Investigation of a new shear deformation method for the production of nanostructures in low-carbon steel

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Abstract. The techniques of severe deformation of steel samples have been investigated – drawing and shear drawing in eccentric dies implemented at room temperature. The paper considers the features of structural changes occurring in low-carbon steel at different types of deformation treatment – conventional drawing and shear drawing of samples made of steel 10. The structural parameters and the nature of distribution of the plastic deformation intensity were investigated. Higher efficiency of the drawing process with shear was revealed in terms of strain intensity accumulation. A comparative analysis of structural changes and microhardness distribution over the bulk of samples produced by the investigated methods was conducted. The repeatability of the stress-strain state parameters obtained through physical and mathematical modeling was shown. The analysis of the obtained results leads to the conclusion that the use of drawing with shear is advanced for the production of samples and billets with high strength and sufficiently high ductility by creating a gradient structure.

Severe plastic deformation (SPD) is one of the most effective techniques to enhance the physical and mechanical properties of metallic materials via refining the structure to obtain the ultrafine-grained (UFG) and nanocrystalline (NC) states. For the formation of UFG and NC structures, complex deformation schemes are usually used: high pressure torsion, equal channel angular pressing, screw extrusion, etc. [1-3]. Despite the differences in loading conditions, all these schemes have one thing in common – the structure is refined due to active shear deformation of the metal under the combined effect of compression and tension. Further development of SPD techniques implies the elaboration of combined loading schemes with a mandatory use of shear deformation.

The most well-known and widespread scheme of simple shear is free torsion [4]. Combining the scheme with reduction may be promising to disperse the structure and, as a result, to enhance mechanical properties.

In recent years the methods of surface deformation treatment have been provoking interest. Among them are the known methods of forging [5], surface friction [6], ultrasonic treatment [7], and others, and also the methods developed not so long ago – ECA broaching and shear drawing [8, 9].

In the present paper we study the influence of two different loading schemes – conventional drawing and shear drawing – on the change in the deformation intensity and corresponding transformation of the structure that occurs in low-carbon steel under this treatment, and also to determine the relationship between these changes and mechanical characteristics.

Additionally we propose here to perform an assessment of the severe plastic deformation intensity using numerical modeling, which would allow comparing the calculation results with the observed changes in the structure and properties.
The materials and methods of investigation

The as-received material was low-carbon steel 10 in the form of a calibrated bar of 10 mm in diameter according to GOST 10702-78.

In the development of a numerical model the rheological properties of steel 10 were chosen as recommended in [10]. The shear drawing is done in the following manner. A sample is deformed due to the application of a traction force through the two consecutive conical dies with their simultaneous rotation. As a result additional shear strain takes place against the rotation axis formed by the conical channel of two dies.

Virtual experiment

The application package DEFORM™3D was used to implement numerical simulation.

In order to conduct modeling in the application package DEFORM™3D, three-dimensional models were created in the software product Kompas-3D.

Conditions and assumptions accepted for modeling

1) The billet material in the initial state is isotropic and has no initial stresses and strains;
2) The temperature was taken as fixed – 20 ºC;
3) The tool is an absolutely rigid body, the tool geometry is taken into account automatically;
4) The billet is a plastic body;
5) 150 steps were taken for modeling that register a full pass of the bar through a deforming tool in order to obtain a stable result;
6) The number of finite elements is 55000;
7) The friction between the tool and the billet was taken as 0.12;
8) The drawing rate – 0.95 mm/s;
9) The degree of deformation per one pass during drawing is 15 ... 20 %.
10) The rate of the drawing die rotation is 500 min⁻¹
11) The degree of deformation per one pass is 15 ... 20 %.

For the tests we used a drawing machine capable of conducting shear drawing through the drawing nozzle.

![Figure 1. Distribution of deformation intensity in the cross section: a) conventional drawing, b) a comparative graph of the two processes) shear drawing](image)
Investigation of the nature of strain intensity distribution showed that after drawing this distribution is relatively uniform (Fig. 1a). At the same time, after shear drawing the strain intensity is distributed non-uniformly, it reaches $\varepsilon \approx 1.6$ (Fig. 1 b, c), which indicates of a more intense deformation impact on the specimen during shear drawing. The highest metal deformation, associated with the geometry of drawing dies and the method of their rotation about the drawing axis, is observed on the surface of the workpiece.

