DISLOCATION STRUCTURE AND AN ACTIVITY OF PLASTIC DEFORNING MEDIA

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Abstract. The evolution of the dispersion laws of autowaves of localized plasticity for successive stages of linear, parabolic strain hardening, as well as the pre-fracture stage is considered. The principles of uniform description of the regularities of plastic flow at different stages of the deformation process are formulated. The main model relationships are proposed that connect the microscopic characteristics of dislocation deformation mechanisms with the properties of an active deformable medium capable of generating the corresponding autowave modes of localized plastic flow.

Keywords: *plasticity, strain hardening, autowaves, dispersion, active medium, dislocations, structure*

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INTRODUCTION

The autowave mechanics of inhomogeneous plastic deformation developed and described in [1-3] is applicable in a wide range of plastic deformations and allows us to explain most of the regularities of plastic flow. It is based on the idea that plastic deformation is carried out by macroscopic autowaves of localised plastic deformation, experimentally observed as a pattern of localisation of plastic flow and serving as mechanisms of self-organisation of the deformed medium. The autowave modes observed in experiment are characterised by spatial (length λ) and temporal (period ϑ) mass scales, and the type of modes is unambiguously related to the stages of strain hardening characteristic of the strain-stress dependence $\sigma(\varepsilon)$. This relation, called the Principle-Consistency Principle, was established earlier [1-3]. Important laws of the autowave theory of plasticity are also the Elastic-plastic invariant, which relates the characteristics of localised plasticity autowaves to the parameters of elastic waves in the deformed medium, and the Dispersion relation for autowaves, i.e., the dependence of the frequency of oscillations in an autowave on its wave number $\omega(k)$ [1-3]. The use of these provisions ensures the success of the autowave approach.

The autowave description of the phenomenon of plasticity has now received a convincing experimental basis, an adequate theoretical apparatus and has been tested on a large number of materials [3]. The consistency of the basic provisions of autowave mechanics, the adequacy and applicability of which can currently be considered fully proven, allows us to consider it as an important part of the search for a general approach to the problem of plasticity. In [4], the experimental and theoretical foundations of the development of localized plastic deformation were generalized and the nonequilibrium nature of the phenomenon of self-organization of defects during plastic flow at all stages of strain hardening was analyzed.

Generation of autowaves of localized plasticity is a general mechanism of self-organization in non-equilibrium systems [5]. It is fundamentally important that generation is possible if the deformable medium possesses activity, which implies the presence of potential energy sources distributed throughout the volume. Their role during plastic deformation can be performed by its carriers, i.e., dislocations and dislocation ensembles of different configurations, which possess elastic stress fields and evolve in a complex manner during the process [6 - 8]. In this case, a question arises about the qualitative and quantitative relationship between the characteristics of the dislocation structure that emerges during plastic flow and the basic laws of autowave plastic deformation. The answer to this question becomes fundamentally important, as it determines the possibility of reconciling the theory of dislocations and the autowave theory, which describe the phenomenon of plasticity at different spatiotemporal scales. An attempt to solve this problem is the subject of the present work.

DISPERSION OF AUTOWAVES AND ACTIVE DEFORMABLE MEDIA

An important informative characteristic of autowaves of localized plastic flow is their dispersion relation, since on the one hand, dispersion is caused by the presence of spatial scales in the medium that characterize structural elements, and on the other hand - the form of the dispersion relation allows determining the type of nonlinear equation describing this process [9, 10]. Such equations, in turn, are derived taking into account physical processes occurring in the active medium. For these reasons, knowledge of the dispersion relation opens the way to understanding the nature of deformation processes and their adequate description.

The correspondence principle allows us to think that the dispersion laws of autowave localized plasticity have different forms at different stages of strain hardening. These stages can be identified on the experimental flow curve $\sigma(\varepsilon)$, approximating it by the Ludwik equation $\sigma(\varepsilon)=\sigma_0+\theta\varepsilon^n$ [11, 12], where σ_0=const and θ – is the strain hardening coefficient. Each stage corresponds to a section of the dependence $\sigma(\varepsilon)$, for which the strain hardening exponent $n=\text{const}$. From the table, it follows that on the flow curves, it is possible to distinguish the stages of Lüders deformation (I), linear (II) and parabolic (III) strain hardening, as well as pre-fracture (collapse of the autowave of localized plasticity) (IV).

