CRITICAL CURRENTS OF SUPERCONDUCTING Nb25 a/o Zr IN HIGH MAGNETIC FIELDS

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ABSTRACT

Measurements of critical current as a function of applied magnetic field were made on wire samples of Nb 25 a/o Zr alloy at 4.22°K and 2.24°K. Curves are plotted for the cases for which the applied magnetic field is parallel to or perpendicular to the current direction. At 4.22°K, $H_c(I \to 0)$ for H perpendicular to I is found to be 70 kgauss, while for H parallel to I, it is found to be 82 kgauss. Reduction of the temperature to 2.24°K results in an increase of 13 kgauss in both cases. For H perpendicular to I, current densities of 4.4×10^4 amp/cm^2 are observed at 60 kgauss and 4.22°K, and at 73 kgauss and 2.24°K. The effective demagnetization factor of the current carrying elements is 0.6π. All measurements were made in a dc magnetic field with quasi-dc currents by observation of the first resistive voltage to appear across the sample.

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INTRODUCTION

Berlincourt, Hake, and Leslie,[1] Kunzler,[2] and Aron and Hitchcock[3] have recently reported high superconducting current densities exhibited at high magnetic fields by certain members of the Nb-Zr alloy system. These reports have stimulated great interest and have indicated the need for extending the range of measurements of the properties of these materials. In this laboratory, we have measured the superconducting-to-normal behavior of 0.025-cm-diam, hard-drawn (> 99% reduction) wire samples of a Nb 25 a/o Zr alloy.

The method of measuring the critical current as a function of the applied magnetic field was chosen for this work. The critical current is that current at which the first resistive voltage appears; the effect on the results of choosing a resistance-ratio criterion is also discussed. Measurements were made at $4.22 \pm 0.01^\circ$K and $2.24 \pm 0.01^\circ$K, with the applied magnetic field oriented both parallel and then transverse to the current direction. The measurements of critical current have been extended beyond the "knee," i.e., the region of magnetic field where the critical current is rapidly falling. At 4.22°K, for a transverse field, $H_c(I \rightarrow 0)$ is found to be 70 ± 2 kgauss, while for a parallel field it is found to be 82 ± 2 kgauss. Reduction of the temperature to 2.24°K results in an increase of 13 kgauss in both cases. In a transverse field, current densities of as high as 4.4×10^4 amp/cm^2 are observed at 60 kgauss and 4.22°K and at 73 kgauss and 2.24°K.

APPARATUS

The measurements were made in a conventional liquid-nitrogen-jacketed, glass, helium dewar placed coaxially in the 93.5-kgauss, 12-cm-i.d., air-core solenoid of the Low Temperature Laboratory, College of Chemistry, University of California.[4] The potential appearing across the sample was amplified by a Beckman Model 14 amplifier and fed to the y-axis of a Moseley Model 3S x-y plotter. The current was supplied to the sample from a storage battery and controlled by a transistorized series amplifier. The current was measured by taking the signal from a standard resistor in series with the current leads and applying it to the x-axis of the plotter. Thus a plot of the voltage as a function of the applied current was obtained. The system noise level in most cases was $\leq 0.2\ \mu$v.

Two types of sample holder were used. The first consisted of two 1.5-cm-thick blocks of copper cut in the form of segments of a 6-cm-diam circle which were separated by and rigidly attached to a 1.5-cm-wide block of Micarta. The sample was placed in a groove milled on a principal diameter of this assembly. In this manner the sample was supported against electro-mechanical forces during the measurement. The sample was soft-soldered to the copper over a length of 2.5 cm at each contact after being ultrasonically tinned at approximately 400°C in a Bi-Cd mixture for approximately 15 sec. Potential leads consisted of a twisted pair of Formvar-insulated BSWG No. 30 copper wires indium-soldered to the sample 1 cm apart. The current was supplied through a twisted pair of No. 10 Formvar-insulated copper wires, each soldered to 100 strands of No. 30 copper wire twisted and in turn soldered to the copper blocks on the side opposite to that of the sample. This enabled the sample assembly to be mounted so that it could be rotated without disturbing the soldered joints.

The second sample holder was similar in design, though it had no provision for rotating the sample. The contact length was shorter (1.5 cm), although the sample length remained the same (6 cm) and the potential leads were 2 cm apart. In both holders, a 0.005-ohm constantan shunt was soldered to the blocks to prevent destruction of the sample when it went normal at high currents. Potential leads were soldered to this wire so as to detect any current that might flow in it rather than through the sample. In no case was it found to be carrying more than one part in 10^4 of the total current. Further, the cutting of this shunt failed to change the results of the measurements in any way.

At this point, some discussion of the problems involved in making current contacts to the sample is in order. In the sample geometry we have chosen, we must consider the temperature rise due to ohmic heating in the copper surrounding the sample and associated heat transfer to the helium bath. On the assumption that the current passes directly from the copper to the superconducting sample over the length of the contacts used, temperature differences of no more than 10^{-4} °K can be expected for a current of 200 amp between the sample and the bath in the geometry used. Therefore, the contact problem reduces to a consideration of the effects of a high resistance film between the copper and the superconductor.

