THE EFFECT OF HYDROSTATIC PRESSURE ON THE CRITICAL CURRENT IN SUPERCONDUCTING Nb-Zr ALLOYS

N. B. BRANDT and E. PAPP

Moscow State University

Submitted July 16, 1968

Zh. Eksp. Teor. Fiz. 55, 2160–2165 (December, 1968)

The effect of hydrostatic pressure up to 20 kbar on the critical current in Nb-Zr alloys is investigated in magnetic fields up to 30 kOe and at liquid helium temperatures. The critical current measurements were carried out by a potentiometric method and by Kim's contactless method. The critical current is found to increase under pressure; in the $Nb_{50}Zr_{50}$ alloy the increase is ~15 percent at P = 17.5 kbar. The increase of the critical current cannot be ascribed to the variation of the main critical parameters of the alloy due to compression (T_c practically does not change at pressures up to 20 kbar and H_{c2} apparently decreases).

INTRODUCTION

REGARDLESS of the fact that an extensive literature has been devoted to questions connected with an investigation of superconductors at high pressures (see, for example,[1]), the effect of pressure on so interesting a parameter of type-II superconductor as the critical current I_c has practically not been investigated. Essentially we know only of one paper[2] in which the effect of the pressure P up to 1750 kbar on the critical current in Nb_3Sn was investigated at a temperature T = 16.5°K (the temperature T_c of the transition to the superconducting state ~18°K). It was noted that I_c decreases under pressure, but because the measurements were carried out at a temperature close to T_c the observed strong decrease of I_c (by about two orders of magnitude at P = 1750 kbar) is apparently the result of a lowering of T_c in Nb_3Sn under pressure.

A characteristic property of type-II superconductors described by Abrikosov's theory[3] is the existence of a mixed state between the critical fields H_{c1} and H_{c2}. In this state the magnetic field penetrates into the sample in the form of quantum vortices. The magnetic and electrical properties of type-II superconductors in the mixed state depend strongly on the physical state of the sample. The effect of structural defects on the critical properties (the critical current and the critical magnetization) of type-II superconductors is connected with the fact that the defects by interacting with the Abrikosov vortices pin them and produce potential barriers in the free energy (this phenomenon has been called "pinning").

The most satisfactory theory of critical phenomena, the Anderson-Kim theory,[4] describes the motion of vortices across barriers as a thermally activated motion under the action of a magnetic pressure gradient appearing for a nonuniform vortex distribution; the velocity of the motion is $\sim \exp[q(F - F_c)kT]$ where F_c is a force characteristic for the pinning effect, F = jB is the Lorentz force (j is the current density and B is the magnetic induction), and q is a constant. The critical current is determined by the condition that the velocity of the vortices does not exceed a certain critical value, i.e. $j_cB = \alpha_c$, where α_c is a parameter characteristic of the pinning whose temperature dependence is according to the theory linear. We note that the formula $j_c(B + B_0) = \alpha_c$ where B_0 is some empirical constant is in better agreement with experiment. One would expect that an investigation of the effect of pressure on the critical current would enable one to obtain additional information about the pinning phenomenon and about the nature of the interaction of vortices with lattice defects.

In this work we investigated the effect of hydrostatic pressures up to 20 kbar on the critical current in Nb-Zr alloys of three compositions: $Nb_{90}Zr_{10}$, $Nb_{75}Zr_{25}$, and $Nb_{50}Zr_{50}$ in magnetic fields up to 30 kOe at liquid helium temperatures.

METHOD OF MEASUREMENT

Hydrostatic pressures up to 20 kbar were produced by means of a pressure booster employing a kerosene-oil mixture[5] as the pressure transmitting medium. The compression was carried out at room temperature after which the pressure booster was slowly cooled down to the experimental temperature. The pressure was determined from the shift of the superconducting transition temperature of a tin manometer detected by an induction method at 22 cps.