From Fig. 1, it follows that the dispersion laws for all stages of the process have a parabolic form $\omega \sim k^\beta$ with an exponent β, that changes discretely during transitions between stages of strain hardening. Using dimensional considerations, the function $\omega(k)$ can be written as:

$$\omega(k) \sim \left(\frac{\Lambda^\beta}{J}\right) k^\beta , \qquad (1)$$

where the coefficient Λ^β/J for a given stage of the process is determined by the linear scale Λ , which depends on the deformation processes at this stage. The time scales (characteristic relaxation times) J , also included in the coefficients of equations (2) - (5), are probably different, but for now are assumed to be the same and equal to the time for shears to overcome local barriers due to thermal fluctuations [11], i.e., $J \approx \omega_D^{-1} \exp\left[(U_{bar} - \gamma\sigma)/k_B T\right] \approx 10^{-4}$ s [3]. Here U_{bar} is the barrier height, γ is the activation volume, k_B is the Boltzmann constant, T is the temperature, ω_D is the Debye frequency.

Fig. 1. Experimental dispersion curves for Lüders deformation (●, I), linear (▲, II) and parabolic (▼, III) strain hardening, and pre-fracture stage (♦, IV).

Table 1. Characteristics of the stages of the plastic flow curve

Stage of the plastic flow curve $\sigma(\varepsilon)=\sigma_0+\theta\varepsilon^n$	Dependence of deformation stress on strain	n	Dispersion relation	β
Lüders deformation, I	σ = const ~ ε^0	0	$\omega(k) \sim k$	1

Linear strain hardening, II	$\sigma \approx \theta_{\mathrm{II}}\varepsilon \sim \varepsilon$	1	$\omega(k) \sim k^2$	2
Parabolic strain hardening, III	$\sigma \approx \theta_{\mathrm{III}}\varepsilon^{1/2} \sim \varepsilon^{1/2}$	1/2	$\omega(k) \sim k^{5/2}$	5/2
Pre-fracture (collapse of the localized plasticity autowave), IV	$\sigma \approx \theta_{\mathrm{IV}}\varepsilon^{n} \sim \varepsilon^{n}$	<1/2	$\omega(k) \sim k^3$	3

Thus, according to the data in Fig. 1 (curve I) for dispersion during Lüders deformation:

$$\omega(k) \sim \left(\frac{\Lambda}{\vartheta}\right) k \sim k, \qquad (2)$$

for dispersion at the stage of linear strain hardening (Fig. 1, curve II):

$$\omega(k) \sim \left(\frac{\Lambda^2}{\vartheta}\right) k^2 \sim k^2, \qquad (3)$$

for the stage of parabolic strain hardening (Fig. 1, curve III):

$$\omega(k) \sim \left(\frac{\Lambda^{5/2}}{\vartheta}\right) k^{5/2} \sim k^{5/2}, \qquad (4)$$

and, finally, for dispersion at the pre-fracture stage (autowave collapse) (Fig. 1, curve IV):

$$\omega(k) \sim \left(\frac{\Lambda^3}{\vartheta}\right) k^3 \sim k^3. \qquad (5)$$

Data on the dispersion of localized plasticity autowaves are summarized in the table. The appearance in equations (1) – (5) of length Λ , area $\Lambda^2 = \Sigma$ and volume $\Lambda^3 = \Omega$, the physical meaning of which will be discussed below, indicates the geometric nature of the proposed interpretation.

