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NUMERCAL SIMULATION OF DYNAMIC CHANNEL-ANGULAR PRESSING OF COPPER SPECIMENS IN 3D STATEMENT

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ABSTRACT

Severe plastic deformation of copper specimens during dynamic channel-angular pressing (DCAP) was numerically investigated in 3D statement for the dynamic scheme of loading. Computations have been carried out by the finite element method within the framework of the elastic-plastic medium model with allowance for fracture. Values of loading pressure and initial velocity are determined to provide the possibility of the DCAP process of copper specimens.

Keywords: dynamic channel-angular pressing, severe plastic deformation.

INTRODUCTION

Bulk nanostructural and ultrafine grained materials are considered to be perspective constructional and functional materials of new generation (Valiev, 2000; Khan, 2010; Meredith, 2012). Investigations of ultrafine-grained metals obtained by severe plastic deformation (SPD) methods have shown that they are characterized by a number of unique properties in comparison with coarse-grained analogues: higher strength combined with high plasticity, low- and high-temperature superplasticity, radiation resistance, etc. A new SPD method such as dynamic channel-angular pressing (DCAP) was proposed, in which pressing of a specimen through intersecting channels is carried out by pulse loading caused by the energy of compressed gases (Zeldovich, 2009). Experimental studies show that there is a need in the large-scale numerical investigations of DCAP processes to determine the effective parameters of SPD (Shipachev, 2010; Skryabina, 2015).

This paper presents an investigation of the DCAP process parameters (initial velocity and pressure) for the copper specimen. The SPD process of the bulk copper specimen with the using of DCAP was numerically investigated in the three-dimensional statement for the dynamic scheme of loading. Computations have been carried out by the finite element method within the framework of the elastic-plastic medium model with allowance for fracture.

COMPUTATIONAL APPROACH

The basic numerical model used in our numerical code for solving high-velocity impact problems comprises the set of differential equations of continuum mechanics such as conservation of mass, momentum, energy, and constitutive relationships. The material model includes an equation of state that provides pressure as a function of the mass density and

internal energy, a deviatoric elastic constitutive relationship, a yield criterion, and a material failure model.

The model for the damaged medium used in the calculations is characterized by the possibility of microdamages formation. The total volume of the medium, W, consists of undamaged volume W_c of density ρ_c and damaged volume W_f of zero density. The overage density of the total volume is given by $\rho = \rho_c(W_c/W)$. The level of the medium damage is characterized by the specific volume of microdamages $V_f = W_f/(W \cdot \rho)$.

The system of equations describing unsteady adiabatic movements of a compressible medium with allowance for the development of microdamages is (Ivanova, 2010; Shipachev, 2010; Gerasimov, 2016):

$$\frac{1}{\rho}\frac{d\rho}{dt} + \frac{\partial v_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{dv_i}{dt} = \frac{1}{\rho}\frac{\partial \sigma_{ij}}{\partial x_j}, \tag{2}$$

$$\rho\frac{dE}{dt} = \sigma_{ij}\varepsilon_{ij}. \tag{3}$$

Here, ρ is the density, t is the time, v_i are the components of velocity, $\sigma_{ij} = P\delta_{ij}+S_{ij}$ are the stress tensor components, E is the specific internal energy, ε_{ij} are the components of the strain rate tensor, $P = P_c(\rho/\rho_c)$ is the overage pressure, δ_{ij} is the Kronecker delta, S_{ij} are the components of the stress deviator, P_c is the pressure in the undamaged substance component.

The pressure in the undamaged substance is a function of specific volume, specific internal energy and specific volume of microdamages; and, throughout the range of loading conditions, it is determined by the Mie-Grüneisen equation of state (Gust, 1982):

$$P_c = \rho_0 a^2 \mu + \rho_0 a^2[1 - \gamma_0/2 + 2(b-1)]\mu^2 + \rho_0 a^2[2(1-\gamma_0/2)(b-1) + 3(b-1)^2]\mu^3 + \gamma_0 \rho_0 E, \tag{4}$$

where $\mu = V_0/(V-V_f)$, γ_0 is the Grüneisen constant; V_0 and V are the initial and current volumes, respectively; a and b are the constants of the Hugoniot shock adiabat, described by relation $u_s=a+bu_p$, where u_s is the shock wave velocity and u_p is the particle velocity behind the shock wave front.

