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# PLASTIC DEFORMATION VIEWED AS EVOLUTION OF AN ACTIVE MEDIUM

L. B. ZUEV AND V. I. DANILOV
Institute of Strength Physics and Material Science, SB RAS; 634021, Tomsk, Russia

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**Abstract**—The process of plastic flow in crystalline solids has been viewed as the evolution of an active medium in an open system far from thermodynamic equilibrium. The formation of lattice defects, the localization of strain and its variation in the different stages of flow are shown to be related to emergence and evolution of active media of definite types, the evolution of plastic flow involving propagation of different types of self-excited waves and formation of dissipative structures. The analogy with processes occurring in solids under deformation and with the emergence of structures in chemical and biological systems is discussed. Possible types of waves and observing conditions have been classified. © 1997 Elsevier Science Ltd.

## 1. INTRODUCTION

Plastic flow in solids under loading is attended by emergence of ensembles of lattice defects of different types (see, e.g., McLean (1963) Honeykombe (1968)). At present, the reasons for their emergence are not clearly understood; neither are the reasons for plastic strain localizing as a stationary or a mobile neck detectable in the early stages of flow. At the same time, spontaneous delamination of initially homogeneous systems is widely encountered and is thoroughly studied in many divisions of solid-state physics. An approach to this problem as based on the concepts of synergism can be found in the literature (Nicolis *et al.* (1989)). The same delamination could be viewed in the spirit of Haken (1988) as the process of self-organization, viz. an emergence in the systems studied of spatial, temporal or functional inhomogeneities in the absence of any specific influence from without. This approach proved fruitful by describing chemical reactions (see, e.g., Krinsky *et al.* (1981)), biosystems (Romanovsky *et al.* (1984)), delamination in the plasma of solids (see Kerner *et al.* (1978)). On the strength of the data reported, Loskutov *et al.* (1990) formulated the concept of an 'active' medium, i.e. such as is capable of self-organization in the sense specified above. It seems worthwhile to consider the emergence of ensemles of defects by plastic flow from the viewpoint developed in Haken (1988), Romanovsky *et al.* (1984), Kerner *et al.* (1978), Loskutov *et al.* (1990), Vasil'ev *et al.* (1987), the more so as abundant evidence available suggests that plastic deformation has a wave nature (see, e.g., Wray (1969), (1970), Naimark *et al.* (1993)).

In point of fact, the deformed medium can in full measure be viewed as an active one, i.e. one capable of forming space or time inhomogeneities without being subjected to any specific action from without (Loskutov *et al.* (1990)) in so far as

- elastic energy is continuously supplied at a constant rate to the specimen under deformation from the loading device;
- a transformation of elastic energy to the energy of defects (dislocations) takes place in the deformed specimen;
- the defects emerging in the material, in their turn, become involved in the formation of stabile dislocation sets of varying complexity.

Thus, in the process of plastic flow, significant changes take place in the properties of the medium under deformation, which manifest themselves in nonelasticity, deformation hardening, hysteresis and other effects. This suggests that use of the term 'active medium' as applied to a deformed solid is reasonably correct.

From the experimental standpoint, research should be carried out along those avenues which might yield a great body of information on the strain relationships in the different parcels of the specimen under deformation as this is essential for clarifying the mechanisms by which lattice defects are formed, plastic strain is localized and other related phenomena occur.

This requirement has, in particular, necessitated development and use of holographic techniques to study plastic flow of materials as these are capable of meeting the challenge.

## 2. EXPERIMENTAL BASIS; EXPERIMENTAL PROCEDURE AND GENERALIZATION OF RESULTS

Owing to the use of the technique of speckle interferometry (see, e.g., Jones *et al.* (1983), Yoshida *et al.* (1994)), more valuable information could be extracted from the experimental data obtained in our work (see, e.g., Frolov *et al.* (1990), Danilov *et al.* (1991), Zuev *et al.* (1991)). This allows us to obtain quantitative data on the distributions of the displacement vectors on a deformed specimen to an accuracy of about $10^{-4}$ mm practically for the entire specimen commonly used, with the visibility scope being $< 100$ mm. The essence of the method is as follows. The surface of the specimen under deformation is exposed to coherent laser radiation which is scattered from the same to produce bright spots, the so-called speckles. Two photographic images of the specimen with the speckles superimposed on its surface $w$ are obtained, with an increment in strain between the two exposures being less than 0.1% of the total amount of deformation. Then optical reconstruction of the values of the displacement vector $\mathbf{r}$ for every particular point of the specimen surface is performed using the double-exposure speckle photographs obtained. And finally, the components of the plastic distortion tensor are calculated by a routine mathematical treatment procedure (see, e.g., Wit de (1970)).

