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The emergence of large-scale correlations in plastic flow

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Within the framework of a two-component model of plastic flow using thermal activation analysis of the kinetics of elementary acts of plastic deformation, the cause is determined and the conditions for the birth of a macroscopic (autowave) scale during the development of localized plastic flow are analyzed. On this basis, the nature of the elastic-plastic invariant of plastic flow, which links the characteristics of the elastic and plastic components of material deformation, is explained.

Keywords: plastic deformation, localization, invariant, thermally activated processes, autowaves.

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The key problem of the autowave theory of plastic flow [1] is the emergence of an autowave of localized plasticity of a macroscopic scale ($\lambda \approx 10^{-2}$ m) in a medium where the main carriers of plastic deformation, which are edge and screw dislocations, have a characteristic scale on the order of the Burgers vector ($10^{-10} \le b \le 10^{-9}$ m) [2]. The huge range of scales encompassed by deformation ($\lambda/b \approx 10^7$) is hard to interpret, but it is absolutely necessary to do it, since the presence of large-scale inhomogeneities of plastic flow in the form of autowave modes of localized plasticity is indicative of a correlation of deformation events in volumes separated by a distance of $\sim \lambda$.

The reason for the emergence of this scale (correlation radius) of $\sim \lambda$ during plastic flow is discussed below. The proposed explanation relies on a two-component model of autowave plasticity [1], which advances the theory of thermally activated plastic deformation [3] where plastic flow is regarded as a set of thermally activated relaxation acts realized spontaneously under the influence of deforming stress. In this case, the rate of thermally activated plastic flow is governed by the Arrhenius relation

$$\dot{\varepsilon} \approx \dot{\varepsilon}_0 \exp\left(-\frac{U - \gamma\sigma}{k_B T}\right), \qquad (1)$$

where $k_B T$ has the usual meaning, $\dot{\varepsilon}_0 = \text{const}$, U is the potential barrier height, γ is the activation volume, and stress σ includes contributions of various nature.

The two-component model of autowave plasticity proposed in [1] complements model [3] in that, in addition to spontaneous relaxation shifts emerging independently of each other during plastic flow, it allows for correlated development of elementary plasticity acts. Correlation is established through the „exchange" of acoustic signals (phonons), which are emitted in a relaxation act, between local stress concentrators. Acting on a stress concentrator in the „waiting" mode, these signals initiate its relaxation due to the acoustoplastic effect [4]. The inclusion of the „exchange" interaction makes elementary shifts in the deformed medium correlated (i.e., not spontaneous), and the correlation effects may be taken into account directly via a proper contribution to effective stress σ in Eq. (1).

The scenario for the emergence of correlation of concentrators in the two-component model is presented in the figure and is implemented by the following sequence of steps. Let us assume that concentrator *1* relaxes at the initial moment of time, both generating new dislocations in its vicinity and emitting an acoustic pulse. New dislocations activate nearby concentrator *2* by contacting it directly and induce accommodative plastic deformation at the plasticity front, ensuring continuous or jump-like motion of the front.

The acoustic pulse emitted during relaxation of concentrator *1* plays a more significant part. It initiates the relaxation of concentrator *3* located at a distance of $\sim \lambda$ from the original via the acoustoplastic mechanism [4]. The numerical estimate obtained in [1] demonstrated that the additive effect of an acoustic pulse reduces the time of thermally activated separation of the plastic front from the local barrier from $5 \cdot 10^{-5}$ to $9 \cdot 10^{-7}$ (i.e., by a factor of more than 50).

One may use the following equality as the start condition for an acoustically initiated relaxation act of concentrator *3*:

$$U - \gamma(\sigma + \delta\sigma_{ac}) = U - bl\frac{\chi}{2}(\sigma + \varepsilon_{ac}G) \approx 0, \qquad (2)$$

upon the fulfillment of which the plasticity front separates from the local barrier and the regime of thermally activated dislocation motion changes to a quasi-viscous one [2,5]. Here, $\chi \approx b$ is the local barrier width, $(bl\chi/2)\varepsilon_{ac}G \approx (bl\chi/2)\delta\sigma_{ac}$ is the acoustic pulse energy transferred to concentrator *3*, l is the length of the plasticity front section between adjacent barriers, ε_{ac} is the amplitude of deformation in an acoustic pulse, and G is the shear modulus.

The figure makes it clear that condition (2) is satisfied if an acoustic pulse generated in relaxation of concentrator *1*

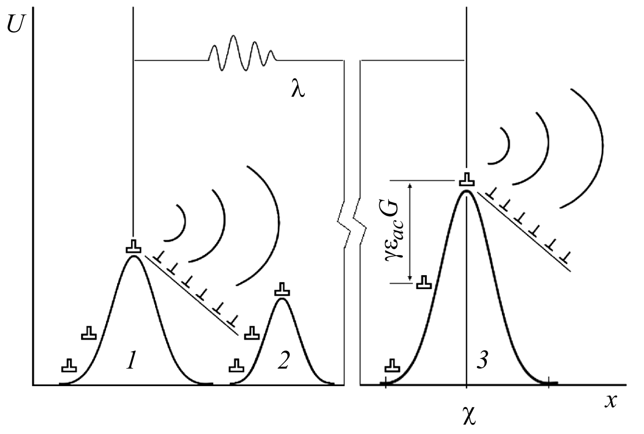

Diagram of development of thermally activated plastic deformation. Emergence of macroscale $\sim \lambda$.

