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NATURE OF LOCALIZATION OF PLASTIC FLOW OF TITANIUM ALLOY 19 UNDER THE CONDITIONS OF ACTIVE DEFORMATION AT 4.2 K

V. N. Nikiforenko and M. E. Bosin

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Consideration is given to a multilevel structural approach to the occurrence of local instability zones under the conditions of active deformation of a superconducting titanium alloy (T_c = 5.4 K). It is noted that the dislocation nanostructural level responsible for the energy activation in dislocation cores and determining the athermic and thermoactive deforming-stress and electrical-resistance jumps is a connecting link between all structural levels.

Keywords: *stepwise change in the deforming stress, electrical resistance, superconducting transition, structural instability levels, high-frequency vibrations.*

Introduction. It is well known [1, 2] that normal-to-superconducting transition is accompanied by the softening of a material. However, the structural approach [3–5] considering plastic flow of a solid material with a local loss of its shearing stability at different scale-structural levels is virtually not taken into account. At the same time, the nature of localization of plastic flow can only be described based on the representation of the deformable body as a multilevel system [5]. The nanostructural dislocation-core level has not been investigated, in practice. In this connection, it is of interest to study the localization of plastic flow of superconducting titanium alloy 19 as a multilevel system under the conditions of active deformation.

Experimental Procedure. At the helium temperature, the titanium alloy containing 6% Al, 2% Zr, and 3% Nb is in a superconducting state with transition temperature $T_c \sim 5.4$ K. The structural state of the samples was investigated using transmission electron microscopy and selective chemical etching. The samples in the initial state had the density of prismatic dislocations $N_p \le 2 \cdot 10^{12}$ m^{-2} and were characterized by β-phase inclusions spaced at intervals of (1.5–3) μm.

Deformation was carried out on an MRK-1 tension testing machine by stretching with a rate of 10^{-4} sec^{-1} at 4.2 K. The dependence $\sigma(t)$ was recorded simultaneously with the change in the electrical resistance, for which purpose a direct current of $i = 0.5$ A was passed through the sample and growth in the electrical resistance according to the compensation scheme was recorded on the recorder in step with the $\sigma(t)$ curve (Fig. 1). To avoid inertial effects that are universally present when recorders are used, we also used a fast procedure intended for obtaining oscillograms in the case of a sharp increase in ΔR of the sample at the instant of suppression of the load (Fig. 2). Growing heat release, which can cause $\Delta\sigma$ and ΔR to grow, is possible with increase in the deforming stress. To record a probable local release of heat in the samples in active loading under the conditions of helium temperatures, we used thermometers with a resolving power of $2 \cdot 10^{-2}$ K, which were placed in special cuts on the sample's working section.

Experimental Results and Their Discussion. The experiment has shown that when the titanium alloy under the conditions of helium temperatures (4.2 K) is deformed, suppressions of the load and jumps of the electrical resistance occur simultaneously (in step) (Fig. 1). It was noted that the jumps of $\Delta\sigma$ and ΔR are accompanied by the formation of prismatic-slip bands (first scale microlevel of the order of 10 μm). The bands consist of prismatic-dislocation clusters (second scale microlevel of the order of 0.1 μm) bounded by obstacles in the form of the β phase, whose break is responsible for the $\Delta\sigma$ and ΔR jumps. The density of the prismatic dislocations corresponds to $N_p \le 2 \cdot 10^{14}$ m^{-2}.

