Anomalous Resistive Transitions and New Phenomena in Hard Superconductors*

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The value of the critical current–critical field of cold-worked Nb, Mo-Re and Nb-Zr wires at constant temperature is not a single-valued function of the field and current direction. The previous history of a specimen during an experiment plays an important role and a measurement of the critical field–critical current can influence the response of the specimen to subsequent measurements. When I_c vs H_c curves are determined by proceeding from low to high fields, anomalous resistive transitions are observed which may not occur in measurements proceeding from high to low fields. Further, it is possible to condition a specimen to enable it to reach maximum values of the critical field and critical current. This phenomenon is also encountered in the operation of superconducting solenoids. The polarity of the field and current during this treatment is seen to be significant. For a given field, the resistive transition depends on the rate of increase of the current. Quenching of the superconductivity on reducing the field has been observed. Low critical current-critical field curves are observed on rotation of a transverse field in the plane perpendicular to the axis of the wire. The influence of current density and temperature on these phenomena has been investigated.

RECENTLY, measurements of critical current vs field have been reported for a number of hard superconductors.[1–6] We have made similar measurements with unannealed wires of Nb, Nb-Zr, and Mo-Re which show many new features which appear under certain specific experimental conditions. Since these features may be common to hard superconductors, we describe our experimental procedures and observations. To illustrate the behavior encountered, we present data obtained with an unannealed wire of Mo-Re (49% by weight) 5 mil in diameter.[7]

Some remarks on our samples are relevant. A continuous piece of specimen wire some 16 ft in length was coiled on a Lucite former at approximately 1-mm intervals, with half the turns wound in opposition to the other half. The orientation of the coil was controlled externally by means of a stainless steel rod attached to the former, and the sample was positioned with the entire length of wire transverse to the field. Electrical contact was made by coiling the end sections of the specimen around copper terminals, electroplating a thick layer of copper on the assembly and soldering copper leads to each terminal. Voltage leads were simply wrapped on the input and output sections of the superconducting specimen. The external circuit resistance was kept at a fraction of an ohm. When a resistive transition occurred, the current dropped abruptly to a small residual value of less than 1 amp and an appreciable voltage developed across the sample. The resistance which appears indicates that the specimen remains in the intermediate state at each measurement.

I

(a) The solid circles in Figs. 1 and 2 represent resistive transitions which occurred with the Mo-Re wire placed in a fixed transverse field as the current was increased slowly from zero. After a "breakdown", the residual current is interrupted briefly to allow superconductivity and thermal equilibrium to be restored, then the current again increased from zero until another "breakdown" takes place. In this way a series of points are obtained at a fixed field. The remarkable feature of each of these series of transitions is that they *progressed towards higher current densities* until a "maximum critical current" was attained. Further transitions occur at this value. Figure 2 exhibits sequences of points obtained at several fields in the course of a single run at 1.5°K proceeding from low to high fields. Figure 1 shows data secured in the same way during another run at 4.2°K. To avoid cluttering the figures, sequences for intermediate fields in each of these runs are not plotted.

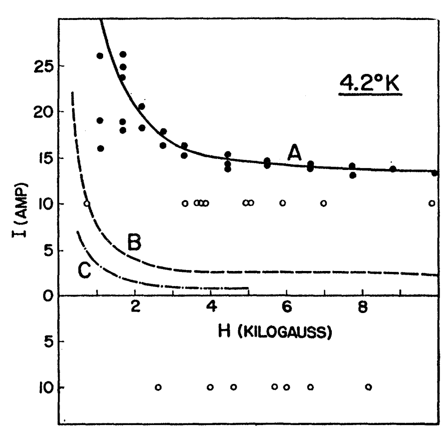

FIG. 1. Training phenomena and anomalous resistive transitions in an unannealed Mo-Re wire at 4.2°K. The curves and points are explained in the text.

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[7] We are indebted to Dr. G. A. Williams, of Bell Telephone Laboratories, for this specimen.

