EFFECT OF SURFACE STRAINS ON THE DIAMAGNETIC AND FIELD-RETAINING PROPERTIES OF TYPE-I HOLLOW CYLINDERS

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(Received 9 January 1968)

High-purity hollow cylinders of type-I superconductors in which the surface strains are minimal show order-of-magnitude decreases from the diamagnetic or field trapping properties described in present literature. The properties can be made to approach the predicted behavior when both surfaces are heavily strained. Both the diamagnetic and field-retaining properties are localized and can result in axial-field gradients in the void that exceed 10^3 Oe/cm.

The diamagnetic and field-retaining properties of hollow rings and cylinders of type-I superconductors have been discussed by a number of authors.[1-5] The thermodynamic and electrodynamic treatment by London[1] requires that the equilibrium state of a simply connected type-I superconductor satisfies the condition $B=0$ and $\dot{B}=0$ where B is the magnetic induction. For the multiply connected superconducting ring, the London conditions[1] are $d\varphi c/dt=0$ or $\varphi c=\text{constant}$, where φc, the fluxoid, becomes the magnetic flux when the wall thickness is greater than the penetration depth. This treatment and the treatment by Shoenberg[4] predict that the systems will shield to that value of the external field which drives some portion of the sample into the intermediate state. The field retained in the void after an external field exceeding H_c is removed is approximately equal to the shielding field. The discussion given by Livingston and Schadler[5] for ideal hollow cylinders (ignoring end effects) predicts that the cylinder will shield to H_c when it abruptly goes normal. When the field is decreased to below H_c, the wall expels the field and the hole retains H_c which remains trapped as the external field goes to zero.

Measurements of the flux trapped in hollow lead cylinders have been reported previously.[6,7] It was observed that, contrary to the predictions for an ideal, infinitely long cylinder, the external field H_{ext} started to penetrate for $H_{\text{ext}}<H_c$ and that a field less than H_c (between $0.5H_c$ and $0.9H_c$) was trapped in the hole when H_{ext} was removed. This deviation from "ideal" behavior was attributed to end effects. However, the present work demonstrates that the field inside the cylinder observed by these authors is a fairly arbitrary function of H_{ext} depending strongly on the state of the surface in the immediate vicinity of the probe. Cylinders in which the surface strains are reduced to a minimum show the greatest deviation from predicted behavior. No variation of trapping with cylinder length, and hence of end effects, could be detected for cylinders between 5 and 25 cm long. Effects associated with the cylinder ends could be detected only within 0.15 cm of either end. The same samples can be made to approach predicted behavior only when both surfaces are heavily strained.

In this Letter the effect of surface treatment on the diamagnetic properties and the retained fields in hollow cylinders, of 99.999% Pb and Sn for wall thicknesses ranging from 0.013 to 0.13 cm, for inside diameters from 0.38 to 2.5 cm and for lengths from 0.025 to 25 cm are summarized. These measurements correspond to conditions where the magnitude and distributions were stable with time and independent of field-sweep speed, i.e., for field sweeps less than 10 Oe/sec. Surface strains were produced by machining, sanding with various grades of silicon-carbide cloth, sandblasting with 50-μ aluminum-oxide particles, strain elongation, mechanical twisting, and various chemical procedures. The effects due to surface straining do not anneal after treatments which produce grain growth in the bulk. The effects can be removed by etching. No visible change in the surface grain size occurs after annealing strained, small-grained Pb samples at 270°C. Removal of the surface layer by etching then shows increases in grain size produced by the heat treatment. The etch solutions used were 20 vol% of H_2O_2 in glacial acetic acid or 5% concentrated nitric acid in methyl alcohol. The field distributions associated with the surface strains described here do not change when the Pb samples are annealed for prolonged periods (~3 months) at room temperature or by annealing in boiling glycerol (~270°C) for several hours. Rapid oxidation of etched Pb samples in 200°C flowing air stream produces a uniform blue-brown oxide in ~15 min. The formation of these oxides on samples which retained fields as low as $0.03H_c$ produced no detectable changes.

