COMPUTER SIMULATION OF COMBINED DEFORMATION METHOD "ECA-PRESSING – DRAWING"

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Received 31 October 2019
Accepted 16 December 2019

ABSTRACT

This article presents the results of modeling of combined process "ECA-pressing - drawing" in the software package DEFORM. On the simulation basis, it can be concluded that during the implementation of the proposed combined deformation method by combining two methods: severe plastic deformation in an equal-channel step matrix and the usual drawing process, a favorable scheme of the stress-strain state is implemented, which allows to obtain a wire of the required size and shape of the cross section with an ultra-fine-grained structure.

Keywords: modeling, wire, stress-strain state, microstructure.

INTRODUCTION

Steel wire is widely used as a structural element in the production of ropes, bimetallic steel wire, non-insulated wires, etc. These metal products determine the safety and reliability of the functioning of railways, bearing building structures, telephone wires, cables, objects of the defense industry, aviation, etc. Main indicators of the quality of these metal structures are their reliability and durability, determined mainly by the strength properties of the steel wire. The main properties of the wire (temporary resistance to fracture, yield strength and fatigue, wear resistance, viscosity), as a structural material, are structurally sensitive, that is, can be controlled by purposeful changes in the structure. One of the promising ways to purposefully change the structure to submicrocrystalline and nanocrystalline are the methods of severe plastic deformation (SPD) [1 - 5].

After analyzing the methods of structure grinding, it can be assumed that the most effective methods in the production of wire are the methods based on torsion. The proposed method of continuous deformation - equal-channel angular drawing (ECAD) [6] uses additional shear deformation by alternating bending and torsion. The equipment for the implementation of this method is well integrated into the line of the drawing machine. However, this method requires additional equipment, and the degree of accumulated shear deformation is limited by the high probability of metal destruction during torsion. The Conform method is well known [7 - 9], which is a kind of continuous pressing with an application in industry. In recent years, a large number of different Conform schemes have been developed and applied.

Also, the combined method of deformation "equal-channel angular pressing – drawing (ECAP-D)" is an innovative method of obtaining wire with ultra-fine-grained structure and an increased level of mechanical properties [10].

This work is devoted to the study of the stress-strain state (SSS) of the metal in the implementation of the combined method of deformation "ECA-pressing-drawing" and the microstructure evolution of the metal, carried out with the help of computer modeling in the DEFORM software package.

PREPARATION OF SIMULATION MODEL

It has long been a proven fact that the modeling of various deformation processes in the metal forming using modern specialized software is a promising technique. Specialized software systems for modeling provide the widest opportunities for work, as they allow to simulate almost any process, bypassing expensive experiments. Modeling allows the researcher to look "inside" the deformation process, to assess the stresses and strains that occur, to predict the appearance of new defects, their development and closure, as well as to follow the evolution of the metal microstructure in the process of its deformation. In addition, the simulation allows to identify the rational parameters of the tool and workpiece for the best process conditions.

In our case, computer modeling of the combined method of deformation "ECA-pressing-drawing" of steel wire was carried out. Steel AISI 1003 was chosen as the workpiece material. The rheological properties of the material from the DEFORM database were taken. The workpiece material before deformation was isotropic, there were no stresses and strains. The workpiece used for the analysis had a cylindrical shape with a diameter of 7.0 mm and a length of 300 mm and it was broken into 180,000 finite elements, with an average element edge length of 0.5 mm. In order to eliminate the jamming of the wire in the matrix channels, the condition of the minus tolerance for the wire diameter and the plus tolerance for the ECA-matrix hole were adopted in the simulation. The material of the equal-channel matrix and the drawing die were adopted as absolutely rigid. The workpiece model was adopted as elastic-plastic. The workpiece temperature, as well as the temperature of the matrix, was chosen equal to 20°C - to obtain the optimal values of the SSS parameters.

Also for the simulated experiment, the value of the friction coefficient between the workpiece and matrix was adopted as 0.08; the heat exchange coefficient with the environment was adopted as 1; the drawing speed was equal to 1.5 m/s as the effective speed on the drawing mill. The pressing speed was set in accordance with the agreement of speeds 1.16 times less than the drawing speed and equal to 1.29 m/s.

