Dislocation mechanisms of low temperature acoustic relaxation and plastic deformation of a high-entropy alloy $Al_{0.5}CoCrCuFeNi$

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INTRODUCTION:

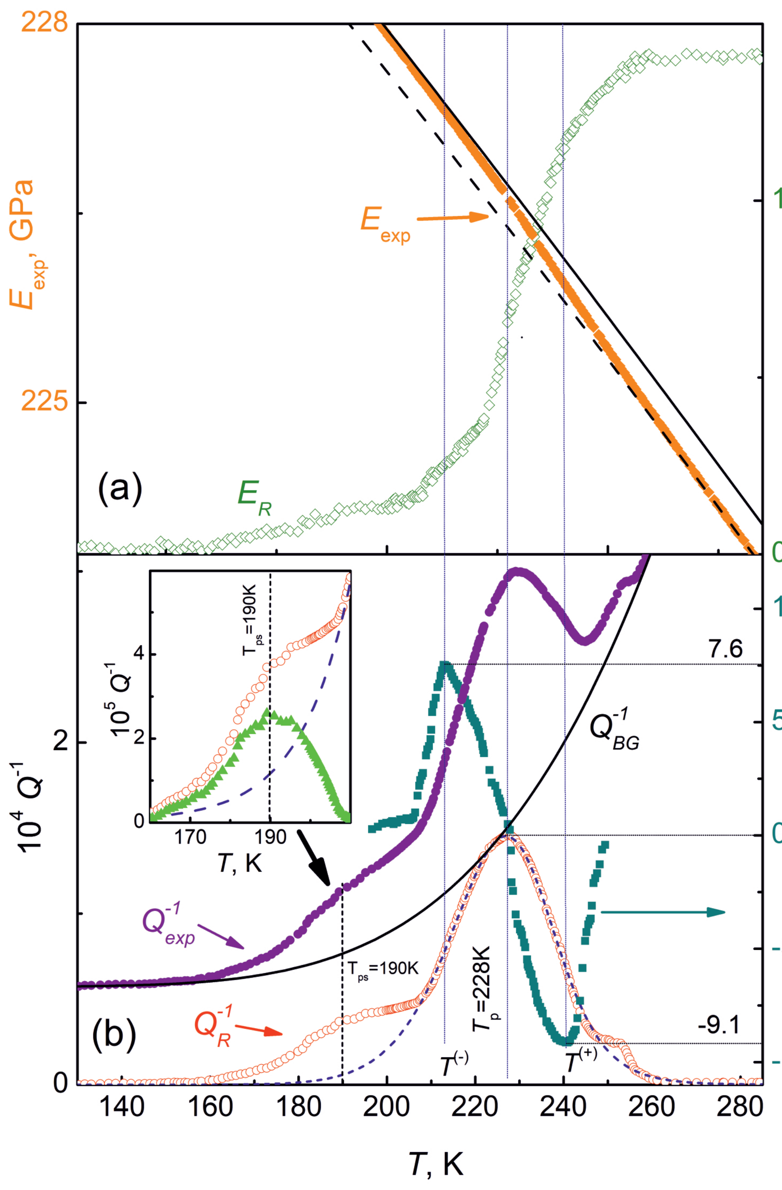
High-entropy alloys (HEA) are solid-state metal systems of five or more components with a concentration close to equiatomic, developed at the beginning of the 21st century [1]. Such alloys are characterized by increased mixing entropy values compared to traditional multicomponent alloys, which explains their name. The significant contribution of the entropy of mixing during the formation of HEAs significantly increases the probability of realizing substitutional solid solutions with simple crystal lattices, while such lattices are significantly distorted, since they are formed by atoms of dissimilar elements with different electronic structures and sizes [2]. Thanks to these features of HEAs, their physical and mechanical properties differ significantly from the properties of traditional alloys; they have a favourable combination of strength and ductility, and high resistance to thermal and mechanical influences [2].