The specific forms of dispersion laws (2) – (5) unambiguously correspond to nonlinear differential equations describing the processes under discussion. At the stage of elastoplastic transition deformation at constant stress $\sigma = \mathrm{const}$ is localized on the moving with constant velocity V_{aw} Lüders front [12], for which the phase and group velocities

$$V_{aw}^{(ph)} = \frac{\omega}{k} \quad \text{and} \quad V_{aw}^{(gr)} = \frac{d\omega}{dk} \qquad (6)$$

are equal, i.e., $V_{aw}^{(ph)} = V_{aw}^{(gr)} = V_{aw}$. Multiplying the right and left sides of the two equations (6) and integrating the resulting products, we obtain

$$\frac{\omega d\omega}{k dk} = \frac{\int \omega d\omega}{\int k dk} = \frac{\omega^2 + c_1}{k^2 + c_2} = V_{aw}^2, \qquad (7)$$

where c_1 and c_2 are integration constants. At $c_2 = 0$ from equation (7) follows the dispersion law $\omega^2 \sim 1 + k^2$, corresponding to the Klein –Gordon equation [9] for displacements u :

$$\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} + u = 0. \qquad (8)$$

This equation describes, for example, the propagation of macroscale excitations such as solitons [10] in active media. The presence of a frequency gap ~1 for the case of Lüders deformation accounts for the abrupt increase in front velocity during nucleation [12]. In the steady-state deformation regime, k >>1, so equation (8) transforms into an ordinary wave equation $\ddot{u} - u'' = 0$ with linear dispersion $\omega \sim k$, suitable for describing the propagation of elastic waves.

At the stage of linear strain hardening when $\sigma \sim \varepsilon$, the autowave characteristics of plastic flow (length λ and velocity V_{aw}) together with the parameters of elastic waves (interplanar distance χ and transverse ultrasound velocity V_t) for the same material form an elastoplastic invariant [1 – 3]:

$$\frac{\lambda V_{aw}}{\chi V_t} = \hat{Z} \approx \frac{1}{2}, \qquad (9)$$

which serves as the fundamental equation of the autowave physics of plasticity and has a number of consequences that explain the patterns of plastic flow.

For example, if in equation (9), in accordance with [13], we replace χ and V_t with expressions through Planck's constant $\hbar = h/2\pi$, electron charge e , its mass m and atomic mass M , Hartree length scales $a_0 = \hbar_2/me^2$ and sound velocity $V_s \approx e^2/\hbar(m/2M)^{1/2}$, then the resulting equation

$$\lambda V_{aw} = \frac{\chi V_t}{2} \approx \frac{\hbar}{2(mM)^{1/2}}, \qquad (10)$$

expressing the autowave characteristics through physical constants, acquires interesting perspectives for analyzing the nature of plasticity. For instance, the value $\lambda V_{aw} \approx 10^{-6}$ m^2/s calculated using formula (10) turns out to be close to the experimentally found values for the studied materials [1 – 3] and sets the minimum value of kinematic viscosity of deformable media.

From equation (10) also follows the quadratic dispersion law of the autowave at the stage of linear strain hardening. Assuming that $\lambda V_{aw} \approx \Lambda^2/\vartheta$, we obtain:

$$\lambda V_{aw} = \frac{\Lambda^2}{J} = \frac{(2\pi/k)^2}{2\pi/\omega} = 2\pi\frac{\omega}{k^2} \approx \frac{\hbar}{\sqrt{mM}} \approx \text{const}, \qquad (11)$$

which leads to the quadratic dispersion equation for this stage, previously obtained [1]:

$$\omega = \frac{\hbar}{2\pi\sqrt{mM}} \cdot k^2 \sim k^2. \qquad (12)$$

It corresponds to the nonlinear Schrödinger equation $i\dot{u} + u'' + 2|u|^2 u = 0$ [9] for the evolution of the displacement field u in a nonlinear system with potential $2|u|^2 u$. Here $i = \sqrt{-1}$. During plastic deformation, this equation is applicable for describing the self-organization process of a sequence of thermally activated elementary shifts [11], which is characteristic of the linear strain hardening stage. At this stage, the medium is self-oscillating, and it corresponds to a *phase autowave* with phase $\omega t - kx = \text{const}$.

