SOVIET PHYSICS JETP VOLUME 29, NUMBER 2 AUGUST, 1969

CRITICAL CURRENTS IN A SUPERCONDUCTING ALLOY WITH A RIGID VORTEX LATTICE

Yu. F. BYCHKOV, V. G. VERESHCHAGIN, V. R. KARASIK, G. B. KURGANOV, and V. A. MAL'TSEV

P. N. Lebedev Physics Institute, U.S.S.R. Academy of Sciences

Submitted August 30, 1968

Zh. Eksp. Teor. Fiz. **56**, 505–515 (February, 1969)

A model of a type-II superconductor with a vortex lattice rigidly fixed on inhomogeneities is proposed in which the destruction of the superconductivity by a current in an external magnetic field is due to the superconducting condensate attaining the critical velocity. The model is verified for a Ti-22 at.% Nb alloy in which highly dispersed transition and equilibrium-phase precipitates uniformly distributed throughout the volume can be obtained. Satisfactory agreement between theory and experiment is obtained. A close relation between the structural state of the alloy and its superconducting properties is established and explained. An explanation is offered for the so-called "peak effect" on the $j_c(H)$ curve.

It is well known that in the mixed state[1] nonvanishing superconducting currents can only exist in the presence of defects which stabilize the periodic structure of the order parameter and prevent it from moving under the action of electromagnetic forces.[2,3] The role of stabilizers can be fulfilled by highly dispersed precipitates of the equilibrium and transition phases precipitating from the metastable solid solution, pores, foreign particles, dislocation aggregates, and defects resulting from irradiation with protons and other heavy particles.[4]

In order to construct a quantitative theory and understand more clearly the connection between the structure of a material and its superconducting properties, it is desirable to investigate alloys in which one of the stabilization mechanisms predominates. The alloy Ti-22 at.% Nb whose structure has been thoroughly investigated by transmission electron microscopy and microdiffraction is particularly suitable in this respect. It is known[5] that by different thermal treatment one can obtain in this alloy the following structural states:

1. A single-phase solid solution with a body-centered cubic lattice (β phase).
2. The same solution containing precipitates of the hexagonal ω phase depleted of niobium (about 17% niobium) uniformly distributed over the volume. The ω-phase precipitates have the shape of ellipsoids whose dimensions and concentration can be controlled by varying the thermal treatment regime.
3. The same solution containing precipitates of the equilibrium α phase (less than 5% niobium and the remainder titanium).

At the same time, the superconducting properties of the alloy Ti-22 at.% Nb were insufficiently investigated: the measurements were carried out in weak magnetic fields,[6,7] and the relation between the critical currents and the structure had not been investigated.[8]

In this paper we have investigated in detail the $j_c(H)$ dependence of this alloy in a transverse magnetic field in the range $0 < H < H_{c2}$. The obtained results have been interpreted on the basis of information on the structural state of the alloy and the proposed[9] model of a rigidly fixed vortex lattice with account of the "proximity effect."

1. METHOD OF MEASUREMENT

The source of the magnetic field in the $j_c(H)$ measurements was a superconducting solenoid with ferromagnetic dysprosium inserts.[10] The solenoid winding was 176 mm long with an inner diameter of 18 mm and an outer diameter of 142 mm and consisted of 9981 turns of superconducting KSMI-6 cable (six superconducting copper-plated strands of 65 BT alloy and one copper strand twisted and impregnated with indium). The solenoid was calibrated by the ballistic method, as well as with a bismuth probe. The current constant $K = 0.651$ kOe/A (± 0.9%). The critical current of the solenoid $J_c = 110$ A and $H_{max} = 62$ kOe. The diameter of the dysprosium poles was 9 mm and that of the pole ends 3 mm. The gap between the poles did not exceed 1 mm. The induction in the gap was determined from the magnetoresistance of copper, $B_{max} = 88$ kG.

The investigated sample was provided with clamped current and voltage contacts and was mounted on a textolite holder on which the dysprosium poles were mounted. The holder was introduced into the solenoid in such a way that the part of the sample located between the poles was in the center of the solenoid in the transverse magnetic field.

