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3D NUMERICAL SIMULATIONS OF THE ECAP PROCESS

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Abstract. This paper describes ECAP variation-difference simulation procedure for a rectangular copper specimen implemented in the DRAKON numerical code. Numerical cell shape and size are chosen. Problem definition and 2D and 3D numerical results are presented. It has been established that numerical results are in good agreement with experimental data.

1. INTRODUCTION

ECAP simulations are important for understanding and predicting results of experimental studies. Meanwhile, experiments provide valuable data for improvement of physical and phenomenological models of materials to be used in calculations, and then simulations can provide an opportunity to considerably reduce the number of required future experiments by optimizing and specimen shape size, as well as conditions to be provided by experimental installation. Thus, it can be stated that numerical simulations are of high importance and value as a part of experimental study. ECAP simulation problems require that the numerical technique should account for and adequately treat the following phenomena:

- Considerable changes of specimen size, which cause high strain level at considerable displacements;
- Specimen contact interactions between with pressing channel walls and removable insert taking friction into account;
- Heat conduction propagation and temperature effects on mechanical properties of specimen and insert materials.

To account for the influence of material structure on its mechanical characteristics the numerical technique must be able to implement appropriate models. The DRAKON code [1], which was developed in VNIIEF and designed for solving stress state in complex spatial structure elements in 2D and 3D with physical and geometry non-linearity and contact interactions under high-intensity mechanical and thermal impacts, is used for numerical simulations of ECAP procedure.

2. THE SIMULATION PROCEDURE

This section presents numerical simulation data on the deformation of a copper specimen during one-pass ECAP, which were computed using DRAKON code.

The problem was defined as follows:

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· specimen material –copper M1 (99.9%);
· specimen geometry –60-mm-long 8x8 mm square bar;
· the ECAP non-deformable channel has a 90° angle and a zero mating radius.

The material state was treated in calculations using a simple isotropic deformation model. The spherical components of stress and strain tensor were related by a Mie-Grüneisen equation of state

$$P = P_x + P_T = \frac{\rho_0 C_0^2}{n}\left(\eta^n - 1\right) + \Gamma\rho E_T,$$
$$E_T = E - E_x, \qquad (1)$$
$$\eta = \frac{\rho}{\rho_0},$$

where ρ_0 is the initial density; C_0 – inisbtial volumetric sound velocity; Γ – Gruneisen's gamma, which was assumed constant; E_c, E_T – cold and thermal components, respectively, of specific (per unit mass) internal energy E. Elastic contribution to internal energy was expressed as

$$E_x = \int P_x \frac{d\eta}{\eta^2}. \qquad (2)$$

The following parameters are used in (1): ρ_0=8.96 g/cm^3, C_0=3.889 km/s, n=4.3, Γ=1.96. Pressure and internal energy were assumed to be zero at the start. Deviatoric stress tensor components were found from the differential theory of thermal plasticity with isotropic hardening. The shear modulus G is given by:

$$G = \frac{3(1-2\nu)}{2(1+\nu)}\rho C_B^2, \qquad (3)$$

where: $C_B^2 = \left(\frac{\partial P}{\partial \rho}\right)_S$ is the volumetric sound velocity in compressed state, ν=0.34. The experimental deformation curve used in the calculations is shown in Fig. 1.

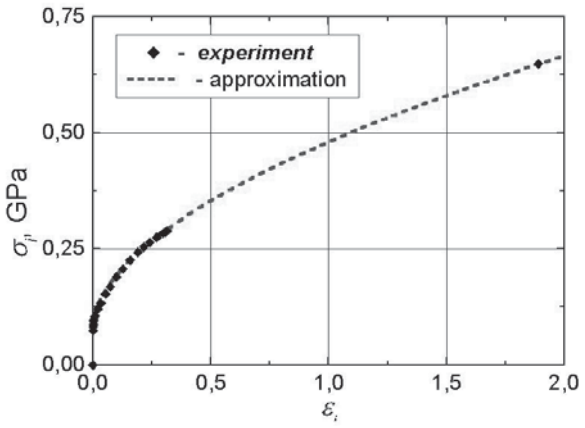

Fig. 1. Deformation diagram of copper.

3. 2D SIMULATIONS

A series of 2D calculations was carried out for numerical scheme development and validation. The main purposes of these simulations were to:
- choose numerical cell shape and size to ensure convergence of numerical solution taking into account available computer resources;
- evaluation of time scaling factor, which is used in DRAKON for solving dynamics equations under quasistatic deformation when dynamic effects (inertia forces) are excluded.

Quadrangular cells in 2D and hexahedral ones in 3D are known to be the best for numerical solution convergence and help save computing resources. If tetrahedral cells are used, 2-fold smaller characteristic cell size is required to achieve a similar result, and this certainly increases the number of cells. Considering this fact, a numerical scheme with rectangular numerical cells was chosen for 2D calculations. Cell size in a specimen was varied from 0.8 mm (ten numerical cells across thickness) to 0.2 mm. Friction was neglected. The punch velocity W_p was chosen so that acoustic wave traveled through the specimen ~10^3 times during the entire process. W_p=6 mm/ms satisfies this condition. The results show good agreement between calculations with variable cell size. Even with 'coarse' numerical discretization Δ_m=0.8 mm the result is tolerable, and with $\Delta_m \le 0.6$ mm numerical results show almost no discrepancies.