$$\nabla \mathbf{r} = \beta_{ij} = \begin{vmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_{yy} \end{vmatrix} + \omega_z. \quad (1)$$

Here $\varepsilon_{xx} = \partial u/\partial x$ is elongation; $\varepsilon_{yy} = \partial v/\partial y$ is transverse necking; $\varepsilon_{xy} = \varepsilon_{yx} = 1/2(\partial u/\partial y + \partial v/\partial x)$ is shear deformation; $\omega_z = 1/2(\partial u/\partial y - \partial v/\partial x)$ is rotation, with both $u$ and $v$ being the components of the displacement vector $r$ along the axis of extension $x$ and the axis $y$, respectively (see Fig. 1).

Use of this technique to study plastic deformation on a wide range of materials, e.g. polycrystalline Al, Fe+3%Si alloy, single Cu-Ni-Sn and TiNi alloy crystals, metallic glasses, etc., permitted establishment of the following trends for the observed distributions

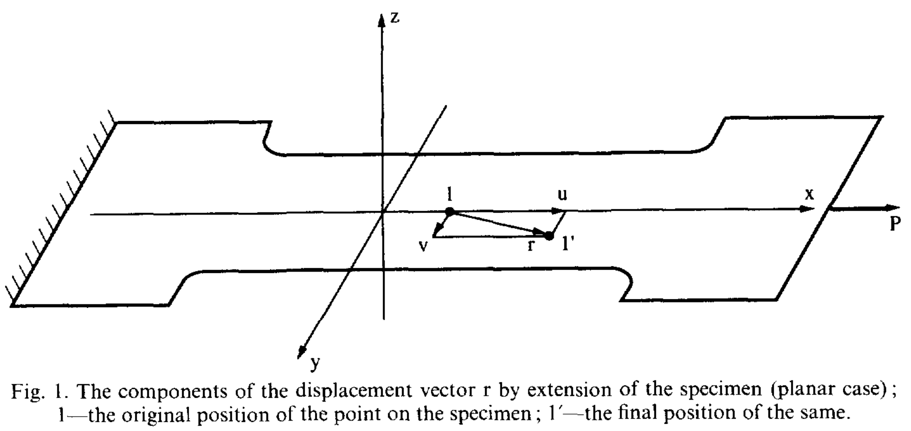


Fig. 1. The components of the displacement vector r by extension of the specimen (planar case); 1—the original position of the point on the specimen; 1′—the final position of the same.

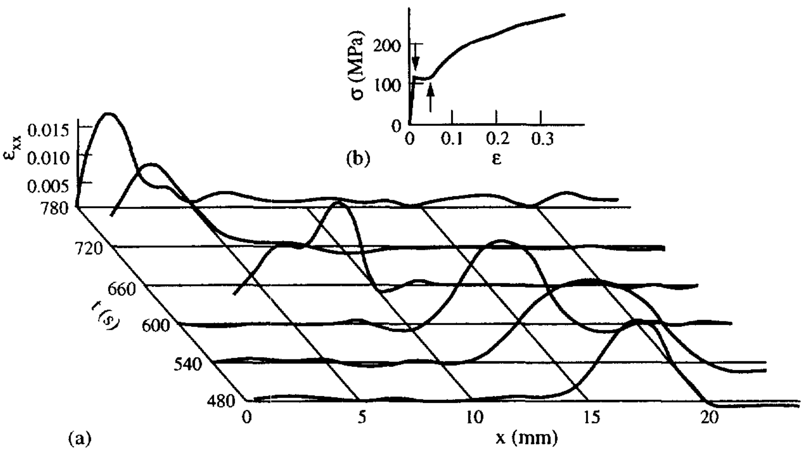


Fig. 2. (a) The space-time distribution of local elongations $\varepsilon_{xx}$ on the yield plateau by deformation of the single TiNi crystal; (b) the deformation curve obtained for the same (the arrows mark the portion of the curve to which the distribution $\varepsilon_{xx}$ corresponds).

