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ABSTRACT

Measurements of the superconducting critical current as a function of applied transverse magnetic field were made on Nb-25 a/o Zr alloy wire which had been heat-treated at a stage of its cold-reduction. There is a peak in the critical current as a function of treatment temperature, consistent with the results of Kneip, Betterton, Easton, and Scarbrough. A broad maximum in critical current, of the type reported by Berlincourt, Hake, and Leslie in Nb-12 a/o Zr alloy was found at magnetic fields between 20 and 70 kilogauss for the higher treatment temperatures. The critical currents for drawn samples of the heat-treatment control wire were measured, and a diameter-squared dependence for the critical current was found for fields to 50 kilogauss. The critical current vs applied magnetic field curves are related to a simple model of the conduction process.

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In an attempt to further understand the conduction process in superconducting Nb-25 a/o Zr alloy wire, measurements were made of the critical current as a function of applied transverse magnetic field at 4.2°K. The samples consisted of commercial 0.010-in.-diameter cold drawn wire from the Wah Chang Corporation which had been heat-treated at an intermediate stage in the cold-reduction process. The data indicate that, in confirmation of the work of Kneip, Betterton, Easton, and Scarbrough[1] at Oak Ridge National Laboratory and Treuting, Wernik, and Hsu[2] at the Bell Telephone Laboratories, the critical current at all values of the magnetic field goes through a maximum at a heat-treatment temperature of approximately 700°C. It was also observed that as the heat-treatment temperature is raised to 1000°C and higher a maximum appears in the critical current (I_c) vs applied magnetic field (H_a) curve. A maximum of this nature was previously observed by Berlincourt, Hake, and Leslie[3] in Nb-12 a/o Zr alloy material.

A second series of samples was taken from a length of the control (unheated) sample and cold-drawn in our Laboratory to smaller diameters. Measurements of I_c vs H_a for these samples indicated that, to 50 kilogauss, I_c is proportional to the diameter squared.

The samples were 2.375 in. long, with 0.500 in. of each end soft-soldered to copper contact blocks. The wires were pretinned with an ultrasonic iron in a 50/50 Bi-Cd mixture. Potential leads were soldered across the central 1.00 in. The samples were shunted by 0.005 ohm of constantan wire soldered to the same blocks as the sample. This was done to prevent damage to the sample upon going normal at high currents. The current was raised at constant magnetic field until a voltage appeared, then reduced rapidly to zero. The system noise level was 0.1 μv. The current was displayed on the x axis, while the voltage, after amplification, was displayed on the y axis of an x-y plotter. The current through the shunt was monitored and the resistance of the copper-to-superconductor contacts was found to be less than 10^{-6} ohm. Previously[4] it was found that this order of resistance would allow more than 200 amperes to pass through the contacts without significant heating ($< 0.2^{\circ}$K). The wire was oriented transverse to the magnetic field and was constrained from moving. The reader is invited to consult reference 4 for a more complete description of the experimental technique.

The samples in all cases were cooled to 4.2°K in the earth's magnetic field. I_c was measured several times, the values agreeing to within the resolution of the current measurement (1%). The field was then increased to 70 kilogauss, the highest field point. I_c was again measured several times. The first value observed was in most all cases lower than all the successive values, which were again reproducible to within 1%. This general behavior was repeated at all successive lower field points, although below 20 kilogauss often more than one measurement was required to achieve a reproducible value. After the field had been reduced to zero, I_c was remeasured. The first measured point was often as much as 50% below the reproducible value achieved after two to five attempts. The final value agreed with the value measured at the beginning of the run to within the experimental error. This effect, which is often referred to as "training," was first described by LeBlanc.[5] The training, as we observed it, appears associated with flux trapped in the superconductor resulting from a changing field environment. The increase of I_c with successive tries is associated with the process of going "normal," as increasing the current to a value below I_c and subsequent reduction to zero without a transition fails to train the samples. It is to be expected, from calculations of the stored energy in the loop formed by the sample, contact blocks and shunt, and estimates of the energy required to warm the sample above the transition temperature, that the process of going normal causes the sample to warm above the transition temperature. It then cools to 4.2°K in the field; hence, no trapped flux can be present. It should be noted that in all cases the reproducible value is the one plotted.

