IOP Conf. Series: Materials Science and Engineering **177** (2017) 012056 doi:10.1088/1757-899X/177/1/012056

Numerical simulation of dynamic channel-angular pressing of copper specimens

A S Bodrov[1] **and S A Zelepugin**[1,2]

[1] National Research Tomsk State University, 36, Lenin ave., Tomsk, 634050, Russia
[2] Tomsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences, 10/3, Akademichesky ave., Tomsk, 634055, Russia

E-mail: alex.bodrov@mail.ru

Abstract. The process of severe plastic deformation of a copper specimen during dynamic channel-angular pressing is numerically investigated in a 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. Loading pressure and initial velocity values are determined to provide the possibility of the process of dynamic channel-angular pressing of copper specimens.

1. Introduction

Bulk nanostructural and ultrafine grained materials are considered to be perspective constructional and functional materials of new generation [1-3]. 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. The study of such materials properties has theoretical and applied importance.

One of the widely used SPD methods is equal-channel angular pressing (ECAP) [1]. A new SPD method such as dynamic channel-angular pressing (DCAP) is proposed, in which pressing of a specimen through channels is carried out by pulse loading caused by the energy of compressed gases [4, 5]. DCAP allows the specimens of considerably bigger sizes and a smaller number of passes to be used, and the specimen material retains a high plasticity in comparison with the ECAP method.

Experimental studies show that there is a need in the large-scale numerical investigations of DCAP processes to determine the effective parameters of SPD. At present, there are few works devoted to the numerical modeling of DCAP processes [6-8]. 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 use 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 [10, 11].

2. 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 [6, 9, 10]

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

$$\frac{\mathrm{d}v_i}{\mathrm{d}t}=\frac{1}{\rho}\frac{\partial \sigma_{ij}}{\partial x_j}, \tag{2}$$

$$\rho\frac{\mathrm{d}E}{\mathrm{d}t}=\sigma_{ij}\varepsilon_{ij}. \tag{3}$$

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:

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

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 [11]:

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

Here, $P^*=\mathrm{P_k}\mathrm{V_1}/(V_f+\mathrm{V_1})$; $\mathrm{V_1}$, $\mathrm{V_2}$, $\mathrm{P_k}$, $\mathrm{K_f}$ are the experimentally determined constants ($P^*>0$).

Shear modulus G and dynamic yield strength σ were assumed to depend on attained damage level [12]:

$$G=\mathrm{G_0}\,K_\mathrm{T}\left(1+\frac{\mathrm{c}P}{(1+\mu)^{1/3}}\right)\frac{\mathrm{V_3}}{(V_f+\mathrm{V_3})} \tag{6}$$

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

$$K_T = \begin{cases} 1, \text{if } T_0 \le T \le T_1, \\ \dfrac{T_m - T}{T_m - T_1}, \text{if } T_1 < T < T_m, \\ 0, \text{if } T \ge T_m \end{cases} \quad (8)$$

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 $K_T(T)$ 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 [13].

3. Computational results

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

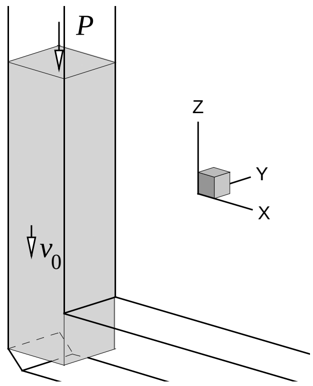

Figure 1. The initial position of the specimen and the geometry of the channels.

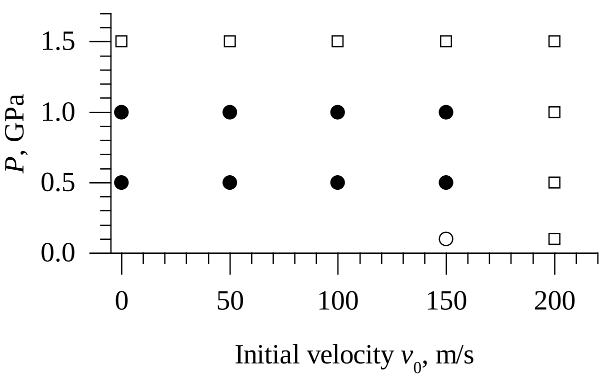

Figure 2. Results of the numerical simulation of the DCAP process: ● – successful passage of the specimen through channels, ○ – the specimen is locked, □ – unstable passage or destruction of the specimen.

