Twinning at low temperatures and the variation of the magnetic properties of superconducting niobium during deformation

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Data are presented on the deformation by compression of niobium single crystals of various degrees of purity and structural perfection in the temperature range from 1.6 to 300 K. Below 150–200 K the deformation of the investigated niobium single crystals occurs discontinuously, and is determined by deformation twinning via the {112}, ⟨110⟩ systems. The stresses at which the developed discontinuous deformation occurs are, within the limits of the data spread, independent of the level of impurity content. The depth of the load jumps decreases appreciably when the impurity concentration is increased and the structural perfection is worsened. It is established that twinning is accompanied by a change in the dislocation density in the deformed samples. This manifests itself most clearly in samples of elevated purity, in which a considerable part of the deformation is effected by dislocation slipping. The set of defects that arise in the course of the low-temperature twinning leads to a sharp change in the shape and parameters of the magnetization curves of superconducting niobium. The density of the "frozen-in" magnetic flux, the field H_{c2}, and the field, H_p, above which the flux penetrates the samples are found to increase appreciably when the deformation is only a few percent. The magnetic flux density in the samples is monitored at the moments of the load jumps. It is established that the twinning processes are accompanied by a short-lived change in the superconducting state of niobium. Penetration or expulsion of the flux is observed, depending on the "magnetic prehistory." These effects can be related with the thermal perturbations in the superconductor during the twinning process. Analysis of the data shows that the thermal effects during twinning are a consequence, and not the cause, of the low-temperature abrupt deformation of the investigated niobium single crystals. The conclusion is drawn from the data on the kinetics of the change in the magnetic-flux density at the moments of the load jumps and the data on the kinetics of the load jumps that the rate of the twinning processes is high and, in particular, that the velocity of migration of the twins is also high ($v \gtrsim 5\times10^4$–10^5 cm/sec).

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A number of anomalies are observed in the behavior of deformable materials as their temperature is lowered.[1,2] The present paper is devoted to the study of one of these anomalies, to wit, of abrupt deformation. This phenomenon is observed during the low-temperature deformation of many materials, in particular, metals with the bcc lattice.[1,2] Essentially, the phenomenon consists in the catastrophic development of deformation during short intervals of time, which is manifested in the form of load jumps on the deformation curves. Possible causes of abrupt deformation are the anomalies in dislocation slipping at low temperatures and the transition to another deformation mechanism: twinning. The realization of these mechanisms depends on the shape and properties of the material, as well as on the deformation conditions. Of interest are information about the nature of the carriers of abrupt deformation in specific materials, their nucleation, and motion and data on the changes that occur in the physical properties of the materials during this type of deformation. The present paper is devoted to the consideration of this set of questions as applied to the low-temperature deformation of niobium.

I. EXPERIMENTAL PROCEDURE

1. Sample preparation

The niobium single crystals were grown with the aid of crucible-less electron-beam zone refining in a (1.3–6.6) $\times10^{-4}$ Pa vacuum in three operations with a recrystallization rate of 1 mm/min. As the starting material we used commercial-grade niobium bars and rods produced by electrolysis of melted salts.

The samples for the mechanical compression tests were cut in the form of a prism with characteristic dimensions after grinding and chemical polishing of $4\times4\times12$ mm and with the direction of the large edge along the growth axis of the single crystals, which was close to the ⟨110⟩ direction. We prepared three groups of samples with resistance ratio $\gamma=\rho(300)/\rho(4.2)$ ranging from several tens to several thousands in a magnetic field of 10 kG directed parallel to the axis. The samples of the first group, which were prepared from single crystals of commercial-grade niobium, had $\gamma=50-100$, while for the samples of the second group, which were prepared from single crystals of electrolytic niobium, γ had values of several hundreds (usually, $\gamma\approx200$). The samples of the third group were fabricated by means of a special heat treatment[3] of samples of the second group. In the first phase of the heat treatment, the samples were subjected to decarbonization in a $P_{O_2}=6.6\times10^{-3}$ Pa oxygen atmosphere at $T\approx2200$ K for 5 hours. In the second phase they were subjected to a 12-hour high-vacuum annealing at a residual pressure of 4×10^{-8} Pa and a temperature $T\approx2550$ K. The induction heating of the samples was carried out in a heated metallic setup, which included a zeolite, magnetic-discharge, and titanium sublimation pumps. The resistance ratio of the

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samples of the third group was several thousands (about 4500). According to the results of a mass-spectroscopic analysis, the total level of metal impurities in the samples of the first group was about 200 at. ppm; in the samples of the second and third groups, about 10 at. ppm. Considering the tendency of niobium to absorb gases, the especially pure samples were stored up to the beginning of the tests at the temperature of liquid nitrogen.

