

SCHEME OF TREATMENT AND ITS EFFECT ON THE STRAIN HETEROGENEITY AND STRUCTURAL CHANGES IN BILLETS OF LOW-CARBON STEEL

СХЕМА НАГРУЖЕНИЯ И ЕЕ ВЛИЯНИЕ НА НЕОДНОРОДНОСТЬ ДЕФОРМАЦИИ И СТРУКТУРНЫЕ ИЗМЕНЕНИЯ В ЗАГОТОВКАХ ИЗ НИЗКОУГЛЕРОДИСТОЙ СТАЛИ

V.I. Semenov^{1,2}, G.A. Aleshin², A.G. Raab², N. Tontchev³, V. Kamburov³, E. Yankov⁴

¹Institute of Strategic Studies, Ufa, Russia

²Ufa State Aviation Technical University, Ufa, Russia,

³Todor Kableshkov Higher School of Transport, Sofia, Bulgaria

⁴University of Ruse Angel Kanchev, Ruse, Bulgaria

Annotation: The paper presents the results of numerical modeling of the conventional drawing and free torsion processes of rods made of low-carbon steel using the "DEFORM-3D" software package. The heterogeneity of the strain intensity distribution in the investigated processes revealed in the model basically corresponds to real physical experiments with similar parameters of the structural heterogeneity. A mutual correspondence of the ductility diagram to the character of the structural changes in the samples deformed by free torsion is established, and the limiting values of the ductility margin, the excess of which leads to the development of fracture processes.

KEYWORDS: SEVERE PLASTIC DEFORMATION, MATHEMATICAL MODELING, DRAWING, FREE TORSION, MICROSTRUCTURE, STRAIN HETEROGENEITY, MICROHARDNESS, DUCTILITY DIAGRAM.

1. Introduction

Severe plastic deformation (SPD) is one of the most effective ways to enhance the complex of physico-mechanical properties of metallic materials by refining the structure to ultrafine-grained (UFG) and nanocrystalline (NC) states. For the formation of UFG and NC structures, as a rule, complex deformation schemes are used: high pressure torsion, equal-channel angular pressing, screw extrusion, etc. [1-3].

Despite the differences in the loading conditions, all these schemes combine one thing - the structure refinement occurs due to active shear deformation of the metal under constrained conditions under the joint action of compression and tension. Further development of SPD methods involves the creation of combined loading schemes with the obligatory inclusion of the shear component of the deformation.

The most known and widespread scheme of pure shear is free torsion [4]. The combination of this scheme with the reduction scheme used for drawing can be promising for dispersing the structure, and as a result, increasing the complex of mechanical properties.

In this connection, the present paper aims to study the effect of two different loading schemes, conventional drawing and free torsion, on the change in the intensity of deformation and the transformation of the structure corresponding to these changes occurring in low-carbon steel with the selected treatments, as well as establishing the relationship between these changes and mechanical properties.

To solve this problem, it is proposed to estimate the intensity distribution of plastic deformation using numerical simulation, which will allow comparing the results of calculations with the observed changes in structure and properties.

2. Material and methods of research

Low-carbon steel Fe-0.1C in the as-received condition - a calibrated rod with a diameter of 10 mm in accordance with RF standard 10702-78 - was used as the material for investigation. When developing a numerical model, the rheological properties of low-carbon steel Fe-0.1C were selected according to the recommendations in [5].

To implement the procedure of numerical simulation, the standard software package "DEFORM-3D" was used.

In order to carry out the simulation in "DEFORM-3D" software package, 3D models were previously created in the software product "Compass-3D".

2.1. Accepted assumptions to the drawing model

- 1) the material of the billet in the as-received state is isotropic and there are no initial stresses and strains in it;
- 2) the temperature of the deformation environment was assumed to be 20° C;
- 3) the tool is absolutely rigid, and the geometry of the tool is automatically recorded;
- 4) the material of the initial billet was assumed to be ductile;
- 5) for modeling, 100 steps were selected, taking into account the full passage of the billet in the dies and obtaining a stable result;
- 6) the billet is divided into 45,000 trapezoidal elements;
- 7) coefficient of friction between the billet and the tool according to Siebel is 0.12;
- 8) drawing speed - 0.95 mm/sec;
- 9) the number of transitions is 6;
- 10) the degree of deformation on one pass is 15 ... 20%.

