FEATURES OF THE BEHAVIOR OF THE CRITICAL CURRENT OF WIRES OF SUPERCONDUCTING NIOBIUM-BASED ALLOYS AS A FUNCTION OF MAGNETIC FIELD AND TEMPERATURE

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Abstract

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FEATURES OF THE BEHAVIOR OF THE CRITICAL CURRENT OF WIRES OF SUPERCONDUCTING NIOBIUM-BASED ALLOYS AS A FUNCTION OF MAGNETIC FIELD AND TEMPERATURE

The most important characteristic of the quality of a superconducting wire, ensuring the greatest magnetic field of a solenoid, is the magnitude of the critical current I_k and the retention of its large value up to high magnetic fields. It is also important that, when it is necessary for a solenoid to operate at temperatures below 4.2° K, the critical current of the solenoid should, at least, not decrease.

At the same time, both from fragmentary literature data for niobium-based alloys ([1,2]); ([3]), pp. 29–35), and from our data, completely different dependences, in character, have been found for I_k of wire in the form of a specimen and of solenoids on temperature and field. Thus, for example, instead of the monotonic decrease of I_k of wire specimens with increasing field, which had already seemed customary, in a number of cases a deep minimum is observed in the course of this decrease (and correspondingly, further on, a maximum). In solenoids made from the same wire no minimum is observed; instead, over a large interval their I_k is independent of the field.

In some solenoids made from, it would seem, identical wire, a decrease of I_k was observed when the temperature was lowered below 4.2° K, and a maximum of the current above this temperature ([4]); ([3]), pp. 229–237). In our investigations it was also found that, in some solenoids, when the temperature was lowered below 4.2° K, I_k increased, while in others it decreased; moreover, the magnitude of this change reached tens of percent. There were no more or less substantiated explanations of the observed effects; moreover, they were regarded as anomalous.

In the present communication we give the results of investigations which, without claiming completeness, essentially explain the nonmonotonic course of I_k of wire specimens with field, the features of I_k of this wire in the form of solenoids, and the temperature dependence of I_k of solenoids.

Series of binary (Nb—Ti) and ternary (Nb—Zr—Ti) alloys were investigated, belonging to the deformable type, in which strong plastic deformation by draw-

Fig. 1

Figure 1: Fig. 1

ing and heat treatment produce an extremely developed spatial network of precipitates of one of the equilibrium phases. This network serves as current channeling and ensures very high current densities ([5])*. The wire was studied in the copper-plated, heat-treated state and in the enamel-insulated state**. The diameter of the wire with copper coating was ~ 0.31 mm, and the diameter of the wire itself was ~ 0.25 mm.

The dependence of I_k on magnetic field was measured at temperatures of 4.2° and 2° K; these dependences were taken for one and the same wire in the form of specimens and in the form of solenoids with fields up to $\sim 90\,000$ oersted ([6]). For the investigations the most homogeneous long pieces of wire were selected.

To bring the test conditions of the specimens closer to the conditions under which the wire operates in a solenoid, the specimens were made in the form of coils consisting of a small number (9—10) of layers with ~ 100 turns per layer. The length of such co-

* These alloys are being developed jointly with Giredmet; wire of the ternary alloy (alloy SG-2: 50 at.% Nb and ~ 25 at.% each Zr and Ti) is currently being produced by the Giredmet Experimental Plant. All the wires studied were made by Giredmet.

** Heat treatment and enameling were carried out at the Physico-Technical Institute of the Academy of Sciences of the Ukrainian SSR.

the sample coils was 30–40 mm, the inner diameter of the turns 4 mm, and the outer diameter of the winding 10 mm. The samples were placed in a superconducting solenoid with a cavity length considerably exceeding the length of the coil. Therefore all the sample coils were in a field whose inhomogeneity was

Fig. 1. Dependence of the critical current on the magnetic field for wire made of alloy CC-2 (A), 60 T, batch I (B) and 60 T, batch II (V). a—samples, $T = 4.2$°K; b—samples, $T = 2$°K; v—large solenoids, $T = 4.2$°K; g—large solenoids, $T = 2$°K

less than 10% over the length of the sample. The solenoid field was transverse to the sample turns.

Figure 1 presents part of the results obtained.

It turned out that the appearance of a minimum of I_k when it changes with the field is not an exception for the samples, but rather the rule. The presence of a plateau in the course of I_k versus field in solenoids becomes understandable. Indeed, in a solenoid with a constant C ($H = CI$) greater than that of the sample coil, the conditions corresponding to the minimum I_k must necessarily be realized, since the turns of the solenoid winding are in different fields—from the maximum H to $H = 0$, including the field corresponding to the current minimum. Increasing the solenoid, its constant, does not remove this condition until the I_k curves of the solenoids intersect the I_k curves of the samples. After this, I_k of the solenoids will decrease along the curve for the samples. Thus, ···

Thus, it is seen that the curve of the dependence of I_k on the field immediately gives the limiting value of the current in solenoids made from this wire—the current value at the minimum.

From Fig. 1A and B it is also seen that, when the temperature is lowered, the minimum and maximum on the curves shift toward higher fields. This is especially clearly seen from Fig. 1B for the dependence of I_k on the field for the alloy Nb—60% Ti. The curves for temperatures 4.2 and 2°K intersect—this leads to the fact that up to $\sim 35\,000$ oersteds the portion of the curve at 2°K lies below the curve taken at 4.2°K, i.e., the critical current decreases here when the temperature is lowered. In fields greater than 35,000 oersteds, the curve at 2°K lies above the curve at 4.2°K, i.e., lowering the temperature leads to an increase in I_k.

In Fig. 1B (also for the alloy Nb—60% Ti, but from another production batch) an intersection of the curves of I_k at different temperatures is likewise seen. However, here at 4.2°K the current minimum is located at fields not measured in the experiment; the minimum field is determined by the self-field of the sample coil and is about 15,000 oersteds; the minimum at 2°K, however, is strongly broadened and practically unnoticeable.

In addition to shifting toward higher fields, as the measurements showed, the minimum of I_k of the samples when the temperature is lowered may either decrease or increase. This also determines the behavior of I_k in solenoids when the temperature changes.

It appears that the phenomenon of the minimum of I_k has a simple explanation. One must bear in mind the well-known circumstance that, up to a certain value of the magnetic field, the latter does not penetrate the alloy at all; at higher fields, on the contrary, the field practically completely penetrates the volume of the sample. Correspondingly, at small fields the superconducting current flows over the surface of the wire; the internal developed network, capable of carrying considerably larger currents, is screened and does not operate. This volume mechanism will switch on in a considerable field. The first mechanism (surface current flow), not differing in principle from that in type-I superconductors, will be suppressed as the field increases (7). As the internal current-carrying mechanism comes into operation (with increasing field), I_k will cease to decrease and, on the contrary, may grow further up to the value provided by the volume current mechanism. With a further increase in the field, this second mechanism will also be suppressed—I_k will pass through a maximum and will decrease.

Lowering the temperature raises the magnetic fields of the process of field penetration into the volume of the superconductor. This leads to a shift toward higher fields of the I_k curves, i.e., of the minimum of I_k.

This explanation corresponds to the found structure of the wire material (5). However, naturally, the detailed picture of the structure has not been studied sufficiently to make it possible to explain all the peculiarities of the course of the curves of the dependence of I_k on the field in the wire when the technology of its manufacture is varied. At the same time, it appears that studying the relation of the I curves to the features of this structure will undoubtedly lead to the most expedient technology for manufacturing the wire.

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Note: Figure translations are in progress. See original paper for figures.