2. The mechanical, magnetic, and temperature measurements

The niobium samples were deformed by compression along an axis close to the ⟨110⟩-type directions, with the loading device compressing at a rate lying in the range 5–200 μ/min. As a reference rate, we chose 50 μ/min. The tests were carried out at temperatures of 295, 77, and 1.6–4.2 K. The apparatus used allowed the recording of the load variation with a sensitivity of 10–50 g in the 0–2500-kg range for a measurement error of 0.5%.

To follow the kinetics of the mechanical perturbations in the testing machine-sample system at the moments when the load jumps occurred, we performed separate experiments in which we placed under the ends of the samples being deformed quartz piezoelectric transducers, the signals from which were fed to an oscillograph.

In the liquid-helium temperature range the samples were deformed in the normal and superconducting states. The state of the samples was changed by a magnetic field directed parallel to the sample axis. For the measurement of the magnetization curves of superconducting niobium, we used an F-18 microvolt-ampere-Weber. The pickup loops, which were made of thin (50 μ) wire, were placed on the samples. In those experiments in which the kinetics of the processes was investigated with intermittent changes in the magnetic flux, Φ, in the samples, the signal from the loop ($U \sim \partial\Phi/\partial t$) was fed to an S8-12 storage oscillograph.

Temperature-monitoring experiments were carried out on the samples deformed at 4.2 K. In this case we welded a Cu-Au thermocouple to the center of a lateral face of the sample.

3. The metallography of the deformed samples

Slip tracks are formed on the sample surface in the course of the low-temperature deformation. To determine the crystallography of the slip tracks, we used the x-ray technique and the technique of determining orientation in local regions of a crystal surface from etch figures. The latter method is based on the fact that, in the course of the solution of metals with the bcc lattice, there are formed on their surface orientational etch figures faceted by the {100}, or {100} and {110}, planes.[4] Specially performed investigations showed that the latter case is realized for niobium. The technique of determining orientation from etch figures allows the determination of the misorientation of microregions (~10 μ) of a surface to within a few degrees.

The monitoring of the dislocation density and distribution was carried out with the aid of the technique of chemical etching of the niobium samples in a $HF:H_2SO_4:H_2O_2:H_2O$ mixture at room temperature.[5] In the process there are produced on the surface facets close to the {100} planes small etch pits on both the fresh and the old dislocations.

With the aid of a telescopic device, we also watched directly for the appearance of slip tracks in the course of the deformation.

II. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

1. Deformation curves and metallography data

In Fig. 1 we show typical deformation curves of niobium single crystals of the various groups. At room temperature the deformation curves of the investigated niobium single crystals are macroscopically smooth, and the plastic-flow stress depends on the degree of perfection of the deformed samples. The lowering of the temperature is accompanied by an increase in the deforming stress σ, and below 150–200 K there appear macroscopic load jumps on the deformation curves.

We investigated the effect of the deformation conditions on the parameters of the abrupt deformation. In the range T = 1.6–77 K the depth, $\Delta\sigma$, of the load jumps and the level of σ at which the abrupt deformation occurs are, within the limits of the spread of the data from sample to sample, independent of the test temperature (see, for example, Fig. 1). And in this sense we can speak of an adiathermal nature of the processes responsible for the abrupt deformation of niobium. In the region of liquid-helium temperatures we did not observe a significant dependence of σ and $\Delta\sigma$ on the state (S, N, or mixed) of the deformed superconductors, as well as on the state of the helium medium (superfluid, normal, or gaseous helium). We did not find σ and $\Delta\sigma$ to depend on the deformation rate in the range 5–200 μ/min. Thus, the parameters of the abrupt deformation do not depend, or weakly depend, on the considered test conditions. At the same time, as will be shown below, the parameters of the abrupt deformation are quite sensitive to the degree of perfection of the deformed niobium crystals.

