MODEL OF THE KINETICS OF METAL PLASTIC DEFORMATION UNDER SHOCK-WAVE LOADING CONDITIONS

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It has been shown by numerous investigations of the compression and rarefaction wave structure in metals under shock loading conditions to pressures of tens of gigapascals that the strength properties of materials that govern the load pulse evolution therein are, to a considerable degree, substantially of relaxation nature under these conditions. This appears in experiment as a diminution in the amplitude of the forerunner as it moves [1-3], the discrepancy of amplitudes of the elastic forerunners in the compression and rarefaction waves [4, 5], the elastic–plastic nature of the "recharging" compression wave under step loading [6, 7], and the drop in the resistance to plastic deformation under successive loading by two compression pulses [5, 8]. A model obtained from examining the dynamics of dislocations is proposed in [9, 10] to describe the kinetics of plastic deformation. Different modifications of this model are proposed in [5, 11-14], but no sufficiently complete quantitative description of the material reaction to a pulse load has been obtained up to now. In this paper, kinetic relationships based on a somewhat different representation of the dislocation deformation mechanism used in [9-14] are proposed to describe plastic deformation.

Comparing the results of gasdynamic computations using the proposed plastic deformation kinetics with experimental data confirms it as realistic at all stages of the process in a compression pulse.

The possible plastic deformation mechanisms in a shock wave and the residual metal structure are discussed most completely in [15]. It should be clarified how detailed the description of the strain mechanism should be in a rheological model. At this time it is not reliable to quantitatively analyze all the details of a multifactor process of plastic deformation at a microlevel for the description of the behavior of a macroscopic body. However, understanding of the basic features of the mechanism of the phenomenon facilitates the selection of parameters describing the average properties of the material, and of the functional form of the kinetic relationships.

The magnitude of the plastic shear strain γ is determined completely by the dislocations N and their mean displacement S [16]:

$$\gamma = bNS \tag{1}$$

(b, Burgers vector). Differentiating (1) yields an expression for the strain rate, determined by the rate of dislocation multiplication $\dot{N}$ and the mean velocity of their motion v_{av} $\dot{\gamma} = b\dot{N}S + bNv_{av}$. Since blocking occurs during the interaction of dislocations with each other as well as with the grain boundaries, inclusions, and other defects, and only a part of the total quantity of dislocations actually possesses mobility, then it is expedient to rewrite the last relationship in the form

$$\dot{\gamma} = b\dot{N}S + bN_m v, \tag{2}$$

where N_m is the density of the moving dislocations, v is the average velocity of the moving dislocations. The first term in (2) is ordinarily neglected [9-15], while the quantities N_m and v are determined by using different empirical or semiempirical relationships. It must be said that in this case only a partial description of the evolution of a compression pulse is actually assured (the law of the drop in the amplitude of the elastic forerunner [9, 10], the profile of a stationary plastic shock [11]). For carefully controllable experiment conditions, satisfactory agreement is obtained between the results of a computation and measurement when the initial moving dislocation density is 1-3 orders above the total dislocation density in the initial material.

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TABLE 1 (continued on top of next page)

Material	c_0, cm/sec	m	G_0, g/cm • sec^2	l	K_1, sec/g
Aluminum $\rho_0=2{,}71$ g/cm^3	$5{,}34\cdot10^5$	1,36	$2{,}27\cdot10^{11}$	1,71	10^{-5}
Iron $\rho_0=7{,}85$ g/cm^3	$4{,}63\cdot10^5$	1,5	$8{,}36\cdot10^{11}$	—1,39	$4\cdot10^{-20}$

On the other hand, if typical values of the dislocation density are taken in metals processed by shocks [15] ($N = 10^{10}$–10^{12} cm^{-2}) and the actual dislocation path length is taken comparable in order of magnitude to the shock front width (10^{-3}–10^{-5} cm) [11, 15], then it follows from (1) and (2) that just multiplication of the dislocations can assure strain values characteristic for plane shocks. This impels turning to a two-term kinetic relationship (2).

It is known that shock loading yields greater hardening and a higher dislocation density than deformation under ordinary conditions [18]. The comparison performed in [19] between the results of processing a copper single-crystal with respect to a smooth, "quasiientropic" compression wave and a shock also shows that hardening of the material is considerably higher in the latter case. The shock specifics in this respect is that higher shear stresses are realized in its front [20], which affords a foundation for introducing dislocation dependent on the acting shear stress in the description of multiplication of the "plastic deformation carriers."

An exponential dependence of the rate of growth and multiplication of the dislocations $\dot{N}$ on the magnitude of the acting shear stress τ is introduced in the model we developed. The selection of such a relationship between $\dot{N}$ and τ is based on the known logarithmic dependence between the flow limit and the strain rate [21]. Since an increase in specimen volume is associated with the dislocation formation, a pressure dependence should be introduced in the governing relationship for $\dot{N}$. Because of the inadequacy of the data, the dependence of $\dot{N}$ on the pressure p is constructed with a computation such that the shear strength of the material would vanish for a pressure corresponding to the ultimate theoretical rupture strength because of the spontaneous generation of dislocations.