reaches concentrator *3* when $U - \gamma\sigma \approx (bl\chi/2)\varepsilon_{ac}G$ is at it. This is possible if time $\vartheta \approx \lambda/V_t$ of propagation of an acoustic pulse to concentrator *3* over a distance equal to the autowave length is the same as time $\vartheta \approx \chi/2V_{aw}$ within which the autowave front shifts by $\chi/2$ along the slope of the local barrier. In this case, we have

$$\frac{\lambda}{V_t} \approx \vartheta \approx \frac{\chi}{2V_{aw}}. \quad (3)$$

Velocities $V_{aw} \approx (2\pi)^{-1}\lambda\omega_{aw} \approx 10^{-4}$ m/s and $V_t \approx \approx (2\pi)^{-1}\chi\omega_D \approx 10^3$ m/s in Eq. (3) are specified by spatial scales λ and χ of the problem and oscillations frequencies: ω_{aw} for an autowave and ω_{D} for an elastic wave, respectively. Thus, it turns out that the relaxation of concentrator *1* is correlated with the relaxation of concentrator *3* located at a distance of $\lambda \gg \chi$ from it, which is what causes the generation of an autowave of localized plasticity [6].

Expression

$$\frac{\lambda V_{aw}}{\chi V_t} = \hat{Z} \approx \frac{1}{2}, \quad (4)$$

which is known as the elastic-plastic deformation invariant, follows immediately from relation (3). The existence of this invariant has already been established experimentally [1]. Verification of the feasibility of invariant (4) revealed that it is valid at the stages of linear strain hardening and easy slip (in FCC single crystals), where $\sigma \approx \theta\varepsilon$ and strain hardening coefficient $\theta = \frac{d\sigma}{d\varepsilon} = \mathrm{const}$. Phase autowaves of localized plasticity emerge in the deformed medium under these conditions [1]. The interest in the nature of this invariant is attributable to its versatility; relation (4) remains valid for different deformation mechanisms: dislocation slip, deformation due to the motion of individual dislocations and phase transformation deformation, and deformation by twinning in γ-Fe single crystals [1]. It follows from the comparison of average values of λV_{aw} and χV_t for the studied metals (see the table) that their order of magnitude is $\sim 10^{-7}$ m^2·s^{-1} in all cases, and their ratio is $\langle\hat{Z}\rangle \approx 1/2$.

Invariant (4) acts as the main equation of the autowave theory of plasticity of solids and relates the characteristics of elastic (χ and V_t) and plastic (λ and V_{aw}) deformation. Numerous corollaries of invariant (4) explain the patterns of development of localized plastic flow [1] and, what is very important, establish a direct connection between the autowave theory of plasticity and the theory of dislocations [2].

Experimental verification of the elastic-plastic invariant

Metal	$\lambda V_{aw} \cdot 10^7$, m^2·s^{-1}	$\chi V_t \cdot 10^7$, m^2·s^{-1}	$\widehat{Z}$
Cu	3.6	4.8	0.75
Zn	3.7	11.9	0.3
Al	7.9	7.5	1.1
Zr	3.7	11.9	0.3
Ti	2.5	7.9	0.3
V	2.8	6.2	0.45
Nb	1.8	5.3	0.33
γ-Fe	2.5	4.7	0.54
α-Fe	2.2	6.5	0.34
Ni	2.1	6.0	0.35
Co	3.0	6.0	0.5
Mo	1.2	7.4	0.2
Sn	2.4	5.3	0.65
Mg	9.9	15.8	0.63
Cd	0.9	3.5	0.2
In	2.6	2.2	1.2
Pb	3.2	2.0	1.6
Ta	1.1	4.7	0.2
Hf	1.0	4.2	0.24

In light of the above estimates, condition (3) may be regarded as the reason for the existence of invariant relation (4), which plays an important part in the autowave description of plasticity. The above is illustrative of versatility and importance of the elastic-plastic invariant in the characterization of plastic deformation processes.

Two explanations for the meaning of the elastic-plastic invariant have been proposed in [1]. In the first one (thermodynamic), the dimensionless ratios of scales and velocities were regarded as scale $w_s = \lambda/\chi \approx 10^7 \gg 1$ and kinetic $w_k = V_t/V_{aw} \approx 10^7 \gg 1$ thermodynamic probabilities, respectively. This allows one to use Boltzmann formula $S = k_{\mathrm{B}} \ln w$ to calculate the summands of entropy of the process of formation of localized plasticity autowaves, which, as it turns out, yield a negative sum. This is a sign of self-organization of the structure of a plastically deformed medium [7].

The second explanation (mechanical) involves the analysis of elastic and plastic displacements during deformation in an autowave of localized plasticity. In this case, products λV_{aw} and χV_t, the ratio of which forms invariant (4), are assigned the meaning of off-diagonal components of a 2×2 matrix of transport coefficients of the autowave plasticity equations for the rates of variation of deformations and stresses ($\dot{\varepsilon}$ and $\dot{\sigma}$). Equating them in accordance with Onsager's principle [8], one may immediately obtain invariant (4) [1].

Unfortunately, both explanations failed to clarify the issue of quantitative interpretation of relation (4). This is achieved in the approach presented here, which provides a consistent explanation of the causes and the mechanism of emergence of macroscopic scales in the process of development of plastic flow. The discussed interpretation is consistent with earlier concepts regarding the nature of the elastic-plastic deformation invariant [1] and verifies the opinion that the autowave model of plasticity is based on the coherence of elastic and plastic deformation processes, which are characterized by substantially different rates.

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Conflict of interest

The author declares that he has no conflict of interest.

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