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Influence of fast dynamics effects on resonant ultrasonic vibrations of polycrystalline metal rods

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A theoretical model for the formation of ultrasonic signals in metallic microcrystalline rods taking into account the metastable behavior of their defective states is proposed. The influence of metastable states of the defective structure of samples on the features of changes in their resonant frequencies in ultrasonic experiments of fast dynamics is analyzed. The decrease in Young's modulus in such processes is explained. The correspondence between theoretical and experimental data is demonstrated for the example of resonant acoustic vibrations of rods made of aluminum alloy D16.

Keywords: nonlinear resonant ultrasonic spectroscopy, defect structure, mechanical stresses, effects of fast and slow dynamics.

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In materials with a complex rheological structure, the dynamic deformation processes, acoustic vibrations, and propagation of elastic waves are often characterized by the appearance of special mechanical properties that cannot be explained by the conventional elasticity theory. One of the important directions in the study of dynamic mechanical processes in such materials is successfully developed within the framework of various relaxation models [1,2]. We shown [3,4] that consideration of relaxation processes makes it possible to correctly describe the experimental data obtained in the study of vibrations of thin aluminum membranes excited by time-modulated optical radiation. This approach also made it possible to explain the behavior of laser ultrasonic signals in stressed samples made of D16 aluminum alloy [5,6].

In the paper [7], the effects of fast and slow dynamics in metal rods made of D16T microcrystalline aluminum alloy were studied using methods of nonlinear resonant ultrasonic spectroscopy. It was shown that in samples with introduced mechanical stresses, noticeable effects of fast and slow dynamics occur, they are associated with the presence in them of metastable states of the defect structure and leading to their elastic modulus dependence on the amplitude of elastic vibrations. In the paper [7] experimental data were obtained confirming the presence of fast and slow dynamic processes in samples in the D16T alloy. The detected change in the resonant frequency of elastic vibrations of the deformed rod was explained by the change in the effective Young's modulus of the material, since its density remained constant. It seems appropriate to supplement the experimental results of the paper [7] with a theoretical justification of the Young's modulus change in the model proposed by us earlier [3–6] to explain the behavior features of laser ultrasonic signals from stressed samples of D16 alloy. At the same time, in the framework of this study, we limit ourselves by discussion of processes of fast dynamics only.

The paper [8] shown that the free energy of body change in the presence of defects in it during deformation is determined by the value $\Omega E \Delta n \varepsilon_{kk}$, where Ω is defect activation volume, E is Young's modulus, Δn is change in defects concentration upon excitation of elastic vibrations, ε_{kk} is first strain tensor invariant. In the simplest one-dimensional model the effect of metastable defects on the longitudinal vibrations of the rod can be described by the equation of motion

$$\rho \frac{\partial^2 \varepsilon_e}{\partial t^2} = E \frac{\partial^2 \varepsilon_e}{\partial x^2} + E\Omega \frac{\partial \Delta n}{\partial x}, \qquad (1)$$

where ρ is density of the rod material, ε_e is elastic deformation, t is time, x is coordinate along the rod axis.

In the general case, equation (1) is nonlinear due to the possible defect concentration dependence on internal stresses, which in the simplest case is determined by the Arrhenius law [9,10]. This dependence in linear approximation allows us to introduce the effective Young's modulus.

To determine the nature of the change of internal stresses and the effective Young's modulus of the sample, we use the results of the papers [11,12] taking into account the weak relaxation of stresses in the absence of external action [13]. In the paper [7] internal stresses were introduced into the rod based on D16T alloy by twisting one of the ends, after which the sample was subjected to elastic harmonic deformation $\varepsilon_e = \varepsilon_m \sin \omega t$, and its resonant frequency change was recorded with a change in the amplitude of elastic oscillations. The experimental diagram of oscillations excitation is shown in Fig. 1. The dynamics of stress changes in the sample under such conditions can be described by the equation

$$\frac{1}{E}\frac{\partial\sigma}{\partial t} = \dot{\varepsilon}_e - \dot{\varepsilon}_p = \varepsilon_m \omega \cos\omega t - \dot{\varepsilon}_0 \exp\left(-\frac{U - \Omega(\sigma - \sigma_p^{(0)})}{k_{\mathrm{B}}T} - \frac{t}{\tau}\right), \quad (2)$$

where $\dot{\varepsilon}_p$ is rate of change of material plastic deformation, U is activation energy of metastable defects, τ is stress free relaxation time, $\sigma_p^{(0)}$ is internal stress in the sample at the initial moment of time, the pre-exponential factor $\dot{\varepsilon}_0$ is assumed to be stress-independent, k_{B} is Boltzmann constant, T is sample temperature.