The main goal of this study is to compare the mechanical properties of HEAs and traditional alloys, as well as to discuss the possibility of using the fundamental principles of modern dislocation theory, which were previously formed in the study of the plasticity and strength of traditional crystalline materials, to interpret these properties. The relationship between the acoustic and mechanical properties of $Al_{0.5}CoCrCuFeNi$ HEAs and the features of the dynamics and kinetics of elementary dislocation processes has been analyzed.

EXPERIMENTAL METHODS:

Data from two different experimental methods were used with different intensities of influence on the dislocation structure in the alloy samples under study:

- method of resonant mechanical spectroscopy – excitation in samples of elastic-plastic deformations with an amplitude of $\sim10^{-7}$, caused by short segments of dislocation strings (dislocation relaxers), which oscillate with amplitudes on the order of the lattice parameter;
- method of active deformation, which is used to achieve fairly large plastic deformations $\sim3\cdot10^{-1}$, caused by the translational movement of extended dislocations over macroscopic distances.



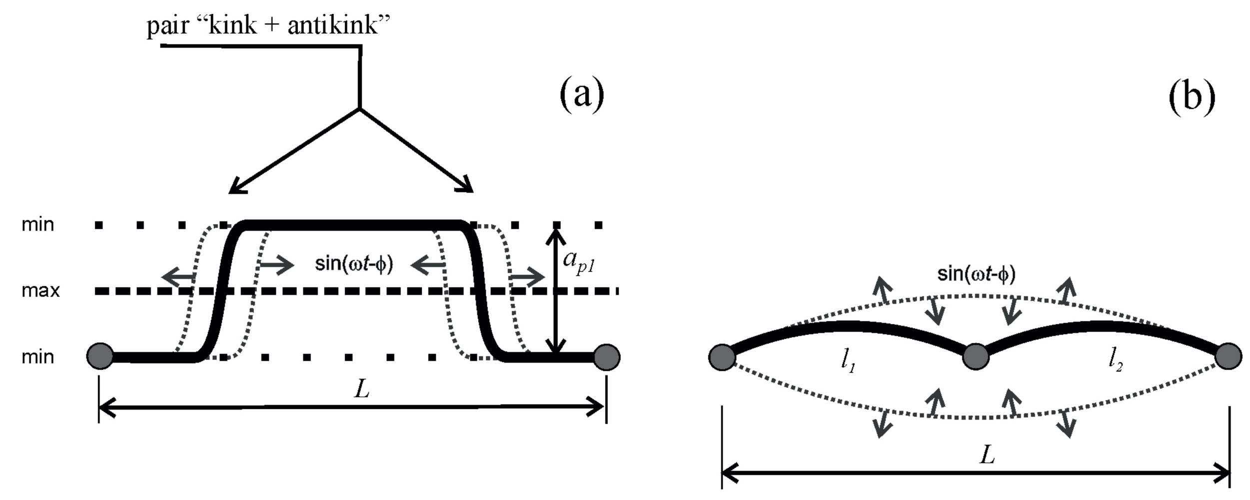
Relaxation resonances in the $Al_{0.5}CoCrCuFeNi$ alloy in the structural state (**II**) [4]: a) temperature dependence of dynamic Young's modulus: ♦ - $E_{exp}(T)$, ◊ - $E_R(T)$; b) temperature dependence of internal friction: ● - $Q^{-1}_{exp}(T)$, ○ – $Q^{-1}_R(T)$. Solid lines show the background of the dynamic modulus E_0-$E_{BG}(T)$ – and the absorption background $Q^{-1}_{BG}(T)$: these graphs are built on the basis of formulas (1). In Fig.(b) also shows the results of numerical differentiation of resonant absorption near temperature T_p: ■ - $\frac{\partial}{\partial T}Q^{-1}_R(T,\omega)$. The dotted lines are drawn through the inflection points $T^{(-)}$, $T^{(+)}$ and the top of the peak T_p=228K, and the dashed line shows the theoretical dependence calculated according to formula (2).
The inset in Fig.1b shows: ○ – resonant component of internal friction $Q^{-1}_R(T)$; the dashed line shows the approximation $\langle Q^{-1}_R(T)\rangle$ for low temperature peak slope T_p=228K; ▲ – absorption peak satellite T_{ps}=190K.

