THE CAUSES OF MAGNETIC HYSTERESIS IN Nb-Sn *SUPERCONDUCTING ALLOYS*

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A correlation is found between the characteristics of magnetic hysteresis and the structural peculiarities of Nb-Sn alloys. The structure defects which retard the magnetic flux in the Nb_3Sn compound are determined. Problems relating to capture of the flux and its escape from the sample are discussed.

1. The irreversibility of the magnetization of superconductors, including ideal type-I and type-II superconductors, is explained by the fact that they contain macroscopic doubly-connected superconducting regions in which there occur ring macrocurrents which maintain in the region not occupied by the superconductor the magnetic flux expelled from it until the superconducting state is destroyed.[1] The magnetic hysteresis of hard superconductors to which the Nb-Sn alloys belong is determined in the first place by their structural features and can be qualitatively explained on the basis of well-known model considerations.[2-5]

According to the filamentary structure model[2,3] a hard superconductor contains a large number of intertwined superconducting filaments which have a diameter of the order of the London penetration depth and which have higher critical parameters than the surrounding material. According to this model the magnetic hysteresis is a result of the multiply-connected nature of the filament system along which the superconducting currents flow.

According to the model of magnetic flux creep[4,5] the magnetic properties of a hard superconductor are determined by the interaction of the quantized magnetic flux filaments with various defects of the crystal structure, and the magnetic hysteresis is the result of pinning of the quantized magnetic flux filaments on such defects of the structure through which the passage of flux filaments turns out to be energetically more advantageous than through the main bulk of the superconductor.

From the results of experimental investigations of specific superconducting materials[6-11] it follows that the magnitude of the hysteresis can depend on the concentration of precipitates of the second phase, the dislocation density, the number of intercrystallite boundaries, the dimensions of the cavities, as well as on the number and dimensions of the other structural elements on which pinning of the quantized flux filaments can occur.

In this work we present the results of a study of the magnetic hysteresis of sintered Nb-Sn alloys (close to the Nb_3Sn composition) related to their structural characteristics.

2. The alloys were prepared by sintering a mixture of niobium and tin powders of a given concentration at a temperature of 1050°C during 4 hours in a vacuum of the order of 10^{-2} mm Hg. The samples in the form of cylinders 5 mm in diameter and 40 mm long were cooled down to 4.2°K in a magnetic field H_0 which was then de-

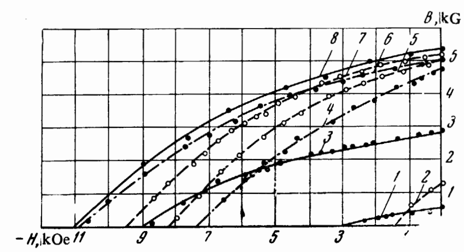

FIG. 1. Sections of the hysteresis curves of Nb-Sn alloys of various concentrations obtained after cooling the samples from room temperature to 4.2°K in a magnetic field H_0: 1–77.5, 2–84.2, 3–77.5, 4–81.9, 5–74.9, 6–75.6, 7–79.8, 8–77.5 at. % Nb in the Nb_3Sn. Curve 1–H_0 = 0, magnetization up to H = 7.5 kOe, 2–H_0 = 6 kOe, 3–H_0 = 3 kOe, 4–8–H_0 = 6 kOe.

creased to zero, and the magnetization $4\pi I$ was measured as a function of the field H directed opposite to H_0. The measurements were carried out with the aid of a ballistic setup by discharging a compensated measuring coil from the sample. On repeating the measurements (after heating the samples to room temperature) the obtained results were fully reproduced. They also remained unchanged after the length of all the samples was decreased to 30 mm, indicating the absence of any demagnetizing effect of the ends of the sample on the measured values of the magnetization. As has already been noted,[12] approximately the same hysteresis properties were obtained for our sample and for a sample of the same stoichiometric composition investigated by other authors,[13] regardless of certain differences in the conditions under which the samples were prepared.

From the results of the magnetic measurements we plotted magnetic induction curves B(H) (Fig. 1) and from these we determined three basic hysteresis characteristics[1)]: the residual induction B_r characterizing the value of the residual moment or of the frozen-in magnetic field, the coercive force H_c characterizing the external magnetic field for which the average field B in the sample vanishes, and the maximum magnetic energy $(BH)_{max}$ stored in the sample.