As a result of the simulation and the study of shape, it was revealed that when implementing the proposed scheme of the combined process "ECA-pressing-drawing", this process proceeds stably, in the equal-channel angular matrix the joints of the channels are completely filled, there are no signs of forced thinning along the entire length of the workpiece (Fig. 1).

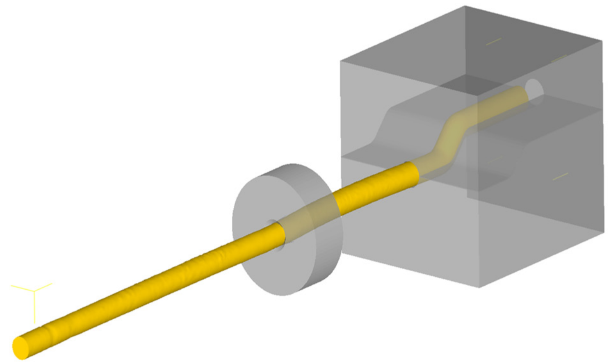

Fig. 1. Combined process "ECA-pressing-drawing".

STUDIED PARAMETERS

For a more detailed analysis of the new scheme of the combined process "ECA-pressing - drawing" a study of the stress-strain state was carried out.

To determine the stress and strain values, it is necessary to find the values of the components of the corresponding tensors, which are very difficult to visualize for a three-dimensional metal flow. Therefore, it is common to use simple strain and stress intensity measures, or so-called equivalent strain and equivalent stress, which include strain and stress components in the following form when considering SSS parameters [11]:

$$\varepsilon_{EQV} = \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_1-\varepsilon_2\right)^2+\left(\varepsilon_2-\varepsilon_3\right)^2+\left(\varepsilon_3-\varepsilon_1\right)^2} \quad (1)$$

$$\sigma_{EQV} = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2} \quad (2)$$

where ε_1, ε_2, ε_3 - main strains, σ_1, σ_2, σ_3 - main stresses.

When implementing the considered combined process "ECA-pressing-drawing" in the workpiece, two deformation foci appear sequentially, which makes this process quite complex. Therefore, to study the SSS parameters it is necessary to investigate not only the equivalent strain and equivalent stress, but also the parameters that allow to estimate the proportion of tensile and compressive stresses in the deformation zone. These are the maximum tensile and compressive stresses σ_1 and

σ_3. Their values are found by the following equations:

$$\sigma_1 = \frac{\sigma_X + \sigma_Y}{2} + \sqrt{\left(\frac{\sigma_X - \sigma_Y}{2}\right)^2 + \tau_{XY}{}^2} \qquad (3)$$

$$\sigma_3 = \frac{\sigma_X + \sigma_Y}{2} - \sqrt{\left(\frac{\sigma_X - \sigma_Y}{2}\right)^2 + \tau_{XY}{}^2} \qquad (4)$$

The component σ_2 is not usually considered as it is the arithmetic mean of σ_1 and σ_3.

In Deform, it is possible to represent each of the main stresses separately. However, it is most convenient to evaluate these parameters comprehensively. For this, Hydrostatic pressure or Stress mean parameter is used.

INVESTIGATION OF STRESS AND STRAIN STATE

When considering the equivalent stress, it should be understood that this parameter does not show which stress acts at a particular point - tensile or compressive. Being a fully rooted expression, its meaning is always positive. It shows the intensity of the stress action, i.e. whether there is a stress at a given point or not. Its value characterizes the average value of all stresses acting at a given point [11]. The results of the distribution of equivalent stresses in the combined process “ECA-pressing-drawing” are presented in Fig. 2.

When considering this parameter, it can be seen that the maximum values of stresses in the combined method of deformation “ECA-pressing-drawing” are concentrated in the zone of joints of the matrix channels. Here the stress reaches a value of 450 - 470 MPa. In the center of deformation of the drawing die, the stress value is much lower - about 190 - 200 MPa. In the area between the matrix and the drawing die there is a zone with reduced stress values – the so-called discharge zone. Here, the value of the equivalent stresses in the steady-state process practically does not change, it is equal to 140 - 150 MPa and remains approximately at the same level with minor deviations up to 4 - 5 %. In the drawing zone (from the drawing to the front end of the workpiece) there is a uniform distribution of stress equal to 80 - 90 MPa.