The constitutive relations connect the components of the stress deviator and strain rate tensor and use the Jaumann derivative. The Mises yield criterion is used to describe the plastic flow. A kinetic failure model of the active type for the simulation of fracture in various metals is used for numerical modeling (Kanel', 1996):

$$\frac{dV_f}{dt} = \begin{cases} 0, \text{ if } |P_c| \leq P^* \text{ or if } (P_c > P^* \text{ and } V_f = 0), \\ -\text{sign}(P_c)K_f(|P_c| - P^*)(V_2 + V_f), \text{ if } P_c < -P^* \text{ or if } (P_c > P^* \text{ and } V_f > 0) \end{cases}. \tag{5}$$

Here, $P^* = P_k V_1/(V_f + V_1)$; V_1, V_2, P_k, K_f are the experimentally determined constants ($P^* > 0$). Shear modulus G and dynamic yield strength σ were assumed to depend on attained damage level (Gorel'skii, 1994):

$$G = G_0 K_T \left(1 + \frac{cP}{(1+\mu)^{1/3}}\right)\frac{V_3}{(V_f + V_3)} \tag{6}$$

$$\sigma = \begin{cases} \sigma_0 \, K_\mathrm{T} \left(1 + \dfrac{c\,P}{(1+\mu)^{1/3}} \right) \left(1 - \dfrac{V_\mathrm{f}}{V_4} \right), \text{if } V_\mathrm{f} \leq V_4, \\ 0, \text{if } V_\mathrm{f} > V_4 \end{cases} \tag{7}$$

$$K_\mathrm{T} = \begin{cases} 1, \text{if } T_0 \leq T \leq T_1, \\ \dfrac{T_\mathrm{m} - T}{T_\mathrm{m} - T_1}, \text{if } T_1 < T < T_\mathrm{m}, \\ 0, \text{if } T \geq T_\mathrm{m} \end{cases} \tag{8}$$

where T_m is the melting point of the material, c, V_3, V_4 and T_1 are the experimentally determined constants. In the computations, function $K_\mathrm{T}(T)$ was chosen to model the nonthermal character of plastic deformation and the dynamic strength of solids at high strain rates (10^4 s^{-1} or higher).

The interaction of the copper specimen with intersecting channels is considered. The initial (at t=0) and prescribed boundary conditions are introduced on the surfaces in Cartesian coordinates for constitutive equations (1)-(8). The sliding conditions are met on the contact surface between the specimen and the channels walls. The rigid wall boundary conditions are imposed on the channels. Constant load P that simulates the pressure of powder gases is applied to the back surface of the specimen (dynamic loading scheme). The modified finite element method (without the global stiffness matrix) is used for the solution of the formulated problem (Johnson, 2011; Gorelski, 1997).

RESULTS

The DCAP process was modelled for copper specimens with linear dimensions of 16x16x65 mm. The angle of the channels intersection is 90° with an inclined plane forming 45° angles to the lateral walls of an external corner. The value of the load P and the initial velocity of specimen v_0 are varied (Fig. 1,a).

The analysis of computational results allows us to determine the combination of v_0 and P values, which can provide successful passage of the specimen through channels (region II in the diagram, Fig. 1,b)
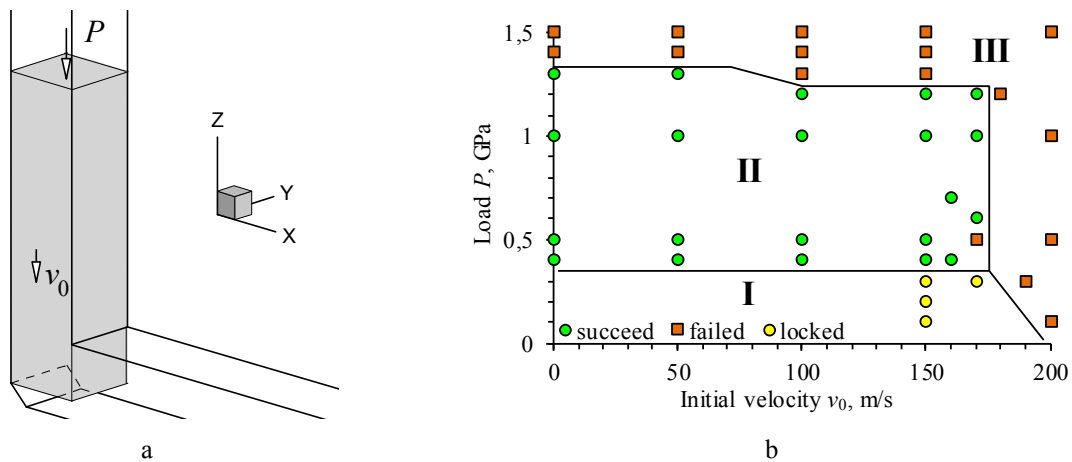