The critical current was measured by two methods: the potentiometric and Kim's contactless method.[6]

In the potentiometric method the sample was a coil of ~1 mm diameter consisting of several turns of superconducting wire of the investigated composition. The coil was mounted on the obturator of the pressure booster in such a way that the plane of its turns was perpendicular and the ends of the coil held in the obturator channel by Araldite resin were parallel to the field. All contacts were placed outside the high-pressure chamber. The measurements were carried out at fixed values of the external field with a slow automatic current increase. After the sample went over to the normal state the current through the sample was switched off with the aid of a fast electronic device. Magnetic fields up to 30 kOe were produced by a superconducting solenoid.

The dependences of the magnetic field H′ inside the superconducting tube of the investigated material on the external longitudinal magnetic field H were measured in Kim's method. The field H′, lower than H in an increasing field and exceeding H in a decreasing field, is given by the relation

$$H' = H \mp \frac{4\pi}{10} \int_{r_1}^{r_2} j_c(B)\,dr,$$

where r_1 is the inner and r_2—the outer diameter of the tube. The difference between H and H′ makes it possible to determine directly the average critical current density

$$\bar{j}_c = \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} j_c(B)\,dr$$

as a function of the average value of the magnetic induction $\bar{B} = (H + H')/2$. The magnetic field H′ inside the tube was measured by a copper magnetoresistance transducer. A tiny coil of copper wire 20 μ in diameter wound

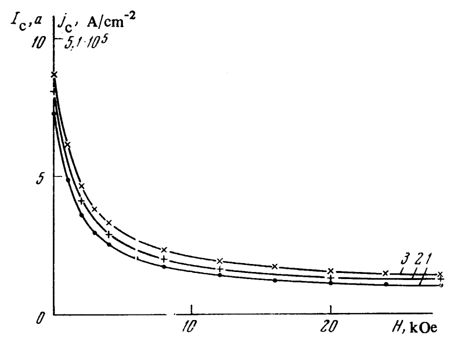

FIG. 1. Critical current of the 50-μ $Nb_{50}Zr_{50}$ wire as a function of the external field at the temperatures: 1 – T = 4.2°K, 2 – T = 3.47°K, 3 – T = 2.59°K.

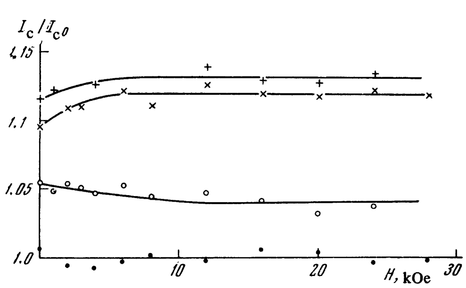

FIG. 2. Relative change of the critical current of a 50-μ wire of $Nb_{50}Zr_{50}$ under pressure: ○ – P. 6.5 kbar, × – P = 15.6 kbar, + – P = 17.5 kbar, ● – P = 0 (after taking off the pressure); T = 4.2°K.

bifilarly was placed at the center of the tube. The transducer was calibrated without pressure and at the maximum pressure. The effect of pressure on the magnetoresistance of the copper turned out to be so small that it could be neglected. The error in the measurement of H′ amounted to 1–3 percent for H′ > 2 kOe and increased considerably in weaker fields. The measurements were carried out in slowly increasing and decreasing magnetic fields. The resistance of the copper transducer was measured with the aid of a photoamplifier. The fields H and H′ were recorded on a two-coordinate chart recorder.

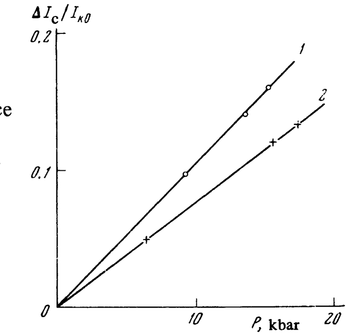

FIG. 3. Pressure dependence of the relative change of the critical current in $Nb_{50}Zr_{50}$ wire for H = 20 kOe. Curves 1 and 2 were obtained with different pieces of wire.