It is known from [12] that the sign of hydrostatic pressure characterizes the physical state of the particle. When the particle is subjected to tensile stress, the hydrostatic pressure is positive, and vice versa, when the particle is subjected to compressive stresses, the hydrostatic pressure is negative. The quality of the metal (the best study of the structure and brewing of internal defects) is positively affected by the presence of compressive stresses inside the deformable body, arising in the process of its deformation. These stresses can be characterized by the distribution of the mean stress (Fig. 3).

The nature of the distribution of average stresses shows that throughout the matrix, with the exception of small zones, compressive stresses prevail, reaching a value of -450 MPa. At the exit from the matrix in the discharge zone, compressive stresses also act, but their value is much lower, about -60 MPa. In the center of deformation of the drawing die is also dominated by compressive stresses, their value here reaches -280 MPa. Zones of tensile stresses on the inclined channel are located at the upper wall, which is explained by the increased value of the coefficient of friction in this area, as well as the action of bending stresses. Here their value reaches 120 MPa. In the drawing zone (from the draw-

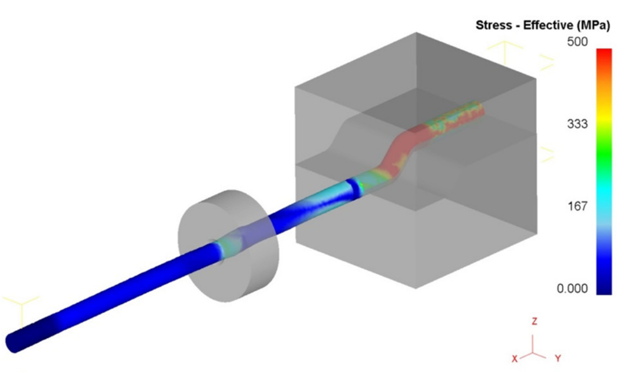

Fig. 2. Equivalent stress distribution.

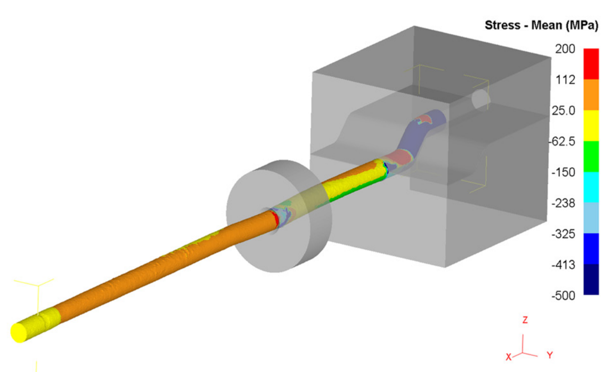

Fig. 3. Stress mean distribution.

ing to the front end of the workpiece) there is a zone of tensile stresses equal to 80 - 90 MPa.

Increasing the role of compression stresses in the overall stress state scheme increases plasticity. Under conditions of pronounced all-round compression, it is possible to deform even very fragile materials. The scheme of all-round compression is the most favorable for the manifestation of plastic properties, since this complicates the intergranular deformation and all deformation proceeds at the expense of the intra-grain one. The increasing role of tensile stresses leads to a decrease in plasticity. Under conditions of comprehensive stretching with a small principal stress difference, when the shear stresses are small for the beginning of plastic deformation, even the most plastic materials are brittle [13].

Thus, the scheme of compression provided in most of the matrix, as well as exceeding in absolute value of compressive stress on tensile, guarantee the absence of macro- and microcracks in the metal and favours the maximum degree of plasticity of the deformable workpiece in the matrix and drawing die.

When studying the deformed state, it is necessary not only to provide a high level of equivalent deformation required for the formation of an ultra-fine-grained structure, but also an uniform distribution of this parameter over the section of the workpiece. Therefore, the consideration of this parameter was carried out in two versions - on the surface of the workpiece and along the axial section (Fig. 4).