At the stage of parabolic strain hardening with $\sigma \sim \varepsilon^{1/2}$ the deformable medium forms a stationary ($V_{aw} = 0$) dissipative structure consisting of immobile centers of localized plasticity. To determine the type of dependence $\omega(k)$ in this case, it is necessary to introduce an effective autowave velocity. Keeping in mind that $V_t \approx 2\chi\omega_D$ and $\hbar\omega_D = k_B\theta_D$, where θ_D is the Debye temperature [14], we write the denominator of equation (9) as $1/2\chi V_t = \chi^2\omega_D$ and obtain:

$$\lambda V_{aw} \approx \frac{1}{2}\chi V_t \approx \frac{\chi^2 k_B \theta_D}{\hbar}, \qquad (13)$$

where the value

$$V_{aw}^{(ef)} = \frac{(\lambda V_{aw})}{\lambda} \approx \frac{k_B\theta_D}{2\hbar} \cdot \frac{\chi^2}{\lambda} \approx \omega_D \frac{\chi^2}{\lambda} \neq 0 \qquad (14)$$

has the meaning of effective velocity and characterizes the increase in deformation within the center of active plastic flow due to an increase in defect density without macroscopic displacement of boundaries. Calculation using equation (14) gives $V_{aw}^{(ef)} \approx 2 \cdot 10^{-3}$ m/s and $\hat{Z} = \lambda V_{aw}^{(ef)} / \chi V_t \approx 1/2$. The coincidence with the usual value of the invariant (9) indicates the validity of its application including for the stage of parabolic strain hardening. By changing the autowave length λ through deformation conditions, it was possible to obtain a dispersion relation $\omega \sim k^{5/2}$. The intermediate value of the exponent 2< β =5/2<3 indicates that the stage of parabolic strain hardening can be considered as a transition from the linear hardening stage with dispersion $\omega \sim k^2$ to the pre-fracture stage (collapse of the autowave of localized plasticity), where $\omega \sim k^3$.

Such a dispersion law was established for the pre-fracture stage, for which $\sigma \sim \varepsilon^n$, a $n < 1/2$, by processing the X - t - diagrams *t* for different metals presented in [1-3]. The dispersion relation of the form $\omega \sim k^3$ corresponds to the Kor - teweg - de Vries $\dot{u} - u''' = 0$ equation, which describes the prop - agation of excitation pulses in active excitable media [9].

Turning to the discussion of the reasons for the change in the dispersion relations in equations (2) - (5) during deformation, it is logical to connect these relations with the evolution of sizes and shapes of dislocation ensembles [7, 8, 15], i.e., with the structural part of the coefficient Λ^{β}/J in equation (5). In this case, the exponent β should depend on the configuration of the dislocation ensemble at the corresponding stage. Indeed, at the yield plateau stage (β =1), the Lüders deformation transforms an elastic medium into a plastically deformable one, which, together with linear dispersion, allows considering the Lüders front *as a switching autowave* [16] in a medium consisting of bistable elements. The role of the latter is played by dislocations transitioning from the initial immobile state to a new mobile state.

To understand the role of the dislocation structure at the stages of linear strain hardening and pre-fracture, let us consider that, as already mentioned, $\Lambda^2 = \Sigma$, and $\Lambda^3 = \Omega$. It follows that the length Λ, area Σ and volume Ω , included in the expressions of dispersion laws for the successive stages of strain hardening (2) - (5), are the geometric characteristics of dislocation ensembles, i.e., inhomogeneities of the medium causing the dispersion of autowaves of localized plasticity. They can be assigned, respectively, the meaning of the size of the substructure element (Λ) , the surface area of dislocation cells at the stage of linear strain hardening (Σ) and the volume of dislocation tangles at the pre-fracture stage (Ω) [8, 15].

As for the stage of parabolic strain hardening, it is known [7, 8, 15] that the cellular dislocation substructure that emerges during its development, for which $\omega \sim (\Lambda^2/J)k^2$, is gradually replaced during deformation by a tangled one, where $\omega \sim (\Lambda^3/J)k^3$. This consideration can be viewed as an argument in favor of the fact that the stage of parabolic strain hardening serves as a transition from linear hardening to the collapse of the autowave of localized plasticity. This is also indicated by the intermediate value β =5/2 in the expression for the dispersion of autowaves of localized plasticity at this stage of deformation.

