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Mathematical Simulation of Stress-Strain State of Low Carbon Steel upon Strain Simulation with use of Bridgman Anvils

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Abstract: The research presents the results of finite element simulation on the effect of Severe Plastic Strain (SPS) in torsion under Quasi-Hydrostatic Pressure (QHP) to the strains and stresses diagrams for low carbon steels. Mathematical simulation of stress-strain state was conducted with use of the finite element method. The effect to plastic torsional strain pattern was analyzed.

Key words: Mathematical simulation, Bridgman anvil, stress-strained state, steel, method

INTRODUCTION

One of the most widely used methods to obtain a nanocrystalline structure is the method of Severe Plastic Strain (SPS) in torsion under Quasi-Hydrostatic Pressure (QHP) that is carried out by means of Bridgman anvils use (Glezer and Tomchuk, 2013; Valiev and Alexandrov, 2007, 2009; Noskova and Mulyukov, 2003). A problem of the analysis of a specimen stress-strain state is determining the parameters that characterize the plastic strain occurring in an arbitrary point within the workpiece. Works devoted to SPS in torsion under QHP in low-carbon steels are mostly experimental (Astafurova *et al*., 2009; Shin *et al*., 2001). Along with well-known and widely used methods there is proposed to solve this problem by means of finite element simulation (Drai and Aour, 2013; Valiev *et al*., 2000). The purpose of this research is to analyze the effect of plastic strain pattern in torsion on the distribution of mechanical properties over the cross section of the specimen on the example of low carbon steel 08kp with use of mathematical simulation method.

MATERIALS AND METHODS

Object and methods of research: Description of plastic effects in the material has great importance in SPS simulation. For this in the research, we have used the Johnson-Cook model which can be represented by the following mathematical expression (Johnson and Cook, 1983):

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left(1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right)\left(\frac{\dot{\bar{\varepsilon}}}{\bar{\varepsilon}_0}\right)^{\alpha}\left(1 - \left(\frac{(T - T_r)}{(T_m - T_r)}\right)^m\right)$$

Where:
$\bar{\sigma}$ = A yield stress
$\bar{\varepsilon}$ = An effective plastic strain, is an effective plastic strain rate
T_m = Melting temperature
T_r = A room temperature and

A B, C, n, m, α are constants of the material. This model takes into account the dependence of the yield stress on temperature, strain rate and the value of cumulated plastic strain. Calculation of stress-strain state for the process model of SPS in torsion under QHP was conducted with use of finite element method in MATLAB/PDE Toolbox package using the calculation principles accepted in continuum mechanics. PDE Toolbox allows defining the geometry of the area, the type and the coefficients of the differential equations system, boundary and initial conditions and also to make the finite element division.

Characteristics of steel 08kp (GOST 1050-88) were taken to specify the mechanical properties of the material under examination in the model. The dimensions of the simulated specimen were set in a form of 10×10 mm plate with thickness of 200 mcm in accordance with (Glezer and Tomchuk, 2013). The model has been divided into the elements of the tetragonal form and the total number of items has amounted to 2500 pcs. Upon such divisioning the average size of a finite element was 0.02 mm. In the course of simulation, the specimen was assumed as a plastic body and the working tool was assumed as a nondeformable rigid body. Diameter of the pane model was 8 mm. A mathematical model for simulating movement of the panes consisted of two components: permanent longitudinal movement at a certain speed of the top pane

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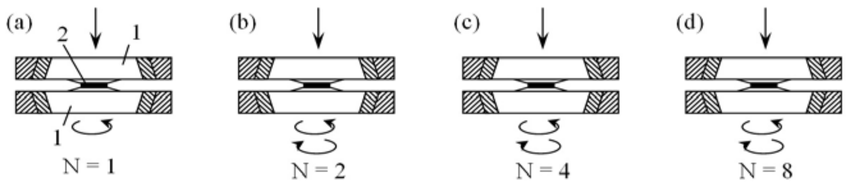

Fig. 1: a-d) Strain patterns for a Bridgman anvil as described in (Glezer and Tomchuk, 2013) 1-pane, 2-compressed specimen, N-the number of rotation direction changes of the pane: Pattern 1-4

simulating specimen compression and rotation of the lower pane. The temperature of the simulated specimen and the panes at the start of strain was assumed to be 20°C. Changes in strength properties of steel after SPS in torsion under QHP have been considered according to the distribution of the effective strain within the range r = 0 ... 3.3 mm in accordance with the strain patterns proposed in (Glezer and Tomchuk, 2013) (Fig. 1) the specimen was subjected to a continuous strain for two complete pane turns in one rotation direction (Fig. 1). The specimen was subjected to strain for one full pane turn in a direction and one full turn in the opposite direction of rotation (Pattern 2). Patterns 3 and 4 are similar to Pattern 2 but there is a larger number of changes of rotation direction: N = 4 (Pattern 3) and N = 8 (Pattern 4). The relative compression strain ε was achieved by two full turns of the pane.

