharov and Khukharova [8] and of Lauterwasser and Kramer [9]. These experiments have shown that the shape of the nonlinear region can change as one passes through the peak in the pinning force, $F_p = I_c \times H$. Kramer [10] has predicted that at fields lower than the peak fields, where flux flow begins by pin breaking, the second derivative of the flux flow characteristic, $\frac{d^2V}{dI^2}$, will be negative in a small current range above I_c . Above the peak, where flux flow occurs by shear, d^2V/dI^2 will be everywhere positive. This prediction was verified by Lauterwasser and Kramer [9] on irradiated $Nb_{90}Mo_{10}$ samples, but not by Goncharov and Khukharova [8], who instead observed an increase in the nonlinearity of the characteristics in a $Nb_{20}Zr_{80}$ alloy in the region of the peak.

We have recently developed a model of flux flow in which we envision that pinning centers are active in interrupting flux motion at all current values,

including those which are well into the linear flux flow region [11]. This model assumes that a specific group of fluxoids, ϕ_i , will move between a particular set of pinning centers with a constant instantaneous velocity, v_i , obtained by setting the Lorentz force, $J\phi_i$, equal to the viscous drag ηv_i . This instantaneous velocity is greater than the average velocity $\bar{v}_i$ determined by the equation:

$$\phi_i (J - J_i) = \eta \bar{v}_i \quad (1)$$

where $\phi_i J_i$ represents the local pinning strength for the particular set of pinning centers involved [12]. Each event gives rise to a voltage pulse characterized in our model by the "flux bundle size", the distance between pinning sites, and the instantaneous and average velocities specific to the event. By an appropriate superposition of these voltage pulses, we obtain an expression for the d-c voltage and the flux flow noise power spectrum [11]. Previously we have shown that the model provides excellent agreement with experimental results for the noise power spectra [11,13], and the purpose of this paper is to show that excellent agreement is also obtained for the flux flow voltage-current characteristics. We also show that parameters of the model can be used to describe quantitatively changes in the characteristics with field.

Our model yields relatively large values for the pinned fraction. The pinned fraction arises from two sources: (1) there will be a range of local pinning strengths, and unless the current provides a Lorentz force everywhere greater than the local pinning strength, some fluxoids will remain pinned; and (2) even in those regions where the Lorentz force is larger than the local pinning force, interactions between pinning centers and fluxoids will temporarily interrupt the flux motion.

We must assume a distribution function for the pinning strengths, $f(I_i)$. The form we choose is $f(I_i) = \frac{1}{I_0} \exp(-\frac{I_0 - I_i}{I_0})$, which is that derived by Baixeras and

Fournet [7]. The resulting voltage-current characteristic also has the same form which we derived, although as noted, our model predicts a larger pinned fraction at any voltage value, because of the contribution from source (2) above. The form of the voltage-current characteristic is:

$$V_{dc} = \frac{B \langle \phi \rangle R \sigma \langle l \rangle}{n n} \left\langle \frac{1}{l} \right\rangle \left[I - I_c - I_0 \left[1 - \exp \left(-\frac{I - I_c}{I_0} \right) \right] \right] \quad (2)$$

where $\langle \phi \rangle$ denotes an average flux bundle size for the sample, $\langle l \rangle$ is the average distance between pinning sites, I_c is the critical current associated with the minimum pinning strength, and I_0 represents a measure of the spread in the pinning strength.

The agreement between eqn. (2) and our data is shown in Fig. 1 for fields of approximately 0.4, 0.6 and 0.9 H_{c2} . The sample is a $Pb_{80}In_{20}$ foil pressed and annealed at room temperature. The solid curves are best fits to eqn. (2) obtained by adjusting I_c and I_0 , and the circles represent experimental points. Fits of this type allow us to study quantitatively changes in the flux flow curves with field. Thus, in Fig. 2 we show plots of the critical pinning force, F_p , and the ratio I_0/I_c as a function of field. I_0/I_c measures the ratio of the spread in pinning strengths to the weakest pinning strength.

Neither our model nor our experimental data yield negative values for $\frac{d^2V}{dI^2}$ at any field or current values, as has been predicted and observed in other samples [9]. However, the behavior of I_0/I_c with field is otherwise consistent with expectations based on a decrease of the fluxoid lattice stiffness constant with increasing magnetic field. Thus, as one approaches the force peak from low fields, there is a gradual and slow decrease of I_0/I_c as the decreased lattice stiffness allows partial synchronization, i.e., placement of fluxoids on stronger pinning sites, a process which eliminates the activity of weaker sites. As one moves from the peak toward higher fields, there is an abrupt and rapid increase in I_0/I_c as plastic shear becomes the dominant mechanism. Qualitatively the reason for

this smearing of the flux flow characteristic, quantitatively measured by the increase in the ratio of I_0/I_c , is the considerable inhomogeneity in the local shear stress.

We conclude by noting that it is somewhat surprising that our model fits our data in the high field region where plastic shear occurs. Qualitatively it appears that in other samples [9] the fit in the high field region exists even though no such fits exist at lower fields. We also note that our model may be adjusted to include other distribution functions for the pinning strengths. Such an adjustment may be necessary in cases where the dominant pinning mechanisms are different than those which exist for the samples reported here.

In summary, our model yields a quantitatively good fit to experimental flux flow curves. Changes in parameters of the model, I_0 and I_c , also allows us to study synchronization and the transition from pin breaking to plastic shear in the fluxoid lattice.