$$\frac{E_{BG}(T,\omega)}{E_0(\omega)} = \beta\cdot T\exp\left(-\frac{T_\eta}{T}\right);\quad Q^{-1}_{BG}(T) = A_1 + A_2\exp\left(-\frac{U_{BG}}{k_B T}\right) \qquad (1)$$

$$\left\langle Q^{-1}_R\right\rangle = Q^{-1}_R(T,\omega;\theta_0,U_0,D) = C_r\Delta_0\int_0^\infty dU P(U;U_0,D)F^{D,K-H}(\omega\theta) \qquad (2)$$

$$P(U;U_0,D) = \frac{C(D)U}{\sqrt{2\pi}U_0 D}\exp\left[-\frac{(U-U_0)^2}{2D^2}\right]$$

$$K = \frac{\max\frac{\partial}{\partial T}Q^{-1}_R(T,\omega)}{\left|\min\frac{\partial}{\partial T}Q^{-1}_R(T,\omega)\right|}$$



Schematic representation of an elementary relaxer:
(a) – Seeger relaxation; (b) – relaxation Koiwa and Hasiguti;

● – local defects on the dislocation string; the symbol L denotes the length of the dislocation segment, the activation of which determines the elementary contribution of the dislocation to the acoustic resonance or the rate of plastic deformation.

$$F^D(x) = \frac{x}{1+x^2},$$

$U_0\sim0.1\text{eV},\ \theta_0\sim10^{-11}\text{s},\ C_r\Delta_0\sim10^{-1}\rho_L L^3$

