Simulation of dynamic channel angular pressing of copper samples using experimental data of loading

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Abstract. The paper represents the numerical simulation of severe plastic deformation of a copper sample under dynamic channel-angular pressing. The initial sample velocity and the value of pressure acting on the back surface of the sample during the process were determined based on the analysis of experimental data. Numerical computations were carried out using the author's numerical code created in the integrated development environment Delphi. A modified finite element method (without constructing a global stiffness matrix) was used as a numerical method. The behavior of the material was described by an elastic-plastic model using the active type fracture model. Testing of the numerical code was carried out on the Taylor problem. The velocity and pressure values required for the successful dynamic channel-angular pressing were determined. A uniform distribution of the ultrafine-grained structure in almost the entire volume of the copper sample was revealed.

1. Introduction
One of the main directions in the field of materials science is the production of materials with improved physical and mechanical properties. At present, the available methods provide a possibility to obtain nanostructured and ultrafine-grained (UFG) metals and alloys with a grain size of about 50-150 nm \cite{1, 2}. Metals with a UFG structure have unique properties and are used in many areas of science and engineering. Increased strength, cold brittleness, radiation resistance, and many other characteristics are closely related to UFG metals, but the ways of obtaining this structure still requires additional studies. The compaction of powders, including explosive compaction \cite{3}, from dispersed metal particles obtained by gas condensation, chemical synthesis, etc., is currently widely used. At the same time, the powder compaction method has serious drawbacks, such as residual porosity, contamination of powders during preparation, and the small size of final products.

Active studies in the field of severe plastic deformations (SPD) provide an opportunity to take a fresh look at the process of grinding and the formation of the UFG metal structure \cite{1, 2}. It is known that during manufacturing processes such as rolling, stretching, and pressing the grain size of metal decreases by several times, but the grains have low-angle boundaries, therefore, special SPD methods are used to obtain high-angle grain boundaries: high-pressure torsion, equal-channel angular pressing (ECAP) \cite{1, 2, 4, 5}, dynamic channel-angular pressing (DCAP) \cite{6}.

This paper considers the DCAP process that is the ECAP modification. The ECAP process is conducted on the pressing equipment. In this case a metal sample has to repeatedly pass through intersecting channels to obtain a uniform UFG structure. In the DCAP process an explosive is used instead of press, and as a result, there is a rapid increase in pressure acting on the back surface of the sample, and the sample can accelerate with a high velocity.

The DCAP method reduces the number of sample’s passes by several times due to high strain rates while maintaining the plastic properties of the sample material. Dynamic channel-angular pressing is applied to many metals and alloys, intermetallic compounds, and structural, functional materials \cite{7-9}.
11], therefore, there is a need in the deeper analysis of this manufacturing process in the context of deformable solid mechanics and fracture mechanics, including numerical simulation [12 -15]. The purpose of this work is the numerical simulation and analysis of the DCAP process with regard to the pressure and acceleration parameters determined from the analysis of experimental data [16]. The main task of the simulation is the choice of the initial sample velocity at which the sample can successfully pass through intersecting channels. The principal difference from the previous works [12, 13, 15] is the study of the DCAP process at lower pressures of 200 - 300 MPa obtained from the analysis of experiments [16].

2. Formulation of the problem. Determining the values of initial velocity and current pressure

The movement of a copper square-section sample (M1) under DCAP is considered. The length of the sample is 65 mm, cross section dimensions is 16 × 16 mm. At the initial time, the sample is in the vertical channel and has an initial velocity \(v_0\) and pressure \(P\) acting on the back surface of the sample. The walls of the channels are considered to be absolutely rigid. Figure 1 shows the intersection of the channels. An inclined platform is in the region of the external channel crossing angle. The inclination angle of the inclined platform is 45°, and the height is 4 mm.

![Figure 1. Formulation of the problem, sizes are given in mm.](image)

Figure 2 shows a curve that interpolates the experimental data of pressure acting on the back surface of the sample. The experimental data are given in [16]. Analyzing the data presented in Figure 2, it can be concluded that the choice of pressure acting on the back surface of the sample is a nontrivial question. Analysis of the numerical DCAP computations [12, 13, 15] was conducted to determine the time required for the passage of the channels, which was 0.8-1.0 milliseconds. The interpolation curve shown in Figure 2 demonstrates that during this time the change in pressure is insignificant. Therefore, the constant pressure averaged over an interval of 1 ms can be chosen for computations. Figure 2 demonstrates this interval that is marked with the dashed vertical lines; value \(P = 310\) MPa is chosen as the average pressure.
Figure 2. Pressure as a function of time, 1 – experimental data [16], 2 – interpolation curve.