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Figure Captions

Fig. 1. Flux flow voltage current characteristics of $\text{Pb}_{80}\text{In}_{20}$ sample taken at $T = 2.15$ K. The solid curves represent fits to eqn. 2. Experimental V-I values were obtained as continuous traces on an x-y recorder but for clarity are presented as circles in the figure. The data shown represent flux flow below and above the pinning force peak.

Fig. 2. Pinning force, $F_p = I_c \times H$, as a function of field for $\text{Pb}_{80}\text{In}_{20}$ (circles), and ratio of I_0/I_c as a function of field (triangles). I_0/I_c represents the ratio of the spread in pinning strengths to the minimum pinning strength.

APPENDIX D

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Physics and Astronomy
Classification Scheme
Number 74.40 GT

Bulletin Subject Heading in
which Paper should be placed
Superconductivity

On the Flux Flow Properties of Type II Superconductors Containing Precipitates*. F. HABBAL, R.G. PIRICH AND W. JOINER, Univ. of Cincinnati.--The properties of flux motion in type II superconductors can be studied by measuring the voltage-current characteristics and flux flow noise spectra. Preliminary measurements of $Pb_{87}Sn_{13}$ samples were made using the above techniques. We find that voltage-current characteristics of samples containing precipitates are dependent on the previous field history and current history through which the sample has been cycled¹. Training effects with respect to rotating the sample in a constant field or repeatedly cycling the current are also observed. These effects are most pronounced after long time aging when tin precipitates become spherical in shape. Low noise is observed in these samples which appears to contradict previously proposed models. Further voltage-current and noise measurements on type II superconductors containing precipitates are being conducted to determine whether hysteresis and low noise are general properties of type II superconductors containing precipitates or whether they are dependent on a particular morphology of the precipitates.

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Abstract

Hysteresis in the Flux Flow Characteristics of a Type II Superconductor Associated with the Presence of Normal Metal Precipitates*

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Unusual history dependent flux flow properties are observed in a $\text{Pb}_{.871}\text{Sn}_{.129}$ alloy as tin precipitates from solution at room temperature. We find that the critical currents and flux flow curves depend upon the field history, the current history, and the orientational history of the sample. Two volume pinning force curves are observed with different force magnitudes and field locations of the force peak depending upon whether the field is cycled to high fields or zero fields before the force is measured. Flux flow noise measurements in these samples yield very low noise, consistent with our recent model which predicts low noise in samples with closely spaced pinning centers that interrupt the flux motion. The experimental results are explained in terms of the formation of a nonequilibrium flux line lattice in the presence of precipitates, and the response of such a lattice to current, field, and orientational changes.

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I. INTRODUCTION

Hysteresis in the magnetization curves of type II superconductors is a well-known phenomenon. In fact, hysteretic magnetization curves are much more commonly observed than are reversible magnetic transitions, so that in order to extract parameters related to the reversible curve, procedures have been developed to deduce the reversible curve from a measured irreversible one.¹⁻³ Hysteresis in the magnetization results because the motion of flux towards the equilibrium configuration is impeded by interactions with flux pinning centers. Equivalently, the hysteresis can also be explained in terms of position-dependent shielding currents using the critical state model.⁴

When a transport current of sufficient magnitude is passed through a sample in the mixed state, flux flow (FF) results. The motion of fluxoids in this instance is also impeded by interactions with pinning centers. However hysteretic behavior in the FF voltage-current characteristics has only been reported in a very few instances. Specifically we have identified only five such reports⁵⁻⁹ in the previous literature. Good and Kramer⁵ observed field history and voltage-current hysteretic effects in a strained Nb crystal, where these effects also showed a time dependence. The observations were attributed to changes in the number of mobile flux line dislocations in the flux line lattice (FLL). Similar hysteretic behavior also has been observed in NbTa by Campbell and Evetts,⁶ and was attributed to similar causes. Other history dependent effects were observed by Steingart et al⁷ in a Nb sample with less deformation than the sample used in ref. 5. In this case there was no mention of the associated time dependent effects reported with the more deformed sample. The history dependence in this instance was explained by differences in the number of effective pins acting on the FLL, and it was assumed that the

number of such effective pins depends upon the method of forming the FLL, and its subsequent alteration by current cycling. In each of these observations of hysteresis, FF curves for decreasing currents yielded lower critical currents than initial FF curves obtained with increasing currents. Further, after cycling through the initially hysteretic FF curve, the voltage-current relationship became reversible.

FF hysteretic effects have been observed in lead-tin eutectic alloys by Brand et al,⁸ and in a $Pb_{77}Sn_{23}$ alloy by Peltier and Baixeras⁹. In the latter case the FF curves were observed at relatively high voltage levels (to 20 mV) and the authors attribute the hysteresis to sample heating. Voltages obtained for an increasing current sweep are higher than obtained with decreasing currents. The curves obtained on increasing the current showed instabilities, while the curve for decreasing current was stable. In the eutectic sample,⁸ data were restricted to low voltages (50 μ V or less), and heating effects were unimportant. Again FF curves with an initial ascending current sweep yielded higher voltages at every current than were obtained with decreasing currents. As in the previous cases, after cycling the current once, the FF curves became reversible.