The load jumps appear in the deformation of samples

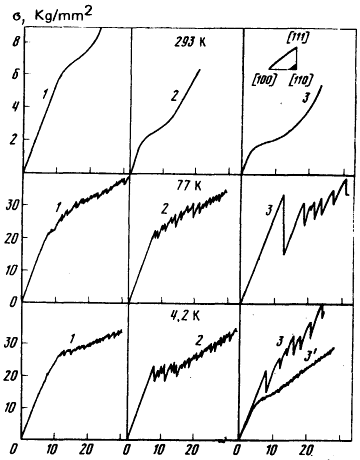

FIG. 1. Typical deformation curves, $\sigma(t)$, of niobium single crystals deformed by compression along the ⟨110⟩ direction at a rate of 50 μ/min: 1) $\gamma \approx 50$, 2) $\gamma \approx 200$, 3) $\gamma \approx 4500$, 3') sample with cold-hardened surface and $\gamma \approx 4500$.

of the first group at relatively low values of σ on those sections of the deformation curves which correspond largely to elastic deformation. As σ is increased, the depth and frequency of the load jumps increases, and a transition to a developed abrupt deformation occurs. The relative depth, $\Delta\sigma/\sigma$, of the load jumps for these samples does not, as a rule, exceed a few percent. In contrast, in the deformation of the niobium samples of the second and third groups, the transition to the abrupt deformation occurs sharply, and the first load jump is observed at markedly higher values of σ. The relative depth of the load jumps increases with increasing purity of the deformed samples (see Fig. 1). In the case of the purest samples of the third group, $\Delta\sigma/\sigma$ attains several tens percent, and in individual cases 50–60% in the initial phase. Virtually no shallow load jumps occur in the deformation of the pure samples. A marked plastic flow before the next load jump is also a distinctive feature of the deformation curves of the pure samples. The plasticity sections on the deformation curves appear only after the first load jump, up to the moment of occurrence of which the deformation is essentially elastic. Estimates show that the contribution of the plasticity sections to the overall deformation does not exceed 10–15%. The main deformation of the samples occurs at the moment of the load jumps, whose depth does not depend on the degree of plasticity on the preceding sections of the deformation curve. Thus, the nature of the abrupt deformation is determined by the degree of purity of the deformed samples. At the same time, the dependence of the σ range in which the developed abrupt deformation occurs on the purity of the investigated niobium crystals is weak, and is masked by the spread in the data (see, for example, Fig. 1).

The deepest load jumps are observed in carefully polished and subsequently vacuum annealed samples. The cold working of the surface of these samples leads to the occurrence of shallow and frequent load jumps (Fig. 1). The behavior of the deformation curves of the samples of the second group is less sensitive to the state of the surface. The state of the surface has virtually no effect on the deformation of the samples of the first group. Careful polishing of these samples does not lead to deep load jumps, and the cold working of their surface does not result in a significant decrease in the depth of the jumps.

Load jumps not only occur during the active deformation of niobium, but also often occur spontaneously and after the loading apparatus has been stopped. They can also be triggered by light tapping (~1 kg for a load on the sample $\sim 10^2 - 10^3$ kg) on the push rod of the testing machine. Moreover, we can by such means induce load jumps also at relatively low values of σ in the elastic region of the deformation curves. The above-presented facts agree with the analogous data given in Refs. 6–8, and possibly indicate the metastability of the processes of nucleation of the abrupt-deformation carriers and their sensitivity to small mechanical perturbations in the testing machine-sample system.

