Numerical simulation of severe plastic deformation of aluminum specimens under dynamic groove pressing

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Abstract. The process of deformation of aluminum samples under dynamic groove pressing for a dynamic loading scheme is studied numerically in a two-dimensional formulation. Areas of intense plastic deformation of the sample are revealed. Localization of plastic deformations is similar for the static loading pattern. The results of damage accumulation in the material are given. The finite element results are in good agreement with the experimentally obtained results in the field of strain rates considered in this study.

1. Introduction
Currently the bulk nanostructured materials are considered as promising, structural and functional materials of a new generation. The main method for the preparation is the formation of nanostructures with severe plastic deformation (SPD). Modification of coarse-grained crystalline structure of light aluminum alloys to an ultrafine-grained state by methods of severe plastic deformation is necessary to improve their physical-mechanical properties [1 – 5].

Unlike the bulk samples, the use of widely developed processing techniques, such as the equal-channel angular pressing and the torsion under pressure [6, 7] is unacceptable for the sheet metal samples from due to their shape. The constrained groove pressing (CGP) can be a new alternative to these methods of processing [8, 9]. The method of CGP for modification of sheet metal samples from light structural alloys has proved to be a promising approach for changing the internal structure of materials and changing their physical and mechanical properties [9, 10].

The study of the ultrafine-grained (UFG) metals, obtained by the SPD, showed that they are characterized by a number of unique properties. There is the increased strength by several times, which is combined with the good ductility, the low and the high-temperature superplasticity, the cyclic and radiation resistance.

The principle of the method of the grooving method and analytical solution are described in [10]. The results of processing by the CGP of the aluminum, magnesium, copper, titanium and nickel alloys are described in detail in [10].

It is of interest to expand the alloys range is capable to undergo structural changes while the physical and mechanical properties are improved. In addition, there is the pressing issue of creating more accurate predictive physical-mathematical models are describing the process of this materials class. In this question, the mathematical modeling is a convenient theoretical tool that allows realizing the identification of the main mechanisms and patterns. Additionally, an adequate physical-mathematical model will allow estimating the magnitude of the forces during pressing, and it will help
to avoid the mistakes in the design of molds and optimization of processing modes. The development of the groove pressing method leads to the use of dynamic pressing techniques. The method of dynamic groove pressing (DGP) will increase the plastic deformation rate of the sample.

The trends in the development of the SPD methods show that the large-scale numerical studies of the DGP processes are needed to identify the features of intense plastic deformation and to establish effective parameters of these processes.

Numerical simulation of the DGP process is carried out in a two-dimensional setting. The main advantage of this method in comparison with the CGP is that the plastic deformation rate increases, as well as shock-wave deformation is added, which increases the overall result of the action.

The purpose of the work was to study the process of the plastic deformation localization and the destruction localization in the material.

2. The mission statement

The Johnson-Cook material model was used to describe the Al-Mg alloy mechanical behavior. The model considers the temperature and strain rate effect on the flow stress and the ultimate degree of material strain:

\[ \sigma = A + B \left( \varepsilon_{pl} \right)^n \left[ 1 + C \ln \left( \dot{\varepsilon}_{pl} \right) \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right) \right] \]

where \( \varepsilon_{pl} \) is the effective plastic deformation, \( \dot{\varepsilon}_{pl} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \) is the dimensionless plastic strain rate for \( \dot{\varepsilon}_0 = 1 \text{s}^{-1} \), \( T_m \) is the melting point, \( T_r \) is the room temperature, \( A \) is the corresponds to the yield stress \( \sigma_{0.2} \) of the material, \( B \) – is a strain hardening factor, \( C \) – is a strain rate constant of the material, \( n, m \) are the strain hardening index and temperature softening index, respectively.

After analyzing the obtained numerical data, it was found that in the area before the maximum load was achieved, the results obtained using the Johnson-Cook model are in close agreement with the experimental data. There is a need to select a failure numerical model, because of the sample destruction during the experiment. Description of the sample destruction process was carried out by the Johnson-Cook failure model:

\[ D = \frac{1}{\varepsilon_f} \sum_i \Delta \varepsilon_p^i \]

where \( \varepsilon_f \) – is the material ultimate strain, \( \Delta \varepsilon_p^i \) – is the element effective plastic strain increment at the i-th integration step over time.