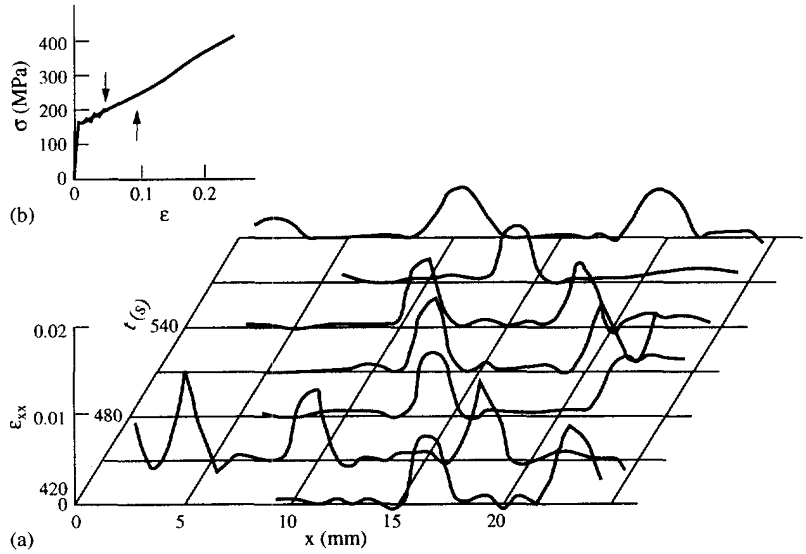


Fig. 3. (a) The space-time distribution of local elongations $\varepsilon_{xx}$ on the linear-hardening stage by deformation of the tempered Cu-Ni-Sn allow single crystal; (b) the deformation curve obtained for the same (the arrows mark the portion of the curve to which the distribution $\varepsilon_{xx}$ corresponds).

of the components of the distortion tensor along specimen axis and for their variation with time (see Figs 2–4).

- Along the specimen length there propagates a solitary seat of plastic flow, with the parcels of material before and after it differing with respect to their structural state (see Fig. 2). This is characteristic of those stages of flow which have a low or a zero coefficient of deformation hardening.
- Along the specimen length there propagates a train of seats of plastic flow (see Fig. 3). This is characteristic of the stage of linear hardening.
- In the specimen investigated there emerge localized stationary zones of plastic deformation which do not shift with time (see Fig. 4). This is found to occur in the stage with a decreasing coefficient of deformation hardening or for the whole loading curve (in the absence of clearly discernible stages).
- Along the specimen axis there are observed chaotic distributions of the components of the plastic distortion tensor. This behaviour is characteristic of a transition from the earliest stage of deformation hardening to the next.

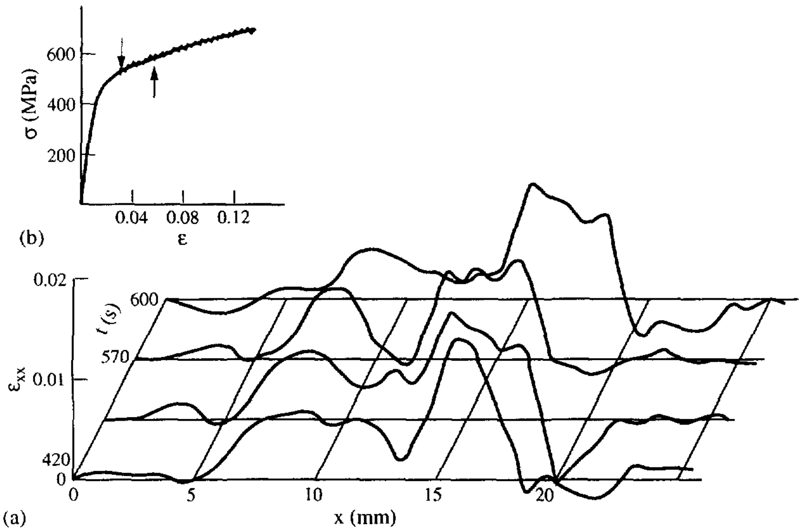


Fig. 4. (a) The space-time distribution of local elongations $\varepsilon_{xx}$ by extension of the aged Cu-Ni-Sn alloy single crystal; (b) the deformation curve obtained for the same (the arrows mark the portion of the curve to which the distribution $\varepsilon_{xx}$ corresponds).

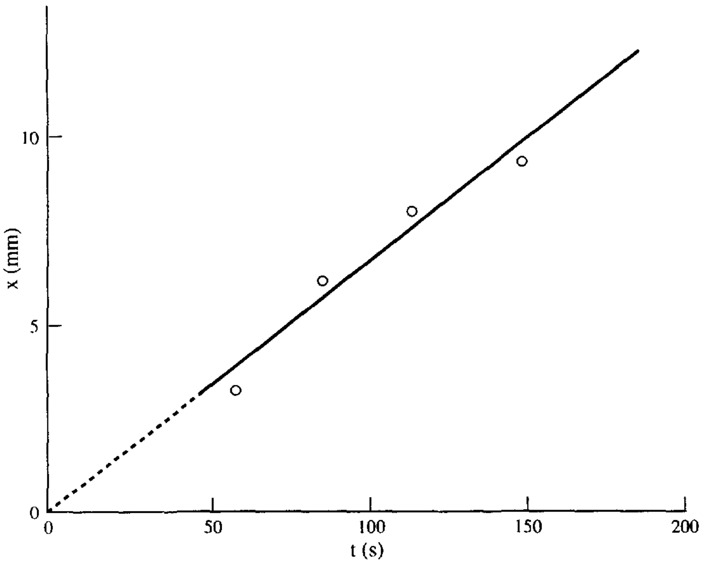


Fig. 5. The displacement of the deformation front in the easy-glide stage by deformation of the Cu-Ni-Sn alloy single crystal (the front position shifting with time is shown).