The current through the sample was adjusted by means of semiconductor rheostats between 0.5 mA and 80 A. The transition to the normal state was determined from the sudden appearance of voltage on the portion of the sample located between the poles. Within an accuracy of 10^{-7}–10^{-8} V no voltage was observed to anticipate the abrupt transition. Only in fields close to H_{c2} was the volt–ampere characteristic of the transition smooth and the critical current was determined from its steepest portion. The voltage was measured with a photocompensating F-116/1 microvoltampere meter with a sensitivity of 10^{-8} V.

The critical temperature was measured for a series of samples. The measurements of T_c were carried out

Method of preparation, phase composition, and the critical temperature of the investigated samples

No. of Sample	d, m	$\beta = \frac{d_0^2}{d^2}$	Recrystallization Annealing		Aging		Phase composition according to x-ray analysis			T_c, °K
			t, °C	τ, hours	t, °C	τ, hours	β-phase	ω-phase	α-phase	
6a	0.270	880	800	1	—	—	+	—	—	6.14
6x	0,265	920	800	1	390	0.25				
6y	0.265	920	800	1	390	0.5				
2c	0.275	19	800	1	390	1	+	+	—	
*3*x*	0.240	70	800	1	390	1				
4c	0.230	170	800	1	390	1				6,59
5x	0.235	650	800	1	390	1.25				
6z	0.265	920	800	1	390	1.5				
2d	0.275	19	800	1	390	3	+	+	—	
4d	0,240	160	800	1	390	3				
4f	0,240	160	800	1	390	10	+	+	—	7,56
6b	0,260	950	800	1	425	1				
6c	0,260	950	800	1	425	3				
6d	0.260	950	800	1	425	10				
1	0.490	6.0	—	—	—	—				
2	0.305	15	—	—	—	—				
3	0.235	72	—	—	—	—				
*3 **	0.220	83	—	—	—	—				
4	0.240	160	—	—	—	—				6.96
9	0.485	270	—	—	—	—				
5	0.235	650	—	—	—	—	+	—	+	
7	0,145	3000	—	—	—	—				
8	0,110	5300	—	—	—	—				
1a	0,480	6.3	—	—	425	1	+	—	+	
2a	0.305	15	—	—	425	1	+	—	+	
3a	0.240	69	—	—	425	1				
4a	0.245	150	—	—	425	1				
9a	0.485	270	—	—	425	1	+	—	+	
5a	0.240	830	—	—	425	1	+	—	+	
7a	0.145	3000	—	—	425	1				
8a	0,110	5300	—	—	425	1				
5b	0,240	630	—	—	425	3	+	—	+	
9b	0.490	260	—	—	425	3	+	—	+	
5c	0.240	630	—	—	425	10	+	—	+	8.30
9c	0.485	270	—	—	425	10	+	—	+	
9d	0,480	280	—	—	390	1	+	—	+	
9e	0.480	280	—	—	390	3	+	—	+	
9f	0.490	270	—	—	390	10	+	—	+	8.61

Note: d is the final diameter of the sample; d_0 is the diameter of the blank at the stage of the intermediate recrystallization; $\beta = d_0^2/d^2$ – reduction of the cross section. An asterisk marks samples which differ only in their diameter.

in a small stirred dewar with the aid of a carbon thermometer.

2. SAMPLES

The samples were in the form of wires 0.1–0.5 mm in diameter and were prepared as follows. The original ingot was melted in an arc furnace in an atmosphere of pure argon. The charge we used was titanium iodide and niobium melted in an electron-beam furnace. After repeated remelting with stirring, 40-g charges were cast into rods of 12 mm diameter, and were turned to a diameter of 8 mm. The following three series of samples were prepared from the obtained rods:

1) Recrystallized samples containing a highly dispersed phase. The rods were rolled and drawn into a wire which at its final diameter was recrystallized in a vacuum of $\sim 5 \times 10^{-6}$ mm Hg at 800°C. The recrystallization was carried out in a stainless steel ampoule with continuous pumping. The oil vapor was frozen out with liquid nitrogen. After being kept at 800 ± 5°C for an hour, the ampoule was taken out of the furnace and immersed in cold water. The samples were then aged at 390 and 425°C; in the course of the aging the ω phase precipitated from the β solid solution.