MEASUREMENT RESULTS

Figures 1–3 show the data of the measurements by the potentiometric method using wires. Figure 1 illustrates the field dependence of the critical current in cold-drawn $Nb_{50}Zr_{50}$ wire 50 μ in diameter at various temperatures. Figure 2 shows the relative change of the critical current with pressure. The critical current increases with pressure. The relative change of the current depends weakly on the external magnetic field. The same kind of change was also observed at lower temperatures. Figure 3 shows the pressure dependence of the relative change of the critical current in a magnetic field H = 20 kOe. Curves 1 and 2 were obtained with different pieces of the same wire. The observed increase of the critical current is fully reversible (see Fig. 2).

Figures 4–6 present results of measurements by Kim's method on a $Nb_{90}Zr_{10}$ sample (sample dimensions: r_1 = 1.35 mm, r_2 = 2.3 mm, length 16 mm)[1]. Figure 4 illustrates the characteristic form of the dependences

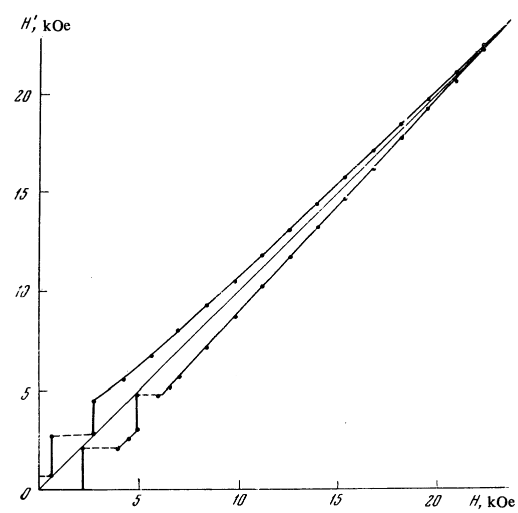

FIG. 4. Dependence of the internal field on the external field in a $Nb_{90}Zr_{10}$ sample with P = 19.8 kbar and T = 2.69°K.

[1]The phase composition of the alloys is unfortunately unknown.

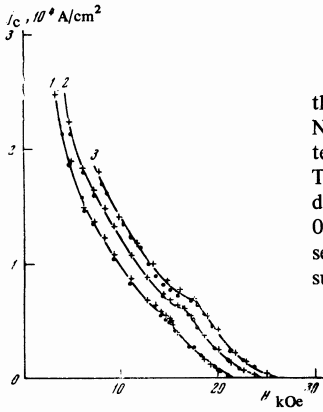

FIG. 5. Field dependence of the critical current density in a $Nb_{90}Zr_{10}$ sample at the following temperatures: 1 – T = 4.2°K, 2 – T = 3.49°K, 3 – T = 2.7°K; ● – data for the initial sample for P = 0; + – data for P = 0 after a series of experiments under pressure.

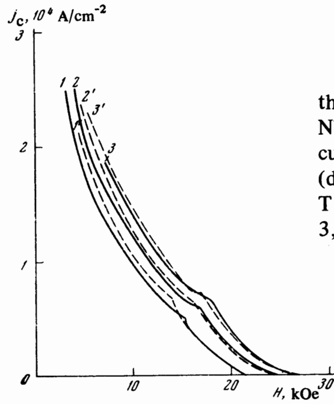

FIG. 6. Field dependence of the critical current density in a $Nb_{90}Zr_{10}$ sample for P = 0 (solid curves) and for P = 19.8 kbar (dashed curves). Curves 1, 1′ – T = 4.2°K; 2, 2′ – T = 3.49°K; 3, 3′ – T = 2.7°K

of the field H′ on H in introducing and extracting the field H. The jumplike change of the magnetic field H′ accompanied by jumps of the magnetic flux inside the tube corresponds to a sudden destruction of the critical state and to complete penetration of the external magnetic field into the tube. This was accompanied by adiabatic heating of the sample. During the subsequent cooling the critical state is gradually re-established. During the process of re-establishment the internal field H′ remains constant. The dependences of $j_c(H)$ for the $Nb_{90}Zr_{10}$ alloys at various temperatures calculated from the H′(H) curves, are shown in Fig. 5. The results of measurements of the initial sample before applying pressure and the results for the same sample after a series of experiments under pressure are plotted in Fig. 5. A characteristic peculiarity of these curves is the presence of a break whose position is shifted on lowering the temperature towards the region of stronger fields. The values of the fields corresponding to the break are close to the values of the critical field H_{c2} of the investigated sample.