We report here a rather extensive study of some extreme hysteresis effects in lead-tin alloys containing tin as a laminar precipitate. As we will demonstrate, critical currents and voltage-current characteristics depend upon the field history, the current history, and the orientational history of the samples. The hysteresis and the specific characteristics depend strongly on the stage of precipitation. In addition to FF characteristics and critical current data, we have made measurements of the FF noise power spectra in our samples in order to try to understand the nature of FF in the presence of laminar precipitates.

II. Sample Preparation and Metallurgy

Magnetization curves and the metallurgy of lead-tin alloys have been studied extensively by Livingston,¹⁰ who reported results using two alloys, one of 12.9 at. % Sn and the other of 17.9 at. % Sn. In our present experiments we have used samples of 12.9 at. % Sn composition. Our samples were solution treated at 240°C, the same temperature used by Livingston. At this temperature the alloy is well within the solid solution region. Livingston found that alloys quenched from this temperature showed typical type II superconducting magnetization curves with critical fields, H_{c_2} , at 4.2K of about 1100 Oe. Near H_{c_2} the magnetization curves are nearly reversible, but at lower fields hysteresis and flux trapping are evident.¹⁰

With room temperature aging, tin precipitates from solution. Precipitation occurs in two stages. The first stage is a "fast reaction" in which cellular or discontinuous precipitation takes place. Thus cells of transformed material nucleate at grain boundaries, and grow into the grains. The cells of transformed material consist of alternating tin lamellae and lamellae of lead based solid solution. The tin lamellae are thinner than the lead lamellae, and the separation of the tin lamellae is typically of the order of 3000-4000 Å. This cellular precipitation process is completed (i.e. transformed material completely fills the grains) at room temperature in about one hour. Until this precipitation process is complete, the magnetization retains a reversible high field tail and the upper critical field does not change. The field at which flux penetration begins, and the amount of trapped flux in decreasing fields, both increase as larger portions of the grains convert to transformed material.¹⁰

The fast reaction process occurs by lateral diffusion within the cell

boundary, and removes much of the excess tin from solid solution. The second precipitation stage, the "slow reaction", proceeds by lattice diffusion, and drains the remainder of the excess tin from solution. This second process may take months to complete. Initially this process broadens and coarsens the tin lamellae, but after two months or so spheroidization of the lamellae begins to take place. Upon completion of the initial precipitation, the high field tail of the magnetization curve disappears, and the field at which $M \rightarrow 0$ decreases slowly as tin is drained from solution. The field at which initial flux penetration occurs increases initially, but decreases after longer times at room temperature, and almost complete flux trapping occurs.¹⁰

Our samples were prepared similarly to those of Livingston,¹⁰ except that they were in the form of foils. As noted, we used only the 12.9 at. % Sn composition studied by Livingston. The lead and tin were melted in a quartz tube under vacuum, and mechanically mixed for a period of 24 hrs. The liquid solution was then quenched by immersing the sample tube into water, forming an ingot which was compressed in several stages to form the final foil shape. Typical foil dimensions were 3 mm wide, 0.8 mm thick, and 25 mm long. Specimen surfaces were cleaned with an electropolishing etch consisting of a solution of 29.5 gm sodium acetate, 157.5 ml glacial acid and 40 ml distilled water. After cleaning, samples were solution treated for various periods by vacuum annealing at 240°C. Upon completion of annealing, the samples were quenched into liquid nitrogen, mounted, and placed into our experimental dewar where they were kept at liquid nitrogen temperatures. Mounting of the samples could be accomplished within approximately 5 minutes at room temperature.

The samples were mounted with their long axis vertical, thus permitting us to rotate the magnetic field about this axis, while maintaining the field always perpendicular to the current direction. Measurements were taken with the magnetic field perpendicular to the broad face of the sample unless otherwise noted. FF curves were taken with the four-probe technique, and noise measurements were taken using procedures described elsewhere.^{11,12}

III. Experimental Results - Metallurgical Effects

A. Initial State

Despite solution treatments of up to three months at 240°C, FF and critical current data indicate that in our samples either the transformed regions never completely redissolve to form a homogeneous solid solution throughout the sample, or that some precipitation occurred in the short time it took to mount the samples. Evidence for the existence of precipitation can be seen in the critical current curve, I_c vs H , shown dashed in Fig. 1. The existence of two "knees" in this curve suggests the presence of two phases with different values of the Ginsburg-Landau parameter, κ . Further evidence for the presence of precipitates is found in instabilities which we observe in the FF V-I characteristics at voltage levels above several hundred microvolts, as previously reported in ref. 9.

Noise power spectra were taken at this stage, and were found to be similar to those found in single phase alloys, with a high frequency decrease in the noise power approximately proportional to $1/f^n$. A typical power spectrum is shown in Fig. 2. The only unusual behavior is the somewhat low noise level, typically $10^{-17} - 10^{-18} \text{ V}^2$ at $f = 0$, as compared to noise levels of perhaps 10^{-16} V^2 , in a well-annealed single phase alloy,

using comparable average fluxoid velocities. Also in the present case $n > 1$, whereas we have previously found $n = 1$ in well annealed alloys.¹¹ In our earlier experiments values of n greater than one were identified with: (1) strong pinning centers, (2) high noise levels (sometimes as high as 10^{-14} V^2), and (3) the absence of very short flux transit times between pinning centers. Conditions (1) and (3) are satisfied in the present case¹³, and we need to understand why we now observe relatively lower noise powers.