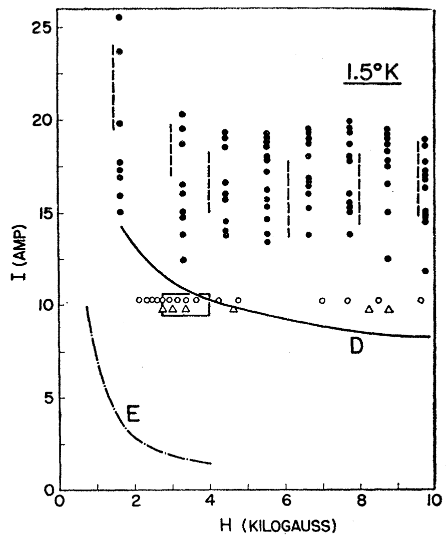

FIG. 2. Training phenomena in an unannealed Mo-Re wire at 1.5°K. The curves and points are discussed in the text.

A process of adaptation, therefore, seems to take place which enables a specimen to pass larger currents until a "maximum" is eventually reached. Whether the occurrence of the intermediate transitions is necessary to this process or merely accelerates the phenomenon of adaptation is not clear. We notice and are puzzled by the fact that although the superconductivity is quenched at successively higher currents, the residual current remains practically constant indicating that a linearly increasing fraction of the specimen is transformed into the normal state. Attempts to "condition" a specimen quickly by driving it further into the intermediate state at the initial or intermediate points yield inconclusive results. It is possible that the adaptation can take place entirely in the state of zero resistance if the time constant of the current rise is sufficiently long in the "dangerous" range. Results given below indicate that the *rate of increase* is important and must be slower at higher current densities.

At 1.5°K the adaptation is observed to be "irreversible," i.e., after the specimen has been "conditioned" to pass the maximum current at a selected field, if this field is altered appreciably and returned to the initial value (cycled), the specimen must again be "trained" to tolerate the maximum current. Whether the adapted state is unstable in a constant field and there exists a relaxation time for its disappearance remains to be investigated.

At 4.2°K this irreversibility is either less evident or not present and the need for training definitely less pronounced. Indeed, the conditioning process can apparently be by passed by a definite procedure. For example, curve A of Fig. 1 was measured by proceeding *from the high to the low fields* with a virgin sample. Some training was required over a narrow range of current at the maximum field, but all subsequent points fell on the curve even though the field was cycled between some of the measurements, and several measurements were made at any given field. It is noted that this curve falls gradually below maximal points observed previously.

(b) Curve B of Fig. 1 and curve D of Fig. 2 show the "maximum" current which can be sent abruptly through the specimen (by closing a switch in our external circuit) in the presence of a transverse field at 4.2°K and 1.5°K, respectively, without causing a resistive transition. That the rate of increase of the current is significant is further confirmed by measurements with different time constants in our apparatus. The previous history can also influence the response of a specimen to rapidly increasing currents in ways which remain to be determined.

The main features of the phenomena described above under (a) and (b) have been observed also in unannealed niobium wires in longitudinal fields where the behavior seems quantitatively less marked. We have not studied Mo-Re and Nb-Zr in longitudinal fields to date.

(c) Immediately after a series of transitions was measured with the current flowing in a given direction at constant field, the direction of current was reversed and a series progressing to higher currents was observed. The latter series are represented by the dashed vertical lines of Fig. 2. The data indicate that a path must be cleared for the current in each direction and the specimen must adapt to the *polarity* as well as the *density* of the current.

The pattern of behavior on further reversals of current at a constant field and after changes of direction of field (but not of magnitude, in view of the irreversibility effects mentioned above) seems complex and is being explored.

II

(a) The open circles in Fig. 1 (upper quadrant) represent successive resistive transitions observed with a steady current of 10 amp flowing through the specimen when the field was increased gradually from zero. After a breakdown had occurred, the residual current was interrupted, the field removed, the current again raised to 10 amp and the field applied gradually once more until another breakdown took place. The remarkable feature of these transitions is that they occur at progressively higher fields. Finally, the field could be raised to 10 kgauss (the maximum field of our magnet) with a current of 10 amp flowing in the specimen, and subsequently removed and reapplied without breakdown occurring. Again, we see that a process of adaptation takes place and the questions raised above in connection with the analogous phenomenon at constant field and increasing currents remain to be studied carefully. There is some preliminary evidence that the rate of increase of field is significant and that a specimen adapted to remain superconducting in the presence of

a slowly varying field of a certain intensity is not necessarily adapted to rapidly varying fields.

