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# Two-component model of autowave plasticity. Macroscale and invariants of plastic deformation

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The structure of a two-component model of localized plasticity and the scenario of the birth of macroscopic scales of plastic flow within its framework are considered. The mechanism of the emergence of a macroscopic autowave scale during the development of plastic deformation is proposed and quantitatively substantiated. The conditions for the stratification of a deformable medium into dynamic and information subsystems are described and their roles in the formation of macroscopic scales of the order of the length of the autowave of localized plasticity are analyzed. The nature of the relationship between the emergence of a macroscopic scale during plastic flow and the elastic-plastic invariant of deformation, previously established experimentally, is explained.

**Keywords:** deformation, plasticity, localization, model, scale, self-organization.

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## 1. Introduction

The autowave plasticity theory [1–3] that is currently being developed is based on the assumptions that the heterogeneity of deformation, which is an integral sign of plastic flow, is the result of self-organization of the defective assembly in the deformed environment. This idea proposed for the first time by Seger and Franck in paper [4], was proposed by the statement of the authors [5] that the plasticity may not be explained on a purely mechanical basis, but should be considered as a part of the problems of non-linear dynamic systems, operating far away from the balance — synergetics.

In synergetics specially developed for explanation of spontaneous origination of structures in such systems, the serious issue is the mechanism of the spontaneous occurrence of large-scale coherence in the media with interactions of microscopic scale [5,6]. The above fully refers to the plastic deformation, too. In the plasticity physics developed on the basis of the dislocation theory [7–9], the spatial scale of interactions are specified by Burgers vector of dislocations $b \approx 10^{-10}$ m. Dislocation assemblies arising in process of plastic flow with specific dimensions $\delta \approx 10^{-6}$ m [9] (Figure $1,a$) and the observed pattern of localized plasticity with macroscopic scale (coherence length) $\lambda \approx 10^{-2}$ m (Figure $1,b$) [1–3] find not explanations within the traditional approaches. Clarification of the physical nature of the ratio $\lambda \gg \delta \gg b$ could have become a key to using the ideas and concepts of synergetics in the study of the plasticity phenomenon. Such attempt is undertaken in this paper devoted to the physical substantiation of the scale ratio problem solution.

## 2. Genesis of two component model of plastic flow

Achievement of the stated goal is not possible without development of an adequate plastic flow model. One of the obvious requirements to be *a priori* applied to such theory consists in the need to use dislocation views, since most operable models of plasticity physics are based on the theory of dislocations [7–9].

### 2.1. Indenbom–Orlov–Estrin thermally activated flow model

For this reason a new plastic flow model was built on the basis of a strictly justified physically and many times tested experimentally theory of thermally activated plastic yield by Indenbom–Orlov–Estrin [10], where the main elements are stagnated dislocation shears (pileups) distributed in the volume of the deformed medium [7,8]. The process of plastic flow in the model [10] is described by the sequence of independent acts of thermally activated relaxation (decay) and origination of concentrators, and it describes the plastic flow as homogeneous, not explaining the effects of localization and origination at macroscopic scale.

The speed of deformation at thermally activated shear in the relaxation act is defined by the Arrhenius ratio [10–12]

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\Big(-\frac{U_0 - \gamma\sigma}{k_B T}\Big), \tag{1}$$

where $\dot{\varepsilon} = \mathrm{const}$, $U_0$ — height of potential barrier blocking the elemental shear, $\sigma$ — existing voltage, $k_B$ — Boltzmann constant, $T$ — temperature. Activation volume of the *a*