Equation (2) can be represented as follows

$$\sigma(t) = E\varepsilon_m \sin\omega t + \sigma_p^{(0)} + \Delta\sigma_p(t), \quad (3)$$

where

$$\Delta\sigma_p(t) = -\frac{k_{\mathrm{B}}T}{\Omega}\ln\left[1 + \frac{\Omega E}{k_{\mathrm{B}}T}\dot{\varepsilon} \times \int_0^t \exp\left(\frac{\Omega E}{k_{\mathrm{B}}T}\varepsilon_m \sin\omega t' - \frac{t'}{\tau}\right)dt'\right],$$

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{U}{k_{\mathrm{B}}T}\right).$$

Expression (3) shows that the rate of internal stresses decreasing in the sample depends on the external harmonic effect in accordance with the acoustoplastic effect [11–13]. The presence of relaxation processes in the sample material affects the nature of stress decreasing.

We will assume that upon elastic vibrations excitation a quasi-equilibrium concentration of defects has time to be established in the sample. Then the concentration change of excited defect centers under the action of external harmonic excitation on the sample can be estimated from the relation

$$\Delta n \cong N\left[\exp\left(-\frac{U - \Omega(\sigma_p^{(0)} + \Delta\sigma_p + \sigma_e)}{k_{\mathrm{B}}T}\right) - \exp\left(-\frac{U - \Omega(\sigma_p^{(0)} + \Delta\sigma_p^{(0)} + \sigma_e)}{k_{\mathrm{B}}T}\right)\right], \quad (4)$$

where N is value of the order of the atoms concentration in the sample material, $\Delta\sigma_p^{(0)}$ is change in time of stress in the sample in the free relaxation mode ($\varepsilon_m = 0$).

When the condition $\Omega E\dot{\varepsilon}\tau < k_{\mathrm{B}}T$ is met, using equalities (3) and (4) for the excited defects concentration, we obtain the expression

$$\Delta n \cong N'\frac{\Omega E}{k_{\mathrm{B}}T}\dot{\varepsilon}\tau\left[1 - \exp\left(-\frac{t}{\tau}\right) - \frac{1}{\tau}\int_0^t \exp\left(\frac{\Omega E}{k_{\mathrm{B}}T}\varepsilon_m \sin\omega t' - \frac{t'}{\tau}\right)dt'\right]\exp\left(\frac{\Omega\sigma_e}{k_{\mathrm{B}}T}\right), \quad (5)$$

where $N' = N\exp\left(-(U - \Omega\sigma_p^{(0)})/k_{\mathrm{B}}T\right)$.

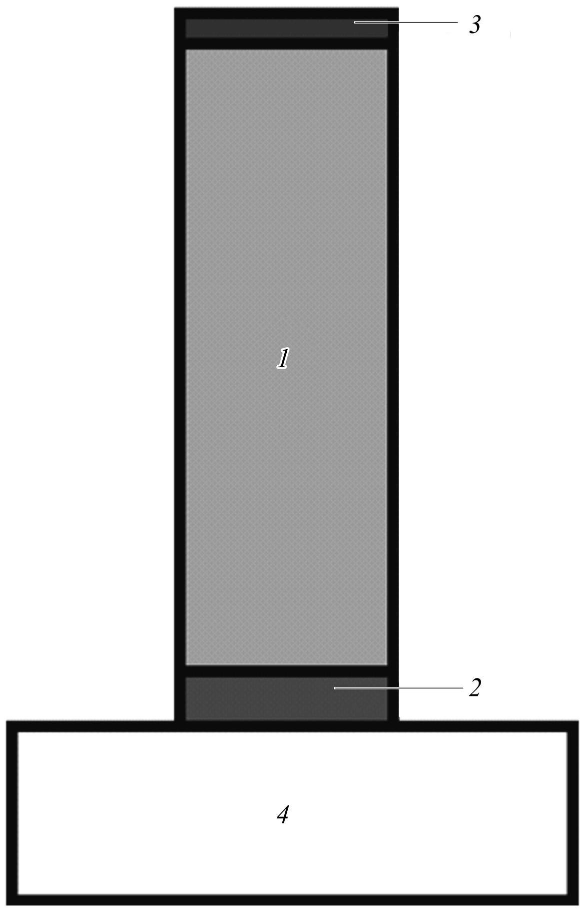

Figure 1. Diagram of excitation and registration of elastic vibrations of the rod [7]. *1* — sample, *2* — exciting piezoceramic transducer, *3* — piezoceramic oscillation detection sensor, *4* — massive base.