Using the measured velocity [16], an interpolation curve of the sample's velocity as a function of time was constructed (Figure 3). Figure 3 shows an almost linear graph at the time of 5–9 ms, which can be approximated by a straight line. The calculated slope of the approximation straight line was used to determine the acceleration of the sample \( a \approx 3.5 \times 10^5 \text{ m/s}^2 \). Knowing the acceleration of the sample, it is possible to vary the velocity of the sample, at which the sample starts passing the intersected channels in a wide range of 0-1800 m/s (according to Figure 3), depending on the distance traveled by the sample along the vertical channel before the start of the DCAP process. Thus, based on the analysis of experimental data [16], in this work the parameters were selected as follows: pressure \( P = 310 \text{ MPa} \) acting on the back surface of the sample under DCAP and the range of the initial velocity of the sample (0-1800 m/s).

Figure 3. Velocity as a function of time. 1 – experimental data [16], 2 – interpolation curve, 3 – approximation straight line.
3. Computational approach

The 3D problem was solved using a modified finite element method. The equation of continuity (1), motion (2) and energy (3) are used as the basic equations [12, 13, 15]:

\[
\frac{1}{\rho} \frac{d\rho}{dt} + \frac{\partial v_i}{\partial x_i} = 0 \tag{1}
\]

\[
\frac{dv_i}{dt} = \frac{1}{\rho} \frac{\partial \sigma_{ij}}{\partial x_j} \tag{2}
\]

\[
\rho \frac{dE}{dt} = \sigma_{ij}e_{ij} \tag{3}
\]

where \(\rho\) is density, \(t\) is time, \(v_i\) is the velocity component, \(x_i\) is the component of spatial variables, \(E\) is specific internal energy, \(\sigma_{ij}\) are the components of stress tensor, \(P = P_c(\rho/\rho_0)\) is average pressure, \(\delta_{ij}\) is the Kronecker symbol, \(P_c\) is pressure in the undamaged material, \(S_{ij}\) is stress deviator, \(e_{ij}\) is the component of strain rate tensor. The volume of the damaged medium \(V\) consists of a condensed phase (undamaged material) \(V_r\) and pores \(V_f\). To describe a damaged medium, the specific volume of microdamages \(V_f\) and the average density of the damaged medium \(\rho = \rho_c(V_r/V_f)\) are introduced.

The damage of the material is simulated using an active fracture model in the numerical code, where \(P^* = P_cP_f/(V_f + V_i)\), \(V_i\), \(V_f\), \(K_c\), \(P_k\) are constants:

\[
\frac{dV_f}{dt} = \begin{cases} 0, & \text{if } |P_c| \leq P^* \text{ or if } (P_c > P^* \text{ and } V_f = 0), \\ -\text{sign}(P_c)K_c\left(P_c^* - P_c\right)(V_2 + V_f), & \text{if } P_c < -P^* \text{ or if } (P_c > P^* \text{ and } V_f > 0) \end{cases} \tag{4}
\]

To describe the plastic strain, the von Mises yield criterion is used; shear modulus and dynamic yield strength depend on the damage of material and the temperature. To describe the behavior of elastic-plastic material under loading, the Mi – Gruneisen equation of state is used (5):

\[
P_c = \rho_0a^2\mu + \rho_0a^2\frac{1}{2} \left[1 - \gamma_0 \frac{\gamma_0}{\gamma_0 + 2(b - 1)}\right] \mu^2 + \rho_0a^2\frac{2}{3} \left[1 - \gamma_0 \frac{\gamma_0}{\gamma_0 + 2(b - 1)}\right] \mu^3 = \gamma_0 \rho_0E \tag{5}
\]

where \(\rho_0\) is the initial density of material, \(\mu = V_0/(V_0 - V_1)\), \(\gamma_0\) is the Gruneisen coefficient, \(V_0\) is the initial volume, \(V\) is the current volume, \(a, b\) are the Hugoniot adiabat constants.