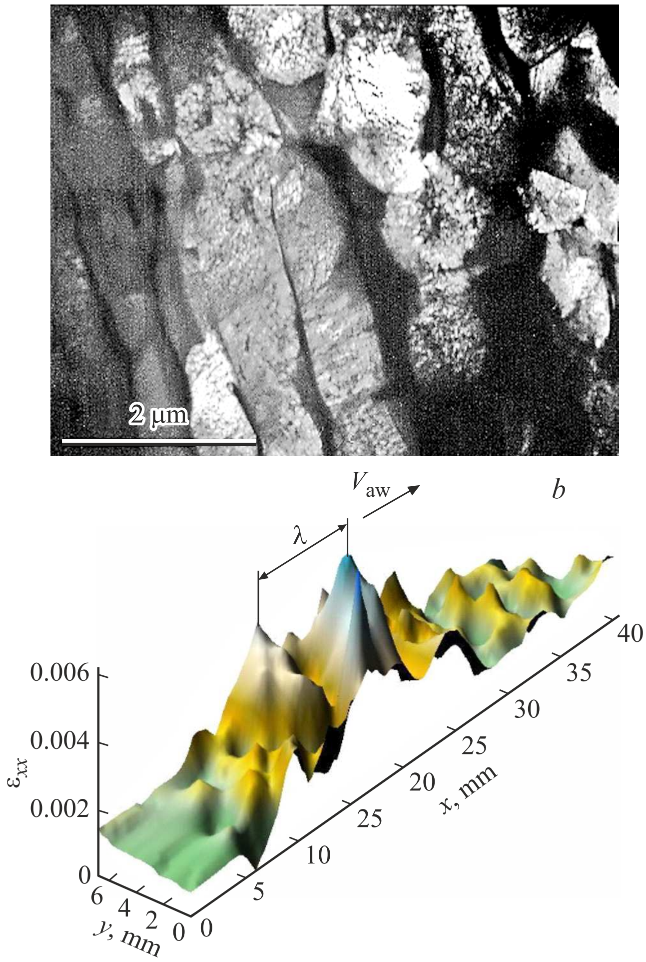


**Figure 1.** Examples of large-scale heterogeneities of the structure in plastic deformation. Dislocation structure of deformed Zr (*a*); pattern of localized plasticity in deformation Al [3] (*b*). $\varepsilon_{xx}$-limit component of plastic distortion tensor.

process of overcoming the barrier $\gamma$ may be seen as a quantitative measure of stress concentration [11].

### 2.2. Two-component model of localized plasticity. Structure

*Two-component model of localized plasticity* [1–3] is built to take into account the correlated development of shears. To translate this possibility into action, the thermoactivation model [10] is supplemented with the principle [13], according to which the self-organizing systems arbitrarily separate into interconnected *dynamic* (*power*) and *information* (*signal*) subsystems. The first includes elements that change the state of the system, and the second one is formed by elements that control the first with low disturbances. It is assumed that the functional interconnection of two subsystems is the reason for occurrence of coherent phenomena in the medium [13].

In the two-component model the deformed medium is presented with the assembly of originating and relaxing stress concentrators (dynamic subsystem), where emitted and absorbed acoustic pulses wander (information subsystem). The required connection mechanism of the subsystems must allow for the quantitative inspection on the basis of the experimentally measured parameters of the material plastic flow. The name *two-component model* is justified taking into account the role of two subsystems.

The dynamic and information subsystems of the deformed medium change in process of the relaxation act. Besides, the dynamics of pairwise connected processes of *origination–relaxation* of concentrators in the dynamic subsystem and *emission–absorption* of acoustic pulses in the information subsystem in accordance with the fluctuation-dissipation theorem [13] is defined by the mechanisms specific for this subsystem.

The functional connection of the subsystems is executed through acoustoplastic effect [14,15], i.e., imposition of acoustic pulse stresses on the stresses at the plasticity front stagnated at the barrier. This initiates the relaxation of waiting concentrators, reducing the time of waiting for the thermally activated relaxation acts of plasticity. Therefore, a specific trait of the two-component model of autowave plasticity is the combination of acoustoemission and acoustoplastic effects that are usually studied separately in its information subsystem.

