Magnetic Flux Jumps in Superconducting 3Nb-Zr Alloy Wires

著者	FUKUROI Tadao, FUKASE Tetsuo
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	16
page range	132-138
year	1964
URL	http://hdl.handle.net/10097/27169

Magnetic Flux Jumps in Superconducting 3Nb-Zr Alloy Wires*

Tadao Fukuroi and Tetsuo Fukase

The Research Institute for Iron, Steel and Other Metals

(Received Sept. 2, 1964)

Synopsis

The magnetic field strength in the center of three kinds of superconducting solenoids wound with 3Nb-Zr alloy wire was measured through the course of a gradual variation of the external magnetic field. The manner of a discontinuous change of a magnetic field, viz. the flux jump which gives a clue to clarify the behavior of penetration and trapping of magnetic filaments through the solenoid was studied. In general, the step height of flux jumps becomes smaller as the external magnetic field becomes stronger.

I. Introduction

Lubell et al.(1) reported that a series of sharp voltage pulses was observed during an increasing and decreasing stages of the external magnetic field applied to a solenoid wound with 3Nb-Zr wire, even though the solenoid was left in the state of open circuit and of no transport current. Hempstead et al.(2) treated the distribution of a magnetic field in the course of variation of an external magnetic field in an open and a closed system and reported the inductive behavior of a superconducting magnet.

II. Experiments

In the present experiments use was made mainly of the alloy wire having the composition of 75 per cent Nb and 25 per cent Zr and the diameter of 0.25 mm. Some times a niobium wire of the same size was used for the comparison's sake. The short sample of this 3Nb-Zr alloy wire could keep its superconducting stage at 4.2°K even in the case that the direct current of 45A, i.e. 9×10^4A/cm^2 is flowed through it in the external magnetic field of 9 kG. Three kinds of solenoids as listed in Table 1 were wound on each bakelite bobbin of 10 mm in diameter and 15.6 mm in length. On transferring one of the solenoids into the superconducting state by cooling to the boiling point of liquid helium, the inner central magnetic field (H_i) of the solenoid was measured to see the behavior of variation of the resultant magnetic field, by applying a uniform external magnetic field in the direction parallel to the axis of solenoid by means of a large Weiss magnet from outside of a Dewar vessel. The

---

* The 1130th report of the Research Institute for Iron, Steel and Other Metals.

(1) M.S. Lubell, B.S. Chandrasekhar and G.T. Mallick, Appl. Phys. Letters, **3** (1963), 79.

(2) C.F. Hempstead, Y.B. Kim and A.R. Strnad, J. Appl. Phys., **34**, (1963), 3226.

Table 1. Dimensions of the solenoids wound with Nb 75 at.%-Zr 25 at.% alloy wire of the diameter 0.25 mm.

'Solenoid A'	wire coated with nylon in the thickness 0.02mm. i.d.: 10mm, e.d.: 16.2mm, l : 15mm. 9 layers, 448 windings.
'Solenoid B'	wire without coating. i.d.: 10mm, e.d.: 12mm, l : 15.6mm. 3 layers, 162 windings.
'Solenoid C'	wire coated with polyester resin in the thickness 0.015mm. i.d.: 10mm, e.d.: 11mm, l : 15.6mm. 1 layer, 56 windings.

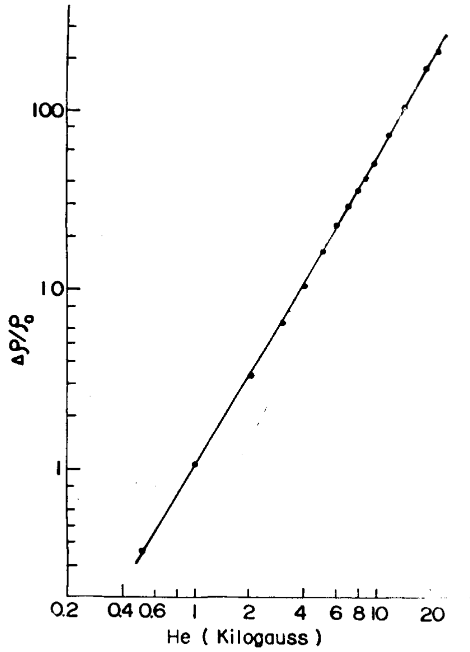

Fig. 1. Magnetoresistance of the antimony probe.