The above-discussed connection between the stages of the deformation process and the dispersion laws of autowaves of localized plasticity allows us to speculate that other characteristics of plastic flow should also be somehow connected with the *Principle of correspondence* . In this respect, the dependence of mobile dislocation density on deformation for different stages of the deformation process is of particular interest.

As is known [6], the density of mobile dislocations ρ_{md} enters the Taylor - Orowan equation:

$$\frac{d\varepsilon}{dt} = b\rho_{md}V_{\text{disl}}, \qquad (15)$$

which underlies most dislocation models of plastic flow and connects the macroscopic rate of plastic deformation $d\varepsilon/dt$ with microscopic characteristics of the dislocation structure: the Burgers vector *b* and the velocity of dislocation movement V_{disl} . The extreme behavior of this value with increasing deformation, predicted by Gilman [6]

$$\rho_{md}(\varepsilon)=\left(\rho_0+\frac{2m}{b}\varepsilon\right)\exp\left(-\frac{\theta}{\sigma}\varepsilon\right), \qquad (16)$$

where ρ_0 – is the initial dislocation density, and *m* is the coefficient of their multiplication, still appears mysterious.

It is easy to assume that both the concept of an active medium and its quantitative characteristics are closely related to the form of the dependence $\rho_{md}(\varepsilon)$. Therefore, it is advisable to consider it, emphasizing the staging of the flow process. For this purpose, based on dimensional analysis, we write the product included in equation (9) as

$$\lambda(\varepsilon)\cdot V_{aw}(\varepsilon)=D_{\varepsilon}(t)=\frac{d}{dt}\left(\frac{1}{\rho_{md}}\right), \qquad (17)$$

where $D_{\varepsilon}\approx\lambda V_{aw}$ is the transport coefficient in the autowave equation of plastic deformation $\dot{\varepsilon}=f(\varepsilon)+D_{\varepsilon}\varepsilon''$, and $f(\varepsilon)$ – is a nonlinear function (point kinetics [2]), describing the local deformation rate. From equation (17), the following relation then follows:

$$\frac{d}{dt}\left(\frac{1}{\rho_{md}}\right)=\frac{d}{d\varepsilon}\left(\frac{1}{\rho_{md}}\right)\cdot\frac{d\varepsilon}{dt}=-\frac{1}{\rho_{md}^2}\cdot\frac{d\varepsilon}{dt}=-\frac{\dot{\varepsilon}}{\rho_{md}^2}, \qquad (18)$$

which leads to the equation for the density of mobile dislocations:

$$\rho_{md}^2(\varepsilon)=-\frac{\dot{\varepsilon}}{\lambda(\varepsilon)\cdot V_{aw}(\varepsilon)}. \qquad (19)$$

Analysis of equation (19) was performed for different stages of the deformation process. It turned out that for Lüders deformation, when $V_{aw}=V_L$, and the number of mobile dislocations grows proportionally to the front displacement

$$\rho_{md}(\varepsilon)=\left(-\frac{\dot{\varepsilon}}{\lambda(\varepsilon)\cdot V_L}\right)^{1/2}\sim\varepsilon, \qquad (20)$$

and at the stage of linear hardening, where $V_{aw}=\text{const}$ and $\lambda=\text{const}$ [1]

$$\rho_{md}=\rho_0\left[1+\exp(-2\kappa\varepsilon)\right]^{-1}\approx\text{const}, \qquad (21)$$

where $\left[1+\exp(-2\kappa\varepsilon)\right]^{-1}$ – is the Heaviside step function; κ is the coefficient. As for the stage of parabolic deformation hardening, for it

$$\rho_{md}(\varepsilon)\sim\frac{\rho_0}{\varepsilon^{3/2}}\sim\varepsilon^{-3/2}. \qquad (22)$$

Fig. 2. Schematic dependence of mobile dislocation density on deformation. The dashed line is the plastic flow curve. Stage numbers (I, II, III) are given in Table 1.

