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Biphase Model of Electroplastic Deformation Metals

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Abstract. A two-phase model of plastic flow based on the concept of deformed material as a heterogeneous medium is proposed. In this approach, wave displacements are considered collisional transitions in this medium. One of his excited phases is involved in restructuring the system, the other is normal and has nothing to do with structural changes. Plasticity waves are the result of the interaction of these two phases. The equation for the filtration model of plasticity, including the laws of conservation of momentum and mass, and the filtration ratio between the phases are obtained. The effect of electric current on the localization of plastic flow of materials during isokinetic deformation was studied. It is found that the pulsed current increases the propagation velocity of plastic autowave by 65%.

INTRODUCTION

One of the troubling problems in the physics of strength and plasticity is the explanation for the non-uniformity of plastic material flow and its stages observed during experiments [1, 2]. Previous methods of modern physical materials science, such as scanning electron microscopy, transmission electron microscopy and double exposure speckle interferometry, show that the process of plastic deformation has wave features [3 – 5]. This is evidenced by stress distributions in a "staggered" order (a "checkboard" effect) at the "surface layer / substrate" interface [3, 4], and non-uniform distributions of displacement fields and strains [5]. increase. These facts indicate that there are regions within the material that do not participate in plastic deformation. According to [5], the characteristic scale of inhomogeneity goes from ~10^{-6} μm to ~10^{-3} m. The stage of plastic deformation is due to the change in the nature of deformation localization, the increase in the number of equidistant localization points in the stages of linear and parabolic hardening and the collapse of plastic waves in the stage of pre-fracture.

A study of dislocation substructures at different stages of plastic deformation [6] suggests that the transition from one stage to another involves transformation from one type of substructure to another, and the transition process showed that the two types of substructures can coexist. The combination of these experimental facts leads to the conclusion that the collective nature of the internal structural changes is responsible for the observed plastic flow regularity [7]. The concept of mechanics in heterogeneous media can be applied to describe plastic deformation [8]. Such an approach was used in [9] to study phase transitions, plastic deformation and other structural transitions in solids. A characteristic of this approach is that he divides the entire set of structural elements (atoms, defects, etc.) of the medium into two subsystems. The shaken ones responsible for restructuring the system and the normal ones that aren't shaken and have nothing to do with structural change. After splitting, the resulting heterogeneous mixture is represented as a set of multiple continuous phases, each described by conservation laws and defining equations.

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RESULTS AND DISCUSSION

The model proposed in this paper uses the laws of conservation of momentum and mass to explain the uneven distribution of displacement under uniaxial deformation [5]. As known in [8], polycrystalline plastic deformation occurs through micro- and macro-displacement. Phase heterogeneous mixture. The first component is the micro shift and the second component is the macro shift. Provides conservation laws for each component. you will be:

$$\begin{gathered}\frac{\partial \rho_1}{\partial t}+\operatorname{div}(\rho_1 \vec{w})=I_{21}, \\ \rho_1 \frac{d_1 \vec{w}}{dt}=\operatorname{div} \tilde{\sigma}_1+\vec{p}_{21}-I_{21} \vec{w}, \frac{d_1}{dt}=\frac{\partial}{\partial t}+\vec{w} \cdot \vec{\nabla}, \\ \frac{\partial \rho_2}{\partial t}+\operatorname{div}(\rho_2 \vec{u})=I_{12}, \\ \rho_2 \frac{d_1 \vec{u}}{dt}=\operatorname{div} \tilde{\sigma}_2+\vec{p}_{12}-I_{12} \vec{u}, \frac{d_2}{dt}=\frac{\partial}{\partial t}+\vec{u} \cdot \vec{\nabla}\end{gathered} \tag{1}$$

where $\rho_1=\alpha \rho_e$, $\rho_2=(1-\alpha) \rho_s$, $\tilde{\sigma}_1=\alpha \tilde{\sigma}$, $\tilde{\sigma}_2=(1-\alpha) \tilde{\sigma}$, ρ_e and ρ_s – the true densities of phases, α – the volume fraction of the first phase, $\tilde{\sigma}$ – the mechanical stress in the mixture, $\vec{p}_{21}=-\vec{p}_{12}$, I_{21}= -I_{12} – intensity of momentum and mass exchange between phases, *w* and *u* – velocities of the first and the second phase, respectively. The intensity of pulse exchange between the phases can be represented as $\vec{p}_{21}=\vec{R}_{21}+I_{21} \vec{u}_{21}$, where R_{21} – interphase force associated with the friction forces, the clutch phases, and $I_{21} \vec{u}_{21}$ – with phase transformations.