Slip tracks are formed on the surface of the samples during the low-temperature abrupt deformation of niobium. They have characteristic faceting, and are of different widths, which attain values of tens of microns. It was established from the visual observation of the appearance of the slip tracks in the course of the deformation and the microscopic investigations of the surface of the deformed samples that there is a correspondence between the number of load jumps and the number of slip tracks only in the initial phase of the deformation when the load jumps are not deep ($\Delta\sigma/\sigma \leq 1\%$). In this case to each jump corresponds a narrow slip track. The deeper load jumps entail the appearance of at least several slip tracks. Two sets of mutually intersecting tracks are usually observed in the initial phase of the deformation. As an instance of a clear noncorrespondence between the number of load jumps and the number of slip tracks, we can cite the data for the pure niobium crystals, for which the relative depth of the first load jump $\Delta\sigma/\sigma \gtrsim 30\%$. In this case tens of slip tracks, far removed from each other, and covering the entire sample surface, can be observed. The distribution of the slip tracks survive a prolonged chemical polishing, and is observed on longitudinal cuts of the samples. The deformation of niobium per load jump is not, in the general case, localized in one region of the crystal, which is in agreement with the data of Refs. 9 and 10 and at variance with the assertion made in Refs. 6–8 and 11 that the deformation corresponding to a load jump is localized in individual slip bands.

X-ray measurements showed that, in the initial phase of the abrupt deformation, the slip formation occurs in planes of the $\{112\}$ type. According to the published data, dislocation slipping occurs in bcc metals mainly in the $\{110\}$ and $\{112\}$ sets of planes, and in the $\{110\}$ planes at low temperatures.[12-14] The set of $\{112\}$ planes is peculiar to twinning processes.[12-15]

The method of orientational etch figures indicates that the orientations of the initial surface and the slip tracks are different. For example, the etch figures having in the $\{100\}$ planes the shape of clearly defined squares go over in a region of slip tracks into rectangles, which corresponds to the $\{110\}$ planes. Similarly, a transition from rectangles to squares occurs in the case of an initial $\{110\}$ surface. This is in accord with the expected orientation exchange during the formation of twin layers.[14] The change in the shape of the etch figures in a region of slip tracks is also observed in the case of other orientations of the initial surface. The set of data allows us to conclude that the low-temperature abrupt deformation that occurs during the deformation by compression of the investigated niobium single crystals is connected with the processes of twinning via the $\{112\}$, $\langle 111 \rangle$ systems.

We investigated the dislocation structure of the deformed niobium single crystals by the method of chemical etching. Production of dislocation slip bands is observed to occur in samples with an initial dislocation density of $\sim 10^5 - 10^6$ cm^{-2} after a slight deformation at room temperature without a significant increase in the density of the "background dislocations" (Fig. 2a). In samples deformed at low temperatures, the twinning processes are accompanied by a noticeable increase in

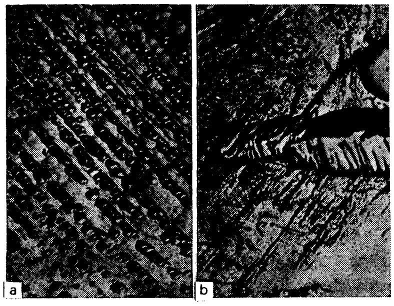

FIG. 2. Examples of chemical etching on a dislocation of niobium single crystals deformed at 293 K(a) and 4.2 K(b).

the density of the "background dislocations" (up to 10^7–10^8 cm^{-2}), and dislocation beams emanating from the twins and having an elevated dislocation density are produced (Fig. 2b). The observed change in the dislocation density after deformation at low temperatures can be attributed partly to the relaxation of the elastic stresses of the twins when the samples are warmed up. However, the marked plasticity of the pure samples before the next twinning event directly indicates dislocation slipping at low temperatures. The absence of appreciable plasticity before the first load jump indicates that, initially, the perfect samples do not contain dislocation sources of sufficient power. This agrees with the results of Sethi and Gibala's investigation.[16] The dislocation sources arise in the twinning process. In less perfect samples the motion of the dislocations is hindered as a result of the high interstitial-impurity content.

The total interstitial-impurity concentrations for the samples of the various groups, as estimated from the values of the residual resistance with the use of the data given in Refs. 3 and 17, are ~400, 100, and 6 at. ppm, respectively. According to the published data,[18] in the samples of the first and second groups, besides the formation of a supersaturated solid solution, the formation of thinly dispersed interstitial phases (of carbides, nitrides, and oxides) is possible. These formations can, during the low-temperature deformation, serve as stress concentrators, in the region of which twin layer can be produced. The growth of the twin nuclei may be restricted by the aggregate of defects present in the crystal. Apparently, it is the differences in the content and state of the impurities that determine the experimentally observed difference in the nature of the abrupt deformation of niobium samples of different purities.