The obtained solutions are schematically presented in Fig. 2, which shows that the dependence $\rho_{md}(\varepsilon)$ is consistent with the staging of plastic flow and satisfies *the Correspondence Rule* , and its extremal nature emphasizes continuity with Gilman's formula.

ACTIVE DEFORMABLE MEDIA: BIRTH AND EVOLUTION

When discussing the nature of active deformable media and the evolution of their properties during localized plastic flow, the problems of excitation of self-oscillations in the deformable medium and mechanisms of birth of active media under different deformation conditions are of primary importance.

According to general views [5, 16], an active medium capable of generating autowaves consists of self-oscillating elements, which, when their oscillations are fully or partially synchronized, give rise to various autowave modes. To understand the nature of autowaves, the question of the "seed" excitation of self-oscillations in a non-equilibrium system, i.e., the birth of a *pacemaker* (rhythm driver) [5], is fundamental. When analyzing autowave processes, especially deformation ones, its existence is usually postulated without discussing the possible mechanism of birth. The reason for refusing to discuss is that the characteristic frequencies of autowaves of localized plasticity $10^{-3} \leq \omega_{aw} \leq 10^{-2}$ Hz are incommensurable with the oscillation frequencies of typical dislocation segments of length $l_s \approx 10^3 b$, which are $\omega_s \approx (b/l_s)\omega_D \approx 10^{10}$ Hz, i.e., $\omega_{aw} << \omega_s$.

Fig. 3. Model of pacemaker birth (a); coordinate dependence of the interaction force of parallel edge dislocations (b) [19].

The proposed pacemaker model considers the passage of an individual dislocation past a dislocation ensemble, which for simplicity can be considered as a planar pile-up of dislocations, with the dislocation moving parallel to the plane of the pile-up (Fig. 3a). The interaction force between the moving dislocation and a parallel dislocation in the pile-up [6]

$$F_{x1} = \pm \frac{Gb^2}{2\pi(1-\nu)} \cdot \frac{x(x^2-y^2)}{(x^2+y^2)^2} \qquad (23)$$

is non-monotonic (Fig. 3b), which causes a region of compression-rarefaction of defects to move along with the dislocation in the planar pile-up, equivalent to oscillations of their density with frequency $\sim V_{\mathrm{disl}}/\delta$.

At a minimum velocity $V_{\mathrm{disl}} \approx 10^{-7}$ m/s and a distance between dislocations in a planar cluster $\delta \approx 10^{-5}$ m it is close to 10^{-2} Hz, i.e., to the characteristic frequency of the autowave.

Obviously, this frequency limits the lower end of the spectrum of possible oscillations of dislocation systems. The considered mechanism is also applicable for dislocation ensembles of more complex configurations and is suitable for explaining the problem of the origin of oscillatory processes during plastic flow.

For the autowave physics of plasticity, an important question is whether the nature of the activity of the deformable medium is determined only by its structure or also depends on the deformation conditions and can change during plastic deformation. To answer this question, let us discuss the results of studying the deformation of polycrystalline α-Fe–0.1 wt.%C in the temperature range of 300–500 K, which is realized by the Lüders mechanism [12, 17, 18].

During tests at ~300 K, the loading diagram of α-Fe (Fig. 4a) has [12] a yield point and yield plateau, characterized by upper $\sigma_y^{(u)}$ and lower $\sigma_y^{(l)}$ yield limits. The Lüders band nucleates at a stress $\sigma \approx \sigma_y^{(u)}$ in the form of a narrow wedge of plastically deformed material, which quickly grows through the cross-section of the sample, and then expands in the direction of the tensile axis [18].

In this case, the band boundaries (Lüders fronts) move uniformly along the sample in different directions at a constant stress $\sigma \approx \sigma_y^{(l)}$. When the entire working part of the sample is swept by these fronts, the yield plateau is replaced by parabolic strain hardening. As mentioned above, the Lüders front transfers the medium from an elastic to a plastically deformable state, separating the elastic and plastic regions of the material. In doing so, it possesses all the characteristics of an *autowave of switching* in a bistable medium [3, 16].