2) Cold-deformed samples. In order to obtain samples with different degrees of cold deformation, the rods which were turned to a diameter of 8 mm were rolled to various diameters (6, 3, 2, and 1.2 mm) and recrystallized by the method described above at 800°C for 1.5 hours; then when cold they were again rolled and drawn into wires. The largest degrees of deformation were obtained when an 8-mm rod was fabricated into wire with a diameter of 0.25, 0.14, and 0.1 mm. The smallest degrees of deformation were obtained when recrystallized rods with a diameter of 1.2 mm were drawn to diameters of 0.5 and 0.3 mm.

3) Cold-deformed samples subjected to thermal treatment and containing precipitates of the α phase. The samples of this series were deformed in the same manner as those described in 2), and were then tempered at 390 and 425°C.

Information on the mode of preparation of the samples is provided in the table.

3. THE RESULTS AND THEIR RELATION TO THE STRUCTURAL STATE OF THE ALLOY

1. Recrystallized Samples Containing the ω Phase

The results of measurements of $j_c(H)$ of samples 6a, 6x, 6y, 6c, 6z, 4d, and 4f recrystallized and subsequently aged for various periods of time at 390°C are shown in Fig. 1.

The $j_c(H)$ curves of the first three samples with aging times of 0, 15, and 30 minutes practically coincide.

In the case of samples 2c and 6z (aged for 60 and 90 minutes) a maximum appears on the $j_c(H)$ curve. For longer aging (4d—3 hours and 4f—10 hours) the maximum is no longer observed and j_c and H_{c2}[1] increase appreciably.

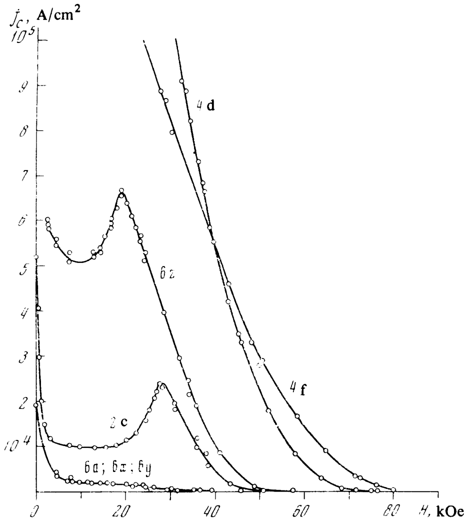

FIG. 1. The $j_c(H)$ dependence for recrystallized samples subjected to subsequent aging for various lengths of time at 390°C. T = 4.2°K, and $j \perp H$.

The obtained results can be explained as follows. For short aging times (0–30 min) the coherent particles of the ω phase produced in the matrix differ little from the matrix in composition and the linear dimensions of the particles are about 50 Å.[5] For very short tempering, the composition of the matrix and its H_{c2} and T_c almost do not differ from the corresponding values in the recrystallized state.

At the same time the dimension of a pair $\xi(T) \approx (\varphi_0/\pi H_{c2})^{1/2} \approx 125$ Å which is greater than the dimensions of a ω particle of ~50 Å (φ_0 is the quantum of magnetic flux). For $\xi(T) > d$ the fluxoids are not stabilized by ω particles and the critical currents are small. In addition, owing to the diffusion of superconducting pairs from the matrix into the ω particles (the "proximity effect"), the superconducting properties of the matrix and of the inclusions are averaged and become similar.