Thanks to such combination, in the two-component model of autowave plasticity it becomes possible to explain the coherent development of elemental acts of plasticity. The latter occurs, when the impulse of acoustic emission emitted by the relaxing concentrator is captured by the waiting concentrator and causes its relaxation. The same mechanism serves as the cause for generation of autowaves of localized plastic flow observed as a pattern of localized plasticity [1–3].

The two-component model does not include the accounting of the input of certain dislocations in the description of plasticity, which, obviously, is not relevant at the dislocation densities of $\rho_{disl} \geq 10^{14}-10^{16}\,m^{-2}$ [9]. It may be noted that the model is characterized with *coarseness* [16] that is common for synergetics, i.e. indifference to small variations of the process course conditions. This makes it possible to identify the most important factors of the model and avoid its over-complication.

### 2.3. Two-component model: scenario and quantitative estimates

The step-by-step scenario of concentrator relaxation act development is explained by Figure 2. The system of three elastic stress concentrators stagnated by barriers is considered. The first step is that concentrator 1 relaxes, generating new dislocations in its neighborhood and emitting an acoustic pulse with the path length of the specimen size order. The arisen dislocations activate concentrator 2,

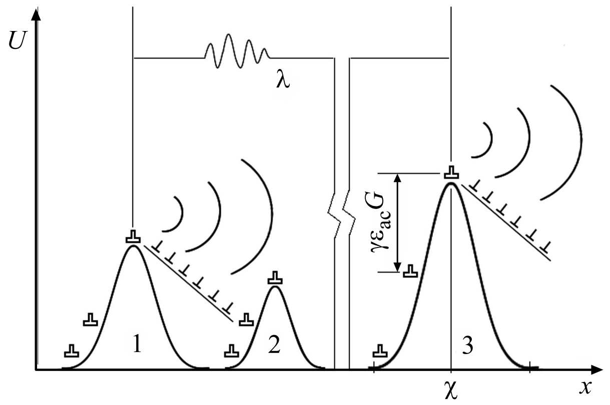


**Figure 2.** Scenario of development of coherent plastic shears in two-component model of plasticity. 1, 2, 3 — locked concentrators of elastic stresses.

contacting with it, causing continuous or intermittent motion of the plasticity front.

The second step is made by concentrator 3, which, having absorbed the energy of the acoustic pulse, relaxes with origination of a new shear in the area remote from concentrator 1 at the distance of the order of the pulse path length. The third step consists in capturing new shears with local barriers and reproduction of the conditions to repeat the listed steps, which provides for the continuity of the plastic flow. The inspection of the scenario correctness reduces to estimation of deformation, time and space scales of the model and comparison of these estimates with the actually observed values.

The deformation scale may be found, having defined the length of the dislocations that originated in the relaxation act as $\sim W/Gb^2$, where $W \approx nGb^2(\ln 4R/L + 1/2)$ — elastic energy of the pileup [10], released during its relaxation, $Gb^2$ — energy of the unit of length of the produced dislocation line [5], $L \approx 10^{-4}$ m — length of the pileup, $n$ — number of dislocations of unit length in it, $G$ — shear modulus, $R$ — crystal size. The estimate for $n = 10$ shows that $W \approx 5 \cdot 10^9$ eV, which is sufficient to form dislocations in the area with the surface area of $\sim L^2$ that have length of $\sim 10^{10}b$, i.e., appearance of $N \approx 10^6$ Franck-Reed sources with length of $10^3 b$ [8]. If every source emits $q \approx 20$ loops prior to locking [7], the entire assembly of the formed loops provides for the summary shear $\delta \approx bqN \approx 2 \cdot 10^7 b$ in the area with size of $\sim L$. The growth of deformation $\sim \delta/L \approx 10^{-3}$ arising under such conditions turns out to be close to the one observed experimentally in intermittent plastic deformation [17].