Graphs in Fig. 1, b show that per one cycle of drawing with shear it is possible to obtain substantially higher strain intensity and, consequently, increase the productivity of the manufacturing process of high-strength elongated articles due to effective submicrocrystalline structure formation. The modeling results lead to the following conclusions: during drawing with shear the accumulated strain intensity reaches 1.6. At the same time, the drawing forces are reduced almost in half, the deformation non-uniformity increases significantly and normal forces on the tool decrease by 1.8 times.

**Physical experiment**

The rods made of steel 10 were subjected to two types of deformation treatment – conventional drawing and drawing with shear. During the investigation, the effectiveness of the deformation impact on the structure during traditional drawing and drawing with shear was compared. The loading schemes were selected so that in the future there would be a possibility to analyze structural and strength changes in the implementation of two different deformation types – compression with shear (during drawing) and compression with shear and rotation (during shear drawing).

The conventional drawing was carried out in several passes on the drawing machine with a force of 30 kN with a stepwise decreasing diameter from 10 mm to 7 mm. The shear deformation was also conducted on a drawing machine with an attachment for the die rotation.

The deformation by drawing was calculated by the formula

$$\varepsilon = \left( \frac{S_o - S_1}{S_o} \right) \times 100\%,$$

where $S_o$ – cross-sectional area of the bar prior to drawing, $S_1$ – after drawing [11-12].

To determine the features of the material microstructure in the initial and strained states, the metallographic analysis was performed on the scanning electron microscope. The average grain sizes, the features of the ferrite cellular and dislocation structure were determined, the nature of microcrack location was studied, the size and distribution of Fe₃C particles were estimated. Besides, the microhardness HV was measured at a load of 1 N and the holding time of 10 s in the cross section of the rods before and after straining. The measurement error did not exceed 12%.

When we investigated the structure of the samples’ cross section after 5 drawing cycles, we established that the alloy structure is relatively uniform, the grains (ferrite) are non-equiaxed and strongly deformed, often curved, the boundaries are sinuous, the grain size is $d_{31} \sim 7.5 \mu m$ (Fig. 2a). In general, the microstructure in the central and peripheral parts of the rods is identical. The nature of distribution and sizes of Fe₃C particles hardly changed.

| Table 1. Microhardness changes in the cross section after different deformation schemes |
|-----------------------------------------------|
| State of the sample | Microhardness, HV 0.1 MPa (cross section) |
|---------------------|-----------------------------------------------|
| Initial             | 190 – 200                                     |
| Drawing, 5 passes   | 265 – 275                                     |
| Drawing with shear  | from 270 (center) to 6960±310 on the surface   |
Figure 2. a) The microstructure of the central part of the rod after 5 drawing passes, x1000. b) The microstructure of the peripheral part of the sample after drawing with shear, x1000. Strongly deformed subsurface area width \( L_1 \approx 45 \mu m \), the transition region \( L_2 \approx 70 \mu m \).

As can be seen from the table and the presented microstructures, the microhardness values in the initial steel 10 rods were approximately the same in the central and peripheral areas of the cross section. After simple drawing, the HV values, along with the increasing strain degree (number of passes), increase uniformly throughout the cross section of the rods. This evidences a relatively homogeneous nature of deformation by simple drawing throughout the rods’ volume, which is supported by the results of structural studies and microhardness values.

In contrast to the uniform increase of HV during simple drawing, after shear drawing, as follows from results of microhardness measurements (Fig. 1), there is a noticeable increase in the heterogeneity of microhardness from the center of the rods. The growth of microhardness values occurs less intensively in the central parts of the blanks, as opposed to the peripheral ones, which is due to non-uniformity of deformation introduced by the rotating die. Both the modeling and the real experiment established that the straining of the rod by drawing with shear results in a significant structural non-uniformity and the mechanical properties gradient from the center of the rod to its surface.

Conclusions

1. Two different kinds of deformation processing were conducted on the rods of steel 10 – conventional drawing and drawing with shear. The substantial non-uniformity of structural changes and the nature of strain intensity distribution was established.
2. It is shown that deformation by simple drawing forms basically a homogenous structure and, accordingly, leads to a uniform change in microhardness along the billet volume. At the same time, during free torsion a heterogeneous, so-called, gradient structure is formed.
3. A comparative analysis of the models of shear drawing and conventional drawing showed that shear drawing of steel 10 at room temperature reduces energy characteristics in half, normal forces on the die – by 1.8, and enhances the strain intensity from 0.5 to 1.6.
4. It was established that during drawing with shear a gradient structure is formed, which increases the microhardness of the surface layer up to values close to 7000 MPa.

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