Relationship between the stress-strain state and the imperfection of the structure of metals with SPD shear

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Abstract. The paper presents the results of the computer simulation and physical experiment for the free and constrained transverse shear of round specimens of steel 10 with an accumulated strain of $e > 1$. The stress-strain state was investigated using computer simulation, and the degree of imperfection of the emerging structures was studied by metallographic methods. The laws governing the relationship between the parameters under study and the degree of imperfection of the structure during severe plastic deformation by shear are established.

1. Introduction
Currently, the metallurgical industry is searching for and developing new technologies for producing high-strength metallic materials with a ductility sufficient for structural applications. As is known [1,2], such methods of severe plastic deformation (SPD) as equal-channel angular pressing (ECAP) and ECAP-Conform, have a high potential for producing a set of enhanced physical, mechanical and performance properties of metals and alloys, but they have a number of tribological problems that hinder the industrial implementation of these methods. In this connection, we consider in this paper two alternative, more technologically advanced methods that use shear deformation in free and constrained conditions, such as free torsion of workpieces and torsion during drawing in a split die, respectively, under elevated hydrostatic pressure [3-4]. These methods use combined non-monotonic deformations, which enable changing effectively the structural states of metallic materials [5-6].

2. Methods
The material under study was low-carbon steel 10 widely used in industry, in the form of a calibrated long rod with a diameter of 10 mm. For the experiments, a modernized laboratory-scale chain drawbench was used to ensure the rotation of the workpieces during axial drawing. The drawing dies had an eccentric profile to provide conditions for torque transfer when twisting the workpieces with respect to the longitudinal axis, the relative compression over the pass was 56%. A phosphate sub-lubricant coating and a lubricant were applied onto the workpieces to improve the tribological conditions during drawing. To implement the method of free torsion, a lathe was used. The number of revolutions relative to the longitudinal axis was 15. The stress-strain state of the produced workpieces studied by computer simulation using the DEFORM-3D software. The used processing methods are schematically presented in figure 1.
Figure 1. Principles of the processing methods:
a – drawing with shear (1 – workpiece, 2 – moving die, 3 – fixed die),
b – free torsion (1 – moving holder, 2 – workpiece, 3 – fixed holder).

3. Results and discussion
This section compares the deformational and processing parameters of workpieces produced by two methods of plastic treatment – free torsion (FT) and drawing with shear (DS) (torsion in constrained conditions) (see figure 1). Figure 2 shows the patterns of the strain state in the cross section of the workpieces. An analysis of the patterns shows that strain does not accumulate uniformly in the workpieces. In the peripheral regions of the workpieces the maximum values of strain intensity are observed, while in the central region the minimum values of strain intensity are revealed, and the diagram of the variation in the accumulated strain has a parabolic shape. Moreover, the difference between the maximum and minimum values is more than two-fold.

Figure 2. Patterns of strain intensity in the cross section: a – drawing with shear; b – free torsion.

Study of the produced structural states revealed a number of features (see figure 3). In the case of drawing with shear, the maximum grain refinement is observed in the peripheral layers of the workpiece that are in contact with the tools. No structural defects in the form of pores are observed. In the case of free torsion at room temperature, after an accumulated strain of \( e = 1.5 \) is attained, the emergence of pores is observed, as shown in figure 3 b, and their quantity and size grow with increasing level of accumulated strain. An increase in the temperature of free torsion to 600 °C enables increasing the level of accumulated strain without pore formation to \( e = 2 \). In this case, the average size of structural fragments is \( 3.7 \pm 1.1 \) μm.
It can be noted that when using the DS method, a gradient type of structure is formed, and the peripheral layers of the workpieces are refined more intensively, down to submicron sizes, at a depth of up to 0.2 mm. In the samples produced by FT at 600 °C, this phenomenon is not observed and a gradient structure is formed with a grain size of $25.3 \pm 6.5 \mu m$ in the center to $3.7 \pm 1.1 \mu m$ in the periphery, without any pore formation.

**Figure 3.** Structural states of the workpieces: a) the microstructure in the cross-section of the workpiece, DS at room temperature; b) the microstructure in the cross-section of the workpiece, FT at room temperature (upon reaching $e = 3.2$, the center of the section); c) the microstructure in the longitudinal section of the workpiece, FT at 600 °C (upon reaching $e = 2$, the periphery of the section); d) the microstructure in the longitudinal section of the workpiece, FT at a temperature of 600 °C (upon reaching $e = 2$, the center of the section)

### 4. Conclusions

- It has been established that in low-carbon steel 10 processed by the studied methods of DS and FT, a gradient type of structure is formed, and the peripheral layers of the workpieces are refined more intensively. At the same time, the samples produced by DS have a surface layer with a thickness of up to 0.2 mm that is very intensively refined, down to submicron sizes, and in the samples produced by FT after accumulation of shear strain over 1.5 pore formation is observed, progressing with increasing level of accumulated strain.

- Computer simulation has revealed that strain in the workpieces does not accumulate uniformly. In the peripheral regions of the workpieces, the maximum values of strain intensity are observed, while in the central region the minimum values of strain intensity are revealed, and the diagram of the variation in the accumulated strain across the cross section has a parabolic shape.
Moreover, the maximum values of strain intensity exceed $e = 1$, and the difference between the maximum and minimum values is more than two-fold.

**Acknowledgments**
The authors gratefully acknowledge the financial support from the Russian Foundation for Basic Research under project No. 17-08-00720/19.

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