2.2. Accepted assumptions to the free-torsion model

- 1) the tool is an absolutely rigid body;
- 2) the material of the initial billet was assumed to be ductile;
- 3) diameter of the initial billet is 10 mm, length 250 mm;
- 4) the number of finite elements is 35,000;
- 5) the simulation was carried out in 180 steps with a time step of 1 sec. and a rotation speed of 12.5 rpm;
- 6) processing temperature is 20° C;
- 7) the number of revolutions is 16.

For in-situ tests, drawing through conical dies was used. Free torsion of the samples was carried out on a lathe with cantilever fixation of both ends of the billet in a rotating and stationary cartridge.

Rods from low-carbon steel Fe-0.1C were subjected to two types of deformation treatment [6, 7] - conventional drawing and shear deformation by free torsion. In the process of research, the effectiveness of the deformation effect on the structure was compared with conventional drawing and free torsion. Loading schemes are chosen in such a way that in the future it will be possible to analyze the structural and strength changes in the realization of two different types of deformation - compression with shear (when drawing) and shearing (with free torsion).

Traditional drawing was carried out in several passes in a drawing mill with a force of 30 kN with a step-wise reduction in diameter from 10 mm to 7 mm. Torsional deformation (pure shear) was carried out on a lathe with a variable speed of rotation, changing the speed from 10 to 30.

The value of the deformation by drawing was calculated from the formula

$$\varepsilon = [(S_0 - S_1)/S_0] \times 100\%, \quad (1)$$

where S_0 – cross-sectional area of rod before drawing, S_1 – after drawing [6-8]

The degree of shear deformation intensity (in the physical experiment) at torsion was determined as

$$\Lambda' = \text{tg } \varphi, \quad (2)$$

where φ – angle of twist of the original generator [7], i.e. the angle between the tangent to the generator and the projection of the axis of the rod to the tangent plane (Fig. 1).

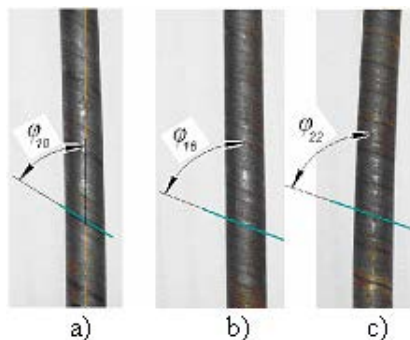


Fig. 1. Scheme for determining the twist angle and the view of the rods after deformation by free torsion: φ - angle of twisting of the rod: a) - 10 revolutions; b) 16 revolutions; c) 22 revolutions.

It should be noted that the quantity Λ' , calculated from formula (2), characterizes the intensity of the accumulated strain directly in the surface layer of the rods. In the volume of rods, the change in Λ' can

be represented in the form $\Lambda' = \frac{\varphi D}{2l}$ [9], where D is the diameter, l is the length of the working part of the rod.

The number of passes for drawing (n_d) and the number of revolutions at torsion (n_{rev}), as well as the diameters and degrees of deformation of the rods are given in Table 1.

Table 1. Deformation regimes of rods from low-carbon steel Fe-0.1C

Simple drawing			Torsion ($\varphi = \varphi_0$)		
n_d	\varnothing , mm	ε %	n_{rev}	φ	Λ'
1	9.6	7	10	57°	1,5
2	9.4	12	16	68°	2,5
3	8.0	36	22	70°	3,5
4	7.7	42			
5	7.0	51			

The initial diameter of the rods is $\varnothing_0 = 10 \text{ mm}$, $t_{def} = 20^\circ \text{ C}$. \varnothing - diameter of rods after deformation, ε % - cumulative deformation at drawing.

To reveal the features of the microstructure of the material in the as-received and deformed states, metallographic analysis was performed on light, as well as scanning and transmission electron microscopes. Mean size of grains, features of cellular and dislocation structure of ferrite were determined, the nature of the location of microcracks was studied, and the size and distribution of Fe_3C particles were estimated [10]. In addition, the microhardness HV was measured at a load of 1 N and a holding time of 10 sec in the cross-section of the rods before and after deformation. The error of measurements of these values did not exceed 12%.

