

Investigation of Plastic Deformation Considering Nanoscale Effects

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The self-consistent theory of plastic deformation in solid was considered within the framework of the presence of the nanoscale defects ensemble. The synergetic equations describing the self-organization of nanoscale defects were analyzed. An effective potential that distinguish plastic and solid states was obtained. For the plastic deformation waves the dispersion law depending on the diffusion coefficient of the defects was considered.

Keywords: Nanoscale defects, Deformation wave, Dispersion law.

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1. INTRODUCTION

Probably the most characteristic feature of the metal is its plasticity, or the ability to be subjected greater deformation without breaking. While practical knowledge about the form-changing metals reach deep into thousand years, our understanding of physical phenomena associated with the plastic deformation, developed only in recent decades. Some of the basic principles were explained, but many related phenomena still require considerable further research before they are fully understood [1-11].

Furthermore the study of plastic deformation in amorphous materials (glassy materials, colloids, granular media, etc.) and crystals and flow of continuous have received great development in recent years [1-6]. The paper [11] studied the plastic deformation in the granular material at a constant angle of inclination of the material. Experiments were carried out for two different types of grains: glass beads and sand.

To describe the process of plastic deformation in crystals one can use a dislocation glide model based on the thermodynamics and kinetics [8,9]. In 1923, G.I. Taylor and C.F. Elam [7] found that plastic deformation occurs by slipping of crystallographic planes in definite directions. Thus the phenomenological description of the material behavior is a basis for describing the plastic flow in solids. The nonlinear theory also implies that harder materials, which do not undergo a microstructural instability, may form isolated shear bands in weak regions or at points of concentrated stress [10].

It is known, that the most impressive feature of metals during plastic deformation is a strain hardening or the ability to become stronger during deformation. Clarification of the nature of the strengthening is a very difficult problem to solve. However dislocation theory provides many useful ideas. Strain hardening leads to a strong consolidation of metal, and much more effective way of increasing its resistance to deformation is doping by other elements. The impact of even very low concentrations of solutes atoms on the strength of metallic crystal can be quite substantial. Trying to understand the behavior of complex alloys during plastic deformation, it is necessary to examine

the impact of the alloying elements in solid solution (that essentially can be regarded as nanoscale defects).

Although the deformation often occurs through sliding, it is not the unique mechanism by which plastic deformation is performed. For thousands of years it was known that metal, machining hardened, can again return the initial plasticity by heating. There are a number of interesting processes that lead to this final result, beginning with the redistribution of defects in deformed crystals and completed with the replacement of the deformed grains (recrystallization).

As shown, a non-conservative movement of dislocations, which are formed at the intersection of dislocations, can lead to the formation of point defects - vacant lattice sites (vacancies) or interstitials. In fact impurity atoms are also point defects. Point defects can occur not only as a result of strain but also when irradiated with nuclear particles; hardening of temperature close to the melting point also captures the excess of vacancies.

The role of vacancies in the diffusion process is well known. When returning from a strain hardening state of the metal at low temperatures as interstitial atoms and vacancies can move in contrast to dislocations. Redistribution dislocation occurs at higher temperatures then vacancies. Interstitial atoms are more mobile than vacancies, and therefore more capable of scattering in various kinds of defects, such as vacancies or grain boundaries, but their formation requires great energy. Therefore quite relevant at the moment is the problem of the influence of point defects on the behavior of the plastic deformation of solids. In this work we propose a phenomenological framework within which the transition from a solid state to a plastic flow is presented as a process of self-organization of the ensemble of nanoscale defects.

2. BASIC EQUATION

The basic laws of plastic flow can be naturally considered within the framework of the hydrodynamic theory [12,13]. The main parameter m of this theory may be defined as the free local volume or as the concentration of vacancies:

$$m = \frac{n_0(r,t) - n(r,t)}{n_0(r,t)}, \quad (2.1)$$

where $n_0(r,t)$ – is the density of “lattice sites”, depending on both the temperature and the strain; $n(r,t)$ is the number of particles per unit volume of material (it depends on the strain) [12]. For amorphous solids and continuous media the density of “lattice sites” has another interpretation: n_0 can be determined as the particle density after the compression at a constant nearest neighbor distance [13]. But simplifying our approach further for parameter m we will use the vacancy concentration denotation.

It turns out that the value of m is critical for the description of the plastic deformation. Indeed, when there are no vacancies $m = 0$ (solid state), in the presence of vacancies $m \leq 1$ (plastic deformation).

Setting the rate of change of vacancy concentration it is convenient to use dynamical equation for the density [14, 15]

$$\frac{\partial}{\partial t} \delta\rho = -\bar{\rho} \operatorname{div} \mathbf{v}, \quad (2.2)$$

where $\bar{\rho}$ is an average density, $\delta\rho$ represents its variation, $\mathbf{v} = \frac{\partial \mathbf{u}}{\partial t}$ is the strain rate.

Usually deformation is accompanied by the changes in the interatomic forces, the measure of which is elastic mechanical stress. Therefore, to describe a complete picture of the plastic deformation is necessary to consider the effect of mechanical stresses σ .