In order to determine whether the minimum in the I_c vs H_a curves for the 1000°C and the 1200°C samples was related to the training phenomenon, a sample was cooled in a field corresponding to the minimum, and I_c was measured. The result was negative, as the I_c measured in this manner agreed with the I_c measured by the standard technique.

For I_c greater than 12 amp the slope of the voltage-vs-current curve went discontinuously from zero to infinity at I_c. At lower currents the appearance of resistance is more gradual and consequently the true I_c becomes uncertain, though at 1 amp the minimum observable ratio between the sample resistance and the normal-state resistance is 10^{-6}.

The samples used in the heat-treatment studies were stated by the manufacturer to have been cold-reduced from the ingot to 0.125 in.-diameter rod, after which they were heated for 1 hr in vacuum at the temperatures shown in Fig. 1. After heating they were cold-drawn to 0.010 in. diameter. They were then delivered to this Laboratory for measurement.

The measurements of the drawn wire were made on four samples, 0.010, 0.0082, 0.0063, and 0.0054 in. in diameter. Figure 2 plots the exponent as a function of H_a. The points were obtained by the method of least squares, and the probable error is given. It would seem justified to assign a value of 2 to the constant "p" in the expression

$$I_c = Ad^p$$

for H_a less than 50 kilogauss. Above this value the exponent appears to drop sharply toward 1. This may or may not be significant. At these fields and with the smaller wires the currents are low and they are in the region previously discussed, where I_c is uncertain owing to the gradual appearance of normal behavior. There is, however, an indication of a decreasing p even at the lower field values where this objection does not apply. If the reality of the points at issue is accepted, then the effect could be interpreted as an increase in the critical current density as the result of the added cold-working the smaller wires received. Measurements to clarify this region are in progress.

The Nb-25 a/o Zr alloy wire discussed here can, by virtue of its high-field superconductivity, be considered to be a member of a class of superconductors referred to as "hard." These materials are characterized by their ability to conduct electric current nonresistively in magnetic fields far higher than their thermodynamic critical fields would seem to allow. This and other properties were difficult to reconcile with the accepted models of superconductors until London predicted, later to be experimentally verified, that the critical field would be enhanced as the dimension of the sample became smaller than the classical depth of penetration of the magnetic field into the surface of a bulk specimen.[6] A typical value of this quantity is 5×10^{-6} cm. Mendelssohn then postulated that a hard superconductor in a magnetic field higher than its thermodynamic critical field be thought of as a superconducting mesh with small filament dimensions in a sea of normal material.[7] This model was adequate to explain, at least qualitatively, some of the properties of this class of superconductor. These materials are known to have their current carrying capacities improved with the introduction, as the result of cold-working, of regions of severe lattice strain. As these regions are known to be of the appropriate dimensions, it is attractive to associate them with the postulated filaments. The mesh or filament postulate suggests that as long as the diameter of the wire is large with respect to the mesh size, I_c depends on the number of filaments normal to the cross section of the wire, or is proportional to the diameter squared, in agreement with the data presented.

It might also be useful to see if the filament model can be invoked to explain the character of the observed I_c-vs-H_a curves. Unfortunately the formal solution of the London equations for a current-carrying element in a transverse magnetic field has not been achieved. In lieu of this solution it will be assumed that the state (superconducting or normal) of a filament is determined, at constant temperature, only by the value of the magnetic field at its site, and that the applied field and the field of the current may be superimposed as scalars as follows,

$$H_{c_i} = A_i H_a + B_i I_{c_i},$$

where H_{c_i} is the critical field of the ith filament, A_i and B_i are constants describing the geometry of the filament, and I_{c_i} is the critical current, assumed positive or zero, of the filament. The field on the interior of the wire as a result of the total critical current (I_c) is neglected, as at 200 amp, for the size of wire used, the field at the surface of the wire is only 3.1 kilogauss, and it is falling off linearly with the radial distance from the surface and with the current. Fields of this order are not expected to be important except possibly for H_a below 10 kilogauss. Rearranging and introducing a constant n_i (the number of filaments with the same characteristics), and summing over all filaments, we have, for I_c,

$$I_c = \sum_i n_i (-C_i H_a + D_i) \qquad \text{for } n_i,\ C_i \text{ and } D_i > 0.$$