It is known that the natural dislocation field reduces the efficiency of their sources [16], this is one of the reasons for deformation hardening. It is shown in a number of papers (see [15-18, 22], for instance) that for a fixed strain rate, the shear stress is proportional to the square root of the dislocation density.

Therefore, taking the above into account, the dependence of the rate of dislocation multiplication on the effective shear stress, pressure, and dislocation density achieved is selected in the form

$$b\dot{N}S = K_1\tau S \exp\left[|\tau|/\tau_0(1 - p/p_{\kappa})\sqrt{1 + K_2Nb}\right]. \quad (3)$$

The quantity p_k was estimated by extrapolation in the negative pressure domain of the shock adiabat or isentropy of the material, while the quantities K_1 and τ_0 are selected from the dependence of the yield point on the strain rate; the hardening factor K_2 was chosen empirically.

To describe the second component in the right side of (2), the density of the moving dislocations and the dependence of their velocities on the effective shear stress must be determined. Recent measurements [22] showed that to velocities commensurate with the speed of sound, the dependence of the strain rate on the effective shear stress can be described by the viscous retardation law:

$$v = \tau b/B, \quad (4)$$

where B is the retardation constant with the value $(1\text{-}10)\cdot10^{-5}$ kg/(m•sec) [10, 12, 23]. The quantity B was assumed dependent on the pressure in the computations as $B = B_0(1 - p/p_k)$ by analogy with (3). When using (4), the moving dislocations should be understood to be just those dislocations (or their sections), which are not fastened at a given instant; dislocations temporarily delayed by an obstacle are considered fastened during the delay time.

TABLE 1 (continued)

Material	τ_0, g/km $\cdot$ sec^2	p_K, g/cm $\cdot$ sec^2	K_2, cm	b/B_0, cm$^2\cdot$ sec/g	$b\cdot N_m^*$, cm^{-1}	t^*, sec	S, cm
Aluminum $\rho_0 = 2.71$ g/cm^3	$5\cdot10^7$	-10^{11}	10^{-2}	10^{-4}	10^{-1}	10^{-8}	10^{-4}
Iron $\rho_0 = 7.85$ g/cm^3	$7{,}5\cdot10^7$	$-2{,}5\cdot10^{11}$	$2\cdot10^{-4}$	$7{,}5\cdot10^{-5}$	10^{-1}	$5\cdot10^{-8}$	$2\cdot10^{-5}$

Complete or partial blocking of the moving dislocations occurs during plastic deformation. Preliminary computations of shock processes and their comparison with the results of experiments [24] showed that the characteristic viscosity of the material in direct proximity to the shock front is substantially less for equal shear stresses than at a distance. This can be conceived as the result of diminishing the moving dislocation density with time because of their being blocked. Such an assumption is in agreement with the dependence of the residual dislocation density on the duration of the compression pulse observed in experiments with conservation of the specimens [25]. Because of the high uncertainty in the question of the kinetics of blocking moving dislocations, a relationship selected by empirical means

$$F = \begin{cases} -(N_m - N_m^*)/t^* & \text{for } N_m > N_m^*, \\ 0 & \text{for } N_m \leqslant N_m^*, \end{cases} \tag{5}$$

was used to describe this process in the computations proposed, where the magnitudes of the "equilibrium" moving dislocation density N_m^* and the characteristic time t* were selected empirically. Therefore, the magnitude of the moving dislocation density is determined by the relationship

$$N_m = \int_0^t (\dot{N} + F)\, dt. \tag{6}$$

To confirm whether the proposed plastic deformation kinetics is realistic, numerical modeling of the one-dimensional flow during the collision of plates was performed. The system of equations, including the continuity and motion equations in the Lagrange form, the equations of state for the global stress and strain tensor components, and the rates of change of the deviator components in the one-dimensional strain case under consideration as well as the plastic deformation kinetics in the form (2)-(6)

$$\begin{gathered} \rho_0 \frac{\partial V}{\partial t} - \frac{\partial u}{\partial h} = 0, \qquad \rho_0 \frac{\partial u}{\partial t} + \frac{\partial \sigma_x}{\partial h} = 0, \\ p(V) = \rho_0 c_0^2 \{\exp[4m(V_0 - V)/V_0] - 1\}/4m, \\ \frac{\partial \varepsilon_{xy}}{\partial t} = \frac{\partial \varepsilon_x}{\partial t} - \frac{\partial \varepsilon_y}{\partial t} = -\frac{1}{V}\frac{\partial V}{\partial t} = \frac{\partial \varepsilon_{xy}^{el}}{\partial t} + \frac{\partial \varepsilon_{xy}^{pl}}{\partial t}, \\ \frac{\partial \varepsilon_{xy}^{el}}{\partial t} = \frac{1}{G}\frac{\partial \sigma_{xy}}{\partial t}, \quad \frac{\partial \varepsilon_{xy}^{pl}}{\partial t} = b\dot{N}S + bN_m v, \\ G = G_0 + \frac{V_0}{V} lp, \quad \sigma_{xy} = \frac{3}{4}(\sigma_x - p), \end{gathered} \tag{7}$$