Fig. 4. Tensile diagrams of αFe samples at 296 (a), 373 (b), and 433 K (c).

Increasing the test temperature to 373 K changes the shape of the flow curve (Fig. 4b). The yield tooth and yield plateau are preserved, but the lower yield point decreases. The main difference is that at this temperature, deformation jumps appear during the parabolic hardening stage. A further increase in temperature to 433 K causes stress jumps to appear already on the yield plateau, as shown in Fig. 4c.

At a temperature of ~300 K, the transition is realized by uniform movement of the Lüders front, while at temperatures above 433 K, it occurs through sequential deformation jumps [18, 19]. With each jump, a narrow deformation band runs along the sample, at the leading front of which the medium is transferred to a plastic state, similar to the propagation of the Lüders front. At the trailing front of the band, the medium returns to an elastic state, so that the plastically deformed state exists only between the leading and trailing fronts at any given moment [18, 19], which allows considering the medium as excitable and the discontinuous deformation band as *an autowave of excitation* [3, 16].

Thus, in the same material under identical deformation conditions but at different temperatures, the emergence of different active media is natural. To explain the role of temperature, we turn to the mechanism of strain aging proposed in [20], according to which in interstitial solid solutions of C and N in α -Fe, as temperature increases, it is possible to re-form condensed atmospheres on dislocations that became mobile during the birth of the Lüders band. This leads to a decrease in the density of mobile dislocations and changes the deformation kinetics. The restoration of atmospheres on mobile dislocations becomes possible at a sufficiently high value of the carbon diffusion coefficient D_{C} in α -Fe.

To assess the required value D_{C} we apply the diffusion approximation $D_{\mathrm{C}} \approx l_{\mathrm{dif}}^2 / 2t$, in which *t* is the duration of the strain jump, and the diffusion length equals the distance between mobile dislocations, i.e., $l_{\mathrm{dif}}^2 \approx \rho_{md}^{-1}$. The assessment shows that with plausible values $\rho_{md} \approx 6 \cdot 10^{8}$ m^{-2} and $t \approx$ 1.6 s, the diffusion coefficient value needed for locking recovery $D_{\mathrm{C}} \approx (2t\rho_{md})^{-1} \approx 5 \cdot 10^{-10}$ m^2/s is achieved at $T \approx$500 K [21], confirming the feasibility of the proposed mechanism. At 300 K the diffusion coefficient $D_{\mathrm{C}} \approx 2.4 \cdot 10^{-21}$ m^2/s is much lower, and the recovery of Cottrell atmospheres on moving dislocations is impossible.

The considerations presented can be generalized by introducing a dimensionless criterion that determines the conditions for the generation of switching autowaves and excitation in a deformable medium. For this purpose, one can use the ratio *of the medium's refractoriness time* τ_{ref} [16], during which the active medium is indifferent to external influences, to the characteristic time of the deformation process $t_{\exp}$, which is taken as the duration of the Lüders front run along the sample length $t_{\exp}$ $10^2 - 10^3$ s, i.e., $\Gamma = \tau_{\mathrm{ref}} / t_{\exp}$. As mentioned, τ_{ref} has a diffusive nature, can be estimated by the relation

$$\tau_{\mathrm{ref}} \approx \frac{l_s^2}{2D_{\mathrm{C}}} \qquad (24)$$

and depends on temperature through the diffusion coefficient. Next, one can compare the criteria for two temperatures corresponding to Lüders and serrated deformations.

At $T \approx 300$ K $D_C \approx 2.4\cdot10^{-21}$ m^2/s, and according to equation (24), $\tau_{ref} \approx 10^6$ s. Consequently, under these conditions $\Gamma = \tau_{ref}/t_{exp} >> 1$, and during the experiment time a new dislocation locking is impossible, so the Lüders front can only run through the sample once.