The analysis of computational results allows us to determine the combination of the initial velocity and load values, which can provide successful passage of the specimen through channels (the black circles in figure 2). The values of load essentially influence the DCAP process (figures 3-4). If the values of load are not high enough, the specimen can be locked in the channels, on the other hand, extremely high values can lead to unstable passage and destruction of the specimen. When the values of load are constant, the increase in the initial velocity leads to elongation of the specimen, and if the load value is insufficient to provide the DCAP process, it can be compensated by increasing the initial velocity. Increasing the load value leads to the fact that the specimen more strongly stretches in the direction of a longitudinal axis (figures 3-4). The speed of the specimen passing through the intersecting channels also increases. As a result, the strain rate increases, the temperature rises inside the specimen. The analysis of the specific energy during shear deformations shows almost full identity of plastic deformation fields in the transverse direction, which testifies the preference of using the square section specimens in DCAP in comparison with the cylindrical ones. At the same time, there is a non-uniformity of deformation occurring along the sample, which is especially seen in the forefront of the specimen and can lead to the necessity of the multiple specimen passes through the channels. It is necessary to notice that the maximum values of specific energy in shear deformations are reached in surface layers of the specimen due to the interaction with the walls of the channels (figure 3b). Melting of the material can take place in these areas. In the upper part of the specimen, the increase of microdamages in the area is observed (figure 4b).

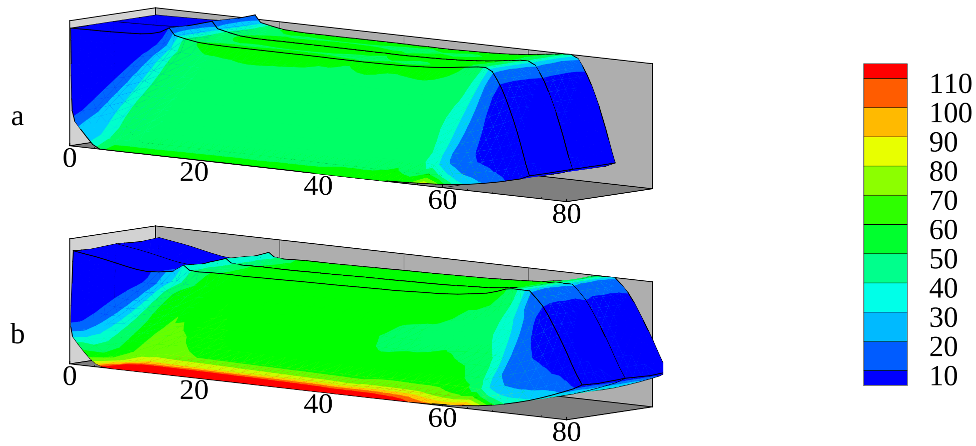

Figure 3. Distribution of the specific energy of shear deformations (kJ/kg) in the specimen: a) P=0.5 GPa, v_0=50 m/s, t=596 μs; b) P=1 GPa, v_0=50 m/s, t=314 μs. The dimensions are in mm.

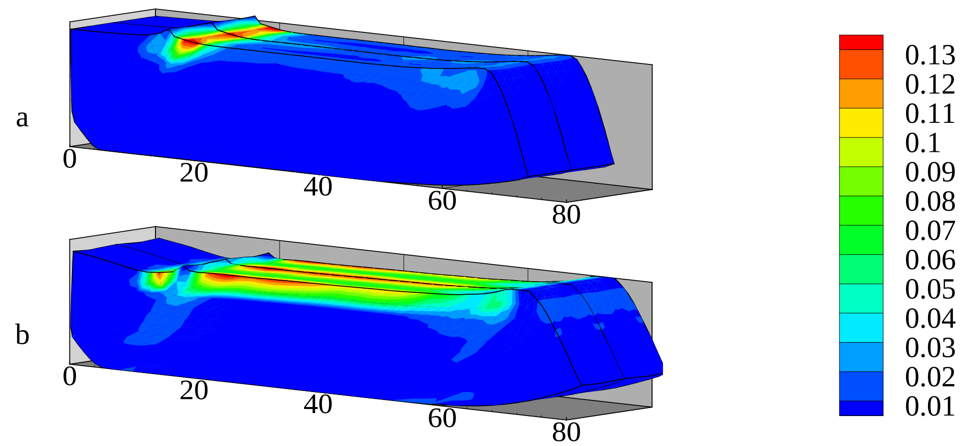

Figure 4. Distribution of the specific volume of microdamages (cm^3/g) in the specimen: a) P=0.5 GPa, v_0=50 m/s, t=596 μs; b) P=1 GPa, v_0=50 m/s, t=314 μs. The dimensions are in mm.