3. Results of experiments and their discussion.

On the basis of the obtained results of mathematical modeling, the deformation intensity Λ by the diameter of the rod was determined, for the sake of clarity, presented in a graphical form in Fig. 2. The graph shows a slight change in the exponent Λ from the periphery

to the center of the sample. Thus, one can testify to the "softness" of such a deformation scheme as simple drawing.

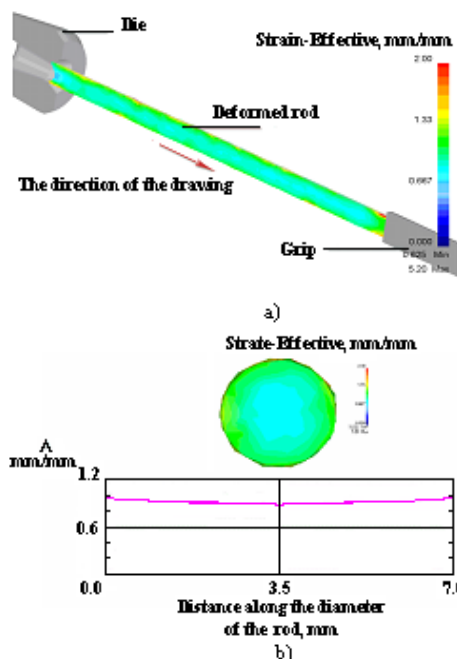


Fig. 2. Mathematical modeling of the distribution of deformation intensity Λ when drawing rods from low-carbon steel Fe-0.1C, the fifth passage: a) general view of the deformable rod, steady-state stage, longitudinal section; b) the change in Λ along the diameter of the rod in the cross section.

Fig. 3 shows the distribution of the intensity of the accumulated strain along the surface, and also in the cross-section of the rod after free torsion. As follows from this figure, the degree of deformation Λ increases nonlinearly from the value $\Lambda \approx 0.5$ at the center to $\Lambda \approx 2.3$ in the peripheral region of the rod, which is a characteristic feature of the development of shear deformation [7]. A similar character of the inhomogeneous distribution of Λ in the radial direction was observed by the author of [11] with free torsion of cylindrical samples from a titanium alloy Ti-6Al-4V

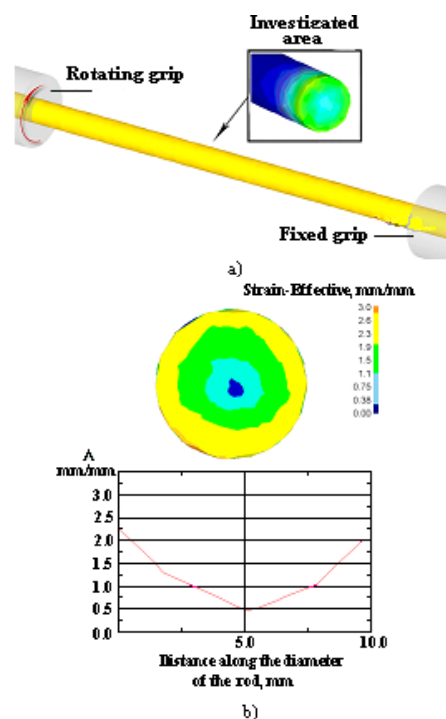


Fig. 3. The pattern of the distribution of the strain intensity of Λ in the cross section of the sample after free torsion (16 revolutions): the general view (a) and the cross section (b) of the deformable rod.

For the analysis and interpretation of the results obtained in the numerical model, field experiments on simple drawing and free torsion were carried out according to the method described above, observing the processing regimes adopted in the model. In order to reveal the peculiarities of plastic deformation in the volume of deformed rods, the microhardness HV was measured by the diameter of the cross-section of the rods. Graphs of variation of HV along the radius of the cross-section of deformed rods are shown in Fig. 4.