Prolonged oxidation in moist air produces surfaces which include oxides, hydroxides, and carbonates with occasional localized pitting. The formation of this type of surface results in a gradual increase in the field-retaining properties with oxidation time. Lightly etched sandblasted samples in which the surfaces are macroscopically rough retain smaller fields than machined samples in which the surfaces are relatively smooth. The field measurements were made with a number of different Hall probes with precision ranging from ±0.1 to ±5 Oe depending on the probe and probe current. The external fields were generated in a 35-cm-long copper solenoid immersed in liquid nitrogen. The inside diameter of the solenoid was 3.8 cm. Probe measurements showed that the maximum axial variation of the solenoid field region in which the superconducting cylinders were placed did not exceed 3% for fields less than 2000 Oe. No measurable radial variation was detected. The effects described here are about 2 orders of magnitude greater than the maximum total estimated errors resulting from all the techniques and calibration procedures used.

Absolute values of H_c were measured to determine if the critical fields varied along the length of the cylinders because of the surface treatments. The measurements defining H_c were made by comparing the probe readings in increasing and decreasing applied fields with the calibration curves of the probes. The calibration curves of the probes were obtained by determining the voltage produced by a change in applied field in the absence of a superconducting sample. The critical field corresponding to a particular position in the etched and strained cylinders was taken as that value of the applied field where the probe reading was the same as the calibration curve. The value of the applied field for which the probe reading corresponded to the calibration curve was found to be independent of position and was the same in both increasing and decreasing fields. The absolute values obtained were the same as the known bulk critical fields of Pb and Sn. The results showed that the surface treatments did not produce increases or decreases in H_c that were detectable in these measurements. In contrast to the properties of Sn, the increases in the critical field of Pb that might have been expected with surface changes do not appear to create currents that are sufficiently large to change appreciably either the gross shielding or the gross field-retaining properties of cylinders with the dimensions studied. Thus it is convenient to plot all fields as a fraction of the bulk critical field.

The field distribution along the length of a sandblasted cylinder of Pb with a wall thickness of 0.038 cm and an i.d. of 0.38 cm is shown in curve 1 of Fig. 1(a). The distribution was obtained after a field exceeding H_c was applied and removed at 4.2°K. The field in the void is uniform along the length to within 0.15 cm from each end with an absolute magnitude of $0.96H_c \pm 2\%$. The field measurements along the length were reproducible to ±0.1%. The fall off in the outer 0.15 cm of an inch at each end amounts to 5 or 6%. Curve 2 was obtained after five 30-sec etches in $4\,\mathrm{CH_3COOH}$

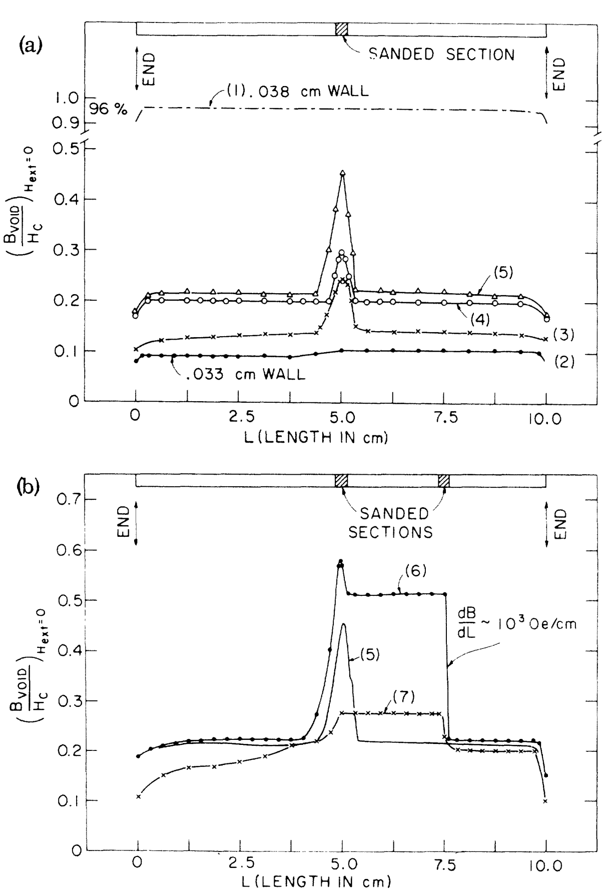

FIG. 1. (a) Field distribution in the void of a Pb hollow cylinder after a field exceeding H_c was removed at 4.2°K for (1) uniformly sandblasted, (2) strain-free or etched conditions, (3) localized sanding on 0.3-cm length of circumference of inside surface, (4) localized sanding on both surfaces, and (5) heavier sanding of local spot in both surfaces. H parallel to long axis. (b) (6) Distribution due to two circumferential strains spaced asymmetrically along axis and (7) effect of 30-sec etch in removing surface strains.