We have previously shown¹⁴ that the noise power, extrapolated to zero frequency, is given by

$$W(f=0) = \frac{2V_{dc}}{L} \frac{\langle \phi^2 \rangle \langle l^2 \rangle}{\langle \phi \rangle \langle l \rangle}$$

where V_{dc} is the dc voltage along the sample, L is the sample width, l represents the distance a flux "bundle" travels before being interrupted by pinning sites, ϕ is the flux bundle size, and $\langle \rangle$ denotes an average over all fluxoids in the sample. Low noise can therefore be attributed either to intrinsically small bundle sizes or to short distances between pinning sites. In the present case we suggest that the moving fluxoids exist within the single phase untransformed material, but that precipitation in the vicinity of the grain boundaries serves to create effective pinning sites which interrupt the flux motion, so that the smallness of the ratio $\frac{\langle l^2 \rangle}{L \langle l \rangle}$ is responsible for the low noise. Other details of the noise measurements and FF in this initial state are not important to the central subject of the present report, and will be described in detail elsewhere.¹⁵

B. Cellular Precipitation

In the as quenched condition after solution treatment, and for room temperature annealing times of less than 1/2 hour, hysteretic effects in the flux flow properties are not observed. During this early stage, H_{c2} , as

determined from the change in slope of a $\ln I_c$ vs H plot, does not change, although the magnitude and shape of the critical current curves do change slightly in some field regions. See Fig. 1. We believe that the H_{c2} which we are observing during this stage is that of the untransformed high kappa material whose properties do not change until it is consumed by the cellular precipitation. This interpretation is entirely consistent with the magnetization results of Livingston.¹⁰ The H_{c2} which we obtain at 4.2K is 1120 Oe as compared to the 1100 Oe obtained from his magnetization measurements. The increase in critical current as this stage progresses can be attributed to the growth of transformed material across the path of fluxoids moving in the transformed regions, thus inhibiting the flux motion. This can also be seen in the reduction of the magnitude of the flux flow noise as this stage progresses.

C. Completion of Cellular Precipitation

When the cellular precipitation has completely transformed all of the single phase regions, a sudden decrease in H_{c2} occurs, indicating that we are now measuring the critical field of the transformed lead rich lamellae. At this point a number of hysteretic effects which form the principal subject of this report became manifest. So long as the transformation was not complete, FF would occur in the single phase regions, and the sample critical current would be the critical current appropriate to those regions. FF in these regions would also be reversible as it is in the case of other single phase samples.

Upon completion of the cellular precipitation, the FF noise over most of the frequency spectrum is reduced to levels below $10^{-18.2} V^2$ which with our present system prohibits our taking spectra over a meaningful frequency range. Again

we interpret this as largely due to the very short distances and small flux bundle sizes which are now involved in FF at low voltage levels. We also note that at this point instabilities in the FF V-I characteristics become very pronounced at levels above a millivolt, and at these levels we may assume that local heating takes place when fluxoids are depinned catastrophically from the strong pinning centers formed by the tin lamellae.

We now describe in some detail the observed hysteretic effects which accompany the complete conversion of the sample to the lamellar structure.

IV. Experimental Results - History Dependent Effects in Flux Flow

A. Critical Currents

In reporting on the field history effects we will illustrate our results on a single sample in order to show the relationships of the magnitudes of the different effects to each other. The particular sample used as an illustration was annealed at 240°C for 24 hrs., quenched, and then left for four weeks at room temperature. Other samples which were homogenized and then allowed to transform completely into the alternating Pb rich and Sn rich lamella show similar behavior. Although hysteresis appears when the cellular precipitation is complete, the hysteretic effects become pronounced after room temperature annealing exceeding one day. This is probably due to more effective pinning by the tin lamellae which are becoming thicker during the lattice diffusion precipitation process. We have not examined samples which have annealed at room temperature for several months so as to cause spheroidization of the tin particles. In our only attempt to examine a sample with such a long annealing time, we were forced to use such a large current that the sample burned out while in the liquid helium bath.

The field history effects on the critical current are illustrated in

Fig. 3. We show as a solid curve the critical current obtained, using a 0.5 μ V criterion, when for each point the magnetic field is first increased to a field high enough to drive the sample completely normal, and then reduced monotonically to the final field of measurement (H_{NF}). The dashed curve is the critical current obtained when for each point the magnetic field is reduced to zero, and then increased monotonically to the field of measurement (H_{OF}). The hysteresis is evident from the graph, and is quite large. In the vicinity of 480 Oe the critical current obtained with H_{NF} is almost 15 times the critical current obtained with H_{OF} !

The hysteresis is characteristically bounded within a limited field range. Although the resistive transition at H_{c2} is smeared in samples annealed for long periods at room temperature, the upper field bound on the hysteresis appears to our best estimate to be the value of H_{c2} applicable to the largest volume of the sample. Our estimates for H_{c2} after various annealing times are close to those obtained by Livingston from magnetization curves for comparable annealing times. The lower field bound on the hysteresis is more elusive, but it is undoubtedly below the value of the lower critical field H_{c1} , and corresponds to the peak in the critical force curve F_v vs H for H_{OF} . Because of the hysteresis, two critical force curves are observed depending upon the method of forming the FIL. These are illustrated in Fig. 4. Note that the critical force curve for H_{NF} exhibits a peak of larger magnitude, and occurs at a higher field than the corresponding peak for H_{OF} . Below the peak for H_{OF} the force curves are identical.