As a result of studies carried out (in conjunction with

[1)] We use here the same nomenclature and notation as are used in considering the magnetic hysteresis of ferromagnets. This nomenclature has so far not been adopted for superconductors, but hardly require any change, since the characteristics of the hysteresis of superconductors and ferromagnets have the same physical meaning, regardless of the differing nature of these materials.

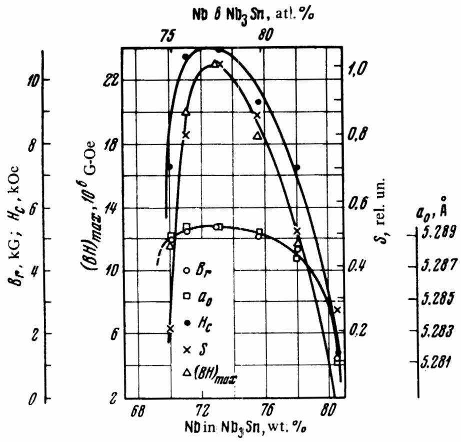

FIG. 2. The dependence of the residual magnetic induction B_r, the coercive force H_c, the maximum magnetic energy $(BH)_{max}$, the lattice parameter a_0, and the relative area of the intercrystallite boundaries S on the niobium content in the Nb_3Sn (H_0 = 6 kOe).

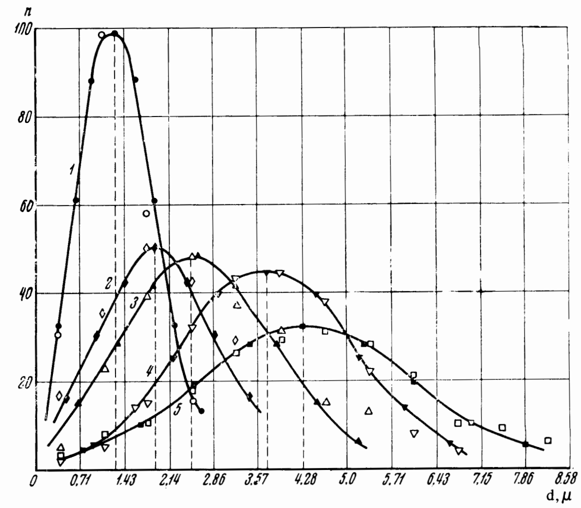

FIG. 3. Curves of the size distribution of the Nb_3Sn grains (220 determinations) in alloys of various concentrations: 1—77.5, 2—75.6, 3—81.9, 4—84.2, 5—74.9 at. % niobium in the Nb_3Sn; light points—experimental, dark points—normal (Gaussian) distribution. For the sample with 79.8 at. % niobium the distrubution curve is close to curve 3 and is not presented in order to simplify the diagram.

G.I. Zaĭkina) by x-ray, metallographic, and x-ray micrographic methods it was established that samples of various compositions had approximately the same phase structure with the Nb_3Sn compound as the main phase[2)], the phase composition (determined with the aid of a microprobe) changing from sample to sample. The critical temperature of all the alloys measured by the change of their electrical resistance turned out to be 18°K, and the width of the transition to the superconducting state was less than 0.1°K.

Figure 2 shows the curves of the dependence of the values of B_r, H_c, and $(BH)_{max}$ on the niobium content in the Nb_3Sn, as well as the values of the lattice parameter a_0 and the relative area of the intercrystallite boundaries S which was found by the following method. By studying the microstructure of each sample, we determined the volume v of the Nb_3Sn phase in the sample and obtained a distribution curve of the dimensions of the Nb_3Sn grains (Fig. 3) from which we obtained the average diameter of the crystallites d_{av}:

Nb in Nb_3Sn, at. %:	74.9	75.6	77.5	79.8	81.9	84.2
v, %:	39.1	34.6	29.3	48.6	30.8	32.0
d_{av}, 10^{-4} cm:	4.3	1.92	1.28	2.78	2.57	3.70

With the obtained values of d_{av} we determined the average area of the intercrystallite boundaries $2/d_{av}$[14] per unit volume of Nb_3Sn and the area of the intercrystallite boundaries of the Nb_3Sn phase within the volume of the entire sample $2v/d_{av}$. The relative area of the intercrystallite boundaries S present in the Nb_3Sn phase of a given sample was obtained as the ratio of the value of $2v/d_{av}$ and of this quantity for a sample with a maximum magnetic hysteresis (77.5 at.% niobium in the Nb_3Sn). The objects of such investigations, as also of the metallographic investigations described below in Sec. 3, were 10—12 mm long cylinders cut off from the samples for which the magnetization had been measured. The cut was prepared on the cross section which had been closest to the central portion of the initial complete cylinder.