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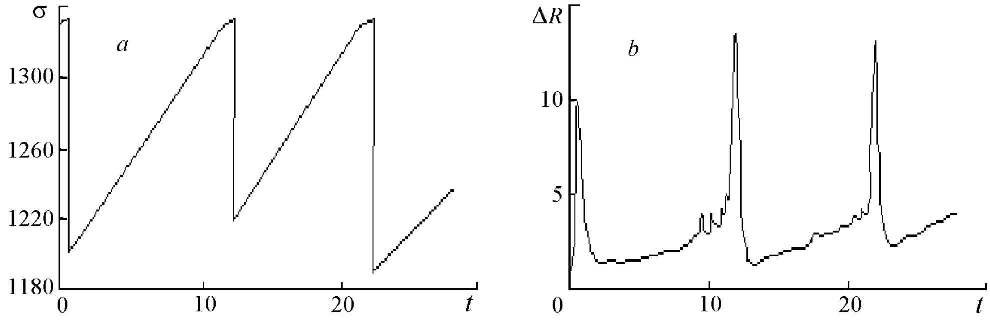

Fig. 1. Correlation between the suppressions (a) of deforming stress and the jumps of electrical resistance (b) of titanium alloy under the conditions of active deformation according to the inertial procedure. ΔR and t, arbitrary units.

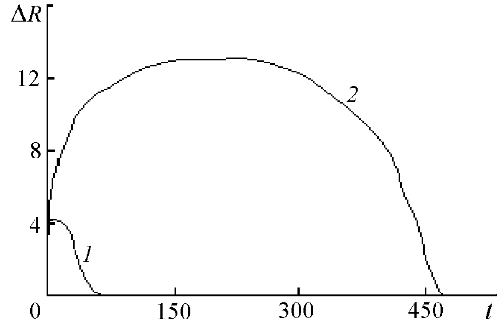

Fig. 2. Characteristic oscillograms of the electrical-resistance jumps initiated by small (1) ($\Delta\sigma_a$ = 1.5 MPa) and large (2) $\Delta\sigma_a$ = 163 MPa) deforming-stress jumps (inertialess procedure resolving a fine ΔR structure). ΔR, Ω; t, 10^{-3} sec.

It was established that the amplitude value of the jump of the electrical resistance is dependent on the level of the deforming-stress jump (Fig. 2) and varies from $\Delta R_{a1} \approx 4\cdot10^{-3}$ Ω to $\Delta R_{a2} \approx 1.3\cdot10^{-2}$ Ω. Small $\Delta\sigma$ and ΔR jumps first appear and initiate the appearance of large $\Delta\sigma$ and ΔR peaks.

The available temperature dependence $R(T)$ (Fig. 3) of the 19 alloy near the superconducting transition enables us to determine the change in the temperature ΔT with maximum increase in the electrical resistance in the jump: $\Delta R_a = 1.3\cdot10^{-2}$ Ω. In this case we have ΔT = 1.2 K and the sample is in a mixed state. When the sample is in a superconducting state, small athermic resistance peaks are most probably due to the electron-electron ($\overline{e}$–$\overline{e}$) interaction (third scale level of the order of 10^{-2} μm).

It can be assumed that stepwise deformation in titanium alloy 19 in the case of $\overline{e}$–$\overline{e}$ interaction is realized within the framework of a dynamic hypothesis [2] according to which obstacles in the superconducting state, because of the undamped dislocations, are overcome owing to inertial effects. However, this assumption calls for refinements when considering the high-frequency features of the behavior of dislocation clusters at low temperatures [6].

The experiments have shown that the maximum change in the temperature at the moment of the $\Delta\sigma$ jump does not exceed 0.8 K. This result enables us to evaluate the contribution of the thermal stresses

$$\sigma_t = E_m \Delta\alpha \Delta T \tag{1}$$

to the total change $\Delta\sigma_a$ = 162 MPa determined experimentally.

When E_m = 1350 MPa, $\Delta\alpha = 2\cdot10^{-6}$ K^{-1}, and ΔT = 1 K, for σ_t, we obtain $\sigma_t = 3\cdot10^{-3}$ MPa, i.e., $\Delta\sigma_a >> \sigma_t$, which points to the small contribution of thermal stresses to the observed minimum change $\Delta\sigma_a$.