In the case of longer aging the ω particles become larger; thus, for example, after aging for 48 hours at 400° C the ω ellipsoids have axes of 560 and 90 Å, and the distance between them amounts to 5×10^{-6} cm.[11]

As a result of the gradual enrichment of the ω particles with titanium, H_{c2} and the critical temperature of the inclusions T_c decrease on increasing the duration of the aging. The appearance of a peak on the $j_c(H)$ curve of sample 2c (1-hour aging) is connected with the transition of the ω particles in a field H ~ 30 kOe into the normal state and with a sharp increase in their ability to stabilize the transport current.[2] On increasing the aging time to 1.5 hours (sample 6z) the dimensions of the ω ellipsoids increase even further and separating from the matrix continue to be enriched with titanium. This is accompanied by a further decrease of H_{c2} of the ω particles and the maximum on the $j_c(H)$ curve shifts towards lower values of the external field. Further increase of the aging time (3 and 10 hours) leads to an appreciable growth of the ω particles and to their enrichment with titanium; the values of H_{c2} and T_c of the matrix which depend sharply on its composition increase appreciably; the peak effect disappears, since for T = 4.2° K the ω particles are in the normal state for practically all values of the external magnetic field exceeding H_{c1}.

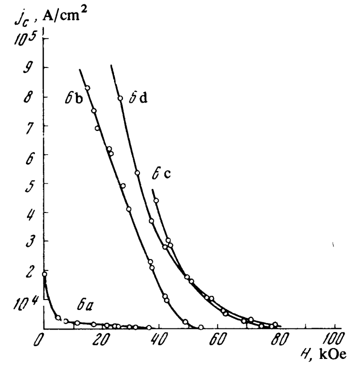

FIG. 2. The $j_c(H)$ dependence for recrystallized samples subjected to subsequent aging for various lengths of time at 425°C. T = 4.2°K, and $j \perp H$.

It should be noted that a similar "peak effect" can be observed in the case of other metastable solid solutions. Thus, the "anomalous" maximum on the $j_c(H)$ curve in the alloy Zr-25% Nb in [13] was observed at T = 1.6° K but was absent at T = 4.2° K. In that work the samples were annealed for 1 hour at 500° C; this led to the precipitation of the finely dispersed α phase containing ~1% niobium. From the curves presented in [13] it follows that the T_c of the inclusions is somewhat below 4.2° K; therefore the "peak effect" corresponding to a transition of the α particles to the normal state only appears at lower temperatures.

Figure 2 shows the $j_c(H)$ dependences for samples which underwent aging at 425° C after recrystallization. Aging at this temperature leads to a more rapid precipitation of particles in the ω phase than aging at 390° C.

The absence of the "peak effect" at 4.2° K is due to two reasons: the low values of T_c of the large particles of the ω phase, and the fact that the proximity effect induces a superconducting state in the ω particles only at a distance $\xi(T)$ from a boundary with the matrix;[3] therefore, for $\xi(T) < d$, $H \gtrsim H_{c1}$ and T = 4.2° K the ω particles are in the normal state. However, it is

---

[1] H_{c2} was approximately taken to be the value of the external magnetic field for which $j_c = 10^2$ A/cm².

[2] The explanation of the peak effect by a transition of the stabilizing centers to the normal state was first proposed by Livingston [12] who investigated lead-indium alloy which contained dispersed tin particles.

[3] Diffusion through distances $\xi(T)$ takes place in "dirty" alloys in which the mean free path $l \gg \xi_0 = 0.18\hbar v_F/k_B T_c$. [14]

not excluded that at lower temperatures they will go over to the superconducting state and a maximum will appear on the $j_c(H)$ curves.

From Figs. 1 and 2 it is seen that a considerable increase of the tempering time is accompanied not only by an increase of H_{c2} and T_c of the matrix, but also by a certain decrease of j_c which leads to the intersection of the corresponding $j_c(H)$ curves (samples 4d and 4f on Fig. 1 and 6c and 6d on Fig. 2). This effect can be explained by the circumstance that the large precipitates of the ω phase which are in the normal state decrease the effective cross section of the sample and also decrease the concentration of superconducting current carriers as a result of the partial suppression of the superconducting properties of the matrix by normal inclusions by virtue of the proximity effect.

2. Cold Deformed Samples

Figure 3 shows the results of measurements of $j_c(H)$ of samples subjected to various degrees of cold deformation. A clearly expressed kink characteristic[15] of the dislocation mechanism of stabilization of j_c (the curve of sample 2) is only observed for small degrees of cold deformation (reduction of the cross section β = 6–83). In the case of strongly deformed samples (samples 5, 7, and 8) the kink disappears. It should be noted that the critical current depends weakly on the degree of deformation.

