Experimental Evidence for a Surface Mechanism for Hysteresis in Low-κ Type-II Superconductors*

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(Received 11 April 1966)

The results of several new types of experiments on low-κ type-II hysteretic superconductors are reported. These include measurements of the detailed structure of hysteresis loops, surface-coating experiments, hollow-cylinder magnetization measurements, transport-current measurements, and magnetization of totally hysteretic samples. These results are interpreted in terms of a surface mechanism for hysteresis.

I. INTRODUCTION

It is now generally accepted that the Abrikosov[1] theory should adequately describe the magnetic behavior of ideal type-II superconductors of infinite extent. According to Abrikosov, the sample is perfectly diamagnetic from $H=0$ to some lower critical field H_{c1} where the field penetrates abruptly in the form of current vortices or fluxoids; the M-H curve has a vertical tangent at H_{c1}. Field penetration continues uniformly to the upper critical field H_{c2} where the transition to the normal state occurs for the bulk; surface superconductivity[2] persists to $H_{c3}=1.69H_{c2}$. No transport current can be carried in the mixed state ($H_{c1}<H<H_{c2}$). The magnetization $M(H)$ is reversible according to this model.

However, it is well known that ideal behavior is not observed in general. The magnetization is not reversible; hysteresis is observed in the M-H plane and a residual magnetic moment is retained in zero field after cycling.[3] Real samples are able to carry considerable current.[4]

Several models have been proposed to account for the observed behavior. The one proposed by Bean[5] envisions a uniform network of high critical field filaments embedded in a matrix of soft superconductor. It assumes that a critical current whose spatial extent is a function of the applied field exists in the sample. Silcox and Rollins[6] and Campbell[7] *et al.* have used the concept of flux pinning at lattice defects to derive hysteretic magnetization curves. The "flux creep" model of Anderson[8] *et al.* explains magnetic properties in a manner similar to Bean's model; the critical current in this picture is field-dependent and is determined by the balance between the Lorentz forces on the flux lines or bundles due to the currents and the pinning forces.

All the above models predict size effects, and internal flux gradients associated with hysteresis. Some size effects have been observed in high-field materials.[5,9] However, several authors found that these size effects were not observed in lower κ type-II specimens,[10] or were observed to coexist with a nonsize-dependent hysteresis.[11] These authors suggested a surface origin of the hysteresis.

Any resistanceless surface current which exists in a region of the magnetization curve where $B\neq 0$ must lead to hysteresis. This is just a result of Maxwell's equations as follows: Since the electric field must vanish along the resistanceless surface,

$$-\mathrm{curl}\mathbf{E}=\frac{1}{c}\frac{d\mathbf{B}}{dt}=0.$$

Performing the usual integrations yields

$$0=\frac{1}{c}\frac{d\phi}{dt}=\frac{1}{c}A\frac{dB}{dt}=L\frac{di}{dt},$$

where A is the cross-sectional area of the sample and L is the self-inductance associated with that area. Thus the existence of a surface supercurrent implies B is constant, or, in other words, a line of diamagnetic slope in the M-H plane. Of course, if the surface current is at its critical value a field change in the direction which corresponds to a current increase leads to an effective resistance and the above argument does not hold. The magnetic properties of superconducting cylinders in longitudinal fields between H_{c2} and H_{c3} are due to surface currents.[12,13] We belabor this point only because it has been our experience that just such an explanation is necessary in many cases.

In the present work we report the results of several new types of experiments in low-field type-II superconductors ($0.8<\kappa<3$) all of which indicate that surface

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] A. A. Abrikosov, Zh. Eksperim. i Teor. Fiz. 32, 1442 (1957) [English transl.: Soviet Phys.—JETP 5, 1174 (1957)].
[2] D. Saint-James and P. G. de Gennes, Phys. Letters 7, 306 (1963).
[3] See, e.g., Rev. Mod. Phys. 36, 1 (1964).
[4] See, e.g., J. E. Kunzler, Rev. Mod. Phys. 33, 1 (1961).
[5] C. P. Bean, Phys. Rev. Letters 8, 250 (1962).
[6] J. Silcox and R. W. Rollins, Rev. Mod. Phys. 36, 52 (1964). J. Silcox and R. W. Rollins, Appl. Phys. Letters 2, 231 (1963).
[7] A. M. Campbell, J. E. Evetts, and D. Dew-Hughes, Phil. Mag. 10, 333 (1964).
[8] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 129, 528 (1963); Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Letters 9, 306 (1962); P. W. Anderson, *ibid.* 9, 309 (1962).
[9] F. J. Morin, J. P. Maita, H. J. Williams, R. C. Sherwood, J. H. Wernick, and J. E. Kunzler, Phys. Rev. Letters 8, 275 (1962).
[10] J. D. Livingston, Rev. Mod. Phys. 36, 54 (1964).
[11] P. S. Swartz, Phys. Rev. Letters 9, 448 (1962).
[12] D. J. Sandiford and D. G. Schweitzer, Phys. Letters 13, 98 (1964).
[13] A. Paskin, M. Strongin, D. G. Schweitzer, and B. Bertman, Phys. Letters 19, 277 (1965).