$-1H_2O_2$. After each etch the sample was rinsed in either water, alcohol, or glycerol, and dried before measuring. Measurements between etches showed a systematic monotonic reduction in retained field with etching. After curve 2 was obtained, the center 0.3-cm section of the inside surface was lightly sanded as shown schematically in the upper part of Fig. 1(a). The field distribution resulting after this procedure is shown by curve 3. Curve 4 was produced after sanding the 0.3-cm section on both surfaces. Other measurements in which one surface was completely etched and one was completely sandblasted show that strains in the outer surface are slightly more effective in increasing field retention than are strains on the inner surface. Curve 5 was obtained by applying more pressure during sanding. A second section of both surfaces was sanded asymmetrically as shown in the upper part of Fig. 1(b) with the resulting distribution given by curve 6.

Probe measurements showed that the fall off of ~150 Oe at the point denoted by 7.5 cm occurs in a region of width between 0.08 and 0.15 cm. Curve 7 was obtained after a 30-sec etch. Further etching reduces the field trapping to curve 2 or slightly lower values depending upon whether the wall thickness is reduced. Samples which exhibit gradients in the void between 10^3 to 10^4 Oe/cm were cycled between 4.2 and 300°K 30 times, annealed at room temperature for 3 weeks, measured with different probes under conditions where the probes were stationary or could be moved at 4.2°K. The maximum spread observed after these procedures was ±5 Oe. It was found that any pair of circumferential strains are highly effective in increasing the overall field-retaining properties between the strains. These fields are highly uniform. The strains apparently act in a manner similar to guard rings.

The field distributions just described were obtained by local surface straining of a sample in which the surface strains were minimal initially. The reverse procedure of removing strains is shown in Fig. 2. The original Pb sample was 10 cm long with a 0.038-cm wall and an i.d. of 0.76 cm. After the sample was machined to these dimensions it was etched until curve 1 was obtained. The sample was then sandblasted resulting in curve 2. A second sandblasting of the ends only resulted in curve 3. Curve 4 was obtained by etching the inside and outside end surfaces over a length of ~1.5 cm. Curve 5 resulted

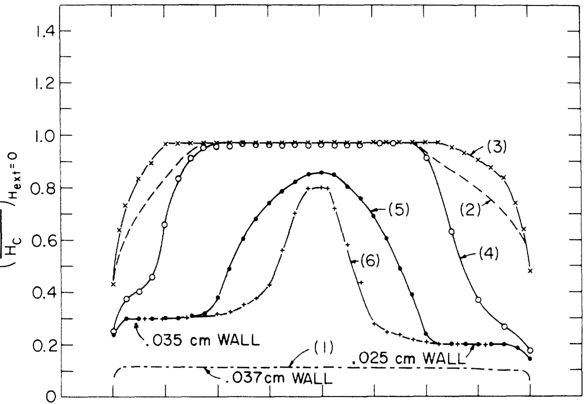

FIG. 2. Distribution of field in the void of a Pb hollow cylinder after removing a field exceeding H_C for (1) etched or minimally strained surface, (2) and (3) sandblasted surfaces, (4) sandblasted surfaces etched over 1.3-cm lengths at each end, (5) 2.5-cm lengths etched at each end, and (6) 3.8-cm length etched at each end.