So using the definition (2.1), the relation with the strain rate \mathbf{v} , with mechanical stress σ , and with the free energy, we obtain the equation [16,18]

$$\dot{m} = -\frac{m}{t_m} + \lambda_0 \nabla^2 \sigma + \lambda_0 A \nabla^2 m + g_m \nu \nabla^2 \mathbf{v}. \quad (2.3)$$

Here t_m is a characteristic relaxation time, λ_0 is a kinetic coefficient, $\nabla = \partial / \partial \mathbf{r}$; A, g_m - are the positive constants.

The dynamic equation for the strain rate can be taken by the form [16,18]

$$\dot{\mathbf{v}} = \frac{1}{\rho} \nabla \sigma + \frac{\eta_0}{\rho} \nabla^2 \mathbf{v} - g_\nu m \sigma, \quad (2.4)$$

where η_0 is the dynamic viscosity, g_ν is a positive coupling constant.

The equation for the mechanical stress

$$\dot{\sigma} = \frac{\sigma_e - \sigma}{t_\sigma} - g_\sigma \nu m \nabla^2 \mathbf{v}. \quad (2.5)$$

accounts the relaxation during time t_σ to the value σ_e , given by the external influences, (g_σ is a positive coupling constant, $\nu = \eta_0 / \bar{\rho}$ is a kinematic viscosity).

Considering all three differential equations (2.3)-(2.5) at once we get analogue of the Lorenz system [17] taking into account inhomogeneities in the coordinate.

The Lorenz system is known as simple scheme that describes the self-organization in different systems [17-19]. It is based on three parameters: order parameter (for our consideration it is a vacancy concentration), conjugated field (strain rate \mathbf{v}), and a control parameter (the stress σ).

As a result, solving the system (2.3)-(2.5) we can describe a solid-plastic transition as self-organization of nanoscale defects. But in general, this system is solved only numerically. So we can use a realistic approximation that the relaxation time of the vacancy concentration is sufficiently larger than other time scales.

As a result, the dependence for the conjugated field and control parameter for the homogeneous case

$$\sigma(t) = \frac{\sigma_e}{1 + m^2 / \gamma^2}, \quad v''(t) = \frac{m \sigma_e}{\gamma^2 + m^2} \quad (2.6)$$

were obtained. Here the dimensionless variables were used the parameter γ is introduced as

$$\gamma^2 \equiv \frac{\eta_0 \tau}{\bar{\rho} t_m \lambda_0 A} \quad (3.9)$$

Substituting Eqs.(2.6) into the dynamic equation for the vacancy concentration we can get the effective potential

$$V(m) = \frac{m^2}{2} - \frac{\sigma_e}{2} \ln \left[1 + \frac{m^2}{\gamma^2} \right], \quad (3.11)$$

which distinguish the order (plastic deformation) and disorder (solid) states

3. WAVE OF PLASTIC DEFORMATION

We now consider the wave deformation mode in the presence of spatial heterogeneity.

Deformation is the variation of the relative position of the particles in solid. So it is linked to the particles displacement relative to each other (so-called relative strain).

Considering the relation of the mechanical stress with relative strain instead (2.5) we get

$$\dot{\sigma} = \frac{\sigma_e - \sigma}{t_\sigma} - g_\sigma \varepsilon + D \nabla^2 \sigma. \quad (3.1)$$

where g is a positive coupling constant again, D is a diffusion coefficient of the defects.

Relative strain is a result of changes in interatomic distances and rearrangement of blocks of atoms. Usually deformation is accompanied by the change in the interatomic forces, the measure of which is the mechanical stress. Complementing Eq.(3.1) by nonhomogeneous Maxwell's equation for the viscous-elastic me-

dium with relaxation time $\tau = \eta / \mu$ (η – shear viscosity; μ – shear modulus) we have

$$\dot{\varepsilon} = \frac{\varepsilon}{\tau} - \frac{\sigma}{\eta} + \nu \nabla^2 \varepsilon. \quad (3.2)$$

Considering the solution of two differential equations (3.1)-(3.2) in the vicinity of the stationary states (which are determined by the conditions $\dot{\sigma} = 0$, $\dot{\varepsilon} = 0$), we used the expansion in the form of plane waves. As a result the dispersion law

$$\omega_k^2 = \omega^2 + \omega(D - \nu)k^2, \quad (3.3)$$

was obtained. It is evident from the equation (3.3) that the frequency of plastic deformation waves depends on the diffusion coefficient of defects.

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4. CONCLUSION

Our consideration was shown that the plastic deformation in solids is determined by the behavior of ensemble of the nanoscale defects. The main parameters as vacancy concentration, strain rate and mechanical stress define the possibility of usage of synergetic representation.

Accounting relative strain and mechanical stress the plastic deformation waves were considered. Wherein the dispersion law was obtained subjected to the diffusion constant of the nanoscale defects.

The mentioned results may be used for analysis of the processes occurring during machining, surface treatment of metals, in order to predict experiment errors and to predict the behavior of the solid system.