

NUMERICAL ANALYSIS OF PLASTIC FLOW LOCALIZATION IN METALS

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The influence of thermomechanical parameters and initial loading rate at the boundaries of a thin isotropic metal layer in pure shear on the process of plastic strain localization is studied by numerical simulation. The dependence of the plastic shear value on the loading rate at the layer boundary has been found to be close to a linear function.

Keywords: simulation, pure shear, strain localization, thin layer, dynamic loading, plastic strain.

The phenomena of localization of plastic strains and formation of adiabatic shear bands have long been known. It is believed that heat released in a local zone during plastic deformation under dynamic loading conditions does not have enough time to spread in the whole volume of the metal. As a result, the strength in the hot zone decreases thus leading to an increase in the plastic strain rate and value and, therefore, to further heat evolution and even melting of the metal in the localized shear zone.

Many processes of machining such as cutting, punching, etc. are accompanied by the localization of plastic strains. The experimental studies of the plastic flow localization are reviewed in [1]. El'kin [2] put forward a one-dimensional model for numerical analysis of the plastic flow localization.

Statement of the Problem. The author considers pure shear in a thin layer of an isotropic elastoplastic material. The initial conditions in the layer are taken to be equal to zero. To induce initial non-homogeneity of the stress-strain state in the layer thickness h , the static resistance of the material in a narrow zone $l = 0.1h$ in the center of the layer was decreased by 20%. At the layer boundaries, the rate v of the shear in the direction of the axis x varying in time (antisymmetrically with respect to the layer center) is preset. To save computation resources, calculations were carried out for one half of the layer. Then, the data obtained were represented antisymmetrically with respect to the axis x :

$$x = x_0 + u(y, t), \quad y = y_0, \quad z = z_0, \quad T = T(y, t), \quad (1)$$

where x , y , z and x_0 , y_0 , z_0 are the current and initial coordinates of the layer points, respectively, u is the displacement in the direction of the axis x , T is temperature, and t is time.

The motion and heat-conduction equations are of the form

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial y} \quad \text{and} \quad \frac{\partial T}{\partial t} = \frac{\dot{\epsilon}_p \sigma}{c_v}, \quad (2)$$

where ρ and c_v are the density and volumetric heat capacity of the material, respectively, σ is the yield stress, and $\dot{\epsilon}_p$ is the plastic shear rate. As evident from Eq. (2), the process was considered to be adiabatic, and only the temperature rise due to the work of plastic deformation was taken into account.

The behavior of the material in the layer was modeled by the refined Johnson–Cook equation in the form

$$\sigma = \sigma_{st} + \mu \dot{\epsilon}_p, \quad \sigma_{st} = \sigma_Y [1 + A(\epsilon_p)^n] [1 - (T/T_c)^b], \quad (3)$$

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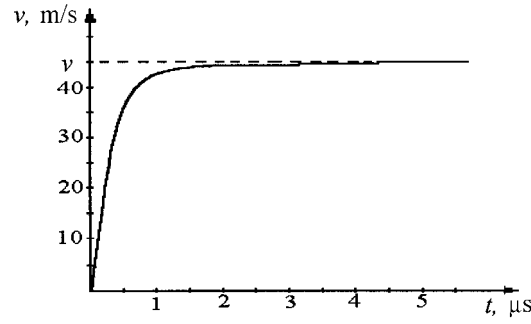


Fig. 1. Variation of the loading rate at the plate boundaries with time.

where μ is the material ductility, σ_Y is the yield stress, A and n are the strain hardening coefficients, ε_p is the plastic strain, T_c is the critical temperature, and b is the temperature-softening coefficient. The ductility of the material is assumed to be constant.

To describe the kinetics of shear strains in the material, we applied Perzhyna's equation [4] for the plastic shear rate in a medium.

Consequently,

$$\dot{\varepsilon}_{ij}^p = \dot{\varepsilon}_p \frac{S_{ij}}{\sigma}, \quad (4)$$

where $\dot{\varepsilon}_{ij}^p$ are the components of the plastic strain-rate tensor and S_{ij} are the components of the so-called active-stress tensor.

The plastic strain was determined using the following expression:

$$\varepsilon_p = \int_0^t \dot{\varepsilon}_p(t) dt. \quad (5)$$

In the calculations, we also considered the dependence of the shear modulus on the layer temperature:

$$G(T) = G_0 (1 - T/T_c), \quad (6)$$

where G_0 is the shear modulus at room temperature.

Calculation Model. In the calculations, the layer was modeled by a two-dimensional matrix of 20×200 elements (200 elements along the axis x and 20 along the axis y) with a spacing $dx = dy = 0.3 \cdot 10^{-3}$ m along the axes x and y , respectively. Thus, the layer had a width of $h = 6 \cdot 10^{-3}$ m. The time step-intervals were chosen from the Courant condition.

The loading rate at the layer boundaries was preset as rapidly exponentially increasing to a given level (Fig. 1). From that point on, the loading rate remained unchanged through the whole deformation process.