As is seen from Fig. 2, the changes in B_r and a_0 are in good agreement with each other, and those of H_c and $(BH)_{max}$—with the value of S. For H = H_0 we have B ≈ H_0[12] and consequently the quantity H_c characterizes the degree of resistance of the sample to the process of decrease of the field B within it to zero; this can be understood as the degree of resistance of the sample to the process in which the quantized magnetic flux filaments escape from it. As the correlation of the H_c and S curves shows, this resistance is determined by the total area of the intercrystallite boundaries of the Sb_3Sn phase in the sample. It can therefore be concluded that the grain boundaries represent those structure defects on which the pinning of the magnetic flux in Nb_3Sn occurs. This conclusion coincides with the result obtained for thin films of Nb_3Sn with crystallite dimensions of 370—2000 Å on the basis of a study of the critical current density in strong magnetic fields up to 70 kOe.[9]

Consequently, first, in order to obtain large hysteresis in Nb-Sn alloys, it is essential to produce a fine-crystallite structure of Nb_3Sn; an additional increase of the hysteresis can be expected in the case of a column-like structure of the grains with a small cross section if the flux filaments are parallel to the extended intercrystallite boundaries, since in this case each filament will be hindered in its motion along its entire length. Such an oriented structure similar to the so-called fibrous structure of deformable superconductors should also make difficult the penetration of the magnetic field into the superconductor and should facilitate an increase of its critical current density.

Secondly, minimum hysteresis can be obtained with a single-crystal sample of Nb_3Sn. It has already been reported that in single-crystal Nb_3Sn one obtains a reversible magnetization curve,[15] at least near the critical temperature T_c. Because of the presence of various defects, whose role has thus far not been ex-

2) The remaining volume is occupied by voids (see below) and small quantities of niobium, niobium oxide NbO, and of the compound Nb_3Sn_2.

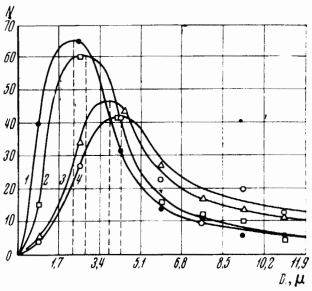

FIG. 4. Size distribution of the cavities (220 determinations): 1—84.2, 2—79.8, 3—74.9, 4—77.5 at. % niobium in the Nb_3Sn.

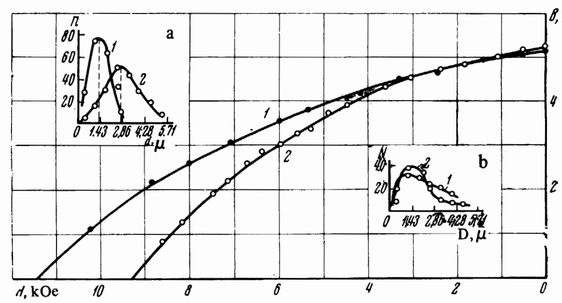

FIG. 5. Sections of the hysteresis curves (H_0 = 6 kOe), size distribution curves of the Nb_3Sn grains (a) and cavities (b) for the alloys with 80.2 (1) and 79.8 (2) at. % niobium in the Nb_3Sn.

plained, a single crystal can also have a certain magnetization hysteresis, but the decisive role of the grain boundaries in pinning the flux and the formation of the hysteresis properties in Nb_3Sn appears now to be obvious.

3. In connection with the above it appears interesting to consider the role of cavities in the pinning of flux filaments in Nb_3Sn. A theoretical consideration of this problem showed[16] that there exists an optimum size of cavities for which maximum flux pinning should occur. This takes place when the distance between the flux filaments, the dimensions of the cavities, and the distances between them are of the same order of magnitude. An experimental investigation of the magnetic properties of sintered samples of pure niobium as a function of the particle size of the original powder and the pressure used for pressing the samples[11] led to the conclusion that the results of[16] are confirmed, although the average size of the cavity exceeded considerably the optimum size of 10^{-5} cm.

