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INSTABILITIES ARISING IN A FORCE-FREE CURRENT FLOW IN THE SUPERCONDUCTING ALLOY Ti - 22 at.% Nb

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In investigations of the critical currents of wire made of the alloy Ti - 22 at.% Nb, we observed an interesting phenomenon - a sharp dip on the plot of the critical current against the external magnetic field parallel to the wire axis.

Typical results are shown in Fig. 1a. We see that when I is parallel to H_0 the current first increases, then decreases by a factor of 1.5 and $H_0 \approx 2$ kOe, goes through a minimum, after which it doubles at $H_0 \approx 5$ kOe.

At $H_0 > 10$ kOe, the experimental data are described with good accuracy by the expression

$$j_k(H_0) = j_0 \exp(-H_0/H_{cr}). \quad (1)$$

Here $j_c = I_c/\pi R^2$, where R is the wire radius, H_{cr} and j_0 are parameters that depend on the structure of the sample (on the dimensions and concentration of the ω-phase particles) [1].

For comparison, Fig. 1a shows the dependence of j_c on the magnetic field directed perpendicular to the sample axis. The $j_{c\perp}$ curve has no dip.

The behavior of the critical current in the region of the dip is characterized by two singularities: a) the value of j_c at the first destruction of the superconductivity is always higher than at the second and all the succeeding ones; b) the value of j_c stabilizes and becomes reproducible only after the first two or three transitions of the sample to the normal state.

Figure 1 shows the steady state values of j_c. In Fig. 1b, where the temperature dependence of $j_c(H)$ is demonstrated, are shown additionally points obtained at 4.2°K following the first transition of the sample into the normal state.

The dip on the $j_{c\parallel}$ curves is observed for samples subjected to aging after prior recrystallization. In such samples, the ω particles destroyed upon decay of the solid solution, which stabilize the Abrikosov vortex lattice, have a uniform and isotropic distribution.

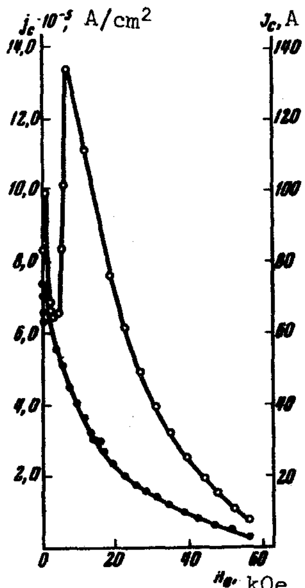

Fig. 1a

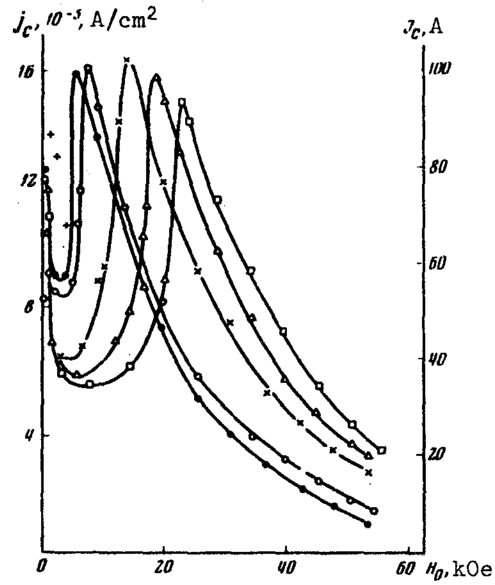

Fig. 1b

Fig. 1a. Sample No. 1. Critical current vs. intensity of external magnetic field: $T = 4.2°K$, $R = 55.5\ \mu$. Treatment: recrystallization at $t = 800°C$ for 1 hour, aging at $t = 425°C$ for 3 hours; o – $I \parallel H_0$, • – $I \perp H_0$, $j_c = I_c/\pi R^2$.

Fig. 1b. Sample No. 2. Critical current vs. external magnetic field intensity: + – 4.2°K (first transition of sample to normal state), • – 4.2°K (second and subsequent transitions), o – 4.0°K, × – 2.99°K, Δ – 2.29°K, □ – 1.71°K, $R = 44.5\ \mu$, $j_c = I_c/\pi R^2$. Treatment: recrystallization at $t = 800°C$ for one hour and aging at $t = 425°C$ for 3 hours.

In samples subjected to aging after cold deformation, the defects are anisotropically distributed, for a texture oriented in the drawing direction is produced when the wire is rolled. The anisotropic distribution of the vortex pinning centers suppresses the instability of the critical current, and the dip vanishes (Fig. 2). To explain the results, we use an idea by Bergeron, who proposed that in superconducting alloys force-free current configurations are realized in the case when $I \parallel H_0$ [2].

We assume that the sample is in the critical state [3] and solve the problem of force-free current flow in a ribbon of thickness 2d[1].

Taking (1) into account, we get

$$\mathrm{rot}\,\mathbf{H} = \alpha \mathbf{H}, \qquad \alpha = \frac{4\pi}{c} j_0 \frac{\exp(-H/H_{cr})}{H}, \tag{2}$$

where H is the total field.

Let the coordinate z vary from -d to d, and let the external field H_0 and the current I be directed along the y axis. Then

[1]It follows from the sequel that the solution of the planer problem has an amazingly simple form and explains our experimental results. In the case of a cylinder, on the other hand, it is necessary to solve a nonlinear differential equation by means of a computer.

$$-\frac{dH_y}{dz} = \alpha H_x, \qquad H_y = H\cos\alpha z,$$

$$\frac{dH_y}{dz} = \alpha H_y, \qquad H_x = H\sin\alpha z. \tag{3}$$

In the solution (3), the integration constant is chosen equal to zero. From (2) and (3) it follows that $H_x^2 + H_y^2 = H^2 = \text{const}$; $\alpha = \text{const}$ (at a given H).