The obtained results can be understood if one takes into account the fact that the Ti-22% Nb alloy is on the stability boundary: arbitrary activating factors, heating or cold deformation, facilitate the dissociation of the metastable β solid solution. In fact, according to the x-ray data (see sample 5 in the table) one observes in the table) one observes in the alloy for strong cold deformation the presence of precipitates of the α phase which changes the dominating mechanism of stabilization of the critical current by dislocation aggregates and facilitates an increase of j_c. A comparison of the curves presented in Figs. 2 and 3 shows that in its efficiency in affecting the critical current a high degree of cold deformation is equivalent to the aging of recrystallized alloy for one hour at 425°C.

3. Samples with α-Phase Precipitates in the Deformed Matrix

In order to clarify the combined action of cold deformation and aging, we carried out three series of measurements, the results of which are presented in Figs. 4–6.

In the first series (Fig. 4) the conditions of aging were unchanged, whereas the degree of cold deformation preceding the aging was varied within a wide range. From a comparison of Figs. 2, 3, and 4 it follows that because of the precipitation of the second phase (see the table) and the enrichment of the matrix with niobium under the combined action of two dissociation stimulators of the β solid solution—cold deformation and aging for one hour at 425°C—H_{c2} reaches the same value (about 85 kOe) as in the case of aging only in the course of 3–10 hours at 425°C without previous deformation, increasing by about 25 kOe compared with H_{c2} of cold-drawn samples. At the same time it is seen that the presence of dislocations facilitates an enhancement of the stabilization of fluxoids and consequently an increase of the critical current; however, the degree of the previous cold deformation affects $j_c(H)$ weakly.

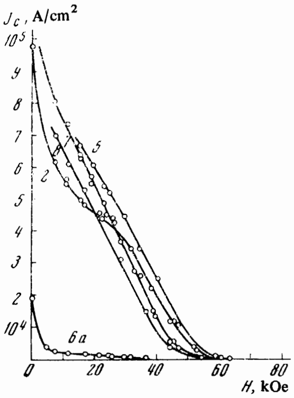

FIG. 4

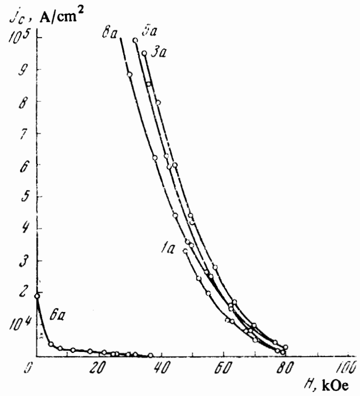

FIG. 3

FIG. 3. The $j_c(H)$ dependence for cold-deformed samples. T = 4.2°K, and j ⊥ H.

FIG. 4. The $j_c(H)$ dependence for cold-deformed samples subjected to subsequent aging for 1 hour at 425°C. T = 4.2°K, and j ⊥ H.

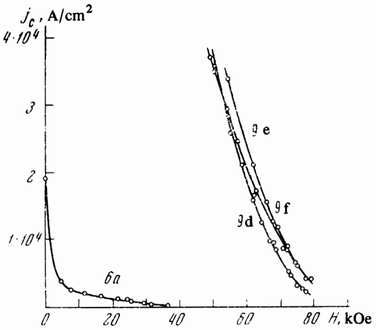

FIG. 5. The $j_c(H)$ dependence for cold-deformed samples subjected to subsequent aging for various lengths of time at 390°C. T = 4.2°K, and j ⊥ H.

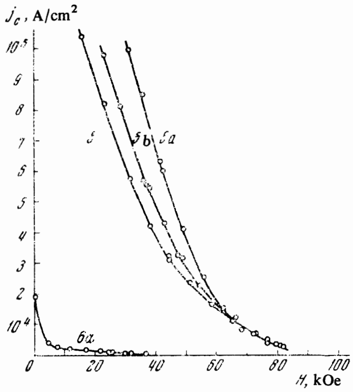

FIG. 6. The $j_c(H)$ dependence for cold-deformed samples subjected to subsequent aging for various lengths of time at 425°C. T = 4.2°K, and j ⊥ H.