For the sample geometry chosen, it is meaningful to idealize to the case of a heat-generating source on the axis of a cylinder, the outer surface of which is in contact with the bath. Fourier heat conduction gives

$$\frac{RI^2}{L} = \frac{2\pi K \Delta T_1}{\ln\left(\frac{r}{r_0}\right)} \qquad (1)$$

Extrapolation from experimental data[5] on heat transfer to liquid He indicates that in the range of interest ($0.001°K < \Delta T_2 < 0.2°K$), the heat transfer may be characterized by

$$\frac{Q}{A} = 7.35\ (\Delta T_2)^{1.7} = \frac{I^2 R}{2\pi r L}\ . \qquad (2)$$

Here ΔT_1 is the difference in temperature between the sample and the surface of the copper, ΔT_2 is the difference in temperature between the surface of the copper and the bath, R/L is the resistance of the film per unit length of contact, r is the radius of the copper r_0 is the radius of the superconductor, K is the thermal conductivity of copper, and I is the current. The units used are watts, ohms, amperes, centimeters, and degrees Kelvin.

In our case, we have $\Delta T_2 = 0.516\ \Delta T_1^{0.56}$. Because ΔT_1 is less than 1°K in the case of interest, ΔT_2 is the dominating temperature drop in this evaluation of contact performance. As the ratio of the current through the 0.005-ohm shunt to the current through the sample was in no case greater than 10^{-4}, the contact resistance must be less than 5×10^{-7} ohms. Evaluation of Eq. (2) for the geometry at hand gives $\Delta T_2 = 10^{-2}\ °K$ for a current of 200 amp.

EXPERIMENTAL TECHNIQUE

The mounted sample was cooled to the bath temperature in the earth's field only. The magnetic field was then raised to a value greater than the $H_c(I \to 0)$. The current was raised slowly and a voltage measured across the sample; then the current was reduced to zero. The field was then reduced until a superconducting-to-normal transition was observed as the current was increased from zero. The current was then rapidly reduced to zero and a new lower field value set. This procedure was continued until the field was reduced to the earth's field or until a critical current of greater than 200 amp was observed, at which point the run was terminated. In several cases, the measurement was begun at zero field and continued to high field values. No differences were noted between the two results.

For measurements with the field parallel, the sample was warmed to room temperature, the sample carrier was rotated without disturbing the solder joints, and the sample was recooled to the measurement temperature. It should be noted that at each field value at least three measurements of the critical current were made. The rate at which the current was raised varied from approximately 20 amp per min to as high as 400 amp per min without significantly changing the value at which the resistive transition occurs--within the limitations imposed by the time constants of the measuring system, of course.

RESULTS

The results are summarized in Figs. 1 and 2. Comparison of the parallel- and transverse-field cases indicates an effective demagnetization factor of 0.6π. This sample showed no significant scatter in the values of the transition current observed either during a single run or after warming to room temperature and resoldering to a different sample holder. Though the value of the critical current seems to be falling very rapidly at the "knee," attempts to determine whether the curve was approaching some value asymptotically or whether one could, with apparatus of sufficient sensitivity, observe superconducting behavior at higher fields failed to give any grounds for choosing between the alternatives. In contrast to the transitions at currents above 10 amp, the transitions in the low-current regions are very broad in current, and the first appearance of the voltage criteria ceases to be very precise. The application of a resistance-ratio criterion to this region only served to raise the currents somewhat in the very steep portion of the curve and, consequently, affected its shape in no meaningful way. The resistivity of this sample was measured at 4.2°K with an applied field of 93.5 kgauss and found to be 1.5×10^{-5} Ωcm.

In some samples just prior to the first definite resistive transition, resistive precursers appeared in the field regions within five to 10 kgauss of the limiting fields. These voltages were between 0.1 μv and 100 μv in amplitude, corresponding to resistance ratios of 2×10^{-6} and 2×10^{-4}. The voltages approached zero as the current was further raised, showing true negative-resistance behavior. After a small increase in current, the full transition occurred. It should be noted that when these voltages appeared, the plotted values of critical current corresponded to the first appearance of the precursor, not the full transition.

We wish to thank Messrs. J. Donald Gow and H. Paul Hernandez for their long interest and encouragement of this work. We wish to commend Mr. Ken Solomon for his excellent electronics work and to thank Dr. David N. Lyon for his cooperation in the use of the Low Temperature Laboratory and Messrs. Theodore Baker and Richard Wolgast for their help in the measurements. We further wish to express our gratitude to Dr. James Wong of Wah Chang Corporation for providing the wire for measurement.