was solved by a through method using a checkerboard mesh and quadratic pseudoviscosity, where V is the specific volume, $\rho_0 = 1/V_0$ is the density of the substance at zero pressure (p = 0), u is the mass flow rate, h is the substantial space coordinate, σ_x, σ_{xy} are the normal (in the compression direction) and maximal shear stresses, taken as positive under compression, c_0, m are coefficients in the linear relationship between the shock velocity and the jump in the mass flow rate, ε_x, ε_y, ε_{xy} are the normal and maximal shear strain components, ε^{el}, ε^{pl} are the elastic and plastic components of the total strain ε, G is the shear modulus, for which the dependence of its magnitude on the pressure was computed from measured values [4, 23, 26] of the longitudinal sound speed and determined by the equation of state p(V) of volume compressibility of the material. The computation is oriented to the relatively low pressures of shock compression of metals at which temperature changes are moderate, hence, the energy equation and temperature components of the equations of state were not taken into con-

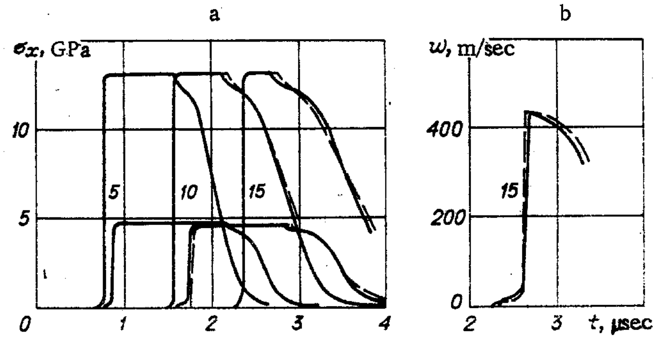

Fig. 1

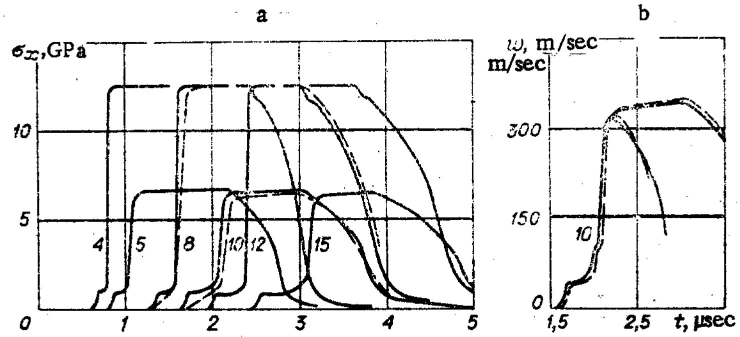

Fig. 2

sideration. Because of the strong dependence of the plastic strain rate on the shear stress, were as in [3, 11-14] it was assumed that plastic deformation only goes in the maximum shear stress directions.

The initial and boundary conditions of system (7) and the material constants were taken corresponding to the cases of loading Armco iron or AD-1 aluminum plates by the impact of an aluminum plate 2-7 mm thick at a velocity of 400-1500 m/sec. The computation results were compared with profiles of $\sigma_x(t)$ in several sections of the specimens, obtained experimentally by using manganin pressure sensors, and with velocity profiles of the free surface of the specimen w(t), measured by using capacitative velocity sensors. A description of the set-up of the experiments and part of the experimental data are published in [24, 27].

Constants of the kinetics of the plastic deformation of materials are presented in the table and assure the best agreement between the computed and experimental data. The profiles of $\sigma_x(t)$ and w(t) for aluminum, obtained from experiments (dashes) and model computations are compared in Figs. 1a and b. The numbers correspond to the initial distance between the section being inspected and the collision surface in millimeters. Computation is compared with experiment for cases of specimen loading by the impact of an aluminum plate of thickness δ = 5 mm w_y = 590 m/sec, and δ = 4 mm, w_y = 1520 m/sec (Fig. 1a); δ = 2 mm, w_y = 460 m/sec (Fig. 1b). The computed and experimental data for iron are compared in Figs. 2a and b. The cases δ = 5 mm, w_y = 590 m/sec (Fig. 2a and b), δ = 7 mm, w_y = 1050 m/sec (Fig. 2a) δ = 2 mm, w_y = 600 m/sec (Fig. 2b) were modeled here.

Taking into account the possibility of inducing systematic distortions in the relatively low pressure range [27] by the inertia of the manganin sensors, it can be noted that in qualitative and quantitative respects the agreement between the computation and measurement results is good enough in all stages of the compression pulse. Therefore, the proposed plastic deformation kinetics assures a detailed description of the evolution of a compression pulse in metals.

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