(b) After the virgin specimen has been "educated" to tolerate changing fields of a certain intensity while carrying the steady current of 10 amp flowing in a given direction, if the direction of this current is reversed (in zero field), it is observed that the specimen must again be conditioned to tolerate progressively higher fields. Once this has been achieved, the sample can now tolerate varying fields up to this intensity with currents of 10 amp flowing *in either direction*. The open circles in Fig. 1 (lower quadrant) indicate the successive transitions experienced by the specimen as it adapted to fields of increasing intensity after the *polarity* of the current was reversed.

The pattern of behavior when the direction of the field is reversed or oriented at intermediate angles in the *plane perpendicular to the axis* of the wire appears complex and is being explored.

(c) At 1.5°K for a steady current of 10 amp the behavior is different, and successive transitions in gradually applied fields do not occur at significantly higher fields. No adaption seems possible. However, one may proceed to higher fields by adopting the following procedure. After the initial transition has occurred and the residual current interrupted briefly, the field is maintained at the value reached and the current again raised to 10 amp slowly. The field is then increased gradually from the previous value until a new breakdown takes place, and this procedure is repeated at each transition. A sequence of transitions observed in a "virgin" sample are shown by the open circles in Fig. 2. After this series had been measured, the field was removed and the procedure repeated. This second sequence of transitions is represented by the open triangles. The points are displaced vertically for clarity of presentation. We note that the higher frequency of transitions in the lower field region is not fortuitous but appears to be a general feature.

(d) The behavior of a specimen in the presence of increasing fields is a function of the current density. Preliminary results indicate four regions of behavior in going from low to high current densities: (i) No anomalous transitions occur; (ii) anomalous transitions occur but adaptation takes place; (iii) anomalous transitions occur but the adaptation is "unstable"; (iv) anomalous transitions occur and no appreciable adaptation is observed.

Finally, we note that these regions shift to *lower* current densities on reducing the temperature.

(e) The interval inside the rectangle in Fig. 2 indicates a region of fields for which resistive transitions occurred at 1.5°K at a current of 10 amp when the field was *decreased* from arbitrary values between this region and 10 kgauss. Anomalous transitions upon reduction of the field were also observed for currents greater than 10 amp and 12 amp at 1.5°K and 4.2°K, respectively.

(f) The performance of a hard superconductor when both the field and current vary simultaneously as in a solenoid is of immediate practical concern. We have tested several solenoids wound with unannealed niobium wire and observed a wide range of resistive transitions progressing to higher field and current values. Generally, after these solenoids have been trained to operate at their optimum value, they can be cycled below this value without breakdown. The performance of solenoids however seems more complex than these remarks indicate. In particular, a niobium solenoid of 2-in. inner diameter and 7-in. length, with optimum field of 8.2 kgauss at 6.8 amp at 1.5°K, has been in frequent use in our laboratory for several months. This solenoid always attains the optimum performance. However, the need for training and the steps in this training procedure, if it is required, vary from run to run. Whether this is associated with the rate of cooling is a possibility under study.

III

Resistive transitions are observed in a specimen carrying a steady current during gradual rotation of a *constant transverse field in the plane perpendicular to the axis* of the wire. Actually in our measurements the field direction remained fixed and the sample was rotated manually clockwise and counterclockwise by 360° or more. Curve C of Fig. 1 and curve E of Fig. 2 show the maximum current which the specimen can carry without breakdown occurring during rotation in a given field at 4.2°K and 1.5°K, respectively, proceeding from low to high fields. The influence of rate of rotation and the existence of a time constant in this effect are being investigated. This phenomenon cannot be attributed to cutting of lines of force by the lateral motion of the specimen during rotation, since resistive transitions occur only at considerably higher current densities when the specimen is moved in and out of the magnet at the given fields. The latter transitions were discussed in Sec. II. Parts of the wire cease to be in a transverse field during the rotation. It is known that critical currents are higher in a longitudinal than in a transverse field of equal intensity.[1,3,5,6] However, there are indications that these sections may play a significant part in causing these anomalous transitions and we are investigating elongated samples which extend far outside the pole faces.

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