In the first deformation zone in the equal-channel step matrix, the workpiece passes successively two channel joints, where shear deformation is realized. The value of equivalent strain after passing the first joint reaches 0.75 in the surface layers and 0.65 in the central layers (difference in the values of equivalent strain reaches 15 %). After passing the second joint, the value of equivalent strain reaches 1.05 in the surface layers and 0.95 in the central layers (difference in the values of equivalent strain reaches 11 %). After the drawing stage, the equivalent strain value reaches 1.55 in the surface layers and 1.45 in the central layers (difference in equivalent strain values is reduced from 15 % to 6.5 %).

Taking into account the fact that the shear scheme increases the intensity of grinding of the initial structure, studies of evaluation the emerging schemes in the deformation zones have been conducted. The Lode-Nadai coefficient was used as a criterion for evaluating the deformation schemes. This coefficient allows to assess the nature of the resulting deformation in the workpiece, i.e. to determine what type of deformation is realized at a particular point - stretching, compression or shear. The Lode-Nadai coefficient was calculated by the equation (5) [14]:

$$\mu = 2 \cdot \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1 \qquad (5)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the main stresses.

The value of the coefficient varies from -1 to 1. A value from 0 to 1 corresponds to compression; a value from 0 to -1 corresponds to stretching; a coefficient value tending to 0 corresponds to shear [14]. To determine the Lode-Nadai coefficient, 70 points along the longitudinal axis with a step of 5 mm were created on the workpiece, on which the SSS parameters were measured.

Conventionally, workpiece can be divided into the following zones (Fig. 5):

- drawing area (points 1 - 27);
- distance between the zones of joints of channels in a matrix and the drawing die (points 28 - 48);
- zone of junction of channels in the matrix (points 49 - 56);
- tail zone (points 57 - 70).

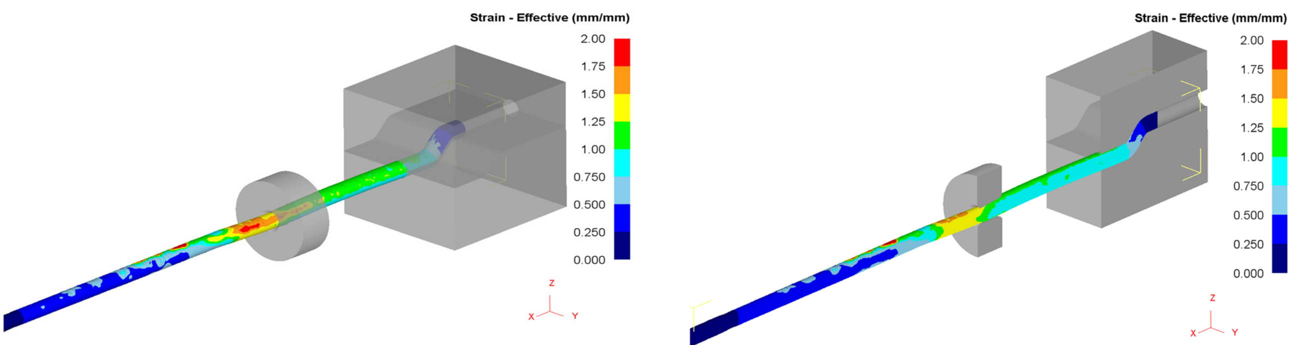

Fig. 4. Equivalent strain distribution.