For a uniform distribution of flux filaments the distance between them is given as $l = (B/\varphi_0)^{-1/2}$ where $\varphi_0 = 2.07 \times 10^{-7}$ gauss-cm^2 is a flux quantum. In our experiments the largest value of B was equal to H_0, i.e. 6 kilogauss, which yields $l \approx 6 \times 10^{-6}$ cm. This value corresponds to the maximum pinning force for $B = H_0$. If the flux filaments do not interact and can move independently of one another, then on decreasing B the optimum value should change continuously and for B = 20 gauss it will reach 10^{-4} cm. In fact, when the flux filaments move there exists a gradient of their concentration. In the case of the curves shown in Fig. 1 the density of flux filaments near the axis of the sample should be larger than at the edges, and the nature of the change of B along the radius[17,18] must be allowed for in estimates of the optimal dimensions of the cavities assuring maximum flux capture. In practice one can apparently assume that in our case the range of optimum cavity dimensions lies approximately between 5×10^{-6} and 5×10^{-4} cm.

In order to estimate the possible effect of the cavities on the magnitude of the hysteresis of the samples investigated by us, we determined first by metallographic methods the volume content of cavities in each sample (it amounted to 45—55 percent and changed irregularly from sample to sample), and then the size distribution of the cavities. For this purpose we used an optical microscope with a magnification of 1425× which assured a resolution of cavities larger than 1×10^{-5} cm, i.e. it covered the main portion of the range of optimum cavity dimensions.

In some samples the accurate measurements of the diameters D of many cavities turned out to be difficult, and for the samples with 75.6 and 81.9 at.% Nb in the Nb_3Sn it even proved impossible, because of the irregular shape of the cavities. Therefore the obtained distribution (Fig. 4) can have no claim to high accuracy. The shape of the distribution curves also does not allow one to obtain a reliable estimate of the average size of cavities in each sample. Nevertheless, certain qualitative conclusions can be drawn from the obtained data.

First, the average dimension of the cavities in all samples is of the order of 10^{-4} cm which is close to the upper limit of the optimal dimensions according to the above estimate. Secondly, the samples with 84.2 and 79.8 at.% niobium in the Nb_3Sn which differ appreciably in their hysteresis properties (see Figs. 1 and 2) have the minimum dimension (i.e., the dimension closest to optimum) and at the same time an almost equal size of cavities. It is just for these samples that the distributions can be considered to be most reliable because of the almost isotropic shape of the majority of cavities. In the sample with the largest hysteresis (77.5 at.% niobium in the Nb_3Sn) the dimensions of the cavities turned out to be rather far from optimal. In the case of curves 1, 3, and 4 (Fig. 4) the volume of cavities in the samples was approximately equal (about 55%) which facilitates the comparison of the properties of the corresponding samples. In the case of curve 2 the volume of the cavities amounted to 45 percent.

As is seen, a comparison of the data obtained in investigations of the cavities with the results of magnetic measurements does not make it possible to draw any conclusion concerning the presence of a contribution of the cavities to the pinning of the quantized flux filaments in Nb_3Sn. The cavities are somewhat large as centers of filament pinning, since each cavity pins not one but a number of flux filaments with the pinning force decreasing rapidly.[16]

These estimates and considerations are valid under the assumption that the flux filaments do not interact and move in isolation from one another. This condition is fulfilled in the case of a small filament density when they are at large distances from one another (near the first critical field H_{c1}). However, since in our samples the filaments were small distances apart and could therefore be coupled with one another (see Sec. 5 below), the region of optimal dimensions of the defects pinning the filaments could be of the order of 10^{-6} cm, i.e., much smaller than the observed dimensions of the cavities.

Therefore, the effect of the cavities on the hysteresis of our alloys is even less probable, and obviously the principal flux capture occurs on other types of defects—as has already been mentioned, on the boundaries between the grains.