supercurrents play a major role in their hysteretic properties. After describing the experimental details and samples, we describe some general properties of hysteresis loops. The experiments and their implications will then be discussed.

II. EXPERIMENTAL

In these experiments, magnetization curves were obtained with two apparatus. One was a high-sensitivity commercial vibrating sample magnetometer of the type described by Foner.[14] The other magnetometer consisted of two identical coils connected in series opposition, the sample being in the center of one of the coils. In the sweep method, the magnetization curves were made by displaying the integrated output of the coils on the vertical axis of a recorder when the external longitudinal field was swept, and the horizontal recorder position was proportional to the magnetic field. In the point-by-point method the field was held constant, and the integrated coil output was observed when the sample was pulled out of the center of its coil a fixed distance. All methods yielded the same results.

Transport-current measurements were also made, a four-wire technique was used, and the critical current was observed by the appearance of the smallest detectable voltage ($\sim$0.001 mV) on a 0.1-mV full scale Kiethley voltmeter.

The samples were cylinders $\frac{1}{16}$ to $\frac{1}{8}$ in. in diameter, and about $\frac{1}{2}$ in. long. Several alloys of Bi in Pb were used, the Bi concentration ranging from 0.085% to 3%. Sn–5% Sb was measured also. The Nb sample was very high purity, triple pass zone refined. The samples were measured in the cold-worked as well as the well-annealed states. In the case of the dilute Pb alloys, it was found necessary to cold work the samples in liquid nitrogen in order to keep the defects from annealing out.

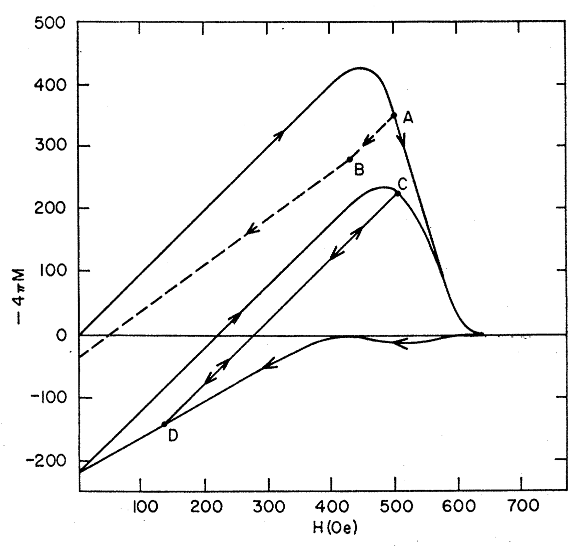

FIG. 1. Magnetization curve for one sense of H of a cylindrical sample of Pb–1.5% Bi in a parallel field. The virgin curve and hysteresis loop are shown. The paths A-B and C-D are reversible diamagnetic lines.

III. GENERAL PROPERTIES

The general features we have observed in magnetization curves of hysteretic superconductors will now be described in detail. These properties form the framework in which the experiments to be described were performed. Figure 1 is a typical magnetization curve in the M-H plane for a hysteretic type-II superconductor. Starting from $H=0$ and $4\pi M=0$, the curve initially has a perfectly diamagnetic slope ($\chi=-1/4\pi$). At some value of H, the field starts to penetrate until at H_{c2}, $B=H$ and the sample is normal (we will ignore the surface superconductivity above H_{c2} for the present purposes). The path described so far is called the virgin or initial magnetization curve.

If we now start decreasing the applied field from above H_{c2}, the lowest curve in Fig. 1 will be the observed path. The value of $+4\pi M$ at $H=0$ is called the trapped or retained flux. Starting up in field again, we always observe the slope of the curve to be $-1/4\pi$; that is, the hysteresis loop for increasing H always starts out on a line parallel to the initial slope of the virgin curve. We call a line whose slope is $-1/4\pi$ a "diamagnetic" line. The loop described above, between the points ($H=H_{c2}$, $4\pi M=0$) and ($H=0$, $4\pi M=$ trapped flux), is unique for any sample; we call this the major hysteresis loop.