The second and third series of measurements (Figs. 5 and 6) were carried out with a fixed degree of cold deformation (β = const) and under various conditions of aging. It turned out that aging for 3 hours at 390°C (sample 9e) stabilizes the current most effectively. An increase of the time of tempering at 390°C up to 10 hours (sample 9f), just as tempering for 1–10 hours at 425°C (samples 5a, 5b, and 5c on Fig. 6) leads to aging and to a corresponding decrease of the critical current. The decrease of the critical current is connected with the increase in the number and size of particles of the α phase which is normal at 4.2°K; these act as reservoirs pumping from the matrix superconducting pairs—the carriers of the transport current—and annihilate them.

The enrichment of the matrix with niobium and the accompanying increase of H_{c2} is the stronger the larger the number of ω and α-phase precipitates.

4) The $j_c(H, T)$ Dependence in Samples Having a Maximum on the $j_c(H)$ Curve

The $j_c(H, T)$ dependence was measured for samples 5x and 3*x (see the table). The results obtained for sample 5x are shown in Fig. 7. It has been established that when the temperature is decreased, the critical fields H_{c2} of the matrix and of the inclusions increase. However, H_{c2} of the ω particles for $T \to T_c$ decreases more slowly, a fact which is clearly seen on Fig. 7.

This fact can be explained as follows. For $T \to T_c$ the dimension of a pair is

$$\xi(T) = 0.85\left(\frac{\xi_0 l T_c}{T_c - T}\right)^{1/2}, \qquad \text{A}$$

where l is the mean free path.[14] Because of the increase of $\xi(T)$ on approaching T_c the magnitude of ξ exceeds at some temperature the dimension of the inclusions and, because of the effective diffusion of the superconducting pairs from the matrix into the ω particles, the properties of the matrix and of the inclusions become alike. The strong increase of j_c with decreasing temperature will be explained below.

4. PHYSICAL MODEL

The course of the $j_c(H)$ dependence obtained in this work does not fit into the framework of existing theories of critical currents in "hard" superconductors[2,15] which require either the presence of a plateau on the $j_c(H)$ curve or a law of the form

$$j_c(H + B_0) = \alpha(T),$$

where B_0 and α are constants.

We assume that the presence of finely dispersed precipitates of the nonsuperconducting phase with dimensions $d \gtrsim \xi(T)$ and a concentration $N \sim (H_{\ 2}/\varphi_0)^{3/2}$ leads to rigid fixing of the vortex lattice. Under these conditions the cause of the destruction of the superconductivity by a current can be the fact that the superconducting condensate reaches a critical velocity.

As is well known,[1] in the absence of transport current the free energy difference between the normal and superconducting states is

$$H_c^2/8\pi = -\int_0^{H_{c2}} M(H)\,dH. \qquad (1)$$

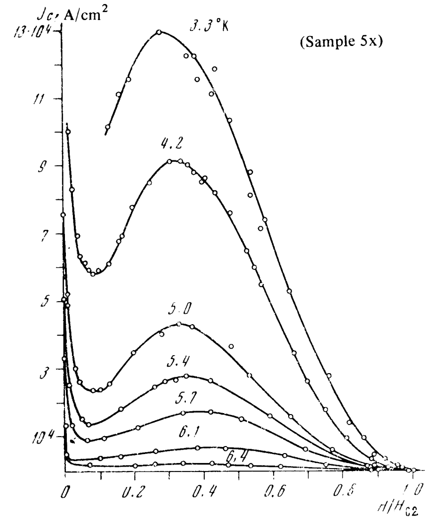

FIG. 7. The $j_c(H/H_{c2})$ dependence for sample 5x in the temperature range 3.3–6.4°K; H_{c2} is the critical field of the matrix.