It appears to us that two circumstances confirm indirectly the fact that the overwhelming role in the pinning of flux filaments and the production of the hysteresis properties of Nb_3Sn is played by structure defects other than cavities. The first of these follows from the well-known relation of Kim et al.[5] which relates the magnetic and electrical properties of hard superconductors, so that a larger or smaller hysteresis due to pinning of filaments on structure defects should affect the critical current density j_c. If the main pinning in Nb_3Sn were due to cavities, then one could not expect a large value of j_c in solid Nb_3Sn without cavities. This is, for example, observed on samples prepared by the reactive diffusion method and is employed in practice in producing superconducting solenoids and electromagnets. At the same time a solid Nb_3Sn sample prepared from the melt has a considerable magnetization hysteresis.[19]

The second circumstance is related to the particle size of the initial niobium powder which was on the average 50 μ. If it is assumed that the smallest particles were spherical with a diameter of the order of 10 μ and in close packing formed tetrahedral and octahedral neighborhoods, then the smallest diameter of cavities obtained is of the order of 1—3 μ, i.e. of the same order as from Fig. 4, but by no means of the order of 10^{-5} or 10^{-6} cm. In fact the fraction of such small particles in the initial powder is small. It is difficult to assume that they produce many neighborhoods with one another, and consequently the overwhelming majority of the cavities should have dimensions which are revealed by the optical microscope and are not beyond its resolving power.

An intercrystallite boundary which is of small but finite thickness represents in fact a transition region with a distorted crystal structure. So far we have no data on the thickness of this region and the limits of its change in Nb_3Sn. Possibly it is of the order of 10^{-6} cm, i.e. of the order of several tens or even hundreds of interatomic distances, and is close to the lower limit of the optimum size of the defects.[16,20,21] As regards the distances between the boundaries, in a series of investigated alloys set up on the basis of increasing hysteresis properties, they decrease gradually towards fulfilling the optimum conditions for maximum flux capture. As has already been noted in[9], the value of d_{av} can be equivalent to the value of l which was estimated above.

Generally speaking, the width of the boundary between the grains depends on their crystallographic misorientation. Therefore in the case of an oriented (column-like) grain structure, which was mentioned in Sec. 2, the boundary thickness will have a narrower range of values than in the case of random grain orientation. In the presence of mutually coupled flux filaments which remain at unchanged distances from each other during the motion caused by the change of the external field, the region of optimal dimensions of defects will become even narrower. One might expect that under favorable conditions, i.e., when the distance between the filaments is close to the dimension of the defect—the boundary thickness—practically all defects will ensure maximum flux capture, i.e., maximum hysteresis, when flux filaments pass through them.

4. So far we have considered a comparison of the properties of alloys differing not only in the crystallite or cavity dimensions, but also in composition. Naturally there appears the question concerning the relation of hysteresis properties of samples of the same composition, but having various grain sizes and total areas of intercrystallite boundaries.

In Fig. 5 we present sections of hysteresis curves for two samples of the Nb-Sn alloy containing about 80 at.% niobium in the Nb_3Sn. Curve 1 was obtained for a sample with $d_{av} = 1.39\ \mu$ and $S = 1.056$. Curve 2 reproduces curve 7 of Fig. 1 for a sample with $d_{av} = 2.78\ \mu$ and $S = 0.88$. The values of the coercive force obtained from these curves yield a ratio $(H_c)_1/(H_c)_2 = 1.22$, and the corresponding values of the relative areas of the intercrystallite boundaries—$S_1/S_2 = 1.20$. Therefore, the considerations developed above concerning the connection of the hysteresis of Nb-Sn alloys with the grain structure of the compound Nb_3Sn are also confirmed in the case of samples of the same niobium content in the Nb_3Sn. One cannot at the same time relate the various properties of these samples with the effect of the cavities (the distribution curves of the cavity and Nb_3Sn grain dimensions for these samples are also presented in Fig. 5).

5. The curves showing the change of the values of B_r, H_c, and $(BH)_{max}$ with composition (Fig. 2) are qualitatively the same (curves with a maximum) and delimit approximately the same region of concentrations. One can therefore assume that these quantities are mutually related, and the obtained correlation of B_r and a_0 and of H_c and $(BH)_{max}$ with S represents two sides of the same phenomenon. This means that a_0 and S should be mutually related; this is rather unexpected for bulk samples. However, in the case of polycrystalline alloys this is possible as a result of the phenomenon of intercrystallite internal adsorption[22] based on the decrease of the energy of intercrystallite transition regions by the replacement of one set of atoms within the regions by others. If this phenomenon really occurs in Nb-Sn alloys, then on changing the crystallite dimensions, that is also the total volume of the intercrystallite transition regions, the number of niobium or tin atoms escaping from the crystallites into these regions or vice versa may change. This may be one of the reasons for the fact that the composition of the Nb_3Sn in the samples of various alloys was not the same, and for this reason the alloys could differ not only in the total area of the intercrystallite boundaries and in their thickness, but also in their content of niobium and tin.