We define a minor hysteresis loop as follows: starting with a virgin sample ($H=0$, $4\pi M=0$) the field is increased to some value for which $B\neq 0$, say point A of Fig. 1. If the field is reversed at point A, the dashed curve will be observed. We call this path plus the path back to point A a minor hysteresis loop. It is *always* observed that the initial slope of the dashed curve, the region between (A) and (B) in this case, is $-1/4\pi$.[15] This has been observed by many workers using dc magnetization techniques; ac susceptibility data also show this.[16]

The major hysteresis loops are obtained by first increasing the field from $H=0$ to $H>H_{c2}$ and traversing the initial magnetization in the forward direction. If the field is then decreased to zero and increased again to H_{c2}, the closed loop in the lower part of Fig. 1 is obtained. Further field increases and decreases between $H=0$ and $H=H_{c2}$ traverse the same boundary curves. This loop is called the major hysteresis loop for one sense of H.

We have found that the major hysteresis loop as defined above has particularly interesting properties. Most of the experiments to be described are concerned with this loop. It should be emphasized here that the

[14] S. Foner, Rev. Sci. Instr. **30**, 548 (1959).

[15] See, e.g., J. G. Park, Rev. Mod. Phys. **36**, 87 (1964); M. A. R. LeBlanc, Phys. Letters **9**, 9 (1964).

[16] M. Strongin, D. G. Schweitzer, A. Paskin, and P. P. Craig, Phys. Rev. **136**, A926 (1964).

properties described below occur at constant temperature, and only one sense of applied field H. The curves for both senses of H are somewhat more complicated, and our observations regarding them will be published separately. Having exceeded H_{c2}, the only points in the M-H plane accessible to the sample lie inside the major hysteresis loop. Conversely, every point inside the major loop is accessible. Starting from a point D on the loop at some field H_0, say in decreasing field on the lower curve, if the field is reversed (increased in this case), a diamagnetic line (slope$=-1/4\pi$) will be followed until the opposite boundary of the major loop is reached (point C), at which point the major loop will be followed until another field reversal. To restate this, there exist a large number of reversible paths each of which has a different value of B which remains constant along the path. These paths connect the forward and reverse boundaries of the major hysteresis loop. This property is very general in the low-κ materials discussed here, and the diamagnetic lines are truly reversible to within the resolution of the instruments used, better than 1 G. Thus, every point inside the major hysteresis loop is accessible to the system no matter what its previous magnetic history. The area enclosed by the major loop, and the amount of retained flux, are functions of the state of cold working, defect concentration, etc., of the sample. An almost reversible sample has a very small area enclosed and a small amount of trapped flux. As a sample becomes less reversible, the area increases to a maximum, then starts decreasing again until, in the limit of irreversibility, the major hysteresis loop is just a diamagnetic ($\chi=-1/4\pi$) line connecting ($H=H_{c2}$, $4\pi M=0$) to ($H=0$, $4\pi M=+H_{c2}$). It should also be mentioned here, that as the sample gets more irreversible, the initial diamagnetic line persists to higher fields,[17] so that the curve corresponding to complete irreversibility looks like the magnetization curve for a hollow cylinder of type-I superconductor.[18]

We can summarize the properties of the major hysteresis loop as follows:

(1) The major hysteresis loop of an irreversible superconductor defines the boundaries of a large number of reversible paths with diamagnetic slopes.

(2) These paths are the only isothermal paths the superconductor can traverse when the field direction is reversed below H_{c2}.

(3) The irreversible paths associated with the major hysteresis cycle are along the two curves bounding a finite enclosed area, when such an area exists.[19]

(4) All the states distinguished by different values of M and H enclosed by the major hysteresis loop exist experimentally.

(5) Only the states enclosed by the major hysteresis curves are always available to the superconductor under isothermal conditions, and only these states do not depend on previous magnetic field cycling.

It is worth stressing here that a reversible diamagnetic path is equivalent to a surface shielding current.[20] Since such a path is always observed on field reversal, we conclude that surface currents must play some role in all hysteresis.

IV. EXPERIMENTS

In this section the results of several experiments are presented. The data are all consistent with the idea that the surface plays a major role in hysteresis.

Surface Coating: The surface of a sample of hysteretic Nb was wetted with a thin layer of Pb; the hysteresis was markedly reduced. Removal of the Pb coating restored the hysteresis; subsequent coating reduced it again. This observation is striking evidence that the surface properties are major factors in hysteretic behavior.