RESULTS AND DISCUSSION

According to the results obtained in the data simulation there was evaluated the intensity of cumulated strain and the intensity of torsional stress within the range r = 0 ... 3.3 mm. Figure 2 shows the charts of effective strain calculated according to following equation:

$$\overline{\varepsilon} = \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + \left(\varepsilon_y - \varepsilon_z\right)^2 + \left(\varepsilon_x - \varepsilon_z\right)^2}$$

where, ε_x, ε_y and ε_z are principal strains. In the case of SPS in torsion under QHP the main metal strain occurs due to torsion of the specimen. As a result of coaxial compression in the central zone of the specimen there has been produced a pressure reaching several GPas that increases the frictional force between the panes and the compressible specimen resulting in transfer of torque from the lower (movable) pane to the specimen and its shear strain.

The obtained results show that for all strain patterns the effective strain value in the specimen center is lower than at its periphery (Fig. 2). In the case of the strain for two complete turns of the pane in one direction of rotation (Fig. 2, pattern 1) the effective strain increases continuously within the range of r = 0 ... 3.3 mm. In the

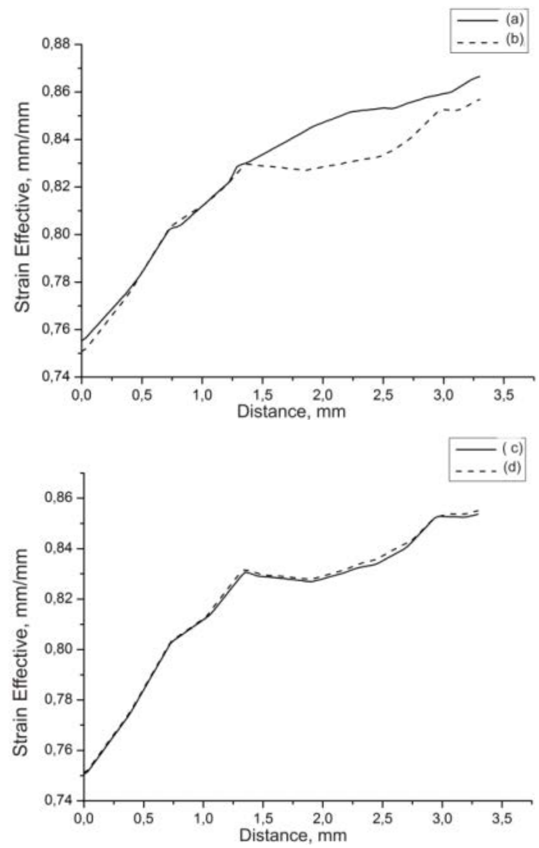

Fig. 2: Charts of the cumulated effective strain:(a) pattern 1, (b) pattern 2, (c) pattern 3, (d) pattern 4

case of the strain with change of rotation direction 2, 4 and 8 times (Fig. 2, Patterns 2-4) the strain at first gradually increases to r ~ 1.3 mm with distance from the center and then decreases. Effective strain values at the section from r~1.3-2.6 mm almost do not change, then the nature of the change is changed to monotonical increasing up to r~3.0 mm and above it remains virtually unchanged again. The obtained results make it possible to suggest that by changing the pane rotation direction (Patterns 2-4) the nature of the distribution curve of the cumulated strain is changed regardless of the number of rotations changes. We canassume that changing in the nature of the accumulated strain distribution leads to formation of non-uniform structure of the specimen under

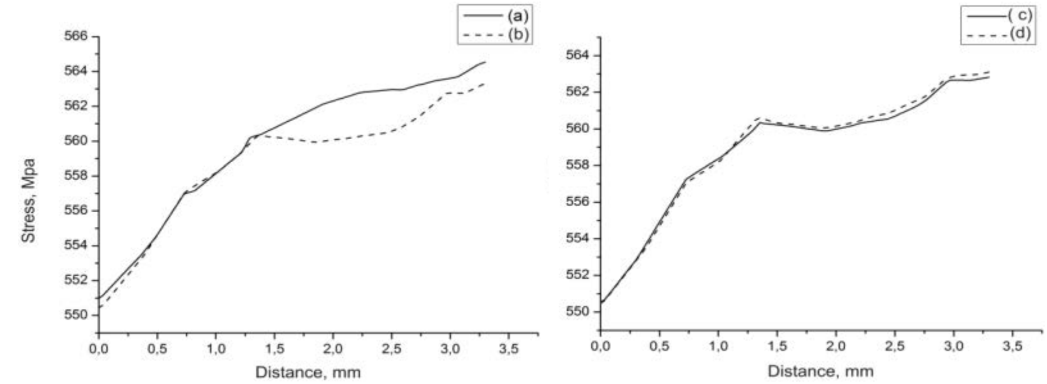

Fig. 3: a-d) Comparison of the stress along the distance from the center of the specimen; pattern 1-4