As the temperature increases by a value of the order of 1 K, we should expect the activation of electron-phonon ($\overline{e}$–$\overline{\nu}$) interaction (scale level of the order of $3\cdot10^{-2}$ μm), which presumably gives rise to resistance peaks of to $1.3\cdot10^{-2}$ Ω. Evaluations of the thermal effect under the assumption that the process of deformation is adiabatic give different values of warmup temperatures depending on the degree of localization of the deformation: from units to 225

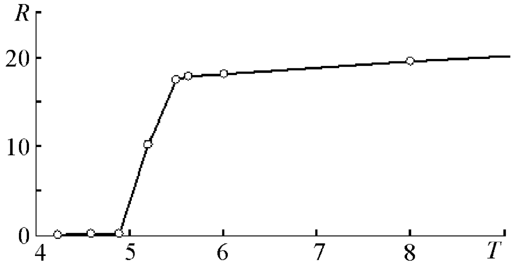

Fig. 3. Temperature dependence of the electrical resistance of titanium alloy 19 near the superconducting transition (dots, experiment). ΔR, Ω; T, K.

K [7]. It is precisely the thermal mechanism of occurrence of the instability of low-temperature deformation that is the most developed and consistent with experiment at present [1, 7–9].

The behavior of dislocations in the case of both electron-electron and electron-phonon interactions is related to the presence, in them, of the electric potential [6] acting at large distances and caused by the distortions of the crystal lattice within the dislocation cores (fifth scale level of about 10^{-9} m, i.e., the nanolevel); these distortions give rise to high-frequency modes whose vibration frequency can be evaluated from the expression

$$\nu_d = \left(ne^2 \Delta R_a \rho_0\right) / (mR_0)\,, \tag{2}$$

where $n = 24 \cdot 10^{28}$ m^{-3}, $e = 1.602 \cdot 10^{-19}$ C, $\rho_0 = 2 \cdot 10^{-8}$ Ω·m, $m = 9.1 \cdot 10^{-31}$ kg, and $R_0 = 2.4 \cdot 10^{-4}$ Ω.

Growth in the additional electrical resistance is determined by the change in the dislocation potential and the frequency ν_d of the interaction; for large resistance peaks, it enables us to infer that $\bar{e}$–$\bar{\nu}$ interaction is the controlling mechanism in this case. The performed evaluations show that for $\Delta R_a = 1.3 \cdot 10^{-2}$ Ω, the frequency $\nu_d = 8 \cdot 10^{15}$ Hz corresponds to the plasma vibration frequency. The role of the frequency factor is considered [1] in partial undamping of dislocations in a superconductor with the resulting growth in ν_d. It is desirable to allow for the influence of the electron-gas viscosity on the process of overcoming of potential barriers by dislocations using thermal fluctuations. The mentioned mechanisms determine one dependence of ν_d or another on the coefficient of damping B. In turn, as has been mentioned in [6], the electron-gas viscosity is related to the change in the dislocation potential and ν_d.

Noteworthy is the fact that irrespective of the type of interaction, even at $\Delta T > 300$ K, the relation

$$h\nu_d >> k\Delta T\,, \tag{3}$$

which points to the dominance of quantum effects within the dislocation cores in the observed phenomenon, holds. Since the interactions of the electron and phonon subsystems with the dislocations [10] can only be described within the framework of quantum representations, evaluation of the maximum quantum change in the electrical resistance

$$\Delta R_a = \left(h\nu_d^2\right) / i^2\,, \tag{4}$$

where $i = 0.5$ A, $\nu_d = 8 \cdot 10^{15}$ Hz, and $\Delta R_a = 2 \cdot 10^{-2}$ Ω, is of interest.

Thus, there are grounds to assume that the basic factors determining the characteristics of the $\Delta\sigma_a$ and ΔR_a jumps are related to the change in the dislocation potential and the quantity ν_d. Titanium alloy 19 dislocations, which represent, in the initial state, a charged high-frequency wave packet of the terahertz range, might be characterized by the resonance interaction with each other and with conduction electrons in the process of breaking through the obstacles.