The original magnetization curve of a cylinder of hysteretic chemically pure Nb in a longitudinal field is shown in Fig. 2(a). The sample was wetted by dipping it into a container of molten Pb, the surface of which was protected from oxidation by a layer of ordinary solder flux. We found that this simple technique is sufficient to obtain good contact between the Pb and Nb. The magnetization for the wetted sample is shown in Fig. 2(b). It is seen that the hysteresis is markedly reduced without changes in bulk properties such as H_{c2}. In particular it is seen that the shape of the initial forward magnetization curve more closely resembles that of a reversible sample, the area of the hysteresis loop is decreased, the reverse curve approaches the forward curve, and the trapped flux is decreased. It is to be noted that the Pb is only a superconductor (at 4.2°K) at fields below ~550 Oe. (Thus, the effect of the coating on hysteresis does not depend on whether the coating is normal or superconducting.) This field corresponds to a field at which the Nb is still diamagnetic. The Pb volume is negligible relative to the Nb volume. This is confirmed by the observation that the slope of the diamagnetic (which is determined by the total volume shielded) does not noticeably change at 550 Oe. After this measurement the Pb layer was removed by etching in HNO_3 followed by a rinse in acetic acid. The magnetization observed is shown in Fig. 2(c). Note that removal of the Pb surface by acid also increases the

[17] J. D. Livingston, J. Appl. Phys. **34**, 3028 (1963).

[18] D. L. Coffey, W. F. Gauster, and H. E. Rorschack Jr., Appl. Phys. Letters **3**, 75 (1963).

[19] While most of the properties *of hysteresis loops* discussed are common to high- and low-κ type-II superconductors, there is one difference. In the high-field materials tested, Nb-Zr, Nb_3Sn, and Nb-Ti, the diamagnetic line within a *minor* hysteresis loop does not extend completely across the loop. Rather, when the field is reversed, the diamagnetic extends to a point close to the boundary, and then starts to curve over joining the opposite boundary continuously. This difference in behavior is consistent with the other observed differences between high- and low-κ materials, i.e., there may be appreciable field gradients in the bulk.

[20] D. Shoenberg, *Superconductivity* (Cambridge University Press, New York, 1962), p. 14.

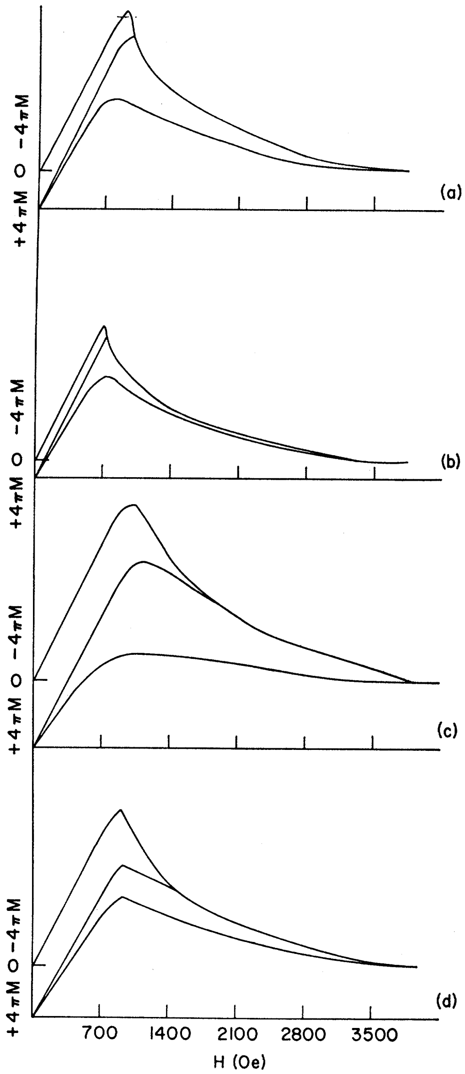

FIG. 2. Initial magnetization and major hysteresis loops for a Nb cylinder in a parallel field at 4.2°K. (a) Original sample—no surface treatment. (b) Sample coated with a thin layer of Pb. (c) Sample after Pb layer was removed by reacting with nitric acid, followed by rinsing in acetic acid. (d) Sample after Pb coating was reapplied and oxidized.

hysteresis relative to the original sample. Reapplication of the Pb layer resulted in the magnetization given in Fig. 2(d). In this case the Pb layer was permitted to oxidize after application. In spite of this much of the hysteresis was again destroyed. Figure 3 is the magnetization data of the same sample in a perpendicular field. The sequence of experiments is the same as above; the same results are observed.