The boundary condition at $z = \pm d$ yields

$$H_0 = H\cos\alpha d. \tag{4}$$

The total current is

$$I = \alpha\int_{-d}^{+d} H dz = 2H_I \tag{5}$$

Equations (4) and (5) constitute the complete solution of the problem.

When $H_0 >> H_{cr}$ we get

$$I_k = 2di_0\frac{4\pi}{c}\exp\left(-H_0/H_{cr}\right). \tag{6}$$

In a zero external field, the critical current is determined from the condition $\cos\alpha d = 0$, or

$$\frac{\pi}{2}(2n+1) = \frac{4\pi}{c}i_0 d\frac{\exp\left(-H_I/H_{cr}\right)}{H_I}; \qquad n = 0, 1, 2, \ldots \tag{7}$$

When $H_0 = H^*$, the total current vanishes. H^* is determined from the equation

$$\frac{4\pi}{c}i_0 d\frac{\exp\left(-H^*/H_{cr}\right)}{H^*} = \pi n. \tag{8}$$

For $n = 0$, the field is $H^* = \infty$. H^* is finite when $n \neq 0$. Therefore solutions with $n = 1, 2, 3, \ldots$ exist in the field interval $0 < H_0 < H^*$.

The results of a graphic solution of Eq. (4) are shown in Fig. 3, where the ordinates represent the magnetic field of the current, H_I, and the abscissas the external magnetic field H_0. The upper curve corresponds to $n = 0$, the middle one to $n = 1$, and the lower one to $n = 2$.

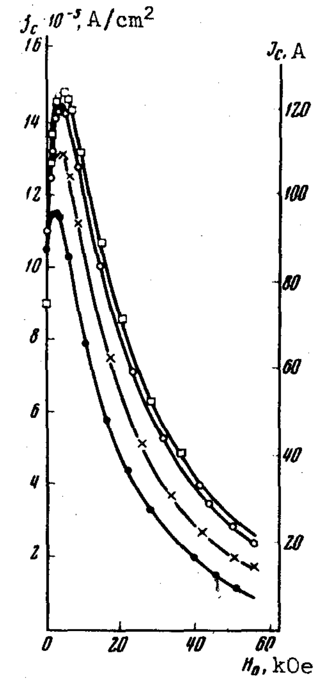

Fig. 2. Sample No. 3. Dependence of the critical current on the external magnetic field: $I \parallel H_0$, $R = 51.5\ \mu$, ● – 4.2°K, × – 3.22°K, o – 2.06°K, □ – 1.27°K. Treatment: cold deformation and subsequent aging at t = 4.25°C for one hour.

Each value of n corresponds to a different force-free configuration.

It can be assumed that the current instability observed in our experiments is connected with a transition from a current with $n = 0$ to one with $n \neq 0$. When $H_0 > H^*$, the initial configuration is restored.

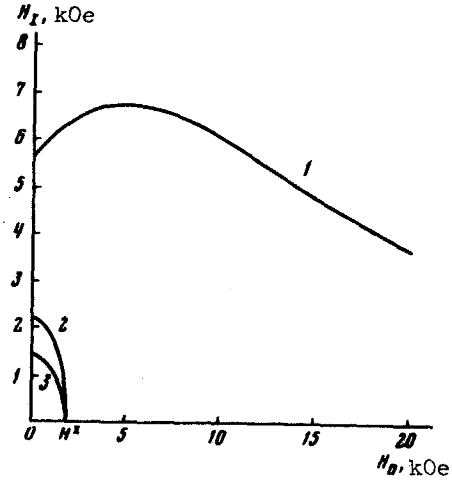

Fig. 3. Calculated curves of the magnetic field due to the current, H_I, as a function of the external magnetic field H_0: d = = 45 μ, j_0 = 2.2 × 10^6 A/cm^2, H_{cr} = 17.62 kOe; 1 - n = 0, 2 - n = 1, 3 - n = 2.

In the presence of anisotropic defects, the realignment is hindered and there is no dip on the $j_{c_\parallel}(H_0)$ curve (see Fig. 2).

We note that substitution in formula (4) of the values of j_0, H_{cr}, and d = R taken from the experimental curves (R - wire radius) leads to good agreement between the calculated and experimental curves.

In conclusion, let us calculate the magnetization connected with the current.

The magnetic moment is directed along H_0 and I, and its value (per unit volume) is

$$M = \frac{1}{4\pi}(H_y - H_0) = \frac{1}{4\pi}\left(\frac{H}{ad}\sin ad - H_0\right). \qquad (9)$$

When $H_0 \to \infty$

$$M \sim I \sim \exp(-H_0 / H_{cr}).$$

When $H_0 = 0$

$$M = \frac{1}{4\pi}\left(\frac{I_0 \sin a_0 d}{a_0 d}\right). \qquad (10)$$

But $a_0 d = \pi(2n + 1)/2$, therefore

$$M_0 = \frac{1}{4\pi}\,\frac{2I_0}{\pi(2n + 1)}; \quad n = 0, 1, 2, \ldots \qquad (11)$$

For the branches with $n \neq 0$, the magnetic moment vanishes when $H = H^*$.

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DEVIATION FROM THE FRANCK-CONDON PRINCIPLE UPON POPULATION OF THE VIBRATIONAL LEVELS OF THE $A^2\pi$ STATE OF CO^+ IONS PRODUCED BY COLLISIONS OF ELECTRONS WITH CO MOLECULES

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Recent publications [1, 2] have reported observation of deviations from the Franck-Condon principle in the population of the vibrational levels of the excited $A^2\pi$ state of the CO^+ ion, produced in collisions between slow ions and