2. Changes in the parameters of the magnetization curves of superconducting niobium during deformation

There are data on the effect of crystal-structure defects on the properties of superconductors. As applied to niobium, such data are contained in, for example, the Refs. 19–21. It will be useful to supplement the existing data with data on the changes that directly occur in the properties of superconductors in the course of low-temperature deformation.

The shape of the magnetization curves of the initial niobium samples depends on the degree of their perfection. As the sample purity is raised, the magnitude of the "frozen-in" magnetic flux, $\Delta\Phi(0)$, in zero magnetic

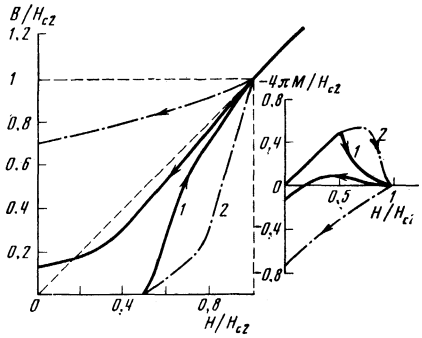

FIG. 3. Dependence of the induction, B, averaged over the sample cross section, on the external magnetic field H: 1) niobium single crystal with $\gamma \approx 4500$ before deformation; 2) same single crystal after deformation at 4.2 K by 10%.

field decreases, and the magnetization curves of the samples become more reversible. If $\Delta\Phi(0)$ in initial samples of the first group is 40–60% of the flux, Φ_c, in the upper critical field H_{c2}, then in samples of the third group $\Delta\Phi(0)/\Phi_c < 10$–15%.

A relatively slight deformation of niobium at liquid-helium temperatures leads to a significant change in the shape of its magnetization curves and an increase in the density of the frozen-in flux (see, for example, Fig. 3). The dependence of $\Delta\Phi(0)/\Phi_c$ on the deformation ratio ε for samples of the first and third groups is shown in Fig. 4a. The measurements were performed after the load jumps that are detectable at 4.2 K had occurred and the testing machine had been stopped. The magnitude of the frozen-in flux in the pure samples becomes equal to the corresponding value for samples with a higher impurity content when the deformation ratio is 5–6%, and the ε dependences of $\Delta\Phi(0)/\Phi_c$ coincide when the deformation is increased further. In the course of the low-temperature deformation of niobium, such parameters of the magnetization curves as H_{c2} and the field, H_p, above which a detectable penetration of the flux into the samples occurs also change. It can be seen from Fig. 4b that H_{c2} and H_p depend on ε roughly in like manner and that, for $\varepsilon > 5\%$, the variation of these parameters does not depend with the limits of the data spread on

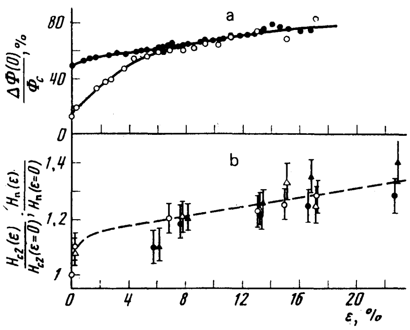

FIG. 4. Dependence on the deformation ratio ε at 4.2 K of: a) frozen-in flux density, $\Delta\Phi(0)$, normalized to the flux, Φ_c, for $H_{c2}(\varepsilon)$ (o—sample with $\gamma \approx 4500$ before deformation, ●—$\gamma \approx 50$); b) the upper critical field, H_{c2}, and the field, H_p, at which there is a detectable penetration of the flux into the sample, normalized to their corresponding values for $\varepsilon = 0$ (o and Δ—$H_{c2}(\varepsilon)$ and $H_p(\varepsilon)$ for sample with $\gamma \approx 4500$, ● and ▲—with $\gamma \approx 50$).

the initial-sample purity. The appreciable increase in H_{c2} and H_p in the initial phase of the deformation ($\varepsilon < 1\%$) in samples of the third group, when the number of twin layers in the process of being formed does not exceed a few tens, should be noted.