In one experiment the coating was incompletely etched. The Pb was removed just to the point at which it was no longer visible. The sample exhibited almost the same magnetization behavior as in the completely coated case, (the width of the major hysteresis loop was increased about 10% of the difference between the coated and uncoated cases). This observation indicates that the thickness of the Pb layer is not an important factor in producing these effects.

Hollow Cylinders: The next experiments to be described are magnetization curves of thin-walled hollow cylinders of type-II superconductors. Using these samples eliminates the possibility of internal flux gradients due to pinning or sponge networks.

In these experiments magnetization curves were taken of thin-walled hollow cylinders of Pb–1.5% Bi alloy, and of a solid cylinder of the same material. For each sample, the alloy was wiped onto the outer surface of a $\frac{1}{4}$-in.-diam copper or brass tube to a thickness of about 0.001 in. A magnetization curve was taken, the sample removed from the Dewar, the surface was mechanically polished, and another magnetization curve taken. This procedure was repeated until the magnetization behavior changed as will be described below.

Figure 4(a) is the major hysteresis loop of the solid sample. Figure 4(b) is the major hysteresis loop of a hollow cylinder before polishing the surface. The hollow sample displays a major hysteresis loop which is qualitatively the same as the solid sample one. Thus flux pinning or gradients in the bulk could not have been the dominant mechanism for hysteresis in the solid sample.

The behavior of curve *b* in Fig. 4 was observed after subsequent polishings until the wall thickness was reduced enough so that curve *c* resulted. We explain this by assuming that the wall thickness was reduced enough so that the critical current alone always limited the

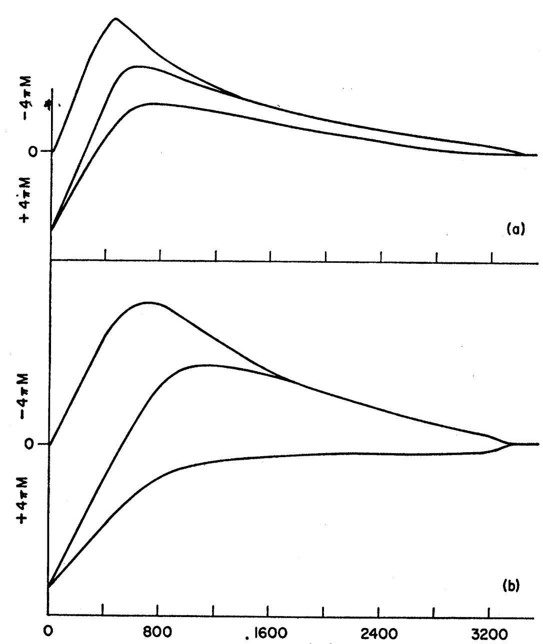

FIG. 3. Initial magnetization and major hysteresis loop for a Nb cylinder in a perpendicular field at 4.2°K. (a) Sample coated with Pb. (b) Sample after Pb layer was removed by reacting with nitric acid followed by rinsing in acetic acid.

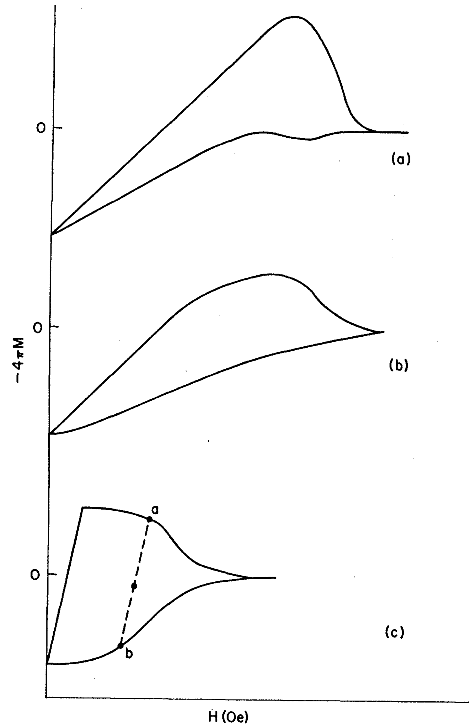

FIG. 4. Major hysteresis loops for Pb–1.5% Bi cylindrical samples in a parallel field at 4.2°K. (a) Solid cylinder. (b) Hollow cylinder. Wall thickness about 0.001 in. (c) Hollow cylinder after the wall thickness had been reduced by polishing. The dashed line is a representative reversible diamagnetic line symmetric about the dot. This curve is on a different scale from curves (a) and (b).