Since the total volume of the intercrystallite regions is small and the crystal structure within them is strongly distorted, they practically do not contribute to the x-ray diffraction patterns and the measured lattice parameter provides information about the body of the grain. Furthermore, since the main defect to which the flux filament "sticks" in the Nb_3Sn is the intercrystallite boundary, it is possible to consider the body of the grain in the first approximation as being free of defects. Consequently, in a rather large volume with linear dimensions $d \gg \delta_0$ (δ_0 is the penetration depth) the initial assumption of a number of theories (see, for example[20]) that the properties of the basis of an inhomogeneous sample are determined by the properties of a homogeneous type-II superconductor and depend weakly on the presence of defects turns out to be correct. Use of the picture of the mixed state of Abrikosov in considering hard superconductors, both in setting up the theory[4,16,20,23] and in discussing experimental data, appears by the same token to be justified. Generally speaking the correctness of this is by far not obvious and gives rise to objections precisely because the picture of the mixed state in Abrikosov's theory is obtained for homogeneous defect-free type-II superconductors, whereas hard superconductors contain a large number of defects.

The fact that the body of the grains is defect-free means that after cooling alloys down to 4.2°K in a magnetic field H_0 the magnetic flux for constant $H = H_0$ can distribute uniformly over the thickness of each crystallite so that at some distance from the intercrystallite boundaries, which distort somewhat the distribution pattern of the field, a periodic structure of flux filaments of the type of an Abrikosov lattice characteristic of homogeneous type-II superconductors can establish itself. On varying H from $H = H_0$ to $H = 0$, 80–90 percent of the flux is retained in most of our samples; this means that compared with the state at $H = H_0$ the flux distribution changes little, at least not near the surface of the sample.

In order to produce a magnetic lattice, the distance between flux filaments should be smaller than the penetration depth δ_0 which in the case of Nb_3Sn is 2.6×10^{-5} cm[24] [according to other data its value is in the interval $(1.5-2.8) \times 10^{-5}$ cm[25]]. Since the estimate made in Sec. 3 of the smallest distance l between the flux filaments shows that for $H = H_0$ it should approximately be 6×10^{-6} cm, then $l < \delta_0$ and the condition for the production of a magnetic lattice is fulfilled. Its period can be estimated from the formula $b_0 = \sqrt{2\pi}\delta_0/\kappa$[26] where κ is the Ginzburg-Landau parameter. Making use of the values of δ_0 cited above and with $\kappa \approx 18$,[15] we find $b_0 \lesssim 3 \times 10^{-6}$ cm. Thus $b_0 < l$ and the establishment of a stable magnetic lattice over the entire Nb_3Sn compound turns out to be hardly possible. By the same token we conclude that it is possible that there exist in our samples bundles of magnetic flux filaments or bunches produced through the interaction of the fields and of the wave functions, which have an internal structure similar to the Abrikosov lattice.[4] At higher filament densities one can expect the establishment of a rigid lattice for the entire material with high critical superconductivity parameters,[23] i.e. for the entire Nb_3Sn compound.

This means that the distribution of the magnetic flux in the initial state of the alloys turns out to be connected with the body of the grain, i.e., with the presence of the correct crystal structure, whereas the escape of the flux from the sample is connected with the pinning of filaments by regions within the intercrystallite transition regions where the crystal structure has been disturbed. Since the behavior of the atoms in the alloy depends on their interaction with one another, and the latter is naturally not the same within the thickness of the grains and in the intercrystallite transition regions, there is no direct quantitative correspondence between the changes of a_0 and S, and consequently also between B_r and H_c [or $(BH)_{max}$]. On the other hand, there is undoubtedly a qualitative correspondence.

6. In considering the experimental data presented in Figs. 1 and 5 our attention is drawn to the fact that certain sections of the hysteresis curves "intersect." If we turn our attention away from the concrete form of the structure defects which serve as the pinning centers of flux filaments, then such a course of the curves can be understood in the case of noninteracting filaments as a result of the differing size distribution of the pinning centers in different samples, and in the case of the production of flux bundles as a result of the differing dimensions of the bundles in different samples.