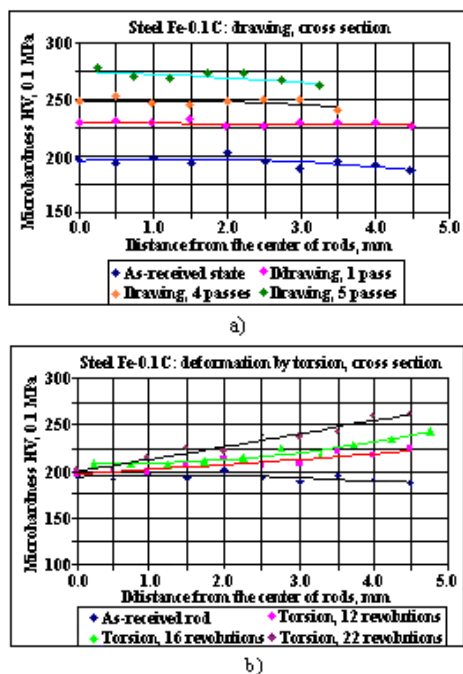


Fig. 4. Changing of microhardness of low-carbon steel Fe-0.1C on the diameter of the cross-section of the rod after deformation processing: a) by drawing; b) by free torsion

As can be seen from the presented graphs, the values of microhardness in the as-received rods of low-carbon steel Fe-0.1C are approximately the same in the central and peripheral areas of the rods. After simple drawing with an increase in the degree of deformation (the number of passes) the values of HV grow almost uniformly throughout the cross section of the rods (Fig. 4a). This indicates a relatively homogeneous character of the deformation by simple drawing along the entire volume of rods, which is confirmed by the results of structural studies. The data presented correspond basically to the results of modeling and indicate a correlation between the intensity of deformation and mechanical properties. A more heterogeneous character of the change in microhardness is observed with torsional deformation (Fig. 4b). Thus, in the central regions of the rods after torsion, the values of microhardness remain at the level of the as-received samples. At the same time, at the periphery they reach a value close to the values of HV after deformation by simple drawing by 51%. Such a picture of the change in microhardness in the central and peripheral regions of the rods correlates with the results of [12] on torsion with the simultaneous expansion of rods from low-carbon steel Fe-0.1C and is directly related to the heterogeneity of purely shear deformation occurring during torsion [11].

The change in microhardness due to an increase in the intensity of deformation is confirmed by metallographic studies. Fig. 5-6 show photographs of the microstructure of rods from low-carbon steel Fe-0.1C in the as-received state and after deformation treatment.

As can be seen in Fig. 5a, basically equiaxed grains of ferrite with comparatively rectilinear boundaries and average sizes of $d_{av} \approx 12-13 \mu\text{m}$ are observed throughout the cross-sectional area of the bars. Rounded, often stretched into chains, particles of degenerate Fe_3C perlite of indefinite shape with dimensions $d_{\text{Fe}_3\text{C}} \approx 0.2-3.0 \mu\text{m}$ are randomly distributed along the boundaries of the ferrite grains (Fig. 5).

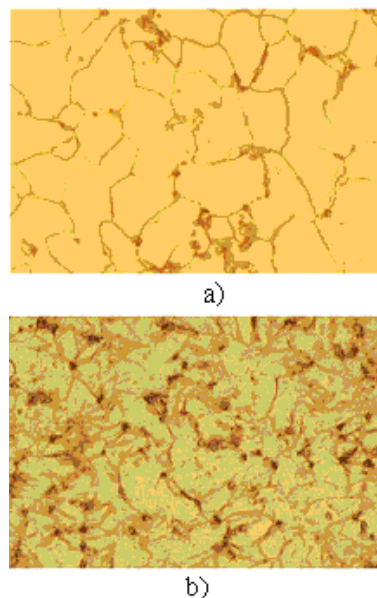


Fig. 5. Microstructure of low-carbon steel Fe-0.1C, cross-section, central areas of rods: a) the as-received state; b) deformation by drawing, 5 passes; $\times 1000$

Table 2 shows the values of the microstructure parameters in the cross sections of these rods.

Table 2. Average size of grains in rods from low-carbon steel Fe-0.1C in the as-received and deformed states

Type of processing	$d_3, \mu\text{m}$, cross-section
As-received state	12.7
Drawing, 5 passes	7.5
Torsion deformation, 16 revolutions, central part of the rod	12.0

When studying the structure in the cross section of deformed rods after 5 deformation passes by simple drawing, it is established that the structure of the alloy is relatively uniform, the grains (ferrite) are non-equiaxed, strongly deformed, often curved, the boundaries are tortuous, the grain sizes are $d_3 \sim 7.5 \mu\text{m}$ (Fig. 5b). In general, the microstructure in the central and peripheral areas of the rods is identical. The nature of the distribution and the dimensions of the particles of perlite practically have not changed.