The \( \Delta \varepsilon_p^i \) value is calculated by the formula:

\[ \Delta \varepsilon_p^i = \left( D_1 + D_2 \exp \left( D_3 \frac{P}{\sigma_{ef}} \right) \right) \left( 1 + D_4 \ln \frac{\varepsilon_p^i}{\varepsilon_0} \right) \left( 1 + D_5 \frac{T - T_r}{T_m - T_r} \right) \]

where \( D_1, ..., D_5 \) – are the material parameters, \( \sigma_{ef} \) – is the effective stress, \( P \) – is the considered element pressure. According to the selected criterion, the final element destruction occurs if the damage parameter \( D = 1 \).

Constants values for the material and fracture models were determined experimentally. The experimental data were obtained earlier during tensile tests on flat specimens from the same material. Experimental data and numerical data obtained using the Johnson-Cook deformation model and the J-C fracture model show qualitative and quantitative agreement throughout the all deformation area. This suggests the correct choice of the determining equation, the failure model, the models constants and the mesh density.

An erosion model was used to visualize the destruction process. The erosion model operation principle was as follows: the element was automatically excluded from the solution when the element's damage parameter \( D \) reached a value of 1, however, it continued to be present in the grid model,
creating the illusion of integrity. When the erosion model was turned on, the elements in which the fracture criterion was achieved were removed. Thus, the erosion model inclusion to the calculation in conjunction with the Johnson – Cook failure model made it possible to obtain a fracture image as close to reality as possible.

The mathematical model obtained in [11] was tested for the high-speed plate penetration.

3. Initial and boundary conditions

Figure 1 illustrates the geometrical models of dies with trapezoidal teeth for pressing of flat specimens and their further flattening. The dimensions of teeth height, interface distance between teeth, top horizontal width of teeth, and projection of sloping plane on x axis and the thickness of the specimen were equal to 1.5 mm.

Initial conditions for dynamic groove pressing at the moment of time $t_0 = 0$ looked as

$$\sigma_{ij}(x, y, t_0) = E(x, y, t_0) = D(x, y, t_0) = 0; \rho(0, x) = \rho_0;$$

where $\sigma$ is a stress, $E$ is energy, $D$ is a damage parameter and $\rho$ is density of a sample.

Boundary conditions for the models are given as

$$U_x|_{AD} = U_y|_{AD} = 0; U_x|_{AB} = U_x|_{CD} = 0;$$

$$V_x|_{BC} = 0, \quad V_y|_{AD} = -V_0 = -1000 \left( \frac{mm}{s} \right);$$

where $U$, $V$ are components of displacement vector and speed of the mold elements. The $x$ and $y$ indices of the components of the boundary conditions are the projection on the corresponding axis.

![Fig. 1. Schematic illustration of: a – grooved dies, b – flat dies.](image)

4. Results and discussion

The sample is placed in between the dies and the pressing is performed such that the gap between the upper die and the lower die is same as that of the sample thickness. This results in pure shear deformation under plane strain condition in the inclined region of the sample. However, the flat region remains undeformed. In the second pressing, the corrugated sample is straightened by means of flat dies. This straightening under the constrained condition ensures that the already deformed region is subjected to reverse shear deformation while the undeformed region remains unaffected. Then the sample is rotated by 180° about the axis perpendicular to plane of the sample. This allows the deformation of the undeformed region due to asymmetry of the grooved die. These successive pressings with a pair of grooved dies and a pair of flat dies result in a homogeneous effective strain throughout the sample.

In the result of the numerical modeling of sheet metal, the distributions of effective plastic deformations in the sample were obtained. During the groove pressing in the sample, plastic deformations are local and uneven. The effective plastic deformation is accumulated in a shearing area. The maximum limit of the cumulative plastic deformation is equivalent to 0.54 (figure 2a). When the samples are straightening, the deformation is summed in the shearing area, that is, after a half cycle, its value increases approximately to 1.12 in local zones (figure 2b).
In the formulation of this problem when analyzing the destruction of the material, it was revealed that there is no destruction in the sample of sheet metal. This result may be associated with good ductility of 1560 alloy.

![Fig. 2. Equivalent plastic strain during: a – grooving, b – flattering.](image)

The numerical experiments revealed that the highest values of the damage parameter is equivalent to 0.33 (figure 3a) during one DGP cycle. It is shown, that during the half-cycle of the CGP the damage growth is observed in the action zone of tensile stresses, which are realized in the zone of the geometry change of the mold protrusions.

Over time, the irreversible deformation is developing. The development of the inelastic deformation may lead to the formation of the main cracks, which cross the entire sample, like test sample (Figure 3б). In a numerical experiment, the configuration of the crack formation is the same as the test sample.

![Fig. 3. Distribution of damage rate: a – modelling, b – experimental sample.](image)

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