The slope of the I_c vs H_a curve is given by

$$s = -\sum_i n_i C_i \ .$$

As one moves in the direction of smaller H_a to $H_a - \Delta H_a$ to bring into the sum the next group of filaments, the new slope is

$$s + \Delta s = -(\sum_i n_i C_i + n_{i+1} C_{i+1}).$$

Therefore

$$\frac{\Delta s}{\Delta H_a} = \frac{-n_{i+1} C_{i+1}}{-\Delta H_a} \ .$$

This implies a positive or zero curvature everywhere along the I_c-vs-H_a curve. In terms of the model described, then, all the curves in Fig. 3 are anomolous. That is, they have regions of negative curvature. The curves showing the maxima-minima can then be thought of as extreme cases.

The above model is almost the simplest filament model possible. It describes the properties of a bundle of current-carrying elements of the most general cross section and critical field distribution, which are assumed not to interact with one another or with other superconducting regions. It would be very surprising if it contained anything more than a mere germ of truth. The great topological complexity inherent in the presumed mesh structure would certainly demand a more sophisticated model. Since the low initial currents observed when the sample was "training" proved to be associated with trapped flux, it would seem that modification of the model to allow for this phenomenon may lead to a better prediction for the slope of the I_c-vs-H_a curve. The theory of superconductivity[6] insists that if trapped flux exists then the superconducting regions that contain it must be multiply connected. It is also clear that flux-trapping regions also exclude flux. A simple picture is that of a single closed loop of a superconductor which, in obeying Lenz's

Law, sets up a circulating current to oppose a change of flux through it. If the most general interaction of this type of region with the current-carrying filament is permitted, then it is easy to see how a negative curvature in the I_c-vs-H_a curve could arise.

Consider a filament in the wire which at some value of the applied field can carry a maximum supercurrent. If the field were then lowered, this filament would, if the linear relationship held, carry a larger supercurrent. However, now that the applied field is lower, assume that the region postulated, sufficiently near the original filament, becomes superconducting. It will now act as a diamagnetic region, as it will keep out the flux generated by the current flowing in the original filament. Since this flux cannot propagate through this new region, the field will be enhanced in the space between the filament and the new superconducting region. The field at the surface of the filament will consequently be higher, causing it to become normal at a current lower than if the second region did not exist. It would seem, then, that if the summation could be performed, including this effect, the appropriate curvature would result.

The interaction proposed is certainly not the only one that would give the observed curvature. For example, it can be seen that two filaments in close proximity, with radically different critical current densities or dimensions such that the current-generated field of one contributes strongly to the field at the site of the other, would also generate the effect. This would require that the constants describing the superposition of the fields at the site of the filament vary over a wide range. This variation has, however, not been demonstrated, though no negative evidence exists, either.

A qualitative picture may now be given of the observed I_c-vs-H_a curves in terms of the model. The region between 70 and 50 kilogauss would correspond to the first case considered, as the curves are either linear or have a positive curvature. In the region between 50 and 30 kilogauss interactions become important, as the density of the filaments would be expected to rise. Below 30 kilogauss the volume of superconductor would appear to be increasing rapidly enough to compete with the interaction phenomenon to give again a positive curvature.

It is intended by the authors that the models and discussion relative to them be considered more as a statement of the problem than as a solution. The possible range of geometric, topological, and critical field variables is as yet too wide to permit sufficiently detailed calculations.

FOOTNOTES AND REFERENCES

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

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5. M. A. R. LeBlanc, Phys. Rev. (to be published) (Nov. 1961).
6. F. London, Superfluids, Vol 1 (John Wiley and Sons, Inc., New York, 1950).
7. For a review of the work of London and Mendelssohn, consult D. Shoenberg, Superconductivity (Cambridge University Press, New York 1960).