It should be noted that in all of the above cases, seats of plastic flow propagate at a very low rate of $10^{-5} < v < 10^{-4}$ m/s (Fig. 5). The pattern of the distribution of the seats of plastic flow in one and the same material varies with its hardening coefficient, viz. with evolution of a subsystem containing ensembles of lattice defects (see, e.g., Honeykombe (1968)).

Thus, it has been found that plastic flow of solids is accompanied by a kind of localization of plastic strain which emerges in the early stages of flow and evolves in the course of the process.

Such a localization can be considered as self-organization of an active medium, i.e. attainment by the same of space-time structure, which is very much pronounced in all the stages of plastic flow irrespective of the properties exhibited by a particular deformed material. Microscopic-scale effects of this kind have long been known (Honeykombe (1968)); they are dislocation sets of various types. Macroscopic-scale regularities are, however, insufficiently studied. It follows from the above data that in a deformed material there forms a something closely resembling a deformation wave, the nature of which must be clarified.

### 3. DISCUSSION OF RESULTS; A SELF-EXCITED WAVE MODEL OF PLASTIC DEFORMATION

On attempted discussion of the whole array of data obtained, the major issue to be clarified is as follows: how could a macroscopic spatial inhomogeneity be formed by plastic deformation in view of all its elementary acts being microscopic ones ($\approx$ 10 mm as opposed to $10^{-3} \ldots 10^{-1}$ mm, respectively)? This is by no means a particular problem, since the fact that plastic deformation involves three scale levels, i.e., a micro-, a meso- and a macroscopic one, which appear to be closely interrelated in hierarchic order, has become common knowledge to date (see, e.g., Panin (1995)). To each level there corresponds a specific process: thus a micro level is related to the motion of individual dislocations, a macro level to processes occurring in the deformed object as a whole and a meso level to formation of defects such as Lueders bands, microshear bands, etc. According to Haken (1988), in the general case, the phenomenological link among the processes that occur on the different scale levels could be established within the framework of the synergetic method. The latter was developed by Krinsky *et al.* (1981) and Vasil'ev *et al.* (1987) who suggested an approach as based on the use of the concept of self-excited waves that are solutions to differential equations of the parabolic type

$$\dot{X} = F(X) + D\Delta X, \tag{2}$$

where $X = X(x, y, z, t)$ is a function characterizing the system; $F$ is a non-linear function; $D$ is a diagonal matrix; $\Delta$ is the Laplacian. Similar approaches are known to have been attempted by contemporary workers to describe phenomena of plastic deformation (see, e.g., Aifantis (1987), (1988), (1992)) and the evolution of lattice defects by plastic deformation (see, e.g., Malygin (1995)).

It is concluded that by plastic deformation, oscillations of deformation proper or of dislocation density occur along specimen axis and with time; the same oscillations are periodic in character and can be interpreted as wave processes of nontrivial type. It should be noted that the solutions to eqn (2) represent not waves but so-called self-excited waves (see Vasil'ev *et al.* (1987)). The difference between the two types of processes exhibiting periodic behaviour is considered in Zuev (1994) and Zuev *et al.* (1995). It consists of the fact that the solutions to the hyperbolic equations of regular-type waves are the functions $\sin(t, x, y, z)$, while the process of wave propagation is determined by the interaction of neighbouring parcels of the material. In the case of parabolic-type equation, e.g. eqn (2), the point kinetics of the system $F(X)$ is responsible for wave process origination, with the self-oscillations in individual parcels of the material being pulled into synchronism by controlling signals, e.g. elastic waves.