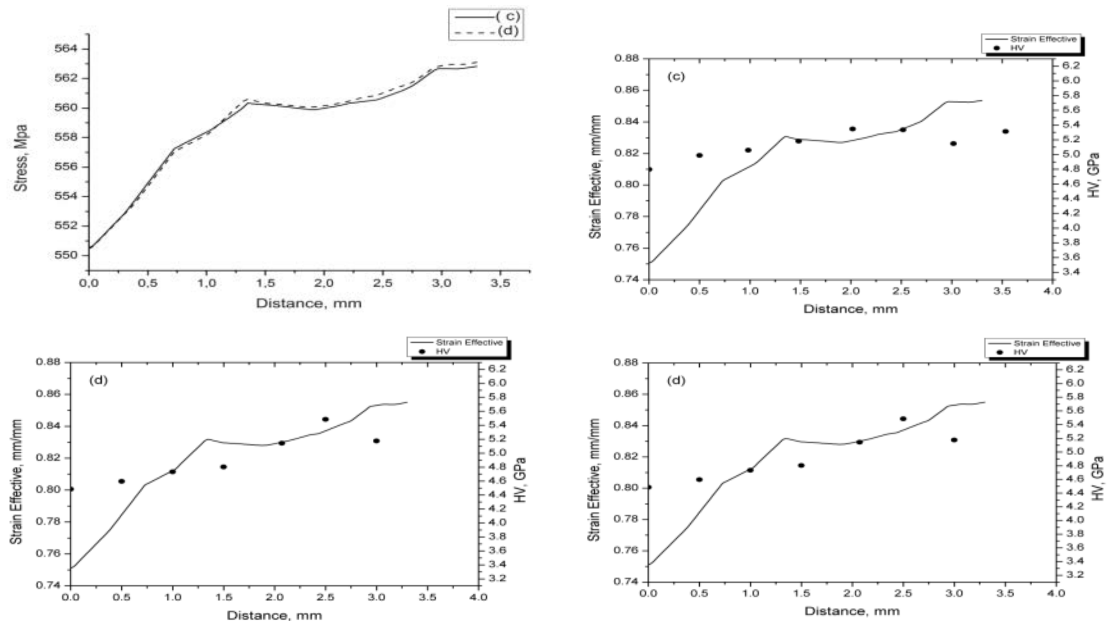

Fig. 4: a-d) Comparison of the effective cumulated strain and microhardness of along the distance from the center of the specimen; pattern 1-4

the set strain patterns. Such heterogeneity observed in the materials deformed by torsion under QHP in Bridgman anvils is caused by the dependence of the strain degree e at QHP on the distance r from the center of the specimen: e~ln r (Valie and Alexandrov, 2007). Figure 3 shows the stress chart along the distance from center of the specimen subject to loading according to the patterns 1-4. When using the pattern 1, stress values increase with distance from the center that can be explained by a higher strain of the metal in the periphery compared to the center of the specimen due to the contribution of torque. When using the pattern 2 it follows that at a distance of ~1.3 ... 3.0 mm from the center there is a decrease of strain that testifies to a loss of strength arising from changes in the direction of rotation. Similar results were observed for the patterns 3 and 4. As the formation of fine-grained structure requires a high intensity of cumulation of plastic strain that can be achieved by deforming with the change of direction of rotation, the observed decrease in stress can be characterized as a possible demonstration of Bauschinger effect (Valiev and Alexandrov, 2007).

Assessing the adequacy of the mathematical model taking into account the demonstration of Bauschinger effect was carried out by qualitative comparison of the nature of changes in calculated values of effective strain with the change of specimen microhardness values depending on the distance to the center of the specimen within the range of r = 0 ... 3.3 mm for strain patterns 1÷4 obtained as a result of the experiment in (Glezer and Tomchuk, 2013) (Fig. 4).

It is known that in the case of a high structure refinement of metals with a cubic lattice there is a significant change in the influence of Bauschinger effect on the mechanical properties (Stolyarov, 2006; Kamyshanchenko *et al.*, 2008). Qualitative matching of changes character for effective strain values obtained by simulation with the microhardness experimental values allows us to assume that the internal stresses increase with increasing the number of changes of rotation direction and Bauschinger effect is a part of this physical process.

CONCLUSION

According to the results of mathematical simulation of SPS in torsion process under QHP for low carbon steel using steel 08kp as an example, it was demonstrated that the change in direction of rotation causes a disproportionate change in the effective strain and stress along the distance from the center of the specimen compared to the monotonous strain. Formation of nonuniform stress distribution along the distance from the center of the specimen in the range r = 0 ... 3.3 mm in the test process began after execution of SPS in torsion process under QHP with changes of rotation direction, that, apparently, is related to the Bauschinger effect.

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