Fig. 1 - (a) The initial position of the specimen and the geometry of the channels;
(b) The diagram of the DCAP process of copper specimen

Diagram in Fig.1,b is divided into three regions: in the region I the specimen is locked, the region II corresponds to the successful passage of the specimen through the channels, the region III corresponds to the unstable passage and destruction of the specimen. The value of the minimum load providing the successful passage of the specimen through the intersecting channels is equal to 0.4 GPa. The growth of the initial speed does not noticeably result in the successful passage of the specimen at the values of $P<0.4$ GPa; there is a border between zones I and III in the right bottom part of the diagram characterised by transition from locking of the specimen in the channels to locking with partial destruction. With the increase in v_0 and P, it was determined the top and right borders of zone II above which the successful passage of the specimen through the intersecting channels is impossible without accumulation of critical level of damages or macro destruction of the specimen (zone III).

Increasing value P at constant v_0 leads to the fact that the specimen stretches more strongly in the direction of a longitudinal axis. The average speed of the specimen passing through the intersecting channels also increases. As a result, the strain rate increases, the temperature rises inside the specimen. In addition, when the P is constant, the increase in v_0 also leads to elongation of the specimen.

The analysis of the specific energy of shear deformations shows almost full identity of plastic deformation fields in the transverse direction. At the same time, there is a non-uniformity of deformation occurring along the specimen, which is especially seen in the forefront of the specimen and can lead to the necessity of the multiple specimen passes through the channels (Fig. 2).
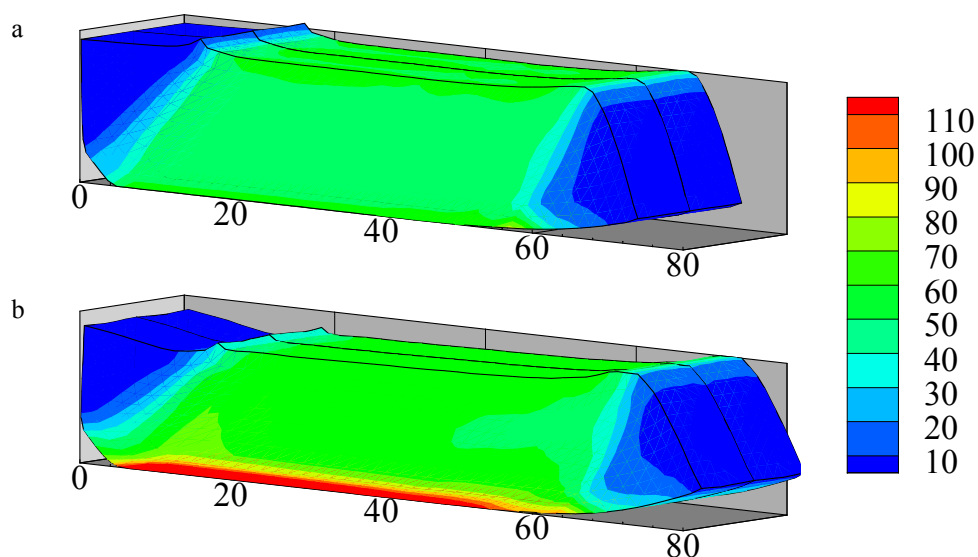

Fig. 2 - Distribution of the specific energy of shear deformations (kJ/kg) in the specimen: (a) $P=0.5$ GPa, $v_0=50$ m/s, t=596 μs; (b) $P=1$ GPa, $v_0=50$ m/s, t=314 μs. The dimensions are in mm.

It is necessary to notice that the maximum values of specific energy of shear deformations are reached in surface layers of the specimen due to the interaction with the walls of the channels (Fig. 2,b). Melting of the material can take place in these areas.

CONCLUSION

Numerical investigation is conducted in the three-dimensional statement for the copper specimen deformation processes during DCAP. The diagram of the DCAP process is obtained for the copper specimen in coordinates v_0 - P (initial velocity of the specimen - pressure applied on a rear surface of the specimen). The computational results show that the increase in the rate of the specimen deformation and initial velocity of the specimen leads to the lengthening of the specimen in a direction of a longitudinal axis, the temperature and microdamages growth.

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