Experimental evidence is also available on such regular distributions which are treated as waves (see, e.g., Panin *et al.* (1989), Frolov *et al.* (1990), Zuev *et al.* (1994), (1995)). Although periodic macroscopic space-time distributions have been observed by deformation of practically all classes of solids, metallic glasses included, their nature is still an open question, and a mathematical treatment procedure for their description has to be elaborated. The inference as to the synergetic nature of these phenomena (see, e.g., Zuev *et al.* (1994)) was not supported by further work, although during the last decade, the method itself has been used with advantage to study processes occurring in open systems far from equilibrium, with which a deformed solid can apparently be classed (see, e.g., Haken (1988), Romanovsky *et al.* (1984), Vasil'ev *et al.* (1987), Kerner *et al.* (1978), Loskutov *et al.* (1990), Krinsky *et al.* (1981)). Should one be guided by the concept of self-excited wave nature of long-periodic distributions of local deformation, then the best known version of description is thought to be a two-factor one, which sets off in a medium an autocatalytic and a damping factor differing significantly with respect to their characteristic times and radii of action (see, e.g., Loskutov *et al.* (1990), Krinsky *et al.* (1981)).

When plastic flow is dealt with, the essential distinctive features of an active medium must invariably be present and conditions necessary for propagation of self-excited waves must be satisfiable. A deformed solid is actually an open system and the energy applied to it is inhomogeneously distributed, so that in the material there appear distinct zones of energy concentration with their greater-than-average elastic stresses. As loading of the specimen increases, the stresses on the stress raisers relax as a result of plastic displacements and a redistribution of the mosaic of the elastic field takes place, the displacements being capable of initiating elementary deformation acts on other stress concentrators or of creating new ones. Thus, the state of a deformed material is determined by elastic stresses distribution patterns and by plastic flow behaviour (see Nicolis *et al.* (1989)). Elastic stresses play the role of a damping factor and plastic deformation of an autocatalytic factor, since elastic extension causes the temperature to drop adiabatically, while plastic shears, on the contrary, bring about heating of the solid and promote its thermally activated deformation.

Then, according to Vasil'ev *et al.* (1987) and Loskutov *et al.* (1990), in a one-dimensional case a system of parabolic equations is obtained for the autocatalytic and the damping factor, i.e.

$$\dot{\varepsilon} = f(\sigma, \varepsilon) + D_\varepsilon \varepsilon'', \tag{3a}$$

$$\dot{\sigma} = g(\sigma, \varepsilon) + D_\sigma \sigma''. \tag{3b}$$

Here $\dot{\sigma}$ and $\dot{\varepsilon}$ are the rates of variation of stresses and of deformation, respectively; the non-linear functions $f(\sigma, \varepsilon)$ and $g(\sigma, \varepsilon)$ represent the point kinetics per unit volume element of the deformed medium; the addends represent the union of volume units, where $\sigma''$ and $\varepsilon''$ are the second derivatives with respect to the coordinate of the respective quantities; $D_\sigma$ and $D_\varepsilon$ are the transport coefficients.

An important point to consider is that the functions of the point kinetics must describe medium's activity. It is appropriate that in their notation account should be taken of the relaxation character of plasticity acts when $\sigma$ and $\varepsilon$ are interdependently variable (see Panin (1995)). The law of plastic flow might be adopted as $f(\sigma, \varepsilon)$ (see Reiner (1956)):

$$\dot{\varepsilon} = f(\sigma, \varepsilon) = -\frac{\varepsilon}{\Theta} + \frac{\sigma}{\eta}, \tag{4a}$$

where $\eta$ is the viscosity of the deformed medium; $\Theta$ is the relaxation time of plastic deformation. The form of the function $g(\sigma, \varepsilon)$ is defined less unambiguously. Thus Frolov *et al.* (1990) and Zuev (1994) used the equation of elastoviscous medium supplemented by a term proportional to $\sigma\varepsilon$. The term was to account for the effect exerted by the energy of the elastic field of defects caused by strain on the rate of relaxation. This presupposes a hyperbolic stress vs strain dependence. At the same time, in view of the fact that relaxation processes have a thermo-fluctuation nature, from the Arrhenius relationship there directly follows a logarithmic dependence (Feltham (1966)). Therefore, the equation from the work of Frolov *et al.* (1990) is supplemented here by a logarithmic term.

$$\dot{\sigma} = g(\sigma, \varepsilon) = -\frac{(\sigma - \sigma_0)}{\vartheta} + A \ln \varepsilon + \frac{B}{(1-\varepsilon)}. \tag{4b}$$

Here $\sigma_0$ is the amount of deformation up to which the relaxation of stresses occurs; $\vartheta$ is the time of relaxation of stresses; $A$ and $B$ are constants.

A qualitative analysis of the point kinetics is performed by constructing the null-isoclinal functions $f(\sigma, \varepsilon)$ and $g(\sigma, \varepsilon)$ (see, e.g., Krinsky *et al.* (1981)) and by considering the phase-plane portrait of the system. According to eqn (4a), the null-isoclinal $\dot{\varepsilon} = 0$ is linear with respect to deformation.