Figure Legends

Fig. 1. I_c vs heat treatment temperature for 0.010-in.-diam wire, (●) 60 kgauss, (■) 50 kgauss, (▼) 40 kgauss, (▲) 20 kgauss, (◆) 10 kgauss, (◗) 6 kgauss.

Fig. 2. P vs H_a, where $I_c \propto r^P$.

Fig. 3. I_c vs H_a for 0.010-in.-diam wire (●) control, (■) 600°C heat, (▲) 1200°C heat.

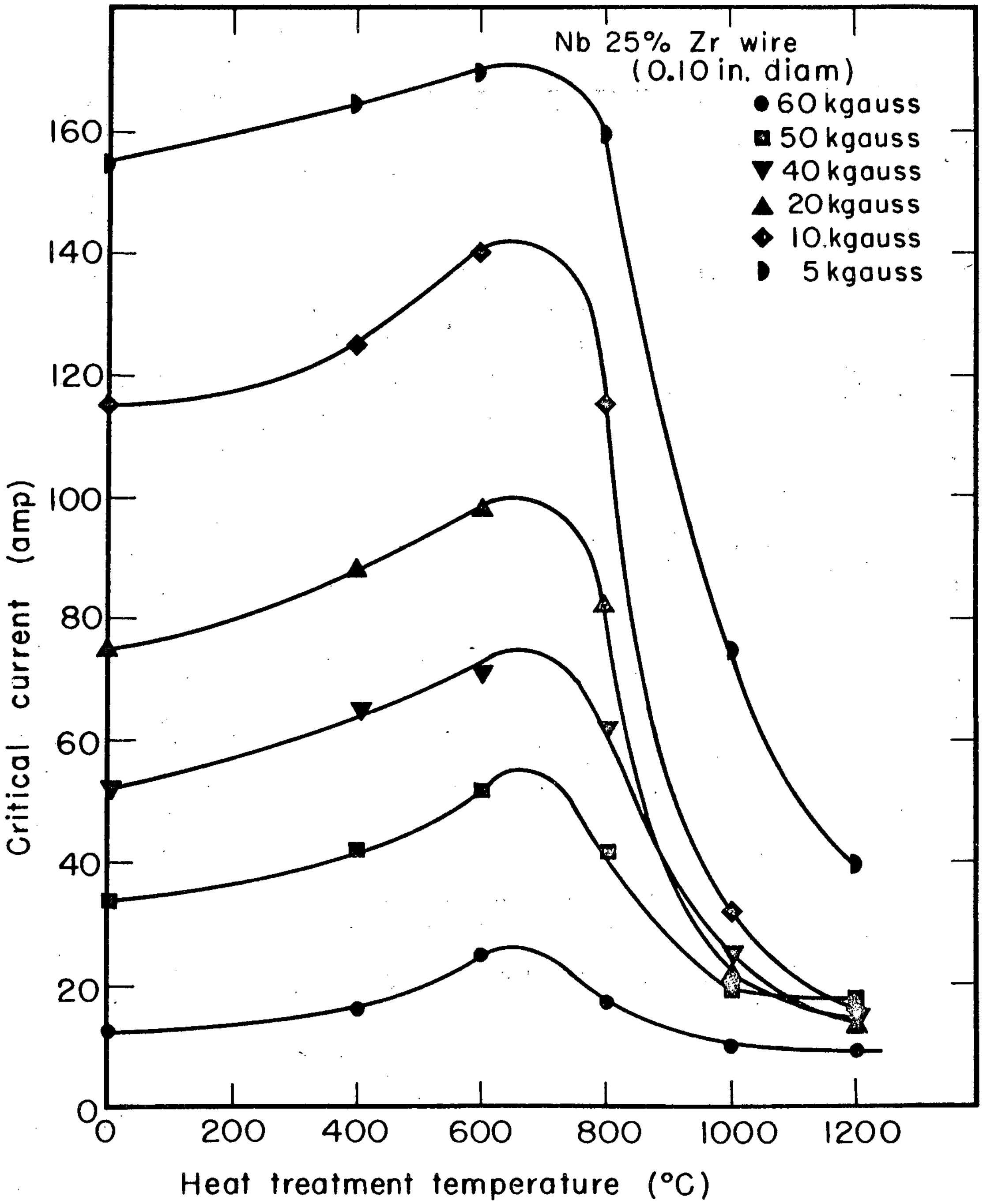

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Fig. 1