Figure 6 depicts $j_c(H)$ curves for a $Nb_{90}Zr_{10}$ sample without pressure and at P = 19.8 kbar. The current j_c increases reversibly under compression below the break (i.e., apparently, for $H < H_{c2}$) and decreases weakly in higher fields. The change of the critical field observed at lower pressures is of a similar nature. A weak increase of the critical current (for $H < H_{c2}$) was also observed in the $Nb_{75}Zr_{25}$ alloy.

DISCUSSION OF THE RESULTS

Among the investigated $Nb_{50}Zr_{50}$, $Nb_{75}Zr_{25}$, and $Nb_{90}Zr_{10}$ alloys the largest change of the critical current under hydrostatic compression occurred for the sample with the $Nb_{50}Zr_{50}$ composition. The critical current of this sample is well described in a broad range of external fields (10–30 kOe) by the dependence $1/j_c \propto 1/H$. This means that in the relation $j_c(H + B_0) = \alpha_c$ (for thin wires $B \approx H$) the parameter α_c increases linearly with the field: $\alpha_c = \beta_c H$. The strong dependence of α_c on the field can be explained by the pinning of vortices on particles of the second phase in the alloy which goes over with increasing external field to the normal state.[7] The parameter β_c exhibits a linear temperature dependence in the investigated temperature range. Pressure does not change the nature of the dependences of j_c on H and T. It is mainly the parameters β_c and B_0 which change under pressure. β_c increases linearly with increasing pressure. The observed increase of the parameter β_c under pressure cannot be explained as being due to a change of T_c on compression. In $Nb_{50}Zr_{50}$ the maximum change of T_c does not exceed ~1 percent (T_c = 10.75°K for P = 0 and 10.85°K for P = 17.5 kbar).

Thus the relatively large change of the critical current (of the order of 15 percent for P = 17.5 kbar) and of the parameter β_c which characterizes it under hydrostatic compression is not a result of a change of the basic critical parameters of the $Nb_{50}Zr_{50}$ alloy under pressure. The critical temperature T_c practically does not change (or increases very weakly); H_{c2}, apparently to the contrary, decreases on compression (Fig. 6).

It is natural to assume that the mechanism of the critical current increase under pressure is directly related with a change in the magnitude of the interaction of magnetic flux vortices with the inhomogeneities of the sample, i.e. with the pinning mechanism.

In conclusion we take the opportunity to thank A. I. Shal'nikov for interest in the work and help in carrying it out.

[1] N. B. Brandt and N. I. Ginzburg, Usp. Fiz. Nauk 85, 485 (1965) [Sov. Phys.-Uspekhi 8, 202 (1965)].

[2] C. B. Müller and E. J. Saur, Rev. Modern Phys. 36, 103 (1964).

[3] A. A. Abrikosov, Zh. Eksp. Teor. Fiz. 32, 1442 (1957) [Sov. Phys.-JETP 5, 1174 (1957)].

[4] P. W. Anderson and Y. B. Kim, Rev. Modern Phys. 36, 39 (1964).

[5] E. S. Itskevich, V. F. Kraĭdenov, E. L. Slavyanikova, and V. A. Sukhoparov, Prib. Tekh. Eksp. No. 1, 187 (1968).

[6] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Letters 9, 306 (1962); Phys. Rev. 131, 2486 (1963).

[7] J. D. Livingston and T. H. Alden, Trans. Tenth International Conference on Low-temperature Physics, Moscow, 1967, vol. IIB, p. 20.

Translated by Z. Barnea
240