We assume that the intensity of mass transfer is small compared to the intensity of the momentum exchange and the mixture components interact according to Rakhmatulin's scheme [8]. Consequently, $\vec{p}_{21}=\vec{R}_{21}$, $\vec{R}_{21}=-p \nabla \alpha+\vec{F}_{21}$, where force $F_{21}=\varphi(\vec{u}-\vec{w})$ is associated with high-speed non-equilibrium phases. With regard to all of the above facts the system (1) takes the form:

$$\begin{gathered}\frac{\partial \rho_1}{\partial t}+\rho_1 \operatorname{div}(\vec{w})=0, \rho_1 \frac{d_1 \vec{w}}{dt}=\alpha \operatorname{div} \tilde{\sigma}+\varphi(\vec{u}-\vec{w}), \\ \frac{\partial \rho_2}{\partial t}+\rho_2 \operatorname{div}(\vec{u})=0, \rho_2 \frac{d_2 \vec{u}}{dt}=(1-\alpha) \operatorname{div} \tilde{\sigma}-\varphi(\vec{u}-\vec{w}).\end{gathered} \tag{2}$$

Assume that first in equation (5) the inertial element $\rho_1 \frac{d_1 \vec{w}}{dt} \approx 0$ and then add (5) to equation (7), we have the relationship:

$$\alpha div \tilde{\sigma}=-\varphi(\vec{u}-\vec{w}) . \tag{3}$$

Equation (3) is the repercussion of the first-phase momentum conservation law, analogous to Darcy's law in filtration theory. Sense of the parameter φ is that it is a factor of resistance to movement of the first phase from the second. The system (2) must be closed with an equation of state. The second phase is a weakly deformable block, so ρ_s = const. For the first phase, assume ρ_e = F(*P*). Now consider the problem in a one-dimensional environment. It is well known that stress in heterogeneous mixtures depends on pressure. Then the (2) and state equations for (3) are

$$\frac{\partial u}{\partial t}+u \frac{\partial u}{\partial x}=-\frac{1}{(1-\alpha) \rho_s} \frac{\partial P}{\partial x}, \frac{\partial \alpha}{\partial t}+u \frac{\partial \alpha}{\partial x}=(1-\alpha) \frac{\partial u}{\partial x}, \frac{\partial P}{\partial t}+u \frac{\partial P}{\partial x}=-\frac{P}{\alpha} \frac{\partial u}{\partial x}+\frac{1}{\alpha} \frac{\partial}{\partial x}\left(B \alpha P \frac{\partial P}{\partial x}\right), \tag{4}$$

We seek a solution in the form $\alpha(x-u_0 t)$, $u_2(x-u_0 t)$, $P(x-u_0 t)$ therefore

$$u'\left(u-u_0\right)=-\frac{1}{\left(1-\alpha\right) \rho_s} P' ; \ \alpha'\left(u-u_0\right)=(1-\alpha) u' ; \ P'\left(u-u_0\right)=-\frac{P}{\alpha} u'+\frac{1}{\alpha}\left(B \alpha P P'\right)' . \tag{5}$$

First integrals of the equations (5) are:

$$\alpha=1-\frac{C_1}{u_2-u_0} ; \ P=\left(C_2-C_1 \rho_s u_2\right) \tag{6}$$

Substituting equations (6) in third equation (5), we obtain:

$$P'(P-a)+PP'\frac{P-a}{P-b}-\frac{b-a}{C_1}B\left(\frac{(b-a)PP'^2}{(P-a)(P-b)}+(PP')'\right), \tag{7}$$

where $a=C_2-C_1\rho_s u_0$, $b=C_2-C_1\rho_s u_0-C_1^2\rho_s$. Equation (7) is reduced to a first-order linear differential equation by replacing $z=PP'$:

$$\frac{dz}{dP}=\frac{1}{D}(P-a)\left(1+\frac{P}{P-b}\right)-\frac{(b-a)z}{(P-a)(P-b)}. \tag{8}$$

The solution of equation (8) has the form:

$$z(P)=D\frac{P-a}{P-b}\left(P^2-bP+C_3\right). \tag{9}$$

The application of the formula $z=PP'$ to (9) leads it to the form:

$$P'=\frac{D}{P}\frac{P-a}{P-b}\left((P-P_1)(P-P_2)\right), \tag{10}$$

where $D=\dfrac{C_1}{(b-a)B}$, P_1 and P_2 correspond to the pressure values at infinity, where the derivative of the pressure in the coordinate is zero. To determine the constants included in equations (6) and (10), we set the boundary conditions:

$$u(0)=u_1^*,\ u(L)=u_2^*,\ u'(0)=0,\ u'(L)=0,\ \alpha(0)=\alpha_1,\alpha(L)=\alpha_2 \tag{11}$$

Taking into account (11), the constant integrations take the form:

$$C_1=\frac{(u_1^*-u_2^*)(1-\alpha_2)(1-\alpha_1)}{\alpha_1-\alpha_2},\ C_2=\left(\left(-\alpha_2+\frac{u_1^*}{(u_1^*-u_2^*)}\right)-\frac{u_2^*\alpha_2}{(u_1^*-u_2^*)}\right)P_0,$$

$$C_3=(1-\alpha_1)(1-\alpha_2)\alpha_1\alpha_2P_0^2,\ P_1=(1-\alpha_1)\alpha_2P_0,\ P_2=(1-\alpha_2)\alpha_1P_0, \tag{12}$$