The calculations were performed by the "prediction-correction" scheme. For the present problem, the "prediction" and "correction" formulas are written as

$$\begin{aligned} y_{m+1}^* &= y_m + [Z(t_m; y_m) + Z(t_{m-1}; y_{m-1})]/2, \\ y_{m+1} &= y_m + [Z(t_{m+1}; y_{m+1}^*) + Z(t_m; y_m)]/2, \end{aligned} \quad (7)$$

where y_{m+1}^* and y_{m+1} are the predicted and corrected arbitrary parameters, respectively, t_m is the time step-interval, and m is the time step-interval number.

TABLE 1. Thermomechanical Properties of the Metals Studied

Material	$\sigma_Y \cdot 10^{-8}$, Pa	$E \cdot 10^{-11}$, Pa	T_c , °C	ν	$\rho \cdot 10^{-3}$, kg/m ³	$\mu \cdot 10^{-4}$, Pa · s [5]
Aluminum	3.80	0.71	650	0.34	2.7	3
Brass	0.91	1.00	1000	0.36	8.5	2
Steel	3.00	2.10	750	0.27	7.8	4

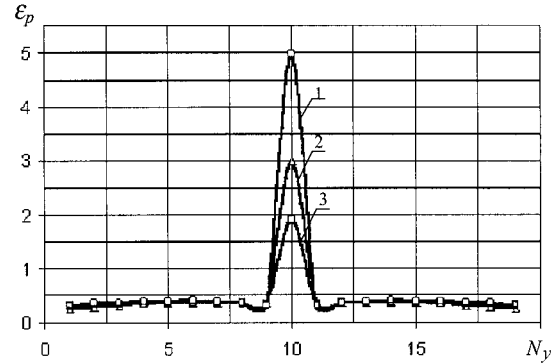


Fig. 2. Plastic shear distribution in the layer thickness for aluminum (1), steel (2), and brass (3) at the 37th microsecond from the beginning of loading.

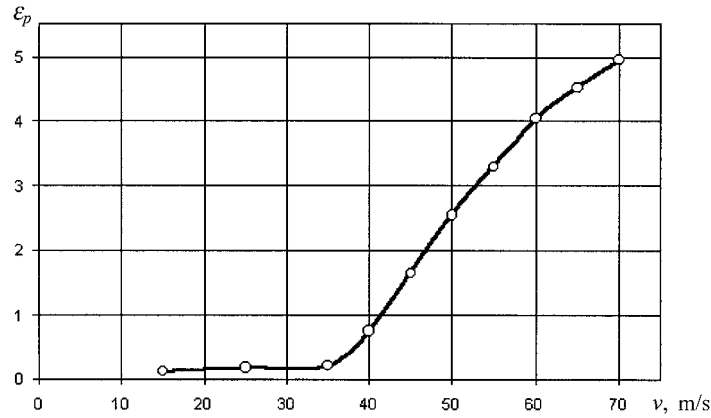


Fig. 3. Plastic shear as a function of the loading rate at the layer boundaries for steel at the 34th microsecond from the beginning of loading.

Analysis of the Numerical Simulation Results. After an early wave-stage of deformation, the plastic strain, stresses, and temperature become uniform throughout the layer thickness. The induced non-homogeneity does not have any noticeable effect on the stress-strain state in the layer ($< 2\%$ of the mean level). However, as the metal of the layer becomes unstable (at the temperature $T \geq 0.95T_c$, $\varepsilon_p \approx 0.3$), the situation changes substantially. The plastic strain is localized in the center of the layer within one row of nodes (a zone of reduced shear resistance) since there is no mechanism of heat transfer between them. The further process involves increasing of the plastic strain level in the central row of the layer nodes. In the other region of the layer, the plastic strain level increases only slightly ($< 7\%$).

To assess the influence of thermomechanical parameters of materials on the plastic strain localization, we used three fundamentally different materials: aluminum, mild steel, and brass. Their main thermomechanical parameters are summarized in Table 1, where ν is the Poisson ratio. The loading rate at the layer boundary was taken to be 45 m/s for all metals.

Figure 2 shows the distribution of the plastic shear through the layer thickness (N_y) for these materials at the 37th microsecond from the beginning of loading. Note that the strain level outside the localization zone differs only slightly (no more than 10%) from metal to metal, while within the localization zone the difference is quite substantial.

For the mild steel, we determined the influence of the loading rate at the layer boundaries on the maximum value of the plastic shear at the 34th microsecond from the beginning of loading (Fig. 3). The loading rate was varied from 15 to 70 m/s.

It is evident that, upon initiation of the localization process ($v > 35$ m/s), the growth of the plastic shear level with increasing loading rate at the layer boundaries is close to linear.

Thus, numerical simulation of the plastic flow localization in pure shear has made it possible to estimate qualitatively the influence of thermomechanical parameters and loading rate at the layer boundaries on the development of the plastic shear.

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