B. Voltage-Current Characteristics

The history dependence of the critical currents is reflected in the V-I curves, which also show a current hysteresis. This is illustrated in Fig. 5

where the curve at low currents is obtained using the sequence H_{OF} , the curve at high currents is obtained using the sequence H_{NF} , and the curve at intermediate currents is obtained by cooling the sample in the field of measurements (CIF). Our results therefore differ from those of Steingart et al.⁷ who found that $I_c(CIF) > I_c(H_{NF})$.

They also differ from previously reported hysteresis⁵⁻⁹ in two other important aspects. First, after achieving FF, previous experimenters found that the V-I curves were reversible on subsequent sweeps, and corresponded to the curve obtained for the initial decreasing current trace. In our experiment the following results were obtained: (1) The CIF V-I loop was stable with respect to current cycling provided that the current was always maintained between the same limits. That is, increasing the current always produce the same voltage trace as obtained initially for increasing current, and decreasing the current always produces the same voltage trace as obtained initially for decreasing current. This stability could be destroyed slightly however, by reversing the current direction. (2) The H_{OF} loop on subsequent cycling between the same current limits becomes narrower with the increasing-current trace moving markedly to higher currents, and the decreasing-current trace moving slightly to higher currents, as can be seen in Fig. 6. The first repetition of the cycle has the most pronounced effect, and changes with additional cycling become progressively smaller. Thus, for the example shown, I_c (using a 0.1 μV criterion) is approximately 1.7, 4.4, 4.5, and 4.6 amps for the first four increasing current sweeps, and changes only from about 5.5 to 5.6 amps for the corresponding decreasing current sweeps. An accelerated shifting of the loop can be achieved by cycling the current in the opposite direction and then returning to the original direction. (3) The first repetition of the current cycling for the H_{NF} loop opens the loop and the crossover

disappears (see Fig. 7). Repeated cycling moves the entire loop to lower currents so that it approaches, but never reaches, the CIF loop. Again the initial recycling produces the greatest relative change, and cycling the current in the negative direction is, after any amount of cycling, more effective in producing a change than is an additional cycling in the positive direction. In every case, cycling the current with $V = 0$ produces no observable changes.

The second important difference in our results from those of refs. 4, 5 and 6 is that in our experiment the voltage obtained at a given current is always less on decreasing the current than it is on increasing the current for CIF, H_{OF} , and on all but the initial cycle for H_{NF} . Thus the critical current in these instances is higher on decreasing the current than it is on increasing the current.

A number of other observations have been made with respect to the V-I cycling. A partial listing of these follows:

(a) No changes in the hysteretic behavior were observed in going through the helium lambda point. (see Fig. 8). Thus heating effects are not likely to play a large role in producing the V-I hysteresis. We have just noted that the voltage for a given current value is always less for decreasing currents than it is for increasing currents, which is just the opposite behavior one would expect if the hysteresis were produced by sample heating.

(b) Time effects were not observed. One could measure a particular V-I point for periods of twenty minutes or more without observing changes. Current sweep rates between 1 mA/sec and 1000 mA/sec produced identical results. Switching the current on very rapidly, however, (~ 100 A/sec) would sometimes produce a slightly reduced critical current.

(c) The amount of hysteresis, measured either in terms of the area

bounded by the V-I loop, or in terms of the ratio of critical currents for current decreasing to current increasing, increases dramatically as the field is reduced for both H_{OF} and CIF, as can be seen in Fig. 9. We were not able to pursue these measurements to very low fields because of the large currents required in this region. Hysteresis loops did not change dramatically with field for H_{NF} . See Fig. 10.

(d) Sweeping to higher voltages had the following effects:

(1) For CIF the voltage at a given current on the decreasing current sweep will be lower the higher the voltage to which the sample is initially cycled, except in the region close to the critical current. The critical current itself is unchanged;

(2) For H_{OF} similar results are obtained.

(3) For H_{NF} the crossover point of the V-I curves for increasing and decreasing I moves to higher currents and voltages the higher the voltage to which the sample has previously been cycled.

(e) For H_{OF} , cycling the field with a current on shifted the hysteresis loop to lower currents provided the V-I curve was taken with the current in the same direction as the current direction during the field cycling. For V-I curves taken with the current in the opposite direction as the current direction during the field cycling, the shift was to higher currents. For H_{OF} , cycling the field with a current on shifts the hysteresis loop to higher currents when the initial current and the current used for the V-I curve are in the same direction, but the shift is to lower currents when the current directions are opposite. For CIF, the hysteresis curve is stable and independent of whether or not a current is on during the process of cooling to the temperature of measurement.

(f) The critical current and V-I differences observed between H_{NF} and H_{OF} are extremes. Intermediate effects are observed if the field of measurement is reached by cycling to some intermediate field, H_I , between O and N. Generally the most rapid changes take place for field excursions close to the field of measurement. For example, in Fig. 11 we show critical current values obtained by cycling the sample to the normal state, then to the intermediate field, H_I , and finally to the field of measurement (which is greater than H_I), as a function of H_I .

(g) The FF is anisotropic. Critical currents are higher for one direction of current flow than for the other. Reversal of both field and current, however, restores the critical currents and FF curves to their values before reversal. Also, if the magnetic field is rotated in the positive direction through a certain angle away from the sample normal, a different flux flow curve is obtained than if the field is rotated through the same angle in the negative direction. These are apparently not surface effects since they are not altered by etching the sample surface.