intensity of external magnetic fields (H_e) was measured through the Hall voltage induced in an n-type germanium probe attached on a pole piece of the Weiss magnet which was described previously(3), and the field strength could be increased and decreased automatically at the rate of about 1500 gauss per minute by changing the exciting current of the motor generator which feeds the direct current to the Weiss magnet. The intensity of the internal magnetic field (H_e) was estimated from the change of electrical resistance of probe which was cut out from a single crystal of antimony. The resistance of the antimony probe at 4.2°K without a magnetic field was of the order of $10^{-5}\Omega$, or the resistivity of $5\times10^{-7}\Omega$ cm, but it increased as shown in Fig. 1 as a function of a magnetic field. By applying the e.m.f. from the above-mentioned probes to the vertical and the horizontal axes ter-

---

(3) T. Fukuroi and Y. Saito, Sci. Rep. RITU, **A 9** (1957), 274.

minals of an x-y recorder we can observe the change of H_i in the course of H_e is increased and decreased smoothly.

Thus, it was observed how the magnetic field was shielded by dint of the superconducting solenoid when the external field was increased, and how the field is trapped when the external field was decreased. That is to say, the difference of the internal and the external magnetic field is expressed as $H_i - H_e = M = Gi$, where M denotes the magnetization of a solenoid; thus it consists of the product of a constant factor G and an induced current i in the solenoid. So, the manner how H_i is changed with regard to H_e, especially the discontinuous changes, viz. the flux jumps can be investigated.

"Solenoid A" was made of 448 windings in 9 layers and the magnetic field generated in the center was given by $H_i = 283i$, in which i is the current in the winding in amp. Both ends of the winding were spot-welded each other at the position 10 cm apart from the main of the solenoid, so that a superconductive closed circuit was established. In this solenoid, as seen in Fig. 2, H_i increased linearly when H_e rose above 3 kG and continued to increase with a number of small flux steps or creep mixed with four marked flux jumps of the order of 1 kG when H_e reached 7, 8, 11 and 20 kG, respectively. After H_e attained to 24 kG on its course of gradual decreasing, H_i also decreased continuously down to 8 kG by flux creep. When 8 kG was attained, a flux creep was discontinued and a flux trapping became perfect, so that a flux concentration was brought about, and H_e turned to rise through a minimum and resulted in the residual magnetic field of about 11 kG when H_e reduced to zero.

The diagram of $M = H_i - H_e$ plotted against H_e is given by Fig. 3. As seen in the figure the magnetic field at which the flux trapping begins to occur is not

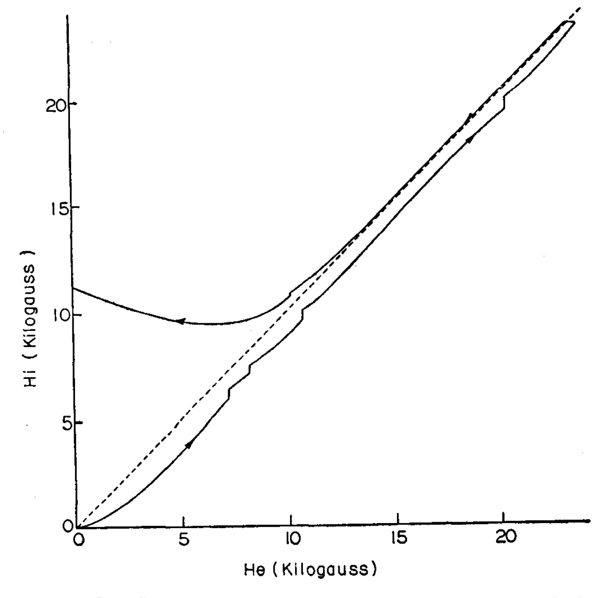

Fig. 2. H_i versus H_e curve for the solenoid A.

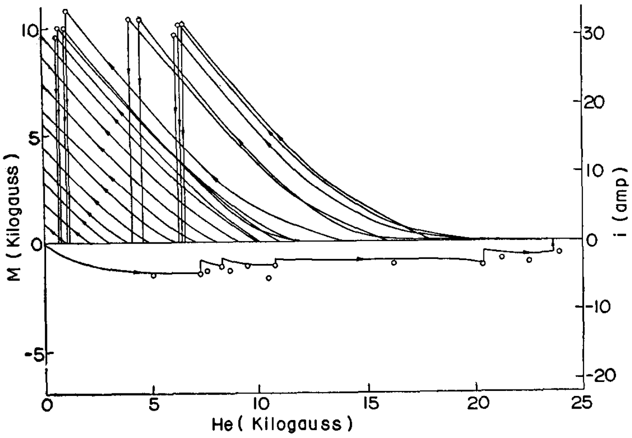

Fig. 3. $M=H_i-H_e$ versus H_e for the solenoid A.