magnetization at fields greater than some field H_0. The shape of the magnetization curve above H_0 in curve *c* is qualitatively the same as that of the J_c versus H curve for a type-II superconductor.[21]

An observation can be made here regarding the nature of the surface current involved. Traversing a path of diamagnetic slope, say *b* to *a* in Fig. 4(c), in a major hysteresis loop corresponds to changing the surface current from its critical value in one direction to its critical value in the opposite direction such that the internal field H_i is constant. Then, applying Ampere's law to the two ends of the diamagnetic line, where H_e is the applied field

$$|\mathbf{H}_e-\mathbf{H}_i|=|4\pi\mathbf{J}_c|=|4\pi\mathbf{M}|\,. \qquad (1)$$

It is observed that the center of a diamagnetic line such as *b-a* is always at $4\pi M=0$; thus from Eq. (1), $|\mathbf{J}_c|$ at *b* is equal to $|\mathbf{J}_c|$ at *a*. The surface currents calculated in the usual way on the basis of the Saint James–de Gennes layer depend only on H.[22–24] We also found that copper plating the sample in no way changed curve *b* of Fig. 4. We therefore conclude that the current involved here is not the same as that usually associated with surface superconductivity at fields above H_{c2}.

Figure 5 shows magnetization data for a solid cylinder (curve *A*) and for several hollow ones (curves *B* through *D*) of Nb. These data were taken from Cline, Tedmon, and Rose.[25] The similarity of the various curves shows that the removal of much of the bulk does not change the hysteretic magnetic behavior much.

When the samples were made simply connected by making a longitudinal cut, the magnetization was that of a solid sample of the appropriate volume. Curve *E* of Fig. 5 shows this for the data of Cline *et al.*; our data on this point are not included.

To summarize, we have observed that hollow cylinders display qualitatively the same magnetization as solid ones. In the limit of thin walls, the magnetization is limited by the critical current. These experiments also indicate the significance of the surface in hysteresis.

Transport Currents: The effect of transport currents on trapped flux was investigated by means of the following experiment: At some fixed temperature the applied longitudinal field was increased to about H_{c2}, and reduced to zero. The sample was then left with trapped flux, whose magnitude was measured. A transport current I_1 was applied in zero field, I_1 being far below the critical current I_c at which resistance was observed. The current was reduced to zero and the trapped flux was measured again. A current $I_2>I_1$ was then applied and removed, and the flux measured again. This process was repeated using increasing values of current until

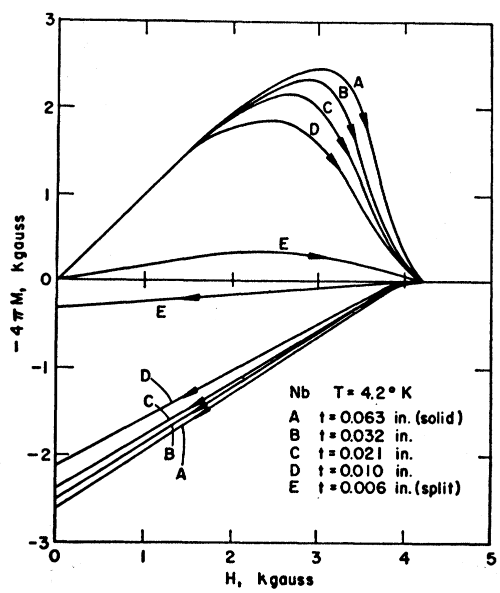

FIG. 5. Magnetization of solid (*A*) and hollow (*B-E*) cylinders of Nb. (Taken from Ref. 25.)

[21] See, e.g., R. R. Hake and D. H. Leslie, J. Appl. Phys. 34, 270 (1963).

[22] A. A. Abrikosov, Zh. Eksperim. i Teor. Fiz. **47**, 720 (1964) [English transl.: Soviet Phys.—JETP **20**, 480 (1965)].

[23] J. G. Park, Phys. Rev. Letters **15**, 352 (1965).

[24] H. J. Fink and L. J. Barnes, Phys. Rev. Letters **15**, 792 (1965); H. J. Fink and R. D. Kessinger, Phys. Rev. **140**, A1937 (1965).

[25] H. E. Cline, C. S. Tedmon, Jr., and R. M. Rose, Phys. Rev. **137**, A1767 (1965).