Figure 5 shows the kinetic energy of the specimen for all successful DCAP processes.

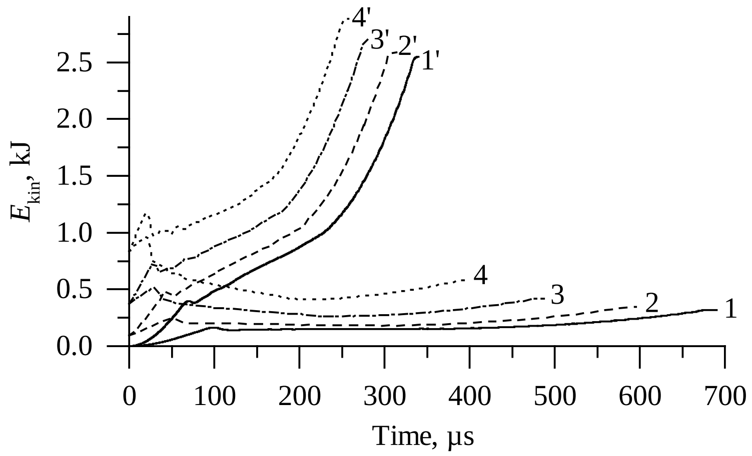

Figure 5. Kinetic energy of the specimen during DCAP for different values of P and v_0:
1 – P=0.5 GPa, v_0=0 m/s,
2 – P=0.5 GPa, v_0=50 m/s,
3 – P=0.5 GPa, v_0=100 m/s,
4 – P=0.5 GPa, v_0=150 m/s,
1' – P=1 GPa, v_0=0 m/s,
2' – P=1 GPa, v_0=50 m/s,
3' – P=1 GPa, v_0=100 m/s,
4' – P=1 GPa, v_0=150 m/s.

4. 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 titanium specimen in co-ordinates $v_0 – P$ (initial velocity of the specimen – pressure acting on a rear surface of the specimen). The computational results show that the increase in the velocity of the specimen passing through channels (rate of the specimen deformation) and initial velocity of the sample lead to the lengthening of the sample in a direction of a longitudinal axis, the temperature growth in the sample and the growth of microdamages.

Acknowledgments

The work was funded by the Ministry of Education of the Russian Federation within state task №2014 / 223 (project no. 1943) and the Russian Foundation for Basic Research (project no. 16-43-700774)

References

[1] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 *Prog. Mater. Sci.* **45**(2) 103
[2] Valiev R 2004 *Nature Mater.* **3**(8) 511
[3] Skryabina N E, Aptukov V N, Romanov P V and Fruchart D 2015 *PNRPU Mech. Bull.* **3** 133
[4] Zeldovich V I, Shorokhov E V, Frolova N Y et al. 2009 *Phys. MET. Metallogr.* **108**(4) 347
[5] Zeldovich V I, Shorokhov E V, Dobatkin S V et al. 2011 *Phys. MET. Metallogr.* **111**(4) 421
[6] Shipachev A N, Il`ina E V and Zelepugin S A 2010 *Deform. Razr. Mater.* **4** 20
[7] Shipachev A N, Zelepugin A S, Il`ina E V and Zelepugin S A 2012 *Deform. Razr. Mater.* **10** 7
[8] Bodrov A S, Olimpieva N V, Zelepugin A S and Zelepugin S A 2016 *Proc. 2015 Int. Conf. MEACS* 7414878
[9] Gerasimov A V and Pashkov S V 2015 *Russ. Aeronaut. Iz.VUZ.* **58**(2) 137
[10] Gerasimov A V, Pashkov S V and Cherepanov R O 2016 *Int. J. Appl. Eng. Res.* **11**(18) 9430
[11] Kanel' G I, Razorenov S V, Utkin A V and Fortov V E 1996 *Shock-Wave Phenomena in Condensed Matter* (Moscow: Yanus-K)
[12] Gorel'skii V A, Zelepugin S A and Sidorov V N 1994 *Int. Appl. Mech.* **30**(3) 193
[13] Johnson G R 2011 *Int. J. Impact Eng.* **38**(6) 456