For timé evaluation of two-component model parameters let us consider the waiting time of the thermally activated overcoming of the local barrier with height of $U_0$ under action of stress only

$$\vartheta_{ab} \approx 2\pi\omega_D^{-1} \exp\left(\frac{U_0 - \gamma\sigma}{k_B T}\right) \tag{2}$$

to the time at the joint action of the stress and the acoustic pulse

$$\vartheta_{ap} \approx 2\pi\omega_D^{-1} \exp\left[\frac{U_0 - \gamma(\sigma + \varepsilon_{ac}G)}{k_B T}\right] \approx \vartheta \exp\left(-\frac{\gamma\varepsilon G}{k_B T}\right)_{ab}. \tag{3}$$

In equations (2) and (3) $U_0 - \gamma\sigma$ — enthalpy of the relaxation act, $\omega_D$ — Debye frequency, $\gamma \approx bl\chi/2$ — activation volume, $\chi \approx b$ — width of potential barrier, $l$ — distance between barriers. The acoustic pulse with the amplitude of elastic deformation $\varepsilon_{ac}$ reduces enthalpy of activation by $\sim \gamma\varepsilon G = \gamma\sigma$, accordingly reducing the waiting time of the relaxation act. For quantitative evaluation let us accept that in formulas (2) and (3) $U_0 - \gamma\sigma \approx 0.5$ eV, $k_B T \approx 1/40$ eV, $\gamma \approx 10^4 b^3$, and $\gamma\varepsilon G \approx 0.1$ eV. Then $\vartheta_{ab} \approx 5 \cdot 10^{-5}$ s and $\vartheta_{ap} \approx 9 \cdot 10^{-7}$ s, i.e., $\vartheta_{ab}/\vartheta_{ap} \approx 50$. Even with evident coarseness this estimate confirms the efficiency of acoustic pulses in acceleration of deformation processes.

Let us evaluate the macroscopic spatial scale of the model by formulating a condition of the start of the acoustically initiated act of concentrator 3 relaxation in the form of an evident equation

$$U_0 - \gamma(\sigma + \sigma_{ac}) = U_0 - lb\,\frac{\chi}{2}\,(\sigma + \varepsilon_{ac}G) \approx 0, \tag{4}$$

where value $\sim (bl\chi/2)\varepsilon_{ac}G$ is elastic energy of the acoustic pulse transferred to concentrator 3. Condition (4) provides for the break of the plasticity front off the local barrier with the joint action of the growing external stress and stress of the acoustic pulse. Upon the break, the thermally activated motion of dislocations in the fields of local barriers is substituted with a quasi-viscous one, depending on the properties of phononic and electronic gases [17,18].

Let us rewrite condition (4) in the form of $U_0 - (bl\chi/2)G\varepsilon_{ac} \approx (bl\chi/2)\dot{\sigma}\vartheta_{pl}$, adding the time of autowave front displacement along the slope of the local barrier by half of its width $\vartheta_{pl} \approx \chi/2V_{aw}$ at continuous growth of deforming stress ($\dot{\sigma}$ — loading speed). Condition (4) is met, if this time coincides with time $\vartheta_{ac} \approx \lambda/V_t$, for which the acoustic pulse emitted in relaxation of concentrator 1, reaches concentrator 3 and is absorbed by it. The resulting equation of times $\vartheta_{pl} = \vartheta_{ac} = \vartheta$ or

$$\frac{\lambda}{V_t} \approx \vartheta \approx \frac{\chi}{2V_{aw}} \tag{5}$$

indicates the causal relationship of relaxation acts in concentrators 3 and 1 at the distance $\lambda \gg \chi$ from each other. In ratio (5) the autowave speed $V_{aw} \approx (2\pi)^{-1}\lambda\omega \approx 10^{-4}$ m/s is specified by spatial scale $\lambda$ and frequency of oscillations in the autowave $\omega_{aw} \approx 10^{-2}$ Hz, and speed of elastic wave $V_t \approx (2\pi)^{-1}\chi\omega_D \approx 10^3$ m/s, accordingly, with barrier width $\sim \chi$ and Debye frequency $\omega_D \approx 10^{13}$ Hz.