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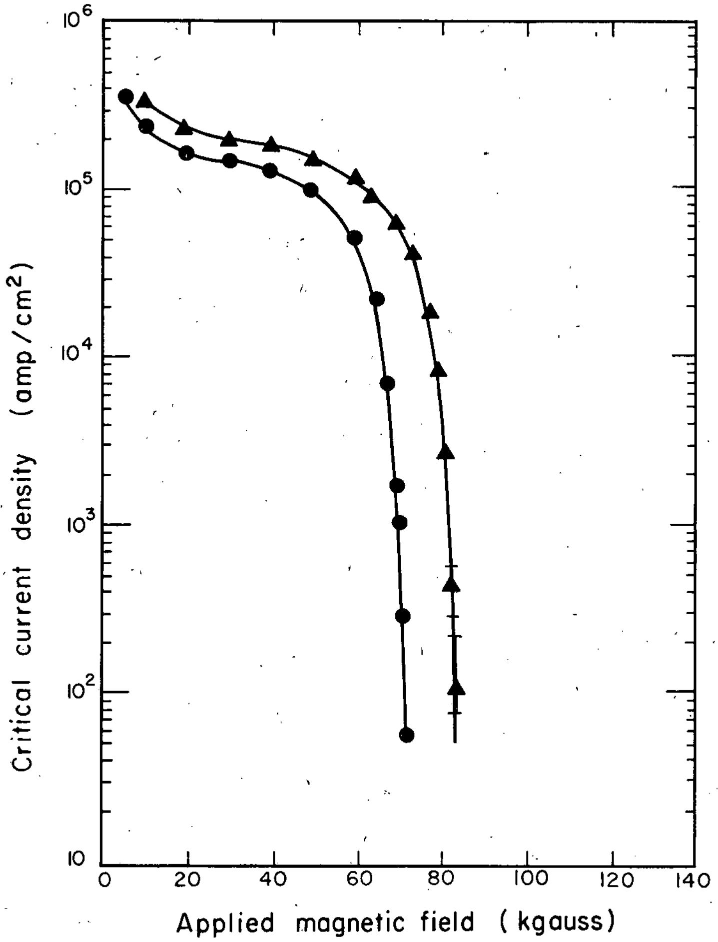
LEGENDS

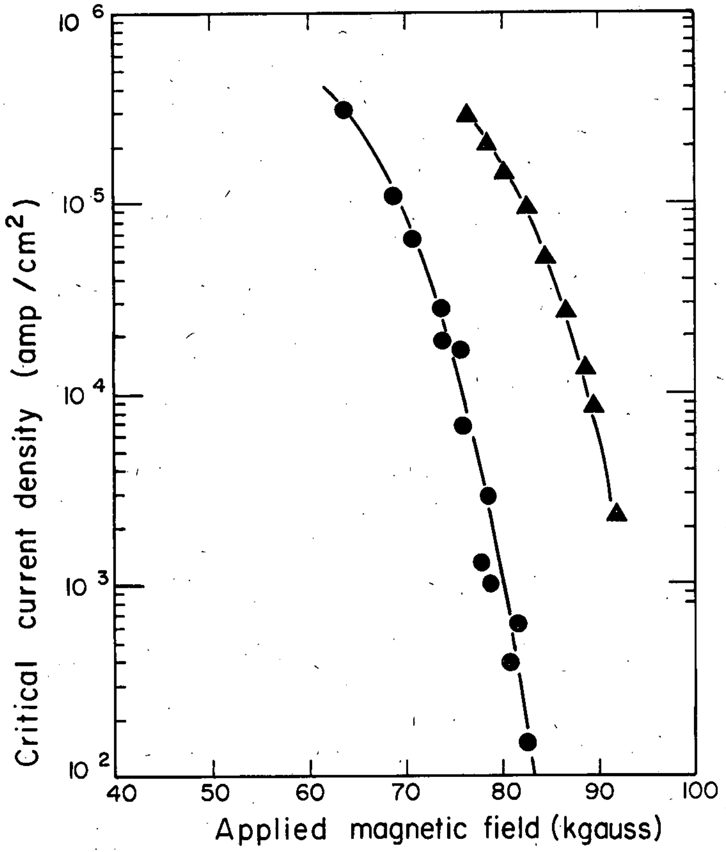
Fig. 1. Critical current density vs applied magnetic field for Sample 1(0.025-cm-diam) with H perpendicular to I, (O) 4.22°K, (△) 2.24°K.

Fig. 2. Critical current density vs applied magnetic field for Sample 1(0.025-cm-diam) with H parallel to I, (O) 4.22°K, (△) 2.24°K.



10^6
10^5
10^4
10^3
10^2
10
Critical current density (amp/cm^2)
0
20
40
60
80
100
120
140
Applied magnetic field (kgauss)

MU-25026


10 6
10 5
10 4
10 3
10 2
Critical current density (amp/cm2)
40
50
60
70
80
90
100
Applied magnetic field (kgauss)

MU-25027