The above-presented data indicate that the defects that arise in the course of low-temperature twinning have a significant effect on the parameters of the magnetization curves. The character of the change in the curves corresponds to the formation of strong pinning centers.[22] It should be pointed out that at low temperatures the deformation occurs mainly in the region of narrow twin layers, in which the most drastic distortion of the crystal lattice occurs, the pinning centers are produced, and, possibly, the parameters of the superconductors significantly vary. It can, for example, be assumed that, because of the change in the Ginzburg-Landau parameter in the region of the twins, H_{c2} increases. This leads to an increase in the effective value of H_{c2} for the whole composite sample. It may be expected that the critical current J has higher values in the region of the twin layers. A consequence of this can be an increase in H_p. According to the available data,[23] for an inhomogeneous pinning-center structure, $J_c \sim H_{c2}^{\beta}$ ($\beta \approx 1-2.3$). This makes it possible for us to hope that the increase in H_p, connected with the change in J_c, will correlate with the increase in H_{c2} (as follows from the experimental data).

3. The change occurring in the state of superconducting niobium at the moment of a load jump

During the deformation of niobium in the region $T < T_c$, we monitored the magnetic-flux density in the superconductors at the moments of the load jumps. It was found that, in the absence of an external field, the initial frozen-in magnetic flux is expelled from the samples during load jumps. If, on the other hand, the samples were free from frozen-in flux and were located in a field $H < H_p$, or were in the mixed state, then the flux penetrated the samples at the moments when the load jumps occurred. Moreover, the magnitude of the penetrating flux coincided with that of the flux that, for the given field H, corresponded to the metal in the N state, or was limited by the ability of the sample to freeze the flux that had penetrated it. In none of the experiments, including those in which the subsequent load jumps occurred, did the magnitude of the penetrating magnetic flux exceed the flux magnitude corresponding to the N state. It should be noted that we did not observe an appreciable change in the magnetic flux in the absence of load jumps, i.e., during elastic deformation and plastic flow before load jumps.

When the flux density changed, there appeared in the loops on the samples an emf $U \sim \partial\Phi/\partial t$. Figure 5 shows examples of the oscillograms of the signals from the loops at the moments of flux penetration and expulsion. Noticeably more often than not, the situation was observed, especially in the pure samples, when the whole change in the flux occurred during one load jump, and the subsequent load jumps for the same value of H no longer changed the flux density. But in the case of shallow load jumps ($\Delta\sigma/\sigma < 0.5-1\%$) it was also possible to

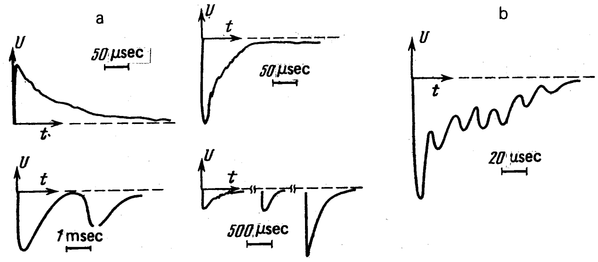

FIG. 5. Signals from: a) the loop on the sample at the moments of penetration ($U > 0$) and expulsion ($U < 0$) of the magnetic flux; b) the piezoelectric transducer under the end of the sample at the moments of the load jumps in the course of deformation at 4.2 K (U in all the plots is in arbitrary units).

observe flux penetration or expulsion in parts (see, for example, Fig. 5a). It was not possible to observe the dependence of the kinetics of the flux change on the state of the ambient helium medium.

We can consider a few of the causes of the change that occurs in the magnetic flux at the time of a load jump: the shift of the crystal lattice relative to the vortex filaments during mechanical vibrations,[22] the dragging of the vortices by moving defects,[24] thermal perturbations in the samples.[22] All these possibilities could be used to explain the expulsion of the metastable, frozen-in flux in zero field. If, however, we take account of the flux penetration data, then because of the dissipation of energy during load jumps, the most probable cause of the flux change is, apparently, the thermal perturbations in the samples.

