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Microstructure Evolution of a Steel Bar during FEM Simulation of Radial-Shear Broaching and Subsequent Drawing

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The paper presents the results of finite element modelling of the microstructure evolution in the implementation of the combined technology of radial-shear broaching and subsequent drawing by JMAK and cellular automata methods. The analysis of the results shows that the simulation results have a high degree of convergence with each other; so, it can be recommended to use any of these methods to obtain information about the grain sizes. Workpiece deformation with a diameter of 30 mm to 20 mm at ambient temperature is the most effective method, since it