Therefore, the completed quantitative estimates of the deformation, timé and space characteristics of the two-component model of plasticity confirm its adequacy. Origination of phenomena of macroscopic scale $\sim \lambda$ in the deformed medium may be considered as the reason for the generation of the localized plasticity autowave.

## 3. Two-component model and invariants of plastic flow

Development of the two-component model of autowave plastic deformation makes it possible to obtain the important general ratios for this process — invariants of deformation, making it possible to achieve deeper understanding of the nature of plastic flow in solid bodies.

### 3.1. Invariants of autowave physics of plasticity

It is clear that equation (5) leads to ratio

$$\frac{\lambda V_{\mathrm{aw}}}{\chi V_t} = \hat{Z} \approx \frac{1}{2}, \qquad (6)$$

known as *elastoplastic invariant of deformation.* Its existence has been established and tested experimentally [1–3]. Within the framework of the specified representations it is clear that invariant (6) may be seen as the consequence of the time equation (5). The invariant relates elastic ($\chi$ and $V_t$) and plastic ($\lambda$ and $V_{\mathrm{aw}}$) characteristics of the deformed medium and serves as the main equation of the autowave theory of plasticity. The consequences from it explain the important patterns of plastic flow, including establish the relationship between the autowave theory of plasticity and theory of dislocations [1–3].

There are at least three variants of interpretation of the physical meaning of invariant [1–3], justified by its importance for the autowave plasticity model. In *the entropic* explanation the ratios $\lambda/\chi = w_s \gg 1$ and $V_t/V_{\mathrm{aw}} = w_k \gg 1$ are deemed to be scale and kinetic thermodynamic probabilities, accordingly. The entropy change in generation of autowaves of localized plasticity calculated using the Boltzmann's formula

$$\Delta S = S_s - S_k = k_{\mathrm{B}}(\ln w_s - \ln w_k) = k_{\mathrm{B}} \ln 1/2 \qquad (7)$$

turns out to be negative ($\Delta S < 0$), which indicates the self-organization of the structure in generation of autowaves of localized plastic deformation [5].

*The field* version of explanation uses the analysis of vector fields of reversible and irreversible displacements in the autowave of localized plasticity. In this case the products $\lambda V_{\mathrm{aw}}$ and $\chi V_t$, the ratio of which forms invariant (6), are non-diagonal components of $2 \times 2$-matrix of coefficients of equations relating the speeds of shears with gradients of deformations and stresses [2,3]. Equating them in accordance with Onsager's principle of symmetry [19], we immediately obtain invariant (6).

Finally, *hydrodynamic* interpretation of invariant (6) follows from its formal likeness to Reynolds number $\mathrm{Re} = us/\nu$ [19], which becomes evident, if in equation (6) you accept that $\chi V_t = \nu_{\mathrm{ph}}$ — viscosity of phononic gas braking the motion of dislocations [18], $\lambda \equiv s$ — geometric, and $V_{\mathrm{aw}} \equiv u$ — speed parameters of deformation. In this case you may write

$$\hat{Z} = \frac{\lambda V_{\mathrm{aw}}}{\nu_{\mathrm{ph}}} \equiv \mathrm{Re}, \qquad (8)$$

and then at the stage of linear strain hardening: $\hat{Z} = \mathrm{Re}_{\mathrm{lwh}} = 1/2$.

The specified variants of interpretation have not fully clarified the nature of invariant (6). This became possible within the specified two-component model of localized plasticity, making it possible to consistently explain the causes and the mechanism of origination of macroscopic scale of plastic flow. The developed point of view confirms that the autowave mechanism of plasticity is controlled by the relation of the processes of elastic and plastic deformation implemented with substantially different speeds and scales.