In view of the concept used in this work, only the ball component of stresses or the pressure affect the change in porosity, and the components of stress deviator are limited by the independent deviator function of yield (6):

\[
2G(e_{ij} - \frac{1}{3}e_{kk}\delta_{ij}) = \frac{dS_{ij}}{dt} + \lambda S_{ij} \tag{6}
\]

Yauman derivative is determined as follows (7):

\[
\frac{dS_{ij}}{dt} = \frac{dS_{ij}}{dt} - S_{ik}W_{jk} - S_{jk}W_{ik} \tag{7}
\]

where \(G\) is shear modulus (8), \(\sigma\) is dynamic yield strength (9), the parameter \(\lambda = 0\) for elastic deformations and is determined for plastic deformations using the von Mises yield criterion.

\[
G = G_0K_T(1 + \frac{cP}{(1 + \mu)^{1/3}})(V_f + V_i) \tag{8}
\]

\[
\sigma = \begin{cases} \sigma_0K_T \left(1 + \frac{cP}{(1 + \mu)^{1/3}}\right) \frac{V_f}{V_4}, & \text{if } V_f \leq V_4, \\ 0, & \text{if } V_f > V_4 \end{cases} \tag{9}
\]

The thermal coefficient \(K_T\) is calculated by the formula (10):
where \( T_m \) is the melting point of substance, \( c, V_i, V_s, T_i \) are material constants.

4. Computational results

Numerical computations were carried out using the author's numerical code created in the integrated development environment Delphi. A modified finite element method (without constructing a global stiffness matrix) was used as a numerical method. Testing of the numerical code was carried out on the Taylor problem. The main task of numerical computations was the choice of the initial sample velocity required for the successful passage of channels at a constant pressure \( P = 310 \) MPa.

\[
K_T = \begin{cases} 
1, & \text{if } T_0 \leq T \leq T_1, \\
\frac{T_m - T}{T_m - T_1}, & \text{if } T_1 < T < T_m, \\
0, & \text{if } T \geq T_m 
\end{cases}
\]  

(10)

Figure 4. Fields of specific energy of shear deformations (kJ/kg) for \( P = 310 \) MPa, \( v_0 = 170 \) m/s; a) \( t = 250 \) µs, b) \( t = 350 \) µs, c) \( t = 550 \) µs, d) \( t = 795 \) µs.
A series of numerical computations showed that the optimum velocity of the copper sample was 170 m/s. An increase in velocity leads to critical strains, and at lower velocities the sample stops moving in intersecting channels.

Figures 4a-d demonstrate the dynamics of pressing and the fields of specific energy of shear deformations. Analysis of the results shows that almost the entire copper sample is subjected to significant plastic deformations, except for the front and back parts, where plastic deformation is negligible. Also, the sample is elongated in the longitudinal direction under DCAP.

Figure 5a shows the temperature distribution in the sample. The maximum temperature $T = 600$ K corresponds to the region of intense interacting the sample with the walls of the channels in the lower part of the sample. It is important that grains do not grow at this temperature [6]. A protrusion is formed when the back surface of the sample approaches the channel intersection region, this behavior of the sample is consistent with the experimental shapes of the sample obtained under DCAP [6].

Figure 5b presents the field of specific volume of microdamages. It can be seen in the figure that the front and back parts of the sample are subjected to maximum damage. The growth of microdamages in the front part is related to the peculiarities of deformation at the initial stage of DCAP, including the formation of the free surface of the sample between the upper plane of the sample and the upper boundary of the horizontal channel. The area of large microdamages in the back of the sample is due to the peculiarities of sample deformation at the final stage of the passage through the intersecting channels.

**Figure 5.** Temperature (K) (a), specific volume of microdamages (cm$^3$/g) (b) at $t = 795$ μs for $P = 310$ MPa, $v_0 = 170$ m/s.

5. Conclusion
The results of 3D numerical simulation of severe plastic deformation of a copper sample under dynamic channel-angular pressing are represented in the paper. Numerical computations were carried out using the author's numerical code created in the integrated development environment Delphi.

The average pressure $P = 310$ MPa acting on the back surface of the sample under DCAP and sample acceleration $a = 3.5 \times 10^5$ m/s$^2$ were determined based on the analysis of experimental data.

Numerical computations were performed to determine the initial copper sample velocity that was equal to 170 m/s. The increase in the initial velocity of the sample leads to critical deformations at the initial stage (0.1–0.15 ms) of the DCAP process, and the decreased velocity of the sample may be a reason for stopping the movement of the sample in intersecting channels. A decrease in pressure at a constant initial velocity of 170 m/s also leads to stopping the movement of the sample. Thus, the
copper sample successfully undergoes the DCAP process at a velocity of $v_0 = 170$ m/s and pressure of $P = 310$ MPa.

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