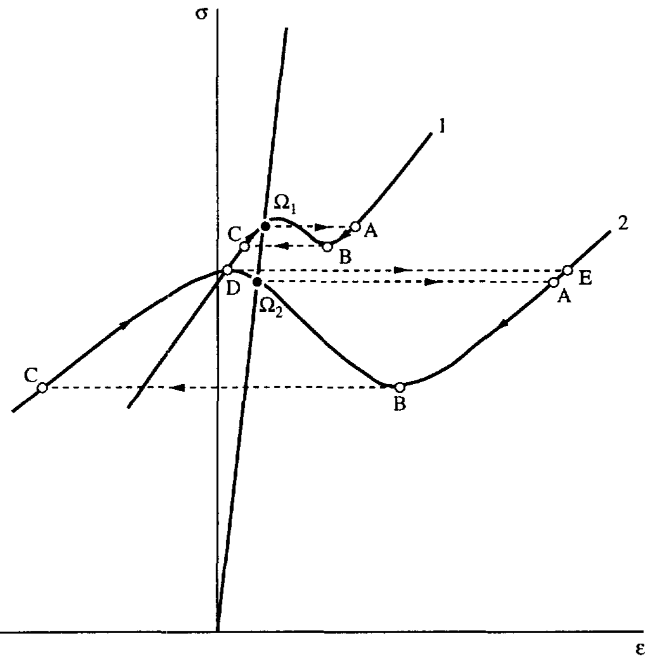


Fig. 6. The phase-plane portraits of the point system at different amounts of prior strain.

$$\sigma = \frac{\eta}{\Theta}\varepsilon = E\varepsilon \tag{5a}$$

($E$ is the elastic modulus). The null-isoclinal $\dot{\sigma} = 0$ from eqn (4b) has the following form

$$\sigma = \sigma_0 + A_1 \ln \varepsilon + \frac{B_1}{(1-\varepsilon)}, \tag{5b}$$

where $A_1 = A\vartheta$, $B_1 = B\vartheta$ and $\sigma_0$ can be estimated from the time relationships of relaxation stresses. These depend on penetrability of barriers, the density of mobile deformation carriers, the material constants of the medium and the testing temperature. By expanding $\ln \varepsilon$ and $(1-\varepsilon)^{-1}$ into power series and by discarding terms to the fourth power and higher, it can be shown that the null-isoclinal is $N$-shaped, which fulfils the necessary conditions providing for self-sustained oscillation solutions (see, e.g., Krinsky *et al.* (1981)).

The position of a special point of intersection of the isoclinal lines $\Omega$ is given, on the strength of analytical results, primarily by the density of mobile deformation carriers as well as by the ratio of the constants $A$ and $\sigma_0$. Figure 6 illustrates a qualitative pattern emerging in a point system at different amounts of prior strain. If a peculiar point $\Omega$ is located to the left of $C$ (Fig. 6, curve 1), then the system's behaviour is stable with respect to minor travels since to each $\sigma$ value there corresponds a strictly specified value $\varepsilon$. It is also the case when $\Omega$ is located to the right of $B$. Both the cases are trivial; therefore, they are not considered hereinafter.

The behaviour of the system becomes more interesting in a situation when the peculiar point $\Omega$ is located between $C$ and $B$ (see, e.g., Fig. 6, curve 1). Then, after the point has reached the position $\Omega_1$ on the line $\sigma = E\varepsilon$, any deviation, however small, would bring about an abrupt transition of $\Omega_1$–$A$ on to the stable branch of the isoclinal $\dot{\sigma} = 0$ and from hence further on along the route $A$–$B$–$C$–$\Omega_1$ to the equilibrium state. It is clear that in this case, a single impulse (seat of strain) at the most would be able to propagate in the system, which is confirmed by the experimental results presented in Fig. 2. It should be noted that such a moving front cannot be viewed as a soliton, since upon collision solitons pass through one another (see, e.g., Dodd *et al.* (1982)), while according to Zuev *et al.* (1991), Lueders bands coming from opposite directions disappear in this situation.

At larger amounts of prior strain, the phase-plane portrait of the system would have a different aspect (see curve 2 in Fig. 6). In this instance, after passing the discontinuity in the curve $\Omega_2$–A, the representative point of the system never returns to equilibrium but makes a complete circuit along the path *B–C–D–E–B*, which is indicative of an emergence of self-excited oscillations in the point system and of propagation of self-excited waves in the distributed system. This situation bears close similarity to the patterns observed in the linear-hardening stage of flow for single Cu-Ni-Sn alloy crystals under deformation (Fig. 3) as well as for coarse-grain polycrystalline Al (see Danilov *et al.* (1991)) and Fe+3%Si alloy (see Panin *et al.* (1989)).