$$a=P_0(1-\alpha_1\alpha_2),\ b=P_0(\alpha_1+\alpha_2-2\alpha_1\alpha_2),\ u_0=\frac{(\alpha_1-1)u_1^*+(1-\alpha_2)u_2^*}{\alpha_1-\alpha_2}.$$

where $P_0=\dfrac{(1-\alpha_1)(1-\alpha_2)\rho_s(u_1^*-u_2^*)^2}{(\alpha_2-\alpha_1)^2}$. Substitution $P=P_0\left(\left(-\alpha_2-\dfrac{u-u_1^*}{u_1^*-u_2^*}\right)\alpha_1+\dfrac{(u-u_2^*)\alpha_2}{u_1^*-u_2^*}\right)$ and $u_1^*=0$ in (10) we obtain

$$\frac{du}{d\eta}=\frac{-1+\alpha_2}{u-1}-\frac{-1+\alpha_1}{u}+\frac{\alpha}{(u+\beta)} \tag{13}$$

where $\beta=(\alpha_2-1)/(\alpha_1-\alpha_2)$, $\alpha=\dfrac{(\alpha_1-\alpha_2)(\alpha_1\alpha_2-1)}{\alpha_1\alpha_2}$, $\eta=\dfrac{(\alpha_1-\alpha_2)^3}{\alpha_1\alpha_2}B\xi$, $u=u/u_2^*$, $\xi=x-u_0t$. The solution of equation (13) has the form:

$$(1-\alpha_1)\ln u+(-1+\alpha_2)\ln(1-u)+\alpha\ln(u+\beta)=\eta+C. \tag{14}$$

The analysis of the obtained dependence shows that there are two special cases. In the first case, when $\widetilde{u}\geq 0$ equation (15) takes the form:

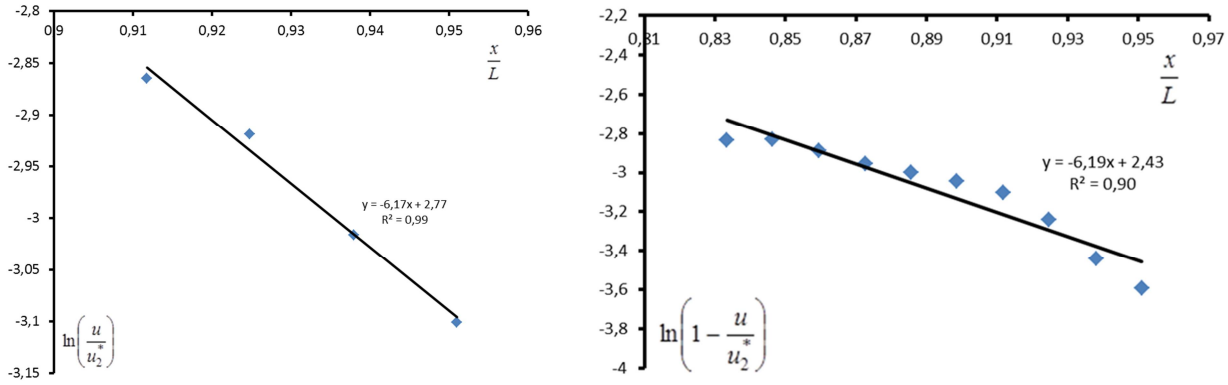
$$(1-\alpha_1)\ln u+\alpha\ln\beta=\eta+C. \tag{15}$$

The second case when $\widetilde{u}\approx 1$ equation (15) it will take the form:

$$(-1+\alpha_2)\ln(1-u)+\alpha\ln(\beta+1)=\eta+C. \tag{16}$$

For the volume fractions determine at the boundaries of localization focus using equations (15) and (16), both in the absence of a pulsed electric current and in its presence, we will use the experimental data [10]. If we rearrange the distributions of displacement velocities in the coordinates (x/L) $-\ln(u/u_2^*)$ and $(x/L)-$ $\ln(1-(u/u_2^*))$, where L – length of work part samples and and to make an approximation by the method of least squares, then by the values of the coefficients that are included in the regression equation, it is possible to determine α_1 and α_2 at the

boundary of the localization focus. In the absence of an electric current (Figure 1a), the volume fractions $\alpha_1 = 0{,}925$, $\alpha_2 = 0{,}838$. When passing a pulsed electric current, the value of the volume fraction $\alpha_1 = 0{,}901$; $\alpha_2 = 0{,}839$ (Figure 1b). The velocity of the localization focus, determined by the formula $u_0 = (1-\alpha_2)u_2^*/(\alpha_1-\alpha_2)$, in the presence of an electric current takes the value $u_0 = 0.517$ mm/min, and in its absence $u_0 = 0.373$ mm/min.



a b

FIGURE 1. Determination of the volume fractions of the first phase at the boundary of the focus of localization (a) left boundary, (b) right boundary

CONCLUSION

With the help of a two-phase filtration model of plastic deformation of materials, the calculation of the limiting velocity of foci of localization of deformation under the influence of electric current was carried out. It is established that the electric current leads to an increase in their speed by 1.38 times. This is due to a change in the volume fraction of the excited phase at its boundaries. Comparison with the experimental results showed the adequacy of the proposed model

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