Let us place the sample in a field $H = H_0$. Then a part of the energy reserve, equal to $-\int_0^{H_0} M(H)dH$, will be exhausted and the remaining part, equal to $\int_{H_0}^{H_{c2}} M(H)dH$ can be realized by switching on an electric field and accelerating the superconducting condensate up to the critical velocity:[16]

$$-\int_H^{H_{c2}} M(H)\,dH = \frac{1}{V}\int_V \frac{1}{2}\rho_s v_{sc}^2\,d\tau, \qquad (2)$$

where ρ_s = nm is the density of the condensate, v_{sc} is its critical velocity, n is the concentration of superconducting electrons, and m is the electron mass.

Extrapolating the course of the magnetization M in the region $H \gg H_{c1}$ by a straight line and using the expression obtained by Abrikosov[1]

$$-4\pi M = \frac{H_{c2} - H}{1.18(2\kappa^2 - 1)}, \qquad (3)$$

where κ is the parameter of the Ginzburg–Landau theory (in our case $\kappa \gg 1$); for $j = j_c$ we have

$$nmv_{sc}^{*2} \approx \frac{H_c^2}{4\pi}\left(1 - \frac{H}{H_{c2}}\right)^2, \qquad (4)$$

where v_{sc}^* is the effective critical velocity of the condensate, and $H_c = H_{c2}/\kappa\sqrt{2}$ is the thermodynamic critical field.

Let us define the critical current density in the form

$$j_c = env_{sc}^*/c. \qquad (5)$$

In order to find the concentration of superconducting electrons n averaged over the volume of the sample, we make use of the fact that

$$B = \nu\varphi_0,$$

where ν is the concentration of fluxoids; their cores which are in the normal state occupy a fraction of the volume

$$\frac{V_N}{V} = \frac{B}{\varphi_0}\pi\xi^2 = \frac{B}{H_{c2}}$$

Then, since for $H \gg H_{c1}$ the constant $B \approx H$, one can write

$$n = n_s \frac{V_s}{V} = n_s\left(1 - \frac{H}{H_{c2}}\right), \qquad (6)$$

where n_s is the concentration of superconducting electrons in the superconducting part of the volume. Taking into account the fact that according to de Gennes[14] in a magnetic field

$$n_s = n_{s0}(1 - H / H_{c2}), \qquad (7)$$

where n_{s0} is the concentration n_s in the absence of the field, we have,

$$n = n_{s0}(1 - H / H_{c2})^2 \qquad (8)$$

Substituting in (5) the values of n and v_{sc}^* obtained from (4) and (8), we finally obtain

$$j_c = \frac{H_c}{4\pi\lambda}\left(1 - \frac{H}{H_{c2}}\right)^2 \quad (H \gg H_{c1}), \qquad (9)$$

where

$$\lambda = \sqrt{mc^2 / 4\pi n_{s0} e^2} \qquad (10)$$

is the London penetration depth.

As has already been said, the presence of normal metal bordering on the superconductor leads in "dirty" alloys to the diffusion of superconducting pairs into the normal regions and to their decay at distances $\xi(T)$. As a result of this the magnitude of the order parameter in the superconductor, and consequently also the concentration of pairs in the superconductor decreases considerably at a distance $\xi(T)$ from the boundary into the superconductor.[17] Therefore in our case n_{s0} (and that means also λ) is an effective parameter which depends on the dimensions of the normal inclusions in the superconducting matrix and on the distance between them, and which changes from sample to sample. Clearly, when $\xi(T)$ is considerably larger than the dimensions of the inclusions d, then the superconducting properties of the inclusions and of the matrix are identical. In the other limiting case when $\xi(T) \ll d$ one can neglect the contribution from the proximity effect if the distances between the inclusions a are large compared with $\xi(T)$. If, on the other hand, $a \lesssim \xi(T) \ll d$, then the inclusions can suppress the superconductivity of the matrix.

A comparison of formula (9) with our experimental results is given in Fig. 8. For comparison we have taken one representative from the subgroup of samples with various types of thermomechanical treatment. The experimental data were related to the theoretical curve by choosing the parameter H_c/λ at the point $H/H_{c2} = 0.5$. It is seen that the experimental points are close to the calculated curve. It also follows from (9), in agreement with our experimental data, that the critical current j_c should decrease strongly with increasing temperature (H_c decreases as the square of the temperature).