$$\left[\frac{E_0}{E_{R0}}\cdot\max Q^{-1}_R\right]^D = 0.5$$

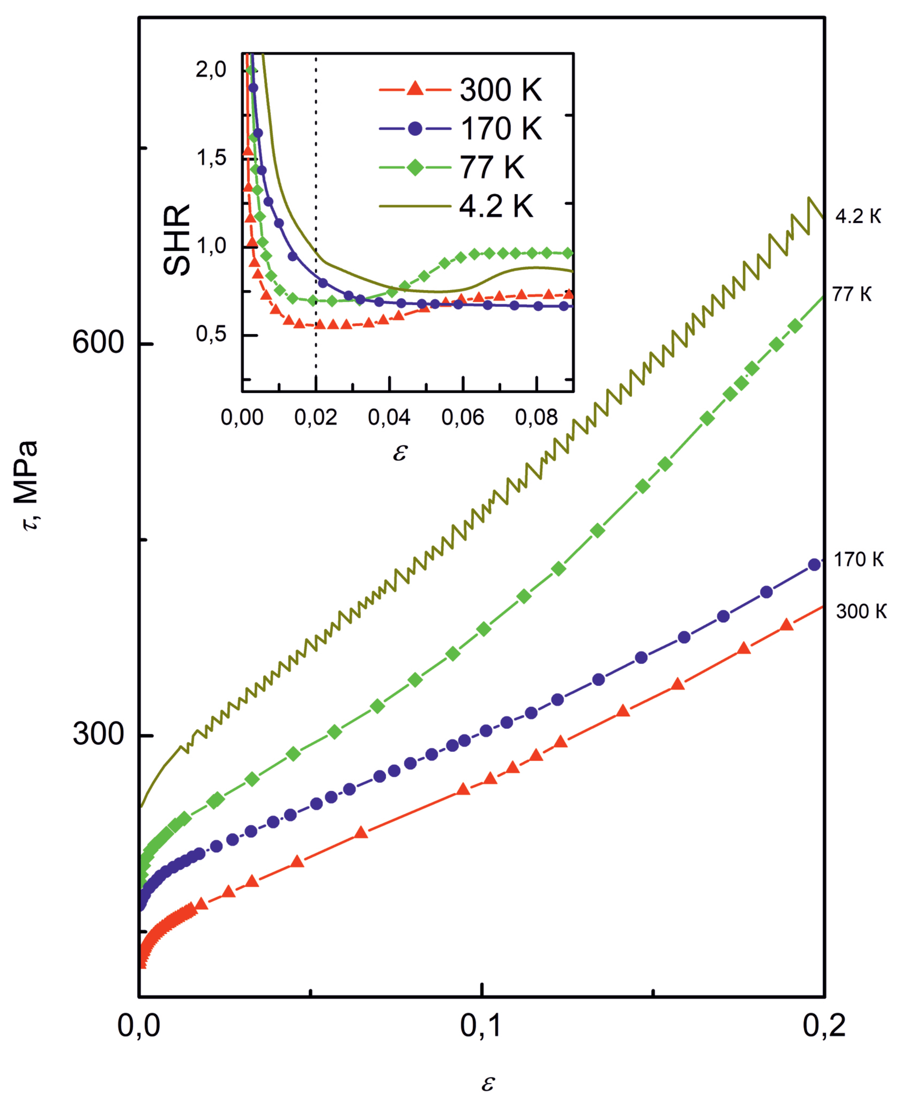
$K_D(\omega\theta_0) > 1.2$

$$F^{K-H}(x) = \frac{x^2}{2(1+x^2)}\left[1-\exp\left(-\frac{2\pi}{x}\right)\right],\quad x=\omega\theta$$

$U_0\sim(0.3\div0.5)\text{eV},\ \theta_0\sim10^{-13}\text{s},\ C_r\Delta_0\sim10^{-1}\rho_L L^3$

$$\left[\frac{E_0}{E_{R0}}\cdot\max Q^{-1}_R\right]^{K-H}\approx0.13$$

$K_{K-H}(\omega\theta_0) < 1.2$



Diagrams of compression deformation of the alloy $Al_{0.5}CoCrCuFeNi$ in "τ–ε" coordinates at different deformation temperatures in structural state (**I**) [3].
The inset shows the strain-hardening rate (SHR) dτ(ε)/dε with deformation ε.

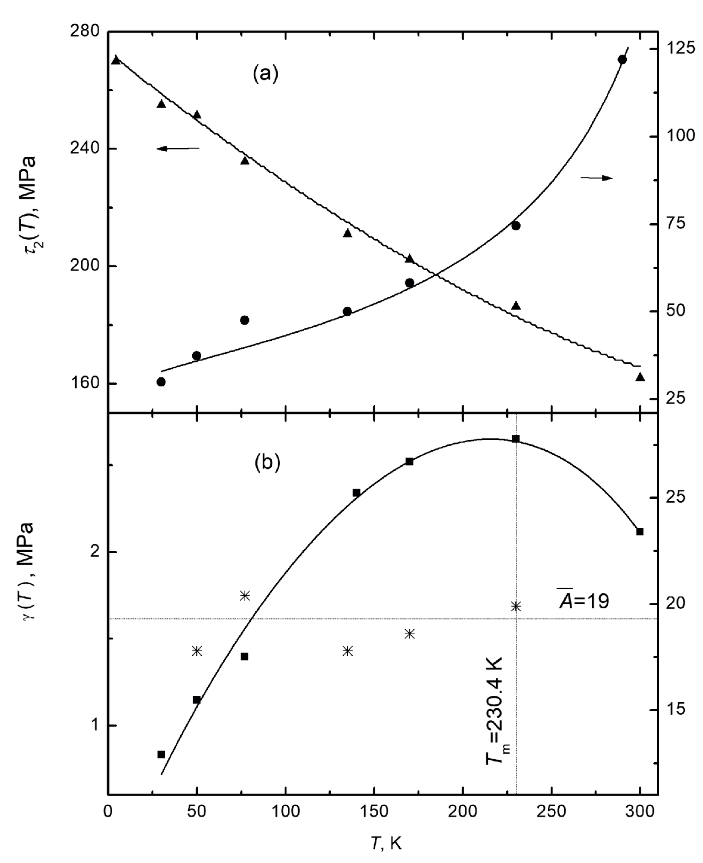
$$\gamma(T) = \frac{\Delta\tau_2(T)}{\Delta\ln\dot\varepsilon}$$