C. Magnetic Field Orientation

History dependent critical currents and FF curves were observed if the FLL is established with the field in one direction and the field is subsequently rotated to a different direction. For example, we show in Fig. 12 FF curves obtained for increasing currents when the magnetic field is cycled H_{OF} at an angle θ to the perpendicular to the broad face of the sample, and is then rotated so that it is perpendicular to the broad face when the measurement is taken. Increasing the angle through which the field is rotated after the formation of the FLL shifts the V-I curve to higher current when the field history is H_{OF} . However, when the field is cycled H_{NF} , the V-I curve

is shifted to lower currents. For rotations of 90° , the curves for both H_{OF} and H_{NF} approach the same limit which is approximately the CIF curve obtained without rotation. This is also illustrated in Fig. 12 where points from a curve of CIF are shown as circles.

DISCUSSION

We have presented data showing very complicated history dependent FF effects, clearly related to the amount and nature of tin precipitates in a Type II lead matrix. As we have noted, the time effects previously reported as accompanying hysteresis⁹ were not observed in the present experiments, which are therefore more nearly comparable to those of Steingart et al⁷ on deformed Nb. In their case they attributed the hysteresis to differences in the number of effective pins which arise because of differences in the manner in which the FLL is formed relative to the available pinning centers. According to their model, the most favorable method of formation, resulting in the maximum number of effective pins, is CIF. The least favorable method is H_{OF} . Furthermore, regardless of the method of formation, they suggest that any subsequent disturbance of the FLL will result in a degradation of the critical current. Thus they predict, and find experimentally

$$I_c(CIF) > I_c(H_{NF}) > I_c(H_{OF}) > I_c(FF)$$

Contrary to this, we find in the present experiments that

$$I_c(H_{NF}) > I_c(CIF) > I_c(H_{OF})$$

and that disturbances of the FLL through FF, or by rotation of the magnetic field, may either raise or lower the critical current, depending upon previous history. Other experimental differences between the two experiments have also been noted; so that some modification of the model of Steingart et al⁷ is re-

quired to explain the present results.

We begin by noting that the FF curves for CIF are stable with respect to current cycling, provided the current is always cycled in the same direction. Moreover, cycling of the FF curves after FLL formation by H_{OF} and H_{NF} tends to shift the curves in the direction of the CIF FF curve. We also have the interesting result that rotation of the magnetic field by 90° after formation of the FLL by either H_{OF} or H_{NF} produces a FF curve very close to that obtained with CIF.

We therefore propose that the previous hypothesis is correct, and that the CIF method of FLL formation provides the maximum number of effective pins appropriate to the equilibrium flux density in the sample at a particular field. We emphasize further the pervasiveness of the tin lamina which provide strong pinning sites for the majority of the fluxoids. At low voltages where the FF curves are stable, those fluxoids which move are most likely forced to do so through rather narrow channels between the lamina. These fluxoids are more weakly pinned. Such channels as may exist will vary in width, and be characterized by a number of constrictions. We note further that the observed hysteresis occurs above the peak in the H_{OF} force curve, the region in which FF is characterized by shear rather than pin breaking.¹⁶

With these basic premises we are able to explain most of our observations. When the FLL is formed by H_{NF} , a flux density greater than the equilibrium density is pinned by the tin lamina and by other pinning sites. This greater than equilibrium flux density tends to fill up the channels in which FF takes place in CIF, and it is therefore more difficult to initiate and sustain flux flow, and one obtains $I_c(H_{NF}) > I_c(\text{CIF})$. When the FLL is formed by H_{OF} , one has the opposite situation. Thus the flux density is less than the equilibrium value, and channels between strongly pinned fluxoids are more open, making FF easier,

and one obtains $I_c(\text{CIF}) > I_c(H_{\text{OF}})$. Cycling the current, or rotating the field, pushes fluxoids onto stronger pinning sites, and tends toward the pinning appropriate for the equilibrium flux density. Thus the H_{OF} FF curves after such cycling move toward the CIF curves. Similarly current cycling or field rotation after H_{NF} dislodges fluxoids from some pinning sites, and also tends toward the equilibrium flux density, thus decreasing the critical current, and moving the FF curves toward those obtained by CIF.

We may similarly understand the nature of the V-I characteristics. We have recently demonstrated that the transition from pin breaking to shear as the mechanism for initiating flux flow is evident in the FF characteristics.¹⁷ By using a Lorentzian distribution of pinning strengths, as originally proposed by Baixeras and Fournet¹⁸, we have obtained an expression similar to that which they obtained for the V-I characteristics¹⁴, i.e.

$$V = \frac{B \langle \phi \rangle R_n \sigma_n \langle l \rangle \langle \frac{1}{l} \rangle}{\eta} \left\{ I - I_c - I_0 \left(1 - \exp \left(- \frac{I - I_c}{I_0} \right) \right) \right\}$$

where R_n and σ_n are the normal state resistance and conductivity, B is the magnetic induction, η the viscosity coefficient, $\langle \phi \rangle$ the average flux bundle size, I_c represents the minimum pinning strength, l represents the distance between pinning sites and I_0 represents the spread in pinning strengths. We find that a sudden increase in the ratio of I_0/I_c takes place in the vicinity of the force peak in $F_v = I_c \times H$, and indicates the onset of shear¹⁷. This ratio continues to increase rapidly as the shear constant decreases to zero on approaching H_{c2} .