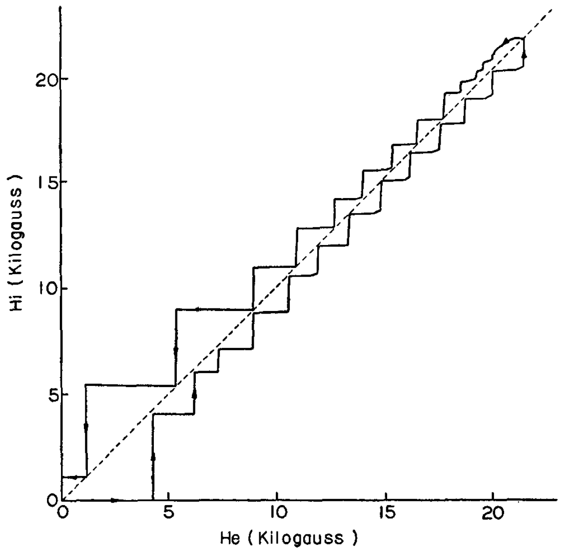

Fig. 4. H_i versus H_e curve for the solenoid B.

definite and the amount of residual magnetic field is almost independent of the strength of the maximum magnetic field. The induced supercurrent in the solenoid corresponding to the trapped magnetic field of 11kG is about 32～35 A.

"Solenoid B" was composed of a 3Nb-Zr alloy wire without any coating and consisted of 162 turns in 3 layers with no special insulation between the layers; nevertheless it was ascertained that a closed superconducting circuit could first be performed through the spot-welded junction of both extremes of the wire.

As shown in Fig. 4, H_i makes a large flux jump at 4 kG of H_e and then gives rise to 12 flux jumps with almost an equal interval, during H_e is increased from 4 to 22 kG. In the course of H_e being decreased from 22 kG to zero field, H_i diminishes by a flux creep from 22 to 20 kG; below 20 kG of H_e, it turns to give rise to 11 flux jumps and then 2 marked flux jumps as large as 3～3.5 kG in each step, before H_e is reduced to zero. Fig. 5 shows the relationship between $M=H_i-H_e$ and H_e,

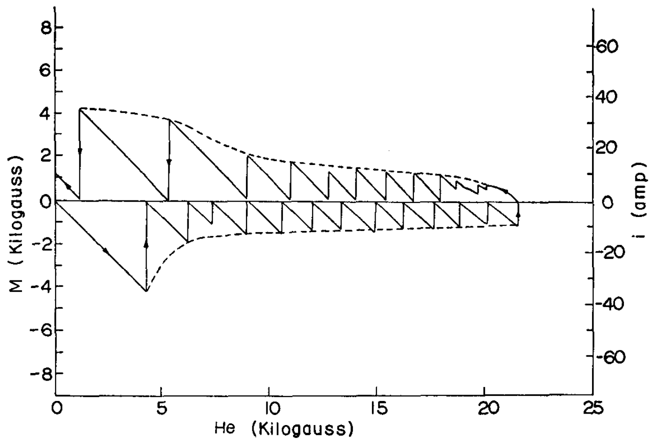

Fig. 5. $M=H_i-H_e$ versus H_e for the solenoid B.

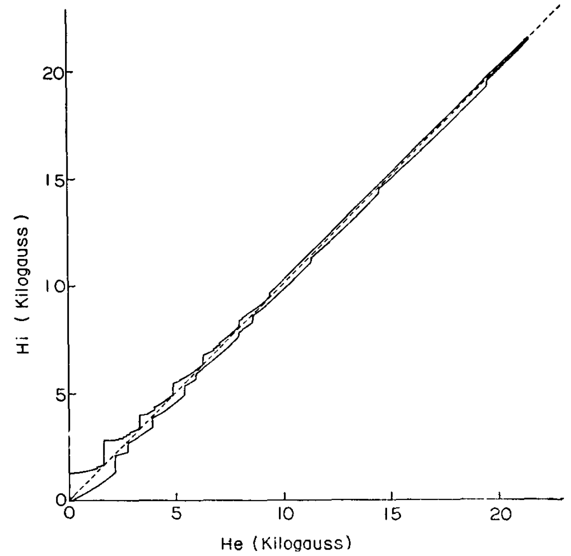

Fig. 6. H_i versus H_e curve for the solenoid C.

in which the curves connecting the maximum and minimum points represent the maximum values of induced supercurrents in the presence of a magnetic field.