Emergence and propagation of self-excited waves are made possible at certain ratios of parameters characterizing the autocatalytic and the damping factor (see Loskutov *et al.* (1990)). These parameters are represented in eqns. (3a) and (3b) by the constants $D_\varepsilon$ and $D_\sigma$, which have the dimension of the diffusion coefficient ($m^2/s$) and can be expressed by the usual means (see, e.g., Manning (1968))

$$l^2 \sim D_\varepsilon \Theta, \tag{6a}$$

$$L^2 \sim D_\sigma \vartheta. \tag{6b}$$

Here $l$ and $L$ are the characteristic scales of the autocatalytic and the damping factor, respectively. In this phase of research some tentative rough estimates of values $L$ and $l$ could be made. Thus, it is necessary to take into account that, according to Krinsky *et al.* (1981), the magnitude of $L$ corresponds to the wavelength, i.e. the width of a solitary seat of reaction, and the magnitude of $l$ to the width of the wave front (pulse front); then from experimental data (Figs 2–4) it follows that $L \approx 10$ mm and $l < 1$ mm. Estimation of the time parameters can rest on the following reasoning. Evidently, $\vartheta \sim L/v^* \approx 10^{-4}$ s for the time of relaxation of the elastic field, with $v^* \sim (F/\rho_l)^{1/2} \approx 10^2$ m/s being the velocity of propagation of elastic waves in the extended specimen ($F$ is the tensile force; $\rho_l$ is the mass per unit length of specimen). Let the lower bound of $\Theta$ be estimated as the waiting time of a thermally activated act of plastic deformation (see, e.g., Fridel (1964))

$$\Theta \sim \omega_D^{-1} (\mathcal{N}/b) \exp H/kT. \tag{7}$$

Here $\omega_D$ is the Debye frequency, $\mathcal{N}$ is the length of the dislocation loop; $b$ is the Buergers vector; $H$ is the enthalpy of activation of the process. At reasonable values of $\mathcal{N}/b \approx 10^2$ and $H \approx 0.75$ eV (see Fridel (1964)), it follows from eqn (7) that $\Theta > 10^2$ s.

In accordance with eqns (6a) and (6b) $D_\sigma \approx 1$ $m^2/s$ and $D_\varepsilon \approx 10^{-8}$ $m^2/s$. Thus, the following relationship has been found to exist between the qualitative characteristics of the autocatalytic $(l, \Theta, D_\varepsilon)$ and of the damping factor $(L, \vartheta, D_\sigma): l < L; \Theta \gg \vartheta; D_\sigma \gg D_\varepsilon$. Then, in all probability, the transport coefficients $D_\sigma$ and $D_\varepsilon$ might be related to the respective scale levels. And indeed, in view of the fact that these are diffusion-type coefficients, some semi-quantitative estimates could be made. Let these coefficients be represented as the conventional diffusion-type ones (see, e.g., Manning (1968)), i.e. $D = \Lambda V$, where $\Lambda$ is the length of free path (an analogue of the scale of structural level) and $V$ is the velocity of motion of particles (an analogue of the rate of transport of interaction). Donth (1957) was the first to apply a similar approach. Later on it was used by Selitser (1989) to show that plastic deformation could be viewed as evolution of a medium composed of a mosaic of regions differing in terms of stresses and strains and could be described by diffusion equations.

Suppose that $D_\sigma$ fits a macro level of the process of deformation; then it may be written

$$D_\sigma = \Lambda_\sigma V_\sigma. \tag{8}$$

Redistribution of elastic stresses in a deformed material occurs at the sound velocity; therefore, $V_\sigma \simeq v_e = \sqrt{E/\rho} \simeq 2 \cdot 10^3$ m/s ($\rho$ is the density of the deformed material). Then, by making use of the above value $D_\sigma \simeq 1$ m$^2$/s, we obtain $\Lambda_\sigma \simeq 10^{-3}$ m $\simeq 1$ mm, which corresponds to the scale of a meso level.