The maximum energy released in the jump of plastic flow is determined by the formula

$$\Delta E_a = \Delta R_a i^2 t\,. \tag{5}$$

We emphasize that at $\Delta R_a = 1.3 \cdot 10^{-2}$ Ω (see Fig. 2, curve 2), $i = 0.5$ A, and $t = 225 \cdot 10^{-3}$ sec, we have $\Delta E_a = 7.4 \cdot 10^{-4}$ J, which enables us to successfully overcome the Coulomb barrier even in the case of heavy atomic nuclei and corresponds to a probable appearance of "heavy" solitons in the form of boson quasiparticles, which has been demonstrated in [11]. Furthermore, the release of an energy of $7.4 \cdot 10^{-4}$ J is quite sufficient to activate interaction mechanisms within dislocation cores.

In cryogenic treatment of materials by electric-current pulses [12–14], it is possible to transfer an energy of 10^3 J per second [13]; this is comparable to the limiting energy level for electrons, which is attainable in linear elementary-particle accelerators. When a solid body is treated, a special role in this process must be allocated to the electron-dislocation mechanism and its related electron-soliton mechanism of interaction. A theoretical approach to consideration of dislocations as soliton sources, undertaken in solving a number of dislocation problems [15], can be used for the experimental detection of solitary waves in a solid body, which was done in [6].

The multilevel nature of localization of plastic flow of 19 titanium alloy, which has been described in the present work, exhibits the properties of dislocations as probable sources of solitons (whose particular form is bosons); they can enjoy wide application based on a possible control of the electric field, which is localized on the dislocations and can accelerate electrons and ions.

Conclusions. Thus, localization of titanium-alloy 19 plastic flow under the conditions of active deformation at 4.2 K can be considered within the framework of the shear-related nanostructural transformation in the alloy, which can ultimately change the electron-phonon interaction in the shear zone. Localization of plastic deformation is an unusual kind of structural-phase transformation that occurs predominantly in the quantum regime. In this case the quantum regime of atomic interaction can exceed, at a maximum, the growth in the $\overline{e}$–$\overline{\nu}$ interaction at the instant the shearing stability is lost in the local zone of the slip band. Consequently, a multilevel description of the phenomenon requires that disturbances be allowed for not only in the case of electron-phonon interaction in the electron subsystem but also in electron-nucleus interaction realized in dislocations.

NOTATION

B, coefficient of damping, MPa·sec; E_m, Young's modulus; e, electron charge, C; $\overline{e}$–$\overline{e}$, electron-electron interaction; $\overline{e}$–$\overline{\nu}$, electron-phonon interaction; i, direct current, A; k, Boltzmann constant, J/K; h, Planck constant, J/sec; m, electron mass, kg; N_p, density of prismatic dislocations, m^{-2}; n, concentration of electrons, m^{-3}; R, electrical resistance, Ω; R_0, electrical resistance of the sample before deformation, Ω; T, temperature, K; T_c, superconducting-transition temperature, K; t, propagation time, sec; ΔE_a, maximum energy in the plastic-flow jump, J; β, new-phase inclusions; $\Delta\alpha$, change in the coefficient of thermal expansion, K^{-1}; $\Delta\sigma$, change in the deforming stress, Ω; $\Delta\sigma_a$, change in the deforming-stress jump, MPa; ΔR, change in the electrical resistance, Ω; ΔR_a, maximum change in the electrical resistance in a jump, Ω; ΔT, change in the temperature, K; $\sigma(t)$, cold hardening, MPa; σ, deforming stress; σ_t, thermal stresses, MPa; ν_d, frequency of dislocation vibrations, Hz; ρ_0, specific resistance of the sample in the initial state, Ω·m. Subscripts: a, amplitude value; c, critical; d, dislocation; m, modulus; p, prismatic; t, thermal; 0, initial state.