This thought allows for an interesting development. By adding to equation (6) the de Broglie mass of phonon $h/\chi V_t = m_{\mathrm{ph}}$ and autolocalizon (quasi-particles compliant with the autowave of localized plasticity [20]) $h/\chi V_{\mathrm{aw}} = m_{\mathrm{a\text{-}l}}$ and using averaging $\langle \ldots \rangle$ by all data, you can write

$$\hat{Z} = \frac{h/\langle \chi V_t \rangle}{h/\langle \lambda V_{\mathrm{aw}} \rangle} \approx \frac{1}{2}. \qquad (9)$$

Calculations [3] have shown that $\langle m_{\mathrm{a\text{-}l}} \rangle \approx \xi$, and $\langle m_{\mathrm{ph}} \rangle \approx \xi$, where $\xi = 1.66 \cdot 10^{-27}$ kg — atomic unit of mass. In other words, $\langle m_{\mathrm{a\text{-}l}} \rangle \approx 2\langle m_{\mathrm{ph}} \rangle$, or

$$\left( \frac{h}{\langle V_{\mathrm{aw}} \rangle} - \frac{h}{\langle \chi V_t \rangle} \right) = \xi. \qquad (10)$$

Equation (10) leads to invariant (6) and ratio

$$\xi^{-1} \left\langle \frac{h}{\lambda V_{\mathrm{aw}}} \right\rangle = \widehat{M} \approx 2, \qquad (11)$$

for de Broglie mass of autolocalizon, which was called a mass invariant. The effects from it (11) [3] enable, having changed from the autowave of localized plasticity to autolocalizon, to describe the plastic deformation as its Brownian motion in phononic gas, to interpret deformation and damage as condensation of autolocalizons and even justify the introduction of quantum representations into the physics of plasticity [3,20].

The product of elastoplastic $\hat{Z}$ and mass $\widehat{M}$ invariants

$$\hat{Z}\widehat{M} = \xi^{-1} \frac{h}{\langle \chi V_t \rangle} = 0.84 \pm 0.11 \approx 1 \qquad (12)$$

also turns out to be an invariant value. Data given in paper [3], confirm the validity of ratio (12), which highlights the decisive role of the crystalline lattice in the development of plastic flow. The meaning of this conclusion consists in the fact that even though the plasticity depends on movement of dislocations, the latter are the mobile sources of elastic field [7,8] and, running on the plane of perfect crystal sliding, do not damage its perfection. The arisen irreversible (plastic) deformations are related to spatial redistribution of dislocations in the deformed medium and to the change of their density.

Invariant (6) may be given a deeper physical meaning, if, in accordance with the approach proposed in paper [21], scale Hartree units are used to describe the autowave plasticity, which are expressed with combinations of physical constants. The length scale then is the Bohr's radius of hydrogen atom $a_0 = \hbar^2/me^2$, and the speed scale in the condensed medium — value $V_s = (e^2/\hbar) \cdot (m/2M)^{1/2}$ [20]. Here $\hbar = h/2\pi$ is reduced Planck constant, $e$ and $m$ — electron charge and mass, accordingly, and $M$ — atom mass. Having made the replacements $\chi \to a_0$ and $V_t \to V_s$ in equation (6), we get

$$2\lambda V_{\mathrm{aw}} \approx \chi V_t \approx \frac{\hbar}{(mM)^{\frac{1}{2}}} \sim M^{-\frac{1}{2}}. \qquad (13)$$

Root dependence $(\lambda V_{\mathrm{aw}}) \sim M^{-1/2}$ is experimentally confirmed in paper [22] with data for nineteen metals. The calculated and experimentally found values $2\lambda V_{\mathrm{aw}} \approx \chi V_t \approx 10^{-7}\,\mathrm{m^2/s}$ are the minimum values of kinematic viscosity of elastic $(\chi V_t)$ and inelastic $(\lambda V_{\mathrm{aw}})$ deformation processes.