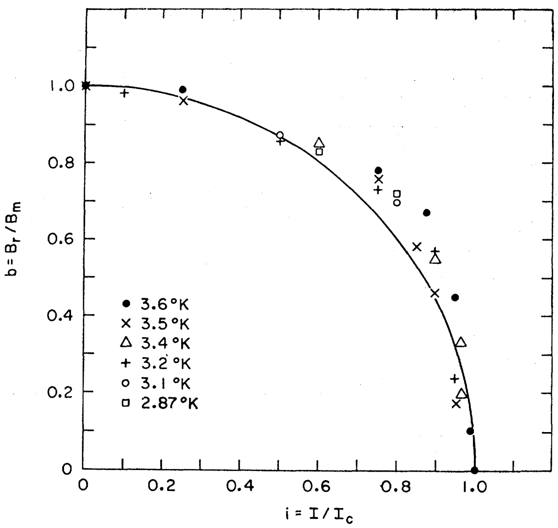

FIG. 6. Reduced values of applied current versus trapped flux for a Sn–5% Sb cylindrical sample as explained in the text.

resistance was observed; no trapped flux remained after resistance appeared. This experiment was repeated for several temperatures, the range covered was $0.3<t=T/T_c<1$.

The reduced data are plotted in Fig. 6. Here all the data are reduced in trapped field $b=B_r/B_{\max}$, and current $i=I/I_c$. The solid line is a quadrant of a circle, which is a reasonably good fit to the points. We interpret these results in terms of a simple model. Consider a cylinder of superconductor in zero applied field with a magnetic moment arising from a persistent supercurrent I in the region of the surface. The current is assumed to be at its critical value I_c. The circulating current flows tangentially perpendicular to the axis of the cylinder, as shown in Fig. 7. Now axial transport

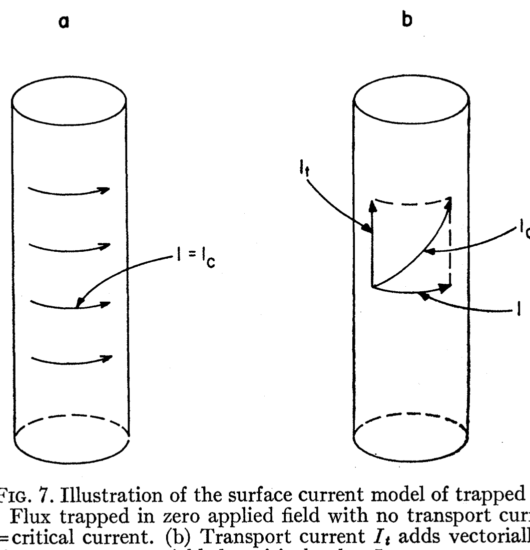

FIG. 7. Illustration of the surface current model of trapped flux. (a) Flux trapped in zero applied field with no transport current. I_c=critical current. (b) Transport current I_t adds vectorially to surface current I to yield the critical value I_c.

current I_t is applied; since I_c is the maximum current which may flow, $\mathbf{I}_c=\mathbf{I}_t+\mathbf{I}$ as shown in Fig. 7. In this case, $I_c^2=I_t^2+I^2$. When the transport current is removed, the circulating current retains this value, and the magnetic moment of the sample is reduced relative to the initial trapped flux. Applying this model to some arbitrary transport current yields

$$I_c^2=I^2+I_t^2,$$

$$1=\left(\frac{I}{I_c}\right)^2+\left(\frac{I_t}{I_c}\right)^2=\left(\frac{B_r}{B_{\max}}\right)^2+\left(\frac{I}{I_c}\right)^2=b^2+i^2.$$

This is just the circle observed in the data.

Complete Trapping: Figure 8 is the magnetization curve for both senses of H for a sample which traps almost all of H_{c2}. The major hysteresis curve as defined

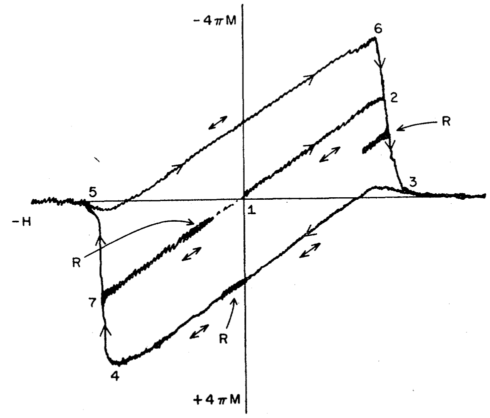

FIG. 8. Magnetization of a solid superconducting cylinder which traps almost all H_{c2}. The parts of the path marked R are field reversals. The double headed arrows indicate reversible parts of the curve.