REFERENCES

1. G. A. Malygin, Influence of the superconducting state on the thermal instability of the plastic deformation of crystals at low temperatures, *Fiz. Tverd. Tela*, **40**, No. 10, 1778–1784 (1998).
2. V. V. Pustovalov, Influence of the superconducting transition on the low-temperature jumpwise deformation of metals and alloys, *Fiz. Nizk. Temp.*, **26**, No. 6, 515–535 (2000).
3. V. E. Panin (Ed.), *Physical Mezomechanics and Computer Construction of Materials* [in Russian], in 2 vols., Vols. 1, 2, Nauka, Novosibirsk (1995).
4. M. E. Bosin, F. F. Lavrent'ev, and V. N. Nikiforenko, On localization of plastic deformation in zinc crystals with the dislocation tree, *Fiz. Tverd. Tela*, **38**, No. 12, 3619–3623 (1996).
5. V. E. Panin, V. E. Egorushkin, A. V. Panin, and D. D. Moiseenko, Nature of the localization of the plastic deformation of solids, *Zh. Tekh. Fiz.*, **77**, No. 8, 62–68 (2007).
6. V. N. Nikiforenko and F. F. Lavrent'ev, Basic features that determine the change in the microcontact spectra and are caused by dislocations, *Dokl. Ross. Akad. Nauk*, **373**, No. 2, 178–180 (2000).

7. V. V. Shpeizman, V. I. Nikolaev, B. I. Smirnov, A. B. Lebedev, and V. I. Kopylov, Low-temperature deformation of nanocrystalline niobium, *Fiz. Tverd. Tela*, **42**, No. 6, 1034–1037 (2000).
8. V. V. Shpeizman, V. I. Nikolaev, N. N. Peschanskaya, B. I. Smirnov, I. A. Aleksandrov, N. A. Enikeev, V. U. Kalykhanov, and A. A. Nazarov, Laws governing the low-temperature plasticity of nanocrystalline titanium and copper, *Fiz. Tverd. Tela*, **79**, No. 4, 644–649 (2007).
9. V. I. Nikolaev, V. V. Shpeizman, and M. V. Sukhanova, Local heating during deformation in the region of helium temperatures and its measurement with the aid of strain gauges, *Fiz. Tverd. Tela*, **50**, No. 3, 417–420 (2008).
10. V. I. Al'shits and V. L. Indenbom, Dynamic retardation of dislocations, in: *Dynamics of Dislocations* [in Russian], Naukova Dumka, Kiev (1975), pp. 232–275.
11. V. N. Nikiforenko and M. E. Bosin, On the problem of experimental detection of the Planck wavelength in a solid body, in: *Proc. 11th Int. Conf. "St. Petersburg Readings on the Problems of the Strength and Growth of Crystals"* [in Russian], Vol. 2, St. Petersburg (2008), pp. 204–205.
12. V. N. Nikiforenko, I. S. Braude, O. P. Salita, and V. G. Khomenko, Change in the structural state of titanium in electrical heating in liquid nitrogen, *Inzh.-Fiz. Zh.*, **66**, No. 2, 93–96 (1994).
13. V. N. Nikiforenko, F. F. Lavrent'ev, I. S. Braude, and O. P. Salita, Electrothermal action on the ABM-1 alloy in the medium of liquid nitrogen, *Probl. Prochn.*, No. 2, 90–92 (1996).
14. V. N. Nikiforenko, F. F. Lavrent'ev, I. S. Braude, and O. P. Salita, Formation of the structural state in certain structural materials as a result of electric-current processing at 77 K, *Dokl. Ross. Akad. Nauk*, **349**, No. 4, 472–474 (1996).
15. A. M. Kosevich and A. S. Kovalev, *Introduction to Nonlinear Physical Mechanics* [in Russian], Naukova Dumka, Kiev (1989).