It is evident from the calculations that the integral pressing force is highly dependent on specimen material shear strength and, as it will be shown below, it is even more dependent on friction between a specimen and channel walls. So, this parameter should be used for verification of numerical solution when comparing it to experimental data. Based on this analysis, a hexahedral numerical cell with the edge size Δ_m=0.4 mm was chosen then for 3D calculations.

Two additional calculations were carried out to verify the correct choice of time scaling factor for solving the quasistatic problem with equations of

dynamics (this factor was varied in the two calculations). Problems involving contact, especially those with friction, can be solved much more easily with dynamics equations, since contact with friction requires that the entire history of the interaction process should be taken into account.

4. 3D SIMULATIONS

The discrete model of a specimen consists of hexahedral cells with the characteristic size Δ_m=0.4 mm. Considering the fact that when a problem is treated within a simple isotropic model of material behavior the system has a symmetry plane, the numerical scheme is only given for 1/2 of it.

While a scheme with hexahedral cells has a considerable advantage, i.e. it saves computer resources and ensures high accuracy, there is also a problem with this scheme. Unless special procedures are used to solve a problem with Lagrangian definition, the numerical grid collapses – this is the well-known sand-glass effect. This effect takes place at the beginning of calculation of the problem addressed here.

This drawback has been eliminated in the DRAKON code by including tetrahedrons along with hexahedral cells. Tetrahedrons are constructed on hexahedral cell edges that begin in the same vertex. As shown by calculations, a small weight factor α=0.01, that determines the contribution of spherical stress tensor component in tetrahedrons to the virtual work permits to avoid the sand-glass effect in this problem. DRAKON also ensures stable solution meanwhile preserving accuracy for oblong cells (the aspect ratio of 5-10). This is essential for development and validation of new models, since now calculations can be performed without restructuring the numerical grid.

Handling friction between specimen surface and channel walls is a major difficulty in ECAP simulations within the simple isotropic deformation model. Friction effect was modeled by Coulomb's friction model with a constant factor without any additional adjustments. Based on the agreement between the numerical results and the experimentally measured value of the pressing force, *f=0.03* was chosen.

Numerical simulations of contact interactions with friction is a very complex problem, and it is, probably, impossible to obtain an accurate solution within a simple isotropic deformation model. The reason is that in the case of contact with friction, a small region is involved in the deformation process, so mesolevel deformation effects are likely to govern this process. Using a special lubricant does not guarantee that it will cover the entire contacting surface, i.e. that there will not be any direct contact between metal surfaces, which complicates the solution process.

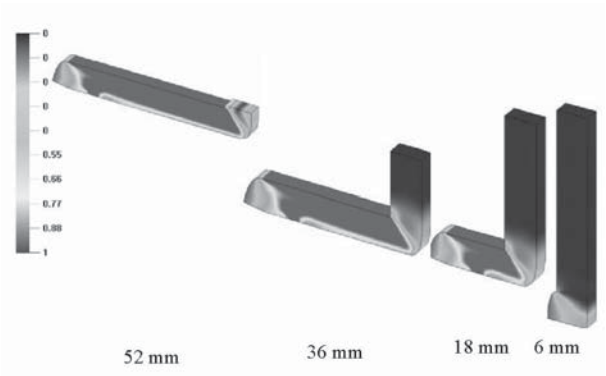

Fig. 2. Accumulated plastic strain distribution in the specimen midsection for different values of punch displacement.

The 3D result is qualitatively similar to the 2D case. Three domains with different strain distribution patterns can be found in a specimen. Edge zones are characterized by essentially non-uniform strain. In the central section, which is, similarly to 2D case, ≈75% of the specimen length, the stress state is uniform along the specimen (the OX *axis*). However, non-uniform accumulated strain was observed through specimen thickness (the OY axis). The numerical results are presented in Figs. 2 and 3.

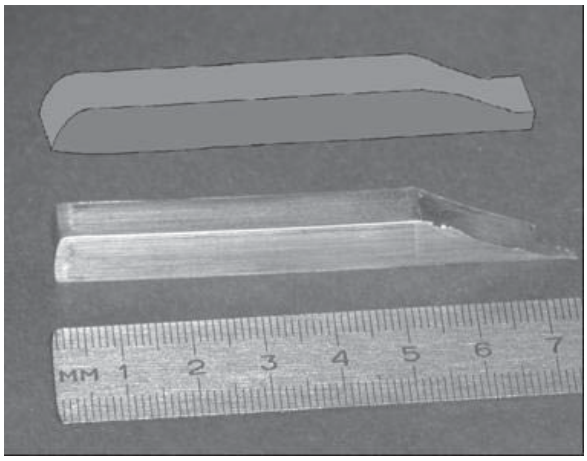

Fig. 3. Numerical and experimental shapes of the specimen after single-pass.

5. CONCLUSION

1. It was established, based on the analysis, that numerical results of ECAP variation-difference simulations agree with experimental data both qualitatively and quantitatively.
2. Three characteristic zones of non-uniform plastic deformation have been identified. The edge zone which is struck by the punch is characterized by the most non-uniform plastic deformation. The other edge zone shows a smaller degree of non-uniformity. The middle zone of the specimen has the most uniform strain level. A qualitative criterion was used, i.e. accumulated plastic strain.
3. Punch force was calculated as a function of its path. It was shown that variation-difference numerical results are in good agreement with measured data.
4. The prospects for future simulations are to account for material internal inter-grain structure for better treatment of mesolevel.

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