$$V(T) = kT\frac{\Delta\ln\dot\varepsilon}{\Delta\tau_2(T)} = \frac{kT}{\gamma(T)}$$

$$\tau_2(T) = \tau_{i2}(T) + \tau_c\left[1-\left(\frac{T}{T_0}\right)^{1/q}\right]^{1/p}$$

$$\gamma(T) = \frac{\tau_c}{pqA}\left(\frac{T}{T_0}\right)^{1/q}\left[1-\left(\frac{T}{T_0}\right)^{1/q}\right]^{\frac{1-p}{p}}$$

$$A = -T\left[\frac{\Delta\tau_2(T)}{\Delta T}\right]\cdot\left[\frac{\Delta\tau_2(T)}{\Delta\ln\dot\varepsilon}\right]^{-1}_T$$



Temperature dependences of plasticity characteristics in state (**I**) at ε=0.02: (a) ▲ – yield stress $\tau_2(T)$ and ● - activation volume of the plastic deformation process $V(T)$; (b) ■ - speed sensitivity of deformation stress $\gamma(T)$ and * - empirical values of parameter A. In both figures, solid lines show analytical approximations of experimental points by theoretical formulas.

THE RESULTING THEORETICAL ESTIMATES

$c_t = \sqrt{\frac{G}{\rho}}\approx3.4\cdot10^3\ \frac{\text{m}}{\text{s}}$ - speed of sound

$U_0 = U_0^s\approx11.2\cdot10^{-21}$ J - activation energy

$\theta_0^s\simeq4\cdot10^{-11}$ s - period of attempts

$(C_r\Delta_0)_L\leq1\cdot10^{-4}$

$m_k\approx5\cdot10^{-3}m_a\approx5\cdot10^{-28}$ kg - mass of the kink

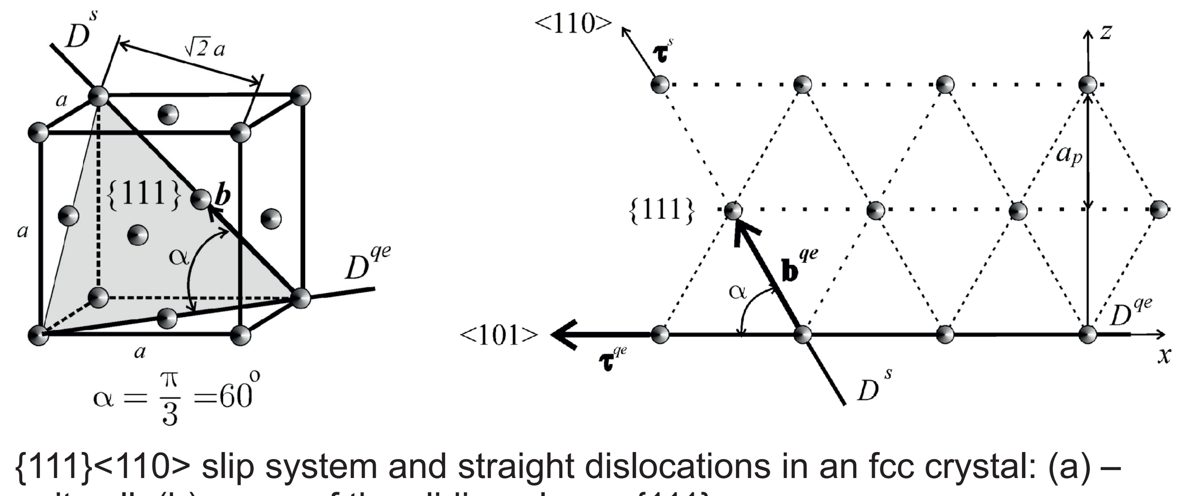
$\lambda_k\approx40a_0\approx1\cdot10^{-8}$ m - width of the kink