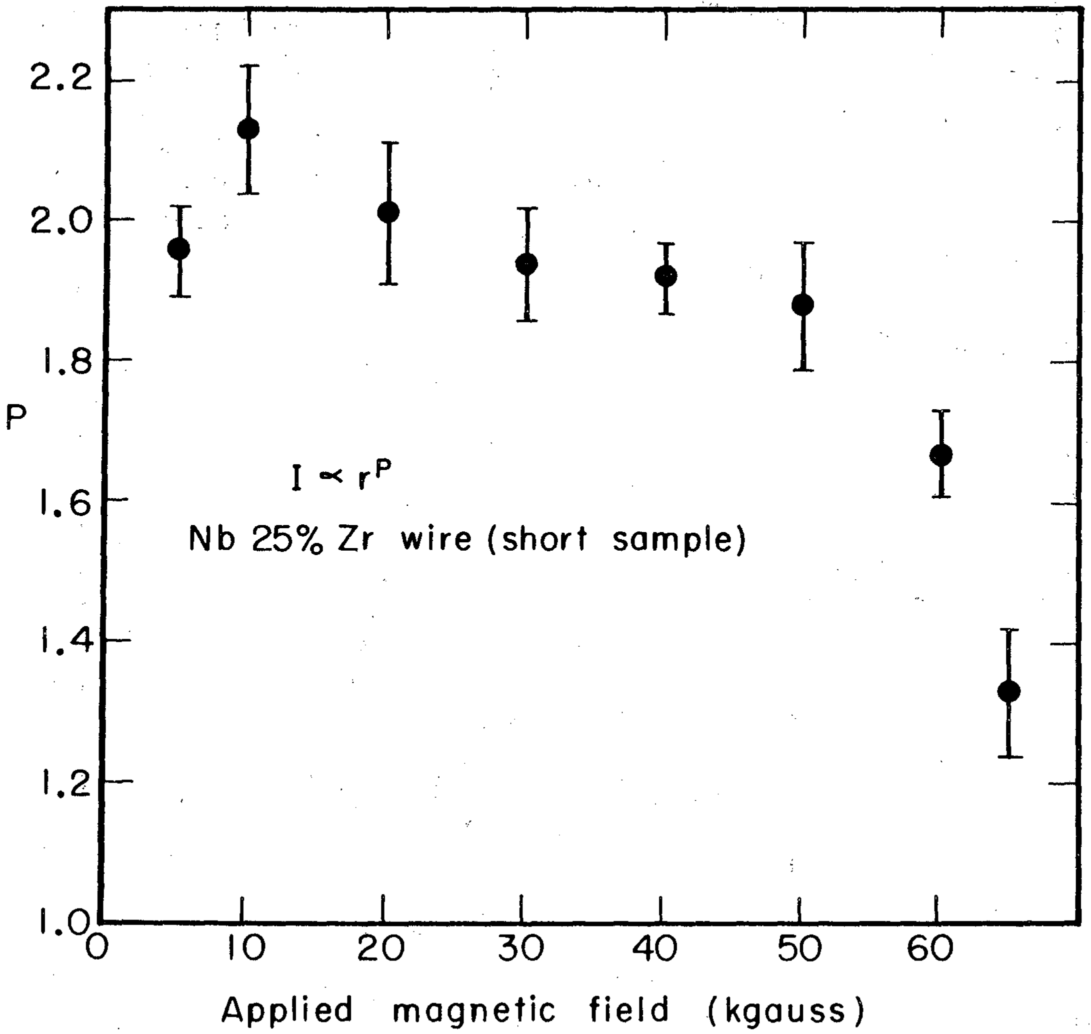

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Fig. 2

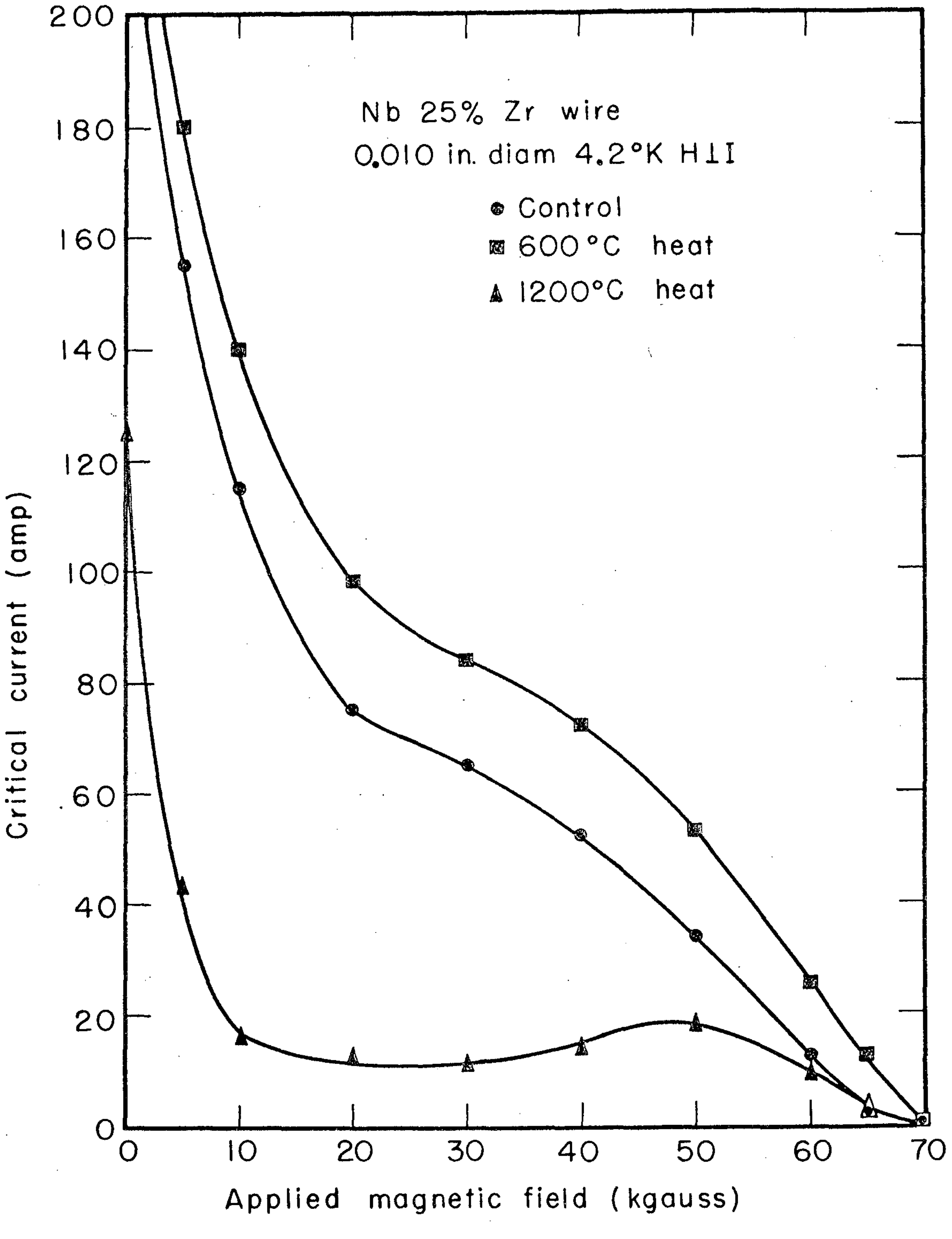

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Fig. 3