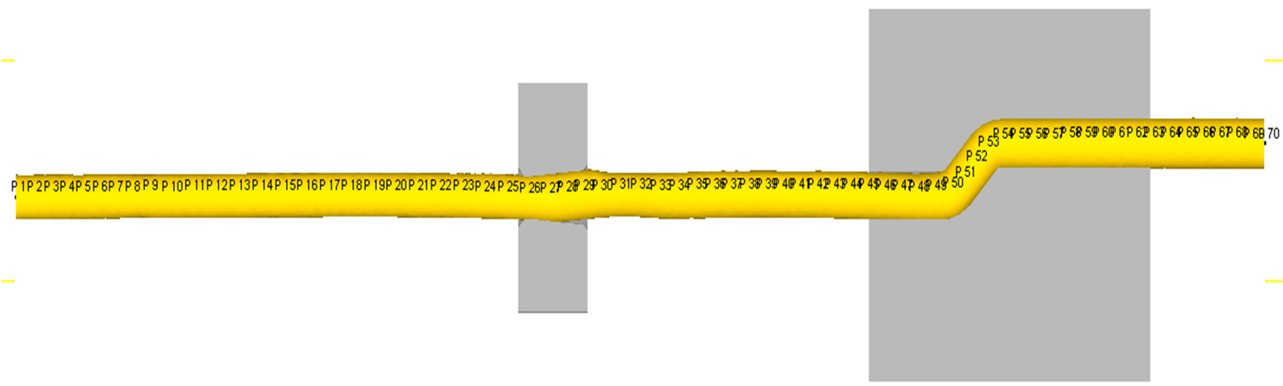

Fig. 5. Location of points for analysis of SSS parameters.

During calculating the Lode-Nadai coefficient, the following results were obtained (Fig. 6). In the first zone, when the workpiece passes through the drawing channel, one type of deformation develops in the deformed metal: stretching (μ = -0.9 ÷ -1), which is a characteristic feature of drawing.

In the second zone, immediately after the drawing deformation zone, which characterizes the distance between the zones of the joints of the channels in the matrix and drawing die, there is a support from the drawing die, even despite the coordination of speeds. As a result, tensile stresses are significantly reduced, up to the occurrence of compression zones (μ = 0,9 - 1), which act approximately to the middle of the zone. The second half of this zone is characterized by a sharp decrease in the influence of the support from the drawing die, because here the compressive stresses are sharply reduced - the value of the Lode-Nadai coefficient is reduced to μ = 0,2 - 0,4.

In the third zone, in the zone of matrix channels joint, the shear deformation prevails (μ = 0 - 0.2), which is a key feature of ECA-pressing. In the fourth, tail zone, compression deformations occur, although not as intense as in the second zone (μ = 0,6 - 0,8). This is due to the action of the backstop on the part of the workpiece, which is only partially in the matrix. As a result, the scheme of comprehensive compression occurs only on a certain part of the workpiece zone.

Thus, the compression and shear schemes provided in most of the workpiece length guarantee the absence of macro- and micro-cracks in the metal and favor the maximum degree of plasticity of the deformed workpiece.

STUDY OF THE MICROSTRUCTURE EVOLUTION

After obtaining an effective model, it was decided to conduct studies of the influence of a new combined method of deformation «ECA-pressing-drawing» on the

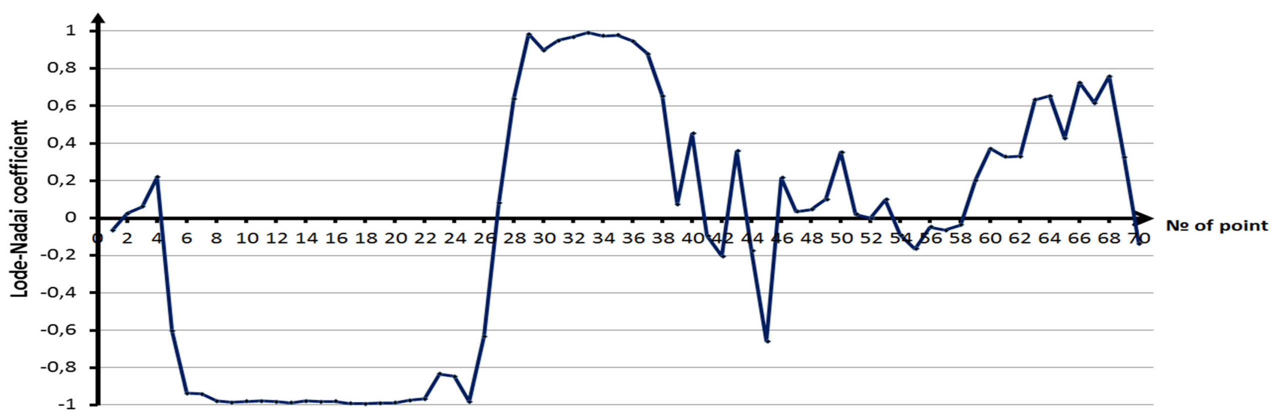

Fig. 6. Lode-Nadai coefficient.

evolution of the microstructure in order to determine the required number of deformation cycles to obtain an ultra-fine-grained structure using Microstructure-3D module of the Deform-3D program. Microstructure-3D module allows to consider the microstructure evolution at each deformation step, without resorting to a real experiment.