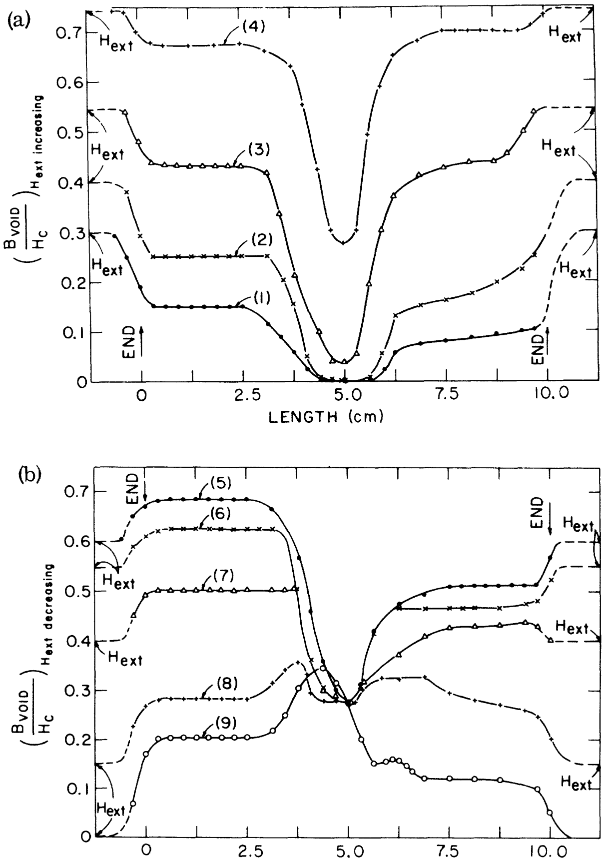

FIG. 3. (a) Distribution of the field in the void along the length for various values of increasing applied fields and (b) for various values of decreasing applied fields.

after etching 2.5-cm lengths at each end and curve 6 resulted from etching 3.8-cm lengths leaving the center 2.5-cm section sandblasted. After these procedures the wall thickness varied at the ends as denoted in Fig. 2.

The curves shown in Figs. 3(a) and 3(b) are representative of the type of distributions of the field in the void that can be obtained in increasing and decreasing external fields. The data were obtained from the sample which produced curve 6 in Fig. 2. The sample was removed from the helium bath, driven normal, and cooled again in the absence of an applied field. The distribution shown by curve 1 in Fig. 3(a) was obtained when the external field was increased from zero to $0.3H_c$. After the measurements were completed, the external field was increased further to $0.4H_c$ resulting in curve 2. Further increases produced the distributions shown by curves 3 and 4. After obtaining curve 4, the external field ($0.74H_c$) was then reduced. The field distributions occurring in decreasing fields are shown in curves 5-9 in Fig. 3(b). Simultaneous measurements of the magnetization of the total system and probe measurements of the field in the void were made to determine the average values of the field in the wall. The results show that the condition $B=0$ for the wall is not fulfilled in decreasing fields for any value of H including zero. Other measurements showing the absence of diamagnetism in the walls of hollow cylinders are given by Schweitzer.[8]

The procedures reported in detail here were adopted to ensure that the observations represent stable configurations. It is concluded that the diamagnetic and field-retaining properties of type-I hollow cylinders are localized phenomena, depending strongly on the localized strains in the cylinder surfaces. The large, stable gradients that can be established in the retained axial fields imply that lines of induction may pass through the cylinder walls in the vicinity of the strained regions without decaying.

A thermodynamic interpretation of the effects of surface strains on the properties of hollow cylinders is presented elsewhere.[8]

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CALCULATION OF ENERGETIC DEUTERON MOMENTUM SPECTRA FROM PROTON-NUCLEUS COLLISIONS AT BeV *

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(Received 3 June 1968)

The momentum spectra of energetic deuterons in proton-nucleus collisions at 1 BeV have been calculated using Feynman-diagram techniques and are compared with the results of recent experiments.

The production of high-energy deuterons in the collisions of 1-BeV protons with nuclei has recently been measured by Sutter et al.[1] The experimental results appear in the form of deuteron momentum spectra at several forward angles with He^4, Li^6, C^{12}, O^{16}, and natural lead as targets. In addition, a measurement is reported of such deuterons in coincidence with protons emitted in the backward direction with C^{12} as a target. Typically, the data (see Fig. 1) show a sharp decrease of the differential cross section versus deuteron momentum followed by a distinct peak at the higher momenta. The authors of Ref. 1 have suggested that the larger cross sections at the lower momenta could be connected with processes which produce pions along with the observed deuterons while the deuterons with momenta corresponding to the high-momentum peak are identified as resulting from a quasielastic knock-out. Their conclusion regarding the high-momentum deuterons was based on observed kinematical similarities with free p-d