$\tau_{p1}\approx3.6\cdot10^6$ Pa $\approx4\cdot10^{-5}G$ - Peierls critical stress

$M\approx1.1\cdot10^{-15}\ \frac{\text{kg}}{\text{m}}\approx2.1\rho b^2$ - linear mass density

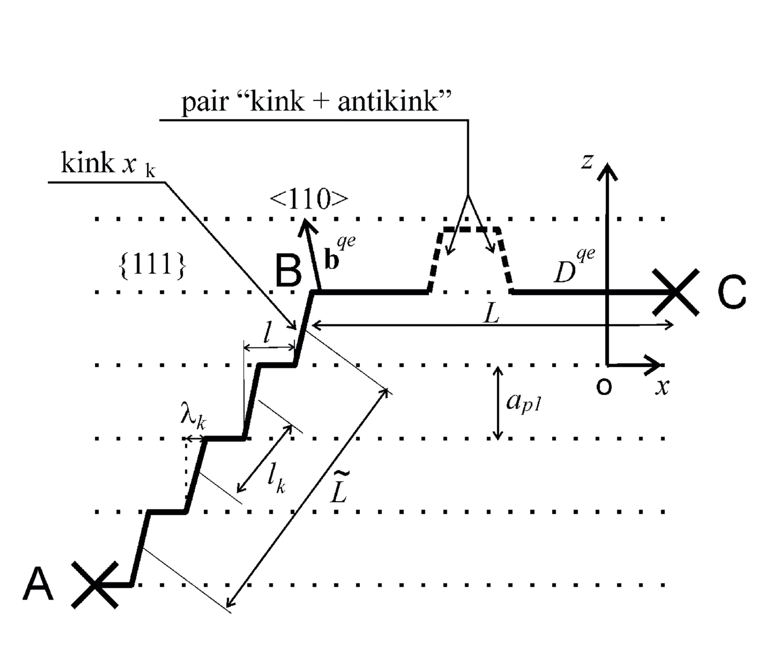
$\Gamma\approx12.4\cdot10^{-9}\ \frac{\text{J}}{\text{m}}\approx2.1Gb^2$ - energy per unit length of a dislocation

$\rho_L L^3\leq10^{-3}$



{111}<110> slip system and straight dislocations in an fcc crystal: (a) – unit cell; (b) – one of the sliding planes {111}.

$a_p = \frac{\sqrt3}{2}a_0 = \sqrt{\frac{3}{8}}a$ Peierls relief period in the direction of easy sliding



Configurations of dislocation lines in the {111}<110> slip system in an fcc crystal: ***ABC*** – curved segment of a quasi-edge dislocation D^{qe} with a Burgers vector $\mathbf{b}^{qe}$, the dotted line indicates the close packing directions; a_{p1} - period of the first kind Peierls relief in the direction of the axis oz; $a_0=b$ - period of secondary Peierls relief; L - length of straight segment ***BC*** in the relief valley; $\tilde{L}$ - length of the chain of ***AB*** kinks between relief valleys; x_k - coordinate of a separate kink along the axis ox; λ_k - kink width; l – distance between the centers of neighbouring kinks.

CONCLUSION:

Analysis and physical interpretation based on modern dislocation theory of the results of a comprehensive experimental study of the processes of plastic deformation and acoustic relaxation in HEA $Al_{0.5}CoCrCuFeNi$ made it possible to establish:

- the most important types of dislocation defects in the lattice structure of the alloy;
- types of barriers that prevent the movement of dislocation lines (strings);
- adequate mechanisms of thermally activated movement of various elements of dislocation strings through barriers under conditions of moderate and deep cooling;

quantitative estimates for the most important characteristics of dislocations and their interaction with barriers.

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