The activation volume of the defect is usually commensurate with the volume of the crystal lattice of the material [14], which for aluminum is $6.6 \cdot 10^{-29}\,\mathrm{m}^3$. With this value of the activation volume, the inequality $\Omega E\dot{\varepsilon}\tau < k_{\mathrm{B}}T$ for the D16T alloy is met for $\dot{\varepsilon}\tau < 10^{-3}$. Estimates show that for D16T at defects concentration $\Delta n \leqslant 10^{26}\,\mathrm{m}^{-3}$, the exponent in expression (5) can be expanded into a series. Under these conditions, at $N'\Omega < 10^{-3}$ the inequality $N'\Omega(\Omega E)^2\dot{\varepsilon}\tau < (k_{\mathrm{B}}T)^2$ is also satisfied, which, in the approximation linear in $\Omega E\varepsilon_e/k_{\mathrm{B}}T$, allows us to reduce the equation of motion to the form

$$\rho\frac{\partial^2\varepsilon_e}{\partial t^2} = E_{eff}(t)\frac{\partial^2\varepsilon_e}{\partial x^2}, \quad (6)$$

where

$$E_{eff}(t) \cong E\left[1 + N'\Omega\left(\frac{\Omega E}{k_{\mathrm{B}}T}\right)^2\dot{\varepsilon}\tau\left(1 - \exp\left(-\frac{t}{\tau}\right) - \frac{1}{\tau}\int_0^t \exp\left(\frac{\Omega E}{k_{\mathrm{B}}T}\varepsilon_m \sin\omega t' - \frac{t'}{\tau}\right)dt'\right)\right].$$

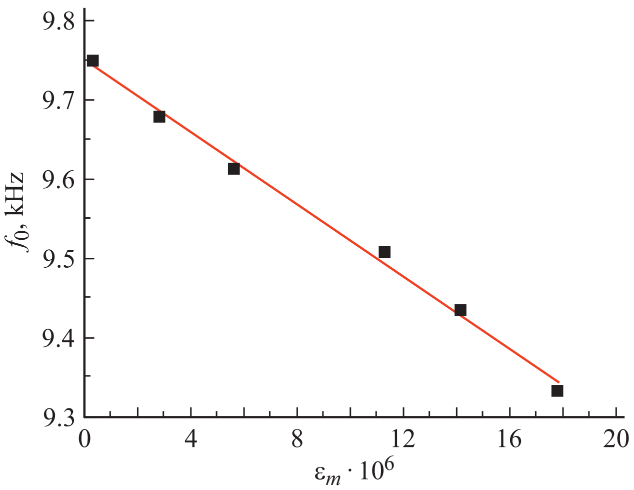

Figure 2. Resonant frequency vs. amplitude of longitudinal deformation. The experimental points are based on the data of the paper [7]. A straight line is the result of a linear approximation.

Korobov et al. [7] experimentally investigated the nature of the frequency change of resonant oscillations of D16T rods in the mode of fast dynamics of relaxation processes. It was found that long-term exposure to harmonic oscillations leads to the resonant frequency stabilization of the rods, and with the oscillation amplitude increasing this frequency decreases. Calculation of the integral in $E_{eff}(t)$ at $t \to \infty$ within the accuracy of terms linear in ε_m leads to the expression

$$E_{eff}(t \to \infty) \cong E\left[1 - N'\Omega\left(\frac{\Omega E}{k_B T}\right)^3 \dot{\varepsilon}\tau \frac{\omega\tau}{1+(\omega\tau)^2}\varepsilon_m\right]. \tag{7}$$