For $D_\varepsilon$ (a meso level), in its turn, it may be written

$$D_\varepsilon = \Lambda_\varepsilon V_\varepsilon. \tag{9}$$

In this case, the transport of interaction among the neighbouring parcels of the deformed material occurs at a rate equal to the velocity of motion of dislocations; therefore, $V_\varepsilon \simeq v_{disl} \simeq 10$ m/s (see, e.g., Fridel (1964)). Then from eqn (9) it follows that $\Lambda_\varepsilon \simeq 10^{-9}$ m $\simeq 5b$ ($b$ is the Buergers vector of dislocations), which corresponds to a micro (dislocation) scale. Thus, a close relationship has been found to exist among the characteristics of neighbouring scale levels, with the parameters of a low-lying level being affected by the kinetics of processes occurring on a high-lying scale level. However, in any event the autocatalytic factor unfailingly has a small radius of action $l$ and a low rate of propagation $v_s = l/\Theta = 10^{-5}$ m/s, while the damping factor, on the contrary, is characterized by a large radius of action $L$ and a high rate of propagation $v^* \simeq 10^2$ m/s. It is precisely at such relationships between the two sets of values (see Loskutov *et al.* (1990) and Krinsky *et al.* (1981)) that necessary conditions providing for self-excitation could set up. This has been found out by tackling a number of problems; the results obtained reveal qualitative similarity to the patterns observed by plastic deformation (see Figs 2–4). In the case of plastic flow, a continuous distribution of elastic strains is observed in the deformed specimen, which is comparable in type to a standing elastic wave having $\lambda \approx L$ and which rearranges slowly with time with changing stress and specimen configuration. Against this background, localized deformation processes occur; however, the zones involved are of much lesser extent ($\simeq l$). The distribution of the elastic field is such that a regular strain concentration pattern is created. At this point, however, plastic flow is capable of being realized in a limited number of zones, the shear occurring in a single grain of a polycrystalline matter is capable of initiating accommodation processes in a neighbouring grain (see Fidel (1964)), so that the flow occurs in a comparatively small zone ($\simeq l$), with the time and space lag for the next seat of flow being $\simeq L$.

Inhomogeneity of plastic flow has been studied on a macroscopic level using a range of materials under active extension conditions. The flow patterns obtained reveal a qualitative similarity. Figure 3 illustrates the distribution pattern of local elongations obtained for single crystals of the tempered alloy Cu + 10%Ni + 6%Sn under extension. The plastic flow curve of this alloy shows three distinct stages. In the stage of easy glide, corresponding to about 1% of the total amount of deformation, a deformation front $\leqslant 1$ mm wide propagates along the specimen from the fixed to the moving clamp of the test machine (see Fig. 5), the local deformations before and after the propagating front being negligibly small. This corresponds to the situation illustrated by curve 1 in Fig. 6 and to the formation of an active medium capable of self-excitation, in which a single excitation pulse at the most can propagate. Following this pulse, there occurs a transition to a refractory state in which the material is incapable of being activated in the given stage of flow (see Loskutov *et al.* (1990)). And indeed, in the stage of easy glide, no interaction occurs among elementary displacements (see Honeykombe (1968)), and the autocatalytic factor is suppressed relative to the damping factor. This medium type corresponds in essence to a macroscopic-scale concentrator moving at a velocity which is controlled by the slow shear processes occurring at the elastic front.

In the linear-hardening stage, the interaction among elementary shears grows appreciable, the autocatalytic factor comes into play, and a transition of the medium to a self-sustained oscillation state takes place (see the phase-plane portrait of the state represented by curve 2 in Fig. 6). As is seen from Fig. 3, in the specimen there are several equidistant deformation fronts following one another, which represent a running self-excited wave. The transition from the former to the latter stage is essentially a transformation of one type of active medium into another that occurs over an interval of chaos.

## 4. CONCLUSION

Experimental data obtained in the study on a macroscopic inhomogeneity exhibited by plastic flow behaviour in a wide range of solids have been generalized and considered in the light of the concept of a deformable object viewed as an open dissipative structure. It has been found that in plastic flow, active media of different classes are actually formed. A considerable body of information has been provided by describing the same media by means of two controlling factors, i.e. a damping and an autocatalytic one, that could be set off in an active medium, with elastic strains playing the role of the former and plastic deformations as such of the latter. As a result, the diversity of the observed distribution patterns of the local components of the distortion tensor can be organized into four characteristic types. These can be accounted for by the origination in a deformed solid of self-excited waves of two kinds and of stationary dissipative structures, with transitions taking place among the same via chaotic states. Quantitative assessment has been made within the limits of the proposed model; this allowed to single out three characteristic dimensions of plastic flow events, i.e. a micro-, a meso- and a macroscopic one. They are determined by the formation of an active medium and by the influence of the above two controlling factors. Thus, the well-known fact that plastic flow occurs on a multiplicity of levels varying widely in scope is seen in a different light. Moreover, the multiplicity of levels is viewed as a natural consequence of the self-excited wave nature of plastic flow.

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