In alloy samples subjected to torsional deformation, a different picture is observed. In the central part of a rod deformed by free torsion, the dimensions of the ferrite grains, as well as the perlite particles, practically did not change (Table 2), although chaotically distributed deformed grains of ferrite are present in the structure. At the same time, in the peripheral parts of the rods the structure is represented mainly by deformed ferrite grains with curved boundaries, similar to the one shown in Fig. 6a. In addition, in the peripheral regions of the samples near the lateral surface of the rods, after only 16 revolutions, single microcracks are observed, mainly at interphase boundaries.

Electron microscopic studies have shown that disoriented cells are observed over the entire volume of rods in deformed ferrite grains after drawing. They are, as a rule, elongated in the direction of drawing, their dimensions are $\approx 0.3-0.5 \mu\text{m}$ wide and $\approx 1-3 \mu\text{m}$ in length. In samples subjected to free torsion by 16 revolutions, elongated cells are also observed in the peripheral regions, but they have a noticeably greater misorientation than after drawing. This is evidenced by the presence not only of azimuthal smear, but also of spot reflexes on electron diffraction patterns. In addition, the cells in the peripheral parts of the samples after torsion are smaller than the cells after drawing - their width does not exceed $0.2-0.3 \mu\text{m}$, and the length is usually not more than $0.5-1 \mu\text{m}$ (Fig. 6).

Despite the peripheral region, in the microstructure of the central part of the samples, after torsion, slightly disoriented arbitrary

shaped cells are observed (Fig. 6a). These results indicate a lower intensity of the accumulated strain in the central region of the samples during torsion, which correlates with the data on the measurement of microhardness and modeling results.

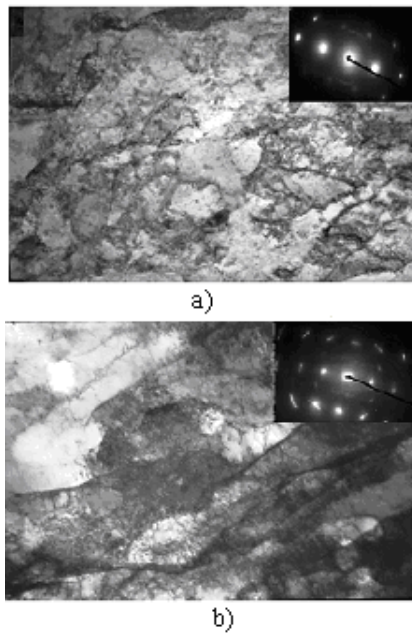


Fig. 6. Electron microscopic images of the structure of samples from low-carbon steel Fe-0.1C, deformed by free torsion: a) the central region of the rod, the axis of the zone [111]; b) the peripheral region of the rod, the axis of the zone [110]; x29000.

In order to determine the margin of ductility during torsional deformation, a ductility diagram of low-carbon steel Fe-0.1C in the as-received state was constructed (Fig. 7). In addition to the basic regime (n = 16), torsion experiments were performed with a smaller (n = 10) and a larger number of revolutions (n = 22).

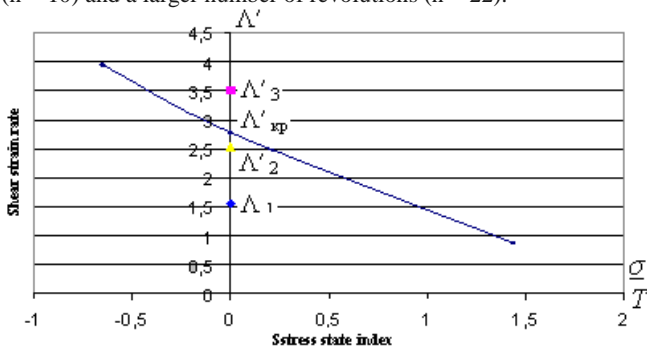


Fig. 7. The diagram of ductility of low-carbon steel Fe-0.1C in the as-received state and the values of the accumulated strain during torsion: $\Lambda'_1 \approx 1.5$ (n = 10 rev.); $\Lambda'_2 \approx 2.5$ (n = 16 rev.); $\Lambda'_3 \approx 3.5$ (n = 22 rev.); $\Lambda'_{cr} \approx 2.8$

As is known [7], the ductility diagram allows us to estimate the level of accumulated strain and determine the margin of the ductility reserve of the investigated material during deformation treatment. In Fig. 7 on the ordinate axis, the points are the value of the accumulated deformation for each number of revolutions during torsional deformation.