In separate experiments performed at 4.2 K, we monitored the temperature of the deformed samples with the aid of thermocouples welded on to their surface. Detectable temperature changes ($>10^{-2}$ K) were observed only at the moments of the load jumps when $\Delta\sigma/\sigma > 0.1\%$. The magnitude of ΔT depends linearly on the change, ΔW, in the elastic energy of the testing machine-sample system, and is equal to 1.5–2 K when $\Delta W \approx 0.1$ J. The detectable temperature changes can serve only as a lower limit to the true thermal perturbations in the sample volume. This is connected with heat transfer from the surface region, deformation localization, as well as the inertia and nonadiabatic nature of the thermocouples. We can attempt to estimate the increase that can occur in the sample-volume temperature when the load jumps occur. For this purpose, we must make the assumption as to what fraction ($\alpha = Q/\Delta W$) of the change occurring in the elastic energy at the time of the load jumps is converted into heat. Opinion is divided on that score at the present time.[7-9] An estimate that has, to some extent, been confirmed by experiment is the estimate $\alpha \approx 0.15$ given in Ref. 6. If we use this value for α, and take into account the temperature dependence of the thermal capacity of niobium,[25,26] then the estimates for the change in the sample temperature for $\Delta W \lesssim 0.1$ J will be roughly 5 times greater than the experimentally observed ΔT values. And for the entire load-jump spectrum ($\Delta W \approx 0.001-1$ J) the corresponding estimates for ΔT at 4.2 K are $\Delta T \approx 0.1-15$ K (at 77 K and for $\Delta W < 1$ J we find $\Delta T < 0.5$ K). In making the estimates we neglected heat removal from the samples, and assumed that they were uniformly heated. For this to be justified, it is necessary that the thermal front in the sample propagated sufficiently rapidly. The data on the kinetics of the flux change (Fig. 5a) do not contradict this assumption. Thus, the changes in the sample-volume temperature can be high enough for them to lead to a change in the state of the superconductor at the moments of the load jumps. As confirmation of such a possibility, we can also cite the data obtained by Bazinski,[6] Show,[9] and Juramoto and Takeuchi,[10] who succeeded in recording substantial temperature increases during the abrupt deformation of various materials.

4. The kinetics of abrupt deformation and the accompanying phenomena

Twinning is accompanied by the variation of the magnetic-flux density, Φ, in superconducting niobium. In this case diversely shaped $U \sim \partial\Phi/\partial t$ signals are observed whose lengths lie in the range 10^{-5}–10^{-3} (Fig. 5a). There is correlation between the length of the registered signals and the depth of the load jumps. For deep load jumps the Φ variation is more abrupt.

The kinetics of the Φ variation is determined in the general case by the aggregate of the processes of energy dissipation occurring during the motion of the twins, heat transfer, and flux migration in the superconductor. As an estimate for the characteristic time of propagation of the thermal front over a distance l in the sample, we can use $t \sim l\rho C/4\varkappa$ ($\varkappa$ is the thermal conductivity, C is the thermal capacity, and ρ is the density).[27] For l equal to the transverse dimension of the samples, $t \sim 3\times 10^{-4}$ sec (the values of C and $\varkappa$ for niobium at 4.2 K were taken from Refs. 25 and 28). This quantity is comparable to the registered Φ-variation times. The dependence of the duration of the registered U signals on the depth of the load jumps is apparently connected with the concentration and power of the thermal sources.[27] Notice that multiple twinning and a high level of dissipated energy are characteristic of deep load jumps. Thus, the heat-transfer processes may govern the kinetics of the magnetic-flux variation. The remaining processes governing the kinetics occur either more rapidly, or during comparable times. Let us point out here that the times after which $\partial\Phi/\partial t$ attains a maximum and over which Φ changes appreciably lie in the interval 10^{-6}–10^{-4} sec. The above-presented characteristic times can be used to estimate the velocity of propagation of the twins. It should, however, be borne in mind that, in the case of deep load jumps, substantial thermal perturbations and, consequently, flux motion can arise even at the initial stage of the twin motion. Therefore, the corresponding estimate for the twin velocity in the case of shallow load jumps, when Φ changes only in parts ($v \gtrsim 5\times 10^3$ cm/sec), will be more correct, since for an appreciable change in Φ it is necessary in this case that the twin travel a distance comparable to the sample dimension and a substantial portion of the energy to be dissipated be evolved.