Although we have also found that deviations from the Lorentzian distribution of pinning strengths may be apparent when FF is examined at low voltage levels, thus requiring care in the application of the above analysis, certain generalizations can nevertheless be made about the V-I characteristics. For the three methods of FLL formation, and for a given field, H_{OF} has the highest

ratio of I_0/I_c , H_{NF} the lowest, and CIF intermediate. One would therefore anticipate that the greatest amount of shear would take place in H_{OF} , and the least in H_{NF} . This is consistent with our picture of FF channels existing between more widely spaced pinned fluxoids in H_{OF} , with the spacing decreasing as one progresses toward H_{NF} . (We note this is also consistent with our results for intermediate field cycling). The greater amount of stiffness at a given field for H_{NF} in the hysteretic field region can also be illustrated by the plot of the forces $F_v = I_c \times H$ for the two methods of FLL formation as shown in Fig. 4. $F_v(H_{NF})$ has a peak at higher fields, and a higher maximum value than $F_v(H_{OF})$.

With one exception, for the several methods of FLL formation the decreasing current sweep V-I curve has a smaller ratio of I_0/I_c , and a higher critical current, than for the increasing current sweep. Once again this can be interpreted as a stiffer fluxoid lattice in decreasing currents over what is found for increasing currents. We suggest that this situation arises because as the moving fluxoids encounter constrictions in the flow channels, a kind of "log jam" results. So long as the Lorentz force is maintained or increased, fluxoids are pushed through the channels although the congestion persists or increases. However when the Lorentz force is decreased, the rate at which fluxoids squeeze through is less than it was for increasing forces because of the increased density within the channels. When the current is reduced to zero, the density returns to normal, and a subsequent current increase lies close to the initial curve except for any permanent pinning or depinning which occurs tending toward the CIF curves. The single exception is the initial current sweep after FLL formation for H_{NF} . In this case the voltages for decreasing current lie below those for increasing current until low voltages where there is a crossover. This crossover may be attributed to the fact that on the first current cycling many of the initially pinned fluxoids are

depinned as the flux density tends toward its equilibrium value. There are therefore two competing processes in this case; i.e. the process described above and depinning. At higher voltages the first process dominates, but at voltages below the crossover the higher number of depinned fluxoids on decreasing the current than there were when the current was increased produces a larger voltage for a given current. This would also explain the fact that the point of crossover moves to higher voltages or currents as the initial maximum value of the current increases, since this would tend to depin more fluxoids.

We have observed that forming the FLL with a current on moves the H_{OF} V-I characteristics to lower currents, has no measurable effect on the CIF characteristics, and moves the H_{NF} characteristics to higher currents. For H_{OF} the flux density is below the equilibrium value and fluxoids have trouble reaching the strong pinning centers where they would be stable. The existence of a current during FLL formation evidently keeps the channels "open" and prevents additional fluxoids from reaching strong pinning centers, thus producing lower critical currents. For H_{NF} the opposite occurs. The channels are congested because of the high flux density and the Lorentz force tends to push fluxoids against the pinning centers, and higher critical currents result. For CIF the equilibrium flux density has been reached, and the presence of a current during FLL formation has no effect.

We have also observed that after several current cycles with the current always maintained in the same direction, a double reversal of current can accelerate the rate at which the V-I characteristics for H_{OF} and H_{NF} approach those for CIF. We believe that this is because of the observed anisotropy in the total pinning force, F_v . Since we have described the effect of current cycling as a process of pinning or depinning which tends toward the equili-

brum flux density, it seems reasonable that if anisotropic pinning walls are present, some of which are more accessible for current flow in one direction and some for current flow in the opposite direction, then allowing fluxoids to sample forces in both directions should speed the approach to equilibrium.

Our observation of very low noise in these samples is consistent with our picture of flux flow occurring by shear, and occurring within narrow channels. We have previously noted that in a recent model¹⁴ we have shown that low noise can be achieved either through small flux bundle size or by a short average distance between pinning centers. Both of these conditions should be present for the channels within which we have assumed flux flow takes place, and the low noise is consistent with this model.

The lead-tin system is obviously a very interesting system from the point of view of FF. The differences in the experimental results and hysteresis which we have observed in this system from those obtained by Brand et al.⁸ in a lead-tin eutectic, suggests that composition and morphology are important in determining the exact nature of the hysteresis. It is also interesting to note that the systems in which hysteresis has been observed have been of relatively low kappa values. It would be interesting to know if this is a necessary condition. It would also be worthwhile to study the effects of normal precipitates, with various morphologies, where the formation of the precipitate did not affect so strongly the composition of the type II phase. Analysis of the present results was hindered by the absence of a sharp transition at a well-defined H_{c2} , which we have attributed to a smearing of kappa as the tin leaves solution at different rates in different regions.

The practical implications of this work are obvious. We have seen that in certain field regions critical currents can be enhanced by over an order of magnitude by appropriate training. It is important to know what factors

determine the limits to critical current enhancements. For example, from the point of view of the present model would it be possible through a different morphology to close the channels through which the initial flux flow takes place, and thus further enhance the critical current?