### 3.2. Intermittence of plastic flow

Both in the two-component model, and in the model [10], plastic flow is seen as the sequence of relaxation jumps of stress and deformation in thermally activated overcoming of local barriers. One may think that intermittence is the common mechanism for deformation processes [23], and the curve of plastic flow consists of many subsequent jumps. They may not be always recorded by the recording equipment, but for some materials the main patterns of macroscopic intermittent deformation have been studied in detail [17,24,25].

The general principles of macroscopic intermittence development within a two-component model are explained, if you accept that specimen length $L$ must accommodate integer number of $i = 1, 2, 3\ldots$ autowaves with length $\lambda$, i. e., $L = \lambda i$. Let us now write equation (13) as

$$\lambda = \frac{\hbar}{2(mM)^{\frac{1}{2}}} \cdot \frac{1}{V_{\mathrm{aw}}} = \frac{\xi}{M^{\frac{1}{2}} V_{\mathrm{aw}}}, \qquad (14)$$

and, accepting that $\lambda \approx \delta L/i$, obtain the specimen elongation from it

$$\delta L \approx \frac{\hbar}{2(mM)^{\frac{1}{2}}} \cdot \frac{i}{V_{\mathrm{aw}}} = \xi \cdot \frac{i}{M^{\frac{1}{2}} V_{\mathrm{aw}}} = \frac{\xi}{\kappa} \cdot i, \qquad (15)$$

where coefficient $\kappa = V_{\mathrm{aw}} M^{\frac{1}{2}}$ takes into account the individual nature of the deformed material via speed of distribution of autowaves of localized plasticity $V_{\mathrm{aw}}$ and atomic mass $M$.

Estimation of value $\delta L$ for the case of extension of a specimen from Al at $i = 1$ and specific speed of the autowave of localized plasticity $V_{\mathrm{aw}} \approx 1.8 \cdot 10^{-4}$ m/s [1], made using equation (15), results in $\delta L \approx 10^{-4}$ m. This corresponds to the growth of deformation in an individual jump $\delta\varepsilon = \frac{\delta L}{L} \approx 10^{-3}$, which is consistent with the many times experimentally measured parameters of individual deformation jumps, given in papers [17,24,25], and with the estimate made above in this article when analyzing the deformation parameter of the two-component model.

## 4. Conclusion

The absence of the adequate explanation of the macroscopic scale origination mechanisms (length of autowave of localized plasticity) has for a long time prevented the understanding of the physical fundamentals for the autowave model of plasticity. The satisfactory understanding of this problem was achieved in this paper due to development of the two-component model of localized plasticity and inclusion of the ideas on the medium separation of the interacting dynamic and information subsystems. The explanation of the reasons for origination of macroscopic scale of localized plasticity obtained on this basis led to the following conclusions.

1. When the nature of phenomena in the deformed medium are analyzed, its spontaneous separation into dynamic and information subsystems should be taken into account. The first units the waiting and relaxing concentrators of dislocation origin, and the second one includes signals of acoustic emission, emitted or absorbed in process of every relaxation act.

2. Plastic form change of the medium is carried out by elements of the dynamic subsystem (relaxation acts), controlled by elements of the information subsystem by impact at their kinetics. Interaction of the named subsystems has the acoustic nature and is responsible for the formation of the pattern of localized plasticity with its specific macroscopic scale.

3. Quantitative estimates of deformation timé and spatial parameters of the two-component model of autowave plasticity based on the mechanism of activation of the relaxation shears by acoustic pulses emitted in disintegration of other concentrators, provide the correct dimensions of the areas of coherent deformation of macroscopic scale in process of plastic flow of crystalline materials.

4. Within the autowave theory of plasticity the physical meaning of elastoplastic invariant of deformation is determined by the interrelated roles of elastic (wave) and plastic (autowave) deformation processes in the deformed condensed medium. The invariant indicates the quantitative strong bond of these processes defining the kinetics of plastic flow.

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### Conflict of interest

The authors declare no conflict of interest.

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