The data on the kinetics of the magnetic-flux variation during the load jumps indicate that the rate of the twinning processes is high. This is also corroborated by the characteristic audible clicks that accompany twinning.[13] The testing machine used did not allow the registration of the true rate of drop of the load if the load jump occurred over a period of time shorter than 0.01 sec. Therefore, to estimate the rate of slip formation, we performed control measurements with the use of piezoelectric transducers under the ends of the test samples. Figure 5b shows the characteristic shape of the pulses registered in these experiments. The beats that can be observed in the background of the registered pulse are, apparently, connected with the natural vibrations in the testing machine-sample system. The registered signals attain their peak after a time $t \sim 10^{-5}$ sec. This time characterizes the rate of deformation at the moment of a load jump, and the corresponding estimate for the velocity of propagation of the twins is $v \gtrsim 5\times 10^4$ cm/sec. This agrees with the data indicating a high velocity for the twin motion.[9,29] The fact that the processes, regardless of their specific nature, occur at a high rate is generally characteristic of abrupt deformation.[1,2,6,7,9,10]

Within the framework of the dislocation mechanism of twinning,[13,30,31] the obtained estimate implies that the twinning dislocations move viscously with velocities approaching the velocity of sound. The available data on the mobility of individual dislocations in decorated niobium[32] yield for the velocity in the range of σ at which twinning occurs values that are lower by many orders of magnitude. In Ref. 9 Show assumes a nondislocation autocatalytic twinning mechanism. Such a mechanism ensures twinning with a velocity close to the velocity of sound. The high rate of formation of the large number of twin layers in the case of deep load jumps can be related with the metastability of the twin nuclei and their actuation under the action of the mechanical perturbations in the samples during the load jumps. At the same time, it should be noted that the problems connected with the twinning mechanisms and the low-temperature mobility of dislocations are at present problems that have not been adequately fully investigated. And only further investigations will allow us to choose the right microscopic mechanism for the high-speed twinning processes.

The data presented in this paper indicate that the cause of the abrupt deformation of niobium is twinning. Heat is released during twinning. In a number of papers[1,6-8,10,11,33,34] the authors treat as the cause of low-temperature abrupt deformation local temperature elevation leading to the formation of dislocation avalanches. In view of this it will be useful to discuss the role of heat release in the low-temperature deformation of the investigated niobium single crystals. If, as in Refs. 6, 8, 10, and 35, we formally estimate the local superheating of niobium in the adiabatic approximation, then the corresponding ΔT values for the regions of slip formation with allowance for their volume and under the assumption that the fraction of heat that can be released is $\alpha \approx 0.15$–0.5 will be 40–70 K and 5–15 K respectively for initial temperatures of 4.2 and 77 K. Even in the adiabatic approximation the superheating in the region of liquid-nitrogen temperatures is not high. On the other hand, the data on the kinetics of the variation of the magnetic flux during load jumps indicate that, in the region of liquid-helium temperatures, the delocalization of the heat occurs over an extremely short period of time, which agrees with the corresponding estimates. For example, over a time $t \sim 10^{-6}$ sec the heat front, according to the estimates, propagates over a distance $l \sim 10^{-2}$ cm, which exceeds the thickness of the twin layers by roughly an order of magnitude. We have no reason to speak of complete localization of the heat even during the very short time intervals corresponding to the motion of the twins with velocities close to the velocity of sound. In the visual observation of the surface of the deformed samples, we, unlike, for example, Klyavin and Nikiforov,[35] failed to observe the boiling up of helium in a region of the slip-formation bands. This is also an indirect confirmation of the rapid delocalization of heat in niobium. Let us, in connection with the discussion of the role of thermal effects in the low-temperature abrupt deformation of niobium, draw attention to the following facts: deep load jumps are accompanied by the production of a large number of twin layers in different regions of the crystal; as the crystal purity is lowered, the depth of the load jumps decreases; the depth of the load jumps do not depend on the deformation temperature in the range 1.6–77 K, the rate of deformation, the state of the superconductor and the ambient helium medium, and the degree of plasticity before the next load jump. The fact that the twinning processes are of a non-heat-activated nature is also indicated by their high rate. Thus, the above-presented data in totality do not allow us to infer a significant role for the released heat in low-temperature twinning processes in niobium. The thermal effects are a consequence, and not the cause, of the twinning of niobium.

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