In conclusion the authors thank B. M. Vul for constant interest in the work, V. V. Shmidt, V. P. Galaiko, I. O. Kulik, and A. I. Rusinov for useful discussions, and N. G. Vasil'ev, I. A. Baranov, R. S. Shmulevich, I. P. Radchenko, G. M. Kryukova, and G. T. Nikitina for help with the work.

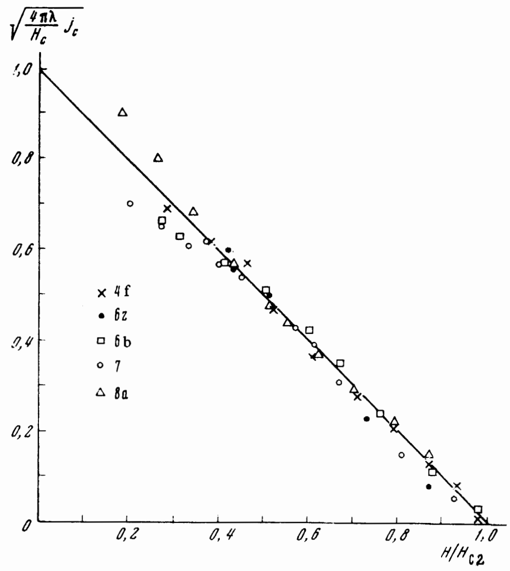

FIG. 8. The $j_c(H)$ dependence in a type-II superconductor with a rigidly fixed lattice of Abrikosov vortices. A comparison of the experimental data with the calculated curve [formula (9)].

---

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

[2] P. W. Anderson, Phys. Rev. Letters **9**, 309 (1962).

[3] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. **139**, A1163 (1965).

[4] J. D. Livingston and H. W. Shandler, Progr. Mat. Sci. **12**, 183 (1964).

[5] W. G. Brammer and C. G. Rhodes, Phil. Mag. **16**, 477 (1967).

[6] J. Sutton and C. Baker, Phys. Letters **21**, 601 (1966).

[7] M. I. Bychkova, V. V. Baron, and E. M. Savitskiĭ, Metallovedenie. Fiziko-khimiya i metallofizika sverkhprovodnikov (Metallography. Physical Chemistry and Metal Physics of Superconductors), Nauka, 1967, p. 48.

[8] A. D. McInturff, G. G. Chase, C. N. Whetstone, R. W. Boom, H. Brechna, and W. Haldemann, J. Appl. Phys. **38**, 524 (1967).

[9] Yu. F. Bychkov, V. G. Vereshchagin, V. R. Karasik, G. B. Kurganov, and V. A. Mal'tsev, FIAN SSSR Preprint No. 112, 1968.

[10] V. R. Karasik, Fizika i tekhnika sil'nykh magnitnykh poleĭ (The Physics and Technology of Strong Magnetic Fields), Nauka, 1964.

[11] D. Kramer and C. G. Rhodes, Trans. Metall. Soc. AIME **236**, 1612 (1967).

[12] J. D. Livingston and T. H. Alden, Trudy X Mezhdunarodnoĭ konferentsii po fizike nizkikh temperatur (Proc. Tenth International Conference on Low-Temperature Physics) **2B**, VINITI, 1967, p. 20.

[13] I. N. Goncharov, I. S. Khukhoreva, M. Litomiskiĭ, and I. Ruzhichka, Trudy X Mezhdunarodnoĭ po fizike nizkikh temperatur (Proc. Tenth International Conference on Low-Temperature Physics) 2B, VINITI, 1967, p. 70.

[14] P. G. de Gennes, Superconductivity of Metals and Alloys, New York, 1966, Russ. Transl. Mir, 1968.

[15] V. V. Shmidt, Zh. Eksp. Teor. Fiz. **45**, 1992 (1963) [Sov. Phys.-JETP **18**, 1368 (1964)].

[16] J. Bardeen, Rev. Modern Phys. **34**, 667 (1962).

[17] P. G. de Gennes, Rev. Modern Phys. **36**, 225 (1964).

Translated by Z. Barnea
64