According to this diagram, the margin of ductility during torsion of rods from low-carbon steel Fe-0.1C is exhausted at a critical strain degree $\Lambda'_{cr} \approx 2.8$. The values of the strain degrees $\Lambda'_1 \approx 1.5$ (n = 10 rev.) and $\Lambda'_2 \approx 2.5$ (n = 16 rev.) are below the value Λ'_{cr} and do not exhaust the margin of ductility. Accordingly, at these strain degrees, microcracks practically do not form and do not develop. However, at $\Lambda'_3 \approx 3.5$ (n = 22 rev.), a well-developed network of microcracks is observed in the alloy structure (Fig. 8), since $\Lambda'_3 > \Lambda'_{cr}$, which leads to the destruction of the sample with further torsion.

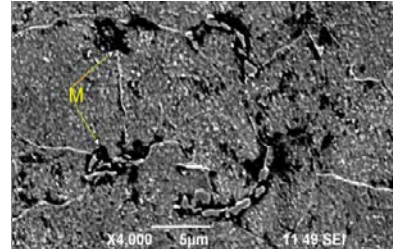


Fig. 8. Deformation by torsion, 22 revolutions, the central part of the rod, SEM, x4000, M - microcracks at the interface boundaries

As noted above, the establishment of direct dependence of the modeling parameters of the deformation processes of alloys and the structural changes that occur in them will allow us to realize new approaches to the development and management of technological processes of deformation processing of metallic materials for grinding the structure and forming the targeted set of their physico-mechanical properties.

As can be seen in Fig. 2 and 3, the strain intensity distribution Λ calculated by modeling is ≈ 0.8 after simple drawing. For the degree of deformation by drawing $\epsilon \approx 51\%$ (respectively, for $\Phi_0 = 10$ mm and $\Phi_1 = 7$ mm), the value of the logarithmic stretching is $e = \ln S_0 / S_1 \approx \ln 78.5 / 38.5 \approx \ln 2.04 \approx 0.71$. The closeness of the values of Λ and e for the process of drawing testifies to a certain correspondence between the data obtained by modeling and in a physical experiment.

Obtained in a physical experiment, Λ after 16 revolutions of free torsion (Table 1) reaches a value of 2.5, which is close to the value $\Lambda \approx 2.3$. It should be noted that the change in the strain intensity (Figures 2 and 3) also mainly correlates with the character of the change in microhardness along the radius of the cross section of deformed rods, the values of which are shown in Fig. 4.

Both in the model and in the real experiment it was established that deformation of the rod by free torsion leads to a significant structural heterogeneity and a gradient of mechanical properties from the center of the rod to its surface.

On the basis of the obtained results, it was proposed to study the shear drawing process to be able to improve the methods of deformation processing of long-length products and significantly increase their operational properties [13, 14]. This scheme, presumably, will allow realizing more fully the advantages of simple drawing and free torsion.

4. Conclusions:

1. Various types of cold deformation processing of rods from low-carbon steel Fe-0.1C were performed - traditional drawing and free torsion. A significant heterogeneity of the structural changes and the nature of the distribution of the intensity of plastic deformation under the given types of deformation processing of the alloy are revealed.
2. It is shown that deformation by simple drawing leads to a practically homogeneous structure refinement and, accordingly, to a uniform change in microhardness in the bulk of the billet. At the same time, under deformation by free torsion, a substantially heterogeneous, so-called gradient structure is formed.
3. The mutual correspondence of the ductility diagram of low-carbon steel Fe-0.1C and the nature of the structural changes in the samples deformed by free torsion is established. The marginal values of the ductility, the excess of which leads to the development of fracture processes, are established.
4. It is shown that the results of modeling of simple drawing and free torsion, basically, correspond to a real physical experiment with similar strain parameters. This testifies to the correctness of the applied approaches and the prospects of the mathematical modeling method for the development and improvement of new technological processes for metal working with pressure.

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