After calculating the model, the following results of microstructure evolution were obtained (Fig. 7). After passing through the channels of the matrix due to the implementation of shear deformation, the grain is crushed from 20 microns to 12 microns. After the drawing stage, the grain size also changes, but less intensively - from 12 microns to 9 microns.

During the drawing process, the peripheral layers are subjected to greater shear deformations in the longitudinal direction than the central ones. Therefore, after the end of the drawing process, the peripheral layers are shortened more than the central ones due to the elastic aftereffect. The integrity of the metal equalizes these shortening, so the appearance of residual stresses stretching in the peripheral and compressing in the central layers of a solid round stretched rod is inevitable.

Central layers of the workpiece during both stages of deformation are worked less intensively - here the grain size varies from 20 microns to 15 microns after ECA-pressing and up to 13 microns after drawing. Thus, after one deformation cycle, the difference in grain size values between the surface and the central zone is 4 microns.

This leads to the conclusion that the implementation of this combined process to elaborate the structure of billet cross section is uneven, and to align properties on the section it is necessary to conduct several cycles of deformation.

Multi pass deformation was carried out under the following conditions:

- 1st pass: the workpiece with a diameter of 7.0

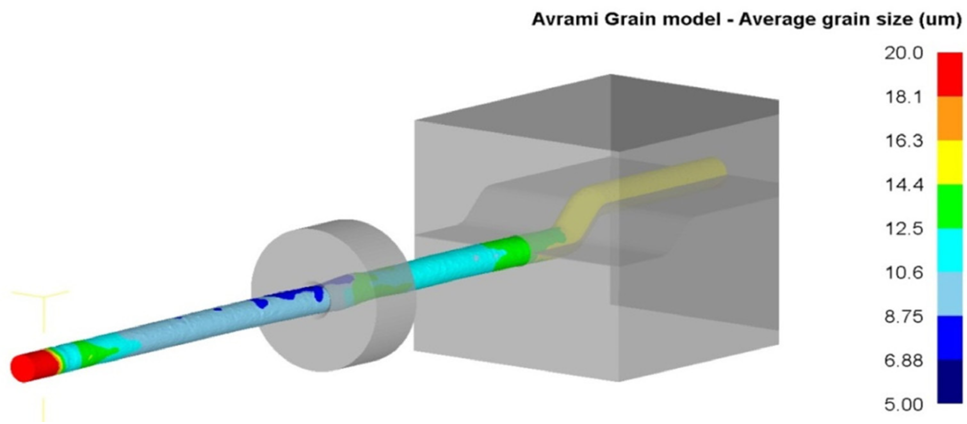

Fig. 7. Grain size change.

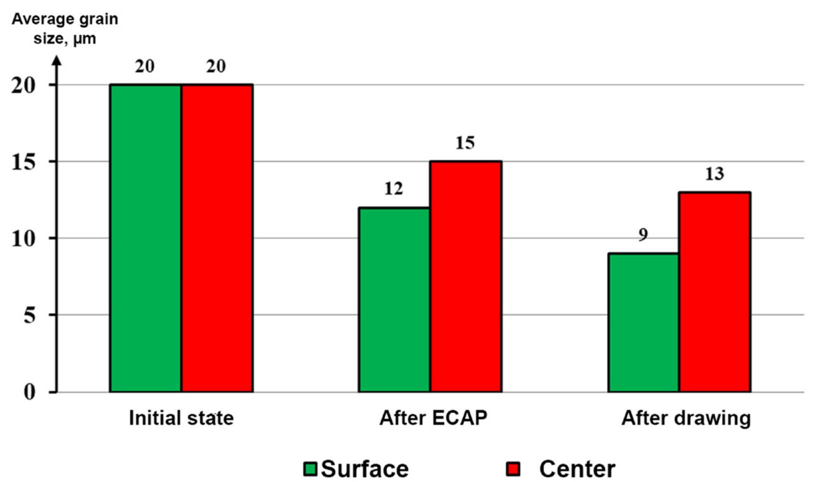

Fig. 8. Results of calculation of microstructure evolution.