above in this case is a reversible diamagnetic line between ($H=H_{c2}$, $4\pi M=0$) and ($H=0$, $4\pi M=H_{c2}$). The initial curve was taken along the path $1\to2\to3\to4\to5\to6\to3$; the arrows in the figure indicate the reversible parts of the curve. Figure 9 is an idealized magnetization curve for an infinitely long thin-walled hollow cylinder of type-I superconductor in a longitudinal field.[18] In this case, the hysteresis loop is due entirely to surface supercurrents. The main features of Fig. 8 are seen to be the same as those of Fig. 9 indicating that the observed hysteresis is equivalent to a surface current. Thus, the limit of complete trapping in type-II superconductors is equivalent to complete surface shielding. Livingston[17] has also observed complete trapping and suggested that surface currents must be responsible. Extreme cold working is necessary to induce this behavior.

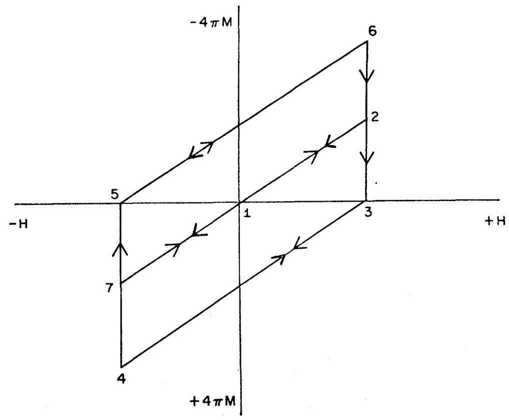

FIG. 9. Idealized magnetization curve for a thin-walled hollow cylinder of type-I superconductor in a longitudinal field.

V. DISCUSSION

We have discussed the results of several experiments in terms of a surface current mechanism for magnetic hysteresis in type-II superconductors. We believe these results require the existence of such a mechanism. Several authors have recently discussed[22–24] and measured[26,27] the surface current associated with the Saint James–de Gennes layer. It is possible that this is involved; however, the lack of effect of copper plating, and the peculiar symmetry observed in the hollow cylinder experiments suggest that it is not the current of major importance in hysteresis. In this regard, we note that there is no necessary or unique correspondence between the Saint James–de Gennes surface current and hysteresis in general. For instance, large surface currents have been observed in lead and lead alloys above H_c and H_{c2};[26] however, these materials can be almost reversible. Swartz and Hart[28] interpret their surface critical current data in terms of a component of surface current whose value goes to zero at H_{c2}, and which is unaffected by copper plating. Thus the literature is not without hints of the surface current mechanism. In fact, the currents responsible for the present effects might be similar to those postulated by the Bean model[5] except that they are very large near the surface allowing very steep, almost discontinuous field gradients in the surface region.

Recently, Cline, Rose, and Wulf[29] have mapped the field distribution inside annealed and cold-worked niobium ellipsoids. Their results show that the internal field has a steep gradient near the surface, and becomes more uniform inside. This effect is much more pronounced in the cold-worked sample, which traps almost all of H_{c2}, than in the more reversible annealed one. This increase in internal uniformity with cold working was predicted by the present authors[30] on the basis of their hysteretic magnetization data. The results of Cline *et al.* constitute striking confirmation of the conclusions drawn in the present work. As mentioned earlier, it is now well known that in the measurement of magnetization of a hysteretic superconductor, when the direction of external field change is reversed, the magnetization always changes along a reversible diamagnetic path. This diamagnetic path is a demonstration of hysteresis and demonstrates the presence of a surface shielding current. These diamagnetic changes with field reversal are found in both ac susceptibility measurements[16] and dc magnetization measurements.[12] It is of considerable importance to note that there is no evidence that any type-II superconductor exhibits reversibility at fields above H_{c1} when subjected to small amplitude ac susceptibility measurements. It therefore appears that there is always some surface shielding current associated with hysteresis.

Thus, we have shown considerable evidence that surface currents play a major role in all magnetic hysteresis in low-κ type-II superconductors. We have not offered an explanation for the origin of the surface currents. In other work we will discuss the possibility that trapped fields and surface currents may be stabilized if they generate sufficient entropy to overcome the increase in internal energy associated with flux retention. Some recent[31] specific-heat experiments on hysteretic superconductors are not inconsistent with the postulate that trapped fields are associated with entropy increases.

ACKNOWLEDGMENTS

We gratefully acknowledge the expert technical aid of Louis Nicolosi and Stanley Pollack. Helpful discussions with Dr. Arthur Paskin and Dr. Myron Strongin contributed much.

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