Another implication of the present work is that one cannot always deduce critical current values from hysteretic magnetization curves, as has often been the practice.¹⁻³ The basis for using the magnetization curves for this purpose is the critical state model which presently does not include the possibility of multi-valued critical currents depending upon previous history.

In conclusion, we have presented some very unusual and complicated history dependent effects in the flux flow properties of a type II superconductor containing normal metal laminar precipitates. The onset and development of the hysteresis correlates well with, and can be explained by, changes in the metallurgical condition of the sample as room temperature precipitation of tin occurs. Details of the hysteresis are explained using current concepts of FLL shear, previously suggested ideas about FLL formation, and a model of low voltage flux flow taking place in narrow channels created by the observed morphology of the precipitates. The model is consistent with the low noise voltages measured in this system.

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FIGURE CAPTIONS

Figure 1: Critical current, I_c , versus magnetic field, H , for $Pb_{87.1}Sn_{12.9}$ sample annealed three months at $240^\circ C$. The solid curve represents data taken on the sample immediately after annealing and mounting, and thus at room temperature for approximately 5 minutes. The dashed curve represents data taken after 15 minutes at room temperature.

Figure 2: Flux flow noise power spectrum for sample annealed three months at $240^\circ C$. Noise data are taken below the lambda point (2.14K) in order to avoid noise associated with helium bubble formation at higher temperatures. Data shown are obtained with a dc voltage of 500 μV and $H = 1250$ Oe. H_{c2} at this temperature is 1600 Oe.

Figure 3: Critical current, I_c , versus magnetic field, H , for sample initially homogenized at $240^\circ C$ and then allowed to precipitate at room temperature for four weeks. Data are taken at 4.2K using a 0.5 μV criterion for the critical current. For solid curve, H_{NF} , field is reduced from above H_{c2} to field of measurement, and for dashed curve, H_{OF} , field is increased from zero to field of measurement. Critical currents are defined here as the measured values obtained on the initial increasing current sweep after each field cycling.

Figure 4: Critical force, $F_v = I_c \times H$, vs magnetic field, H , for same sample as Fig. 3. Data are taken at 4.2K using a 0.5 μV criterion for I_c . Solid curve is taken using the cycling procedure H_{NF} ; dashed curve, using H_{OF} . The linear increase of F_v with H at low fields results from the flat critical current curve at low fields.

Figure 5: Flux flow V-I characteristics for sample of Fig. 3 taken at $T = 4.2\text{K}$ and $H = 520\text{ Oe}$, and showing field history effects.

H_{OF} and H_{NF} represent cycling procedure described in Fig. 3, and CIF represents data obtained when the sample is cooled in the field at which the measurement is taken.

Figure 6: Flux flow voltage-current characteristics obtained at 4.2K and $H = 440\text{ Oe}$ using the cycling procedure, H_{OF} . Solid curve is obtained immediately after field cycling; dashed curve is second current sweep.

Figure 7: Flux flow voltage-current characteristics obtained at 4.2K and $H = 520\text{ Oe}$ using the cycling procedure, H_{NF} . Solid curve is obtained immediately after field cycling; dashed curve is second current sweep.

Figure 8: Flux flow voltage-current characteristics obtained at 2.52K and 2.14K at the same reduced field, $h = H/H_{c2} = 0.63$. Data are used to show that field history effects are similar above and below the lambda point, and do not result from sample heating.

Figure 9: Flux flow voltage-current characteristics obtained at 4.2K using the field cycling procedure, H_{OF} . The current hysteresis becomes much broader at low fields.

Figure 10: Flux flow voltage-current characteristics obtained at 4.2K using the field cycling procedure, H_{NF} . The current hysteresis in these curves does not change dramatically with field.

Figure 11: Critical currents, I_c , obtained at 4.2K using a $0.5\mu\text{V}$ criterion and cycling the sample to the normal state, reducing the field to H_I , and then increasing it to $H = 520\text{ Oe}$, as a function of H_I . Data show

field history effects occur most dramatically for field excursions near the field of measurement. Critical currents shown are those obtained on the initial increasing current sweep after each field cycling.

Figure 12: Flux flow voltage-current characteristics obtained for increasing currents at 4.2K and $H = 520$ Oe. Field is cycled at an angle θ , and the field is then rotated so that it is perpendicular to the broad face of the sample when the measurement is taken. For large angles of rotation the curves for H_{NF} (solid lines) and H_{OF} (dashed lines) approach each other, and also approached the curve obtained by CIF without rotation.

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APPENDIX E

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Bulletin Subject Heading in
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Superconductivity

Evidence of Shear in the Fluxoid Lattice from
Voltage-Current Curves of Type II Superconductors*.
W.C.H. JOINER, University of Cincinnati. --We have develop-
ed a model¹ for flux flow in type II superconductors which
includes interactions between moving fluxoids and pinning
centers. This model predicts the voltage-current relation-
ship during flux flow, and by fitting this model to exper-
imental data, it is possible to obtain I_0/I_C , the ratio
of the spread in pinning strengths to the minimum pinning
strength. Using previously reported data on PbTi alloys
with weak pinning², we show that the ratio I_0/I_C increas-
es rapidly at the force peak for samples exhibiting a
peak in the volume pinning force. For samples which do
not demonstrate such a peak, a less rapid increase is
seen in this ratio very close to H_{C2} . We interpret this
result as further evidence of shear in the fluxoid lat-
tice at fields above the force peak.

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