At $T \approx 400$ K the increase in the carbon diffusion coefficient to $D_C \approx 2.4\cdot10^{-17}$ m^2/s reduces the refractoriness time, calculated using equation (24), to $\sim 4\cdot10^2$ s. In this case $\Gamma = \tau_{ref}/t_{exp} \approx 1$, i.e., during the front run time, the dislocation locking has time to recover, and repeated strain jumps are observed on the yield plateau.

Without involving diffusion characteristics, let's consider the case when $\Gamma = \tau_{ref}/t_{exp} << 1$. Since $\tau_{ref} \approx \vartheta << t_{exp}$, the refractoriness of the active medium in this case is insignificant. Then the elements of the deformable medium do not lose their activity and, synchronizing with each other, form phase autowaves characteristic of the stage of linear strain hardening [3].

This leads to the conclusion that physically different types of active media can emerge in the same deformable material at different temperature intervals. Their plastic flow and strain hardening are realized through different dislocation mechanisms [6-8].

It is natural to assume that the kinetics of the movement of Lüders fronts and discontinuous plastic deformation fronts is determined by the velocity of dislocation movement in the field of applied stresses [22]. Then understanding the discovered difference can be achieved by comparing the dependencies $V_{disl}(\sigma)$ for these cases. The movement of the Lüders front is controlled by thermally activated dislocation movement, so that, in accordance with [3, 4, 18], its velocity can be described by an exponential relation characteristic of thermally activated processes of dislocation movement [11]:

$$V_L \sim V_{disl}(\sigma) \approx V_0 \exp\left(-\frac{U_{bar} - \gamma\sigma}{k_B T}\right) \sim \exp\sigma \cdot \qquad (25)$$

Such dependence is valid near the lower boundary of the temperature interval indicated above. However, at high stresses and temperatures corresponding to the development of discontinuous deformation, the value of $(U_{bar} - \gamma\sigma)/k_B T$ in equation (25) may become small. Assuming then, as usual, that $e^{-x} \approx 1 - x$, we obtain a stress-linear equation for the velocity of overbarrier movement of discontinuous plasticity fronts:

$$V_{sp} \sim V_{disl}(\sigma) \approx V_0\left(1 - \frac{U_{bar}}{k_B T} + \frac{\gamma}{k_B T}\sigma\right) \sim \sigma \cdot \qquad (26)$$

Thus, the transition from Lüders deformation to the discontinuous deformation with increasing temperature turns out to be associated with a change in the mechanism from thermally activated overcoming of local barriers to an over-barrier mode of dislocation motion, which is controlled by phonon and electron drag mechanisms [23]. It can be considered that the change in the motion regime of plasticity carriers initiates the transformation of an active bistable deformable medium into an excitable one and is accompanied by a restructuring of the autowave structure of the deformable medium, in which the switching autowave (Lüders front) is replaced by an excitation autowave (discontinuous deformation band). The conditions for the implementation of these mechanisms were theoretically substantiated in [24] using the basic provisions of the theory of non-equilibrium media [25].

CONCLUSION

The comparison of dislocation and autowave approaches to the nature of plastic flow shows that the dislocation structure provides the activity of the deformable medium due to the appearance of distributed energy sources, which are the elastic fields of dislocation ensembles. In turn, the emergence of an active medium makes it possible to generate autowave modes of localized plasticity in it. The birth and evolution of autowaves determine the kinetics and dynamics of the development of an active deformable me dium. The coherence of the processes of forming an active medium and generating autowaves in it underlies the *Principle of correspondence* [1 - 3].

The emerging new view on the nature of plasticity is that dislocation effects ensure the emergence of activity in the deformable medium and the subsequent generation of autowave processes, while the autowaves of localized plasticity generated in the medium form a macroscopic heterogeneity in their spatial distribution and differences in the kinetics of development of active elements of dislocation nature. The proposed perspective on the relationship between multi-scale deformation processes makes it possible to reconcile the geometric scales of plastic flow phenomena.

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CONFLICT OF INTERESTS

The authors of this work declare that they have no conflict of interest.

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