In paper [7] the samples were excited in the mode of a quarter-wave elastic resonator. Its first resonant frequency is given by $f_0 = \sqrt{E/\rho}/(4L)$, where ρ is density, L is sample length. If we assume that during the experiments the density and length of the samples did not change, then the influence of the effects of fast dynamics on the resonant frequency of the samples can be estimated using this equality at $E = E_{eff}$. Together with expression (7), it allows one to determine the shift of the resonant frequency of the samples at large times in the approximation linear in the oscillation amplitude ε_m

$$\Delta f_m \cong -\frac{1}{8L}\sqrt{\frac{E}{\rho}}\Omega N'\left(\frac{\Omega E}{k_B T}\right)^3 \dot{\varepsilon}\tau \frac{\omega\tau}{1+(\omega\tau)^2}\varepsilon_m. \tag{8}$$

Expression (8) shows that the amplitude increasing of elastic vibrations of rods with defective states leads to their resonant frequency decreasing. The result obtained corresponds to the experimental data of paper [7]. Fig. 2 shows the resonant frequency dependence on the amplitude of the longitudinal deformation of the rod. This dependence is close to linear with a slope coefficient of $-24\,\mathrm{Hz}\cdot\mathrm{m}/\mu\mathrm{m}$. In accordance with the estimates made above and expression (8), such a change in the resonant frequency of the rod corresponds to relaxation times 10^{-5}–10^{-6} s at $\rho = 2700\,\mathrm{kg/\,m^3}$, $L = 140\,\mathrm{mm}$, $E = 71\,\mathrm{GPa}$, $N'\Omega \approx 10^{-3}$. This estimate for the relaxation time correlates well with the value obtained by us in experiments on laser generation of ultrasound in stressed samples D16 [3,5,6].

The proposed theoretical model makes it possible to explain the effects of fast dynamics in metal rods with defects. It relates the dynamics of the material Young's modulus change in time with such characteristics of its defective subsystem as the concentration of defects, their relaxation time, and activation volume.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] J.Y. Yoritomo, R.L. Weaver, Phys. Rev. E, **102**, 012901 (2020). DOI: 10.1103/PhysRevE.102.012901
[2] J. Kober, A. Kruisova, M. Scalerandi, Appl. Sci., **11**, 8631 (2021). DOI: 10.3390/app11188631
[3] A.L. Glazov, K.L. Muratikov, Tech. Phys. Lett., **46** (5), 477 (2020). DOI: 10.1134/S1063785020050223.
[4] A.L. Glazov, K.L. Muratikov, J. Appl. Phys., **128**, 095106 (2020). DOI: 10.1063/5.0013308
[5] A.L. Glazov, K.L. Muratikov, Phys. Rev. B, **105**, 214104 (2022). DOI: 10.1103/PhysRevB.105.214104
[6] A.L. Glazov, K.L. Muratikov, J. Appl. Phys., **131**, 245104 (2022). DOI: 10.1063/5.0088327
[7] A.I. Korobov, N.I. Odina, D.M. Mekhedov, Acoust. Phys., **59** (4), 387 (2013). DOI: 10.1134/S106377101304009X.
[8] A.M. Kosevich, *Fizicheskaya mekhanika real'nykh kristallov* (Nauk. dumka, Kiev, 1981). (in Russian).
[9] S.N. Zhurkov, Int. J. Fract., **1**, 311 (1965). DOI: 10.1007/BF03545562
[10] S.N. Zhurkov, V.E. Korsukov, J. Polym. Sci. Polym. Phys., **12** (2), 385 (1974). DOI: 10.1002/pol.1974.180120211
[11] A.V. Kozlov, S.I. Selitsen, Mater. Sci. Eng. A, **102**, 143 (1988). DOI: 10.1016/0025-5416(88)90568-X
[12] G.A. Malygin, Phys. Solid State, **42** (1), 72 (2000). DOI: 10.1134/1.1131170.
[13] A.V. Kozlov, S.I. Selitsen, Mater. Sci. Eng. A, **131**, 17 (1991). DOI: 10.1016/0921-5093(91)90340-S
[14] F.Kh. Mirzoev, V.Ya. Panchenko, L.A. Shelepin, UFN, **166** (1), 3 (1996). (in Russian). DOI: 10.3367/UFNr.0166.199601a.0003 [F.Kh. Mirzoev, V.Ya. Panchenko, L.A. Shelepin, Phys. Usp., **39** (1), 1 (1996). DOI: 10.1070/PU1996v039n01ABEH000125].