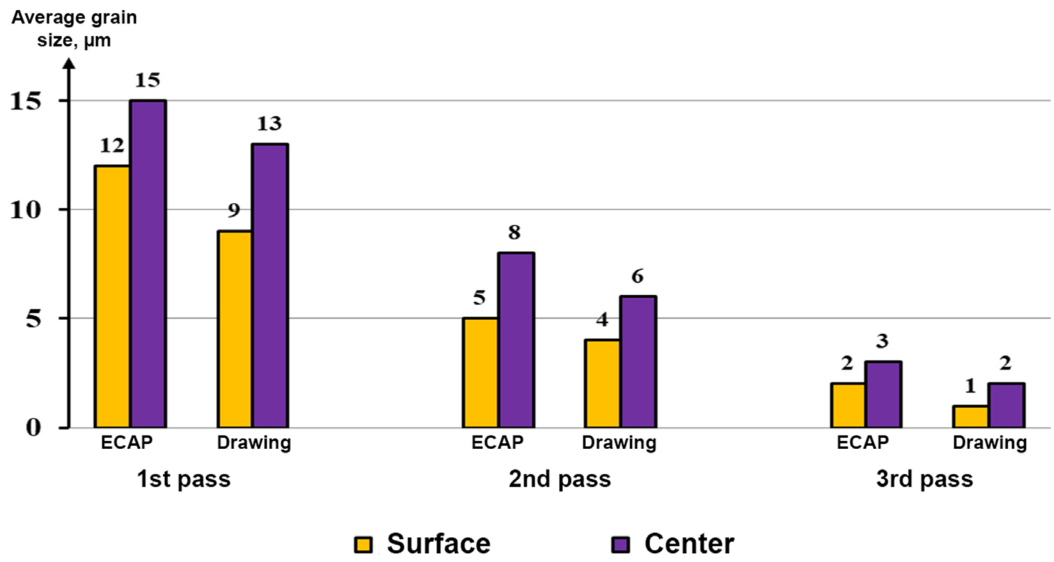

Fig. 9. Grain size change during multi-pass deformation.

mm passed through a matrix with a channel diameter of 7.0 mm and then was dragged through a die with a diameter of 6.5 mm;

- 2nd pass: the workpiece with a diameter of 6.5 mm passed through a matrix with a channel diameter of 6.5 mm and then was subjected to drawing through a die with a diameter of 6.0 mm;

- 3rd pass: the workpiece with a diameter of 6 mm passed through a matrix with a channel diameter of 6.0 mm and then was dragged through a die with a diameter of 5.5 mm.

As a result, the following data were obtained (Fig. 9). After the second pass, the grinding of the grain is not as intense as in the first pass. Here the average diameter of the grain after ECAP in the surface zone was 5 µm, in the central zone - 8 µm (difference was 3 µm). After drawing, the grain size in the surface zone was 4 µm, in central zone the grain size was 6 µm (difference was 2 µm).

After the third pass, the average grain diameter after ECAP in the surface zone was 2 µm, in central zone the grain size was 3 µm (difference was only 1 µm). After drawing, the grain size in the surface zone was 1 µm, in central zone the grain size was 2 µm (difference was also 1 µm).

Thus, as a result of studying the model with several deformation cycles, it was revealed that with an increase in the number of passes, not only the overall decrease in the average diameter of the grain occurs, but also a gradual alignment of this parameter between the central and surface zone.

CONCLUSIONS

The simulation of the new combined method of deformation "ECA-pressing – drawing" showed that when implementing the proposed method of deformation of the wire by combining two separate processes: severe plastic deformation in equal channel angular matrix and a conventional drawing process, the favourable scheme of the stress-strain state is implemented, which allows to obtain a wire with ultrafine-grained structure with the requirements of size and geometry.

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