Indeed, let two samples be cooled from room temperature to 4.2°K in the same magnetic field H_0, and let them have in the field H_0 identical values of the magnetic induction $B \sim H_0$. It is then natural to assume that in the sample which has the larger number of effectively operating (i.e. optimal) small defects at large magnetic flux densities the values of B on the initial section of the hysteresis curve (curve 2 of Fig. 5) should fall more slowly with H than in the sample with the smaller number of such defects (curve 1). The relationship between the curves can reverse if the first sample has a smaller number of such defects whose dimension is optimal for maximum pinning at small densities of the magnetic flux.

In the case of bundles the situation will be more complex. The mobility of bundles is determined not only by the size of the retarding centers, but also by the size of the bundles themselves. Suppose, for instance, that in one sample for $H = H_0$ "small" flux bundles are formed for some reason, whereas in another sample "large" ones are formed. For a large bundle to overcome the potential barrier connected with a defect, one must impart to it a larger energy than to the small bundle. One can therefore expect that the same change of the external field ΔH (starting from H_0) for both samples will initially lead to a slower change of B in the case of large bundles. This will then correspond to curve 2 on Fig. 5. On the other hand, at some value of H there may be an instant at which the total number of defects will have an effect, and if there are fewer of them in the sample with large bundles than in the other sample, then the decrease of B will occur more rapidly. In addition, on this section of the hysteresis curve the total number of flux filaments in the sample is considerably smaller than in the initial state, and the bundles can gradually "fall apart" into isolated filaments, and then the situation considered in the preceding instance may be repeated.

The same behavior as in Fig. 5 is also demonstrated by curves 6 and 7 or 5 and 6 on Fig. 1. The various values of the coercive force H_c found from them characterize the different magnitude of the external efforts which must be made in order to bring alloys from an identical initial state with $B = H_0$ to an identical state with $B = 0$. The basis of these differences is, as has been shown, the total area of the intercrystallite boundaries. However, it is clear that one can also expect some additional effect from such details as the thickness of the boundary and the limits between which it varies in the alloy (we have touched upon this question in Sec. 3), and also from the size of the bundles. Of course, this treatment is grossly simplified and schematic, and its only purpose is to indicate a physically possible mechanism with which the magnitude of the hysteresis of hard superconductors can be connected.

Unfortunately we do not have the data necessary to apply these considerations even semi-quantitatively to the investigated alloys, since the thickness of the intercrystallite boundaries in Sb_3Sn and the limits between which it varies are unknown. However, the experimentally observed mutual intersection of the curves and the indicated considerations lead one to think that at least in the case of cooling of hard superconductors below T_c in a magnetic field it would be useful to characterize the degree of irreversibility of their magnetization not only by the magnitude of the residual moment but also by the magnitude of the field H_0 for which the average magnetic field B in the sample vanishes. This extends to the region of values H_0 from H_{c1} to $H^* > H_m$, where H_{c1} is the first critical field, H_m is the field corresponding to the maximum diamagnetic moment on the magnetization curve, and H^* is a certain characteristic field known from a number of papers.[3,27,28] Cooling in the field H^* leads to a maximum hysteresis cycle[27,28] so that for all $H_0 > H^*$ the values of B_r and H_c should be the same.

7. Our investigation shows the important role of grain boundaries in determining the magnetic hysteresis properties of the compound Nb_3Sn. In investigating the value of the hysteresis in connection with the grain structure, one must obtain information about the total area of the intercrystallite boundaries, their direction (in the case of oriented structures), the thickness of the boundaries and the distances between them, the thickness distribution of the boundaries, and their niobium and tin content.

As has already been noted above, the main result of this work—the pinning of magnetic flux on the intercrystallite boundaries of Nb_3Sn—obtained in an investigation of sintered Nb-Sn alloys coincides with the result obtained for thin films of Nb_3Sn in strong magnetic fields. A refinement of the ideas concerning the nature of the pinning of quantized flux quanta in the compound Nb_3Sn prepared by various methods is, on the one hand, of important practical significance in connection with the utilization of this compound in the construction of highly efficient magnetizing and other devices, and is, on the other hand, obviously impossible without additional information about the intercrystallite boundaries themselves as pinning centers. It appears therefore very desirable to set up special physical investigations which would be able to provide such information.

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