"Solenoid C" consisted of a single layer coil wound 56 turns with 3Nb-Zr wire having an insulating coating of polyester-resin, 0.015 mm thick, sintered at 450°C. Both ends of the solenoid were spot-welded at the point about 10 cm apart from the main coil.

As illustrated in Fig. 6, on increasing H_e from zero to 22 kG, H_i also attained the maximum value by making 10 flux jumps and a number of minute flux creeps. But in the course of decreasing H_e, no flux jump was observed from 22 to 10 kG and H_i decreased smoothly with a flux creep; 6 flux jumps came about below 10 kG and the residual magnetic field of 1.3 kG was remained without an external field.

When the same solenoid was re-examined after a week, the flux creep at a high field region transferred to the flux jumps and almost all variations of field were

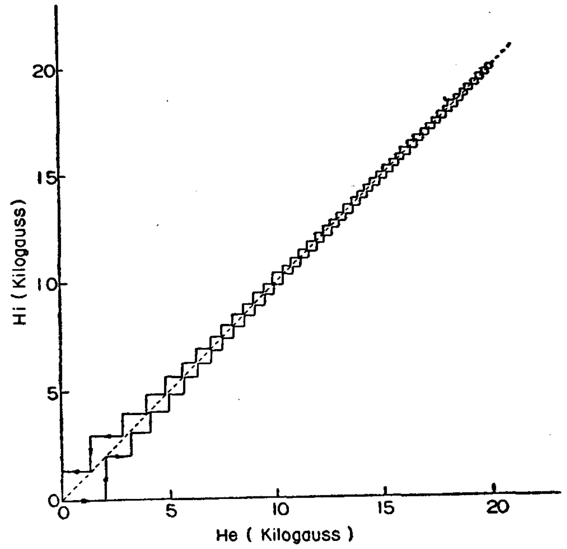

Fig. 7. H_i versus H_e curve for the solenoid C.

done by flux jumps at the end as shown in Fig. 7.

On increasing H_e from zero to 20 kG, H_i made the first jump at 2 kG and the field interval at which a flux jump occurred became narrower, i.e. the 47 jumps were observed in all at an interval of $300 \sim 250$ G. In the decreasing course of H_e from 20 kG to zero, it was noticed that the steps of H_i jumps became larger as the H_e field became lower, i.e. they grew coarser from 250 to 400G wide, but through this range still 47 jumps in all were observed.

III. Discussions

Many theories have been proposed to interpret the behavior of flux penetration in a hard superconductor.

As is well known, under a weak field viz., below H_{c_1} the Meissner effect works effectively for a flux expulsion or a flux shielding of the external field. So, H_{c_1} is concluded to be less than the field strength at which the lowest flux jumps is observed, and it is of the order of a few hundred gauss as inferred from the above-mentioned experimental results.

In the field between H_{c_1} and H_{c_2}, a mixed state of superconductive and normal one would be formed, and flux filaments will creep in a matrix by a Lorentz force. When the flux filaments are pinned by a structural irregularities, flux bundles will be formed at several places. Flux jumps will give rise to occur in case of these flux bundles being released as a cluster.

Summary

(1) The magnetic field at which some definite flux jumps occur is not always fixed and at variance for every experiment even with the same solenoid.

(2) H_{c_1}, viz. the field below which the Meissner effect holds good, is of the order of a few hundreds gauss for the wires under consideration.

(3) Flux jumps are generated in smaller and more frequent steps as the external field becomes stronger. The amount of penetration or the repulsion of a magnetic field becomes less, which means that the strength of an induced supercurrent is smaller at higher magnetic field.

(4) The maximum induced supercurrent, which shields or traps the magnetic field, is estimated to be 35 A viz. $5.6\times10^4 \mathrm{A/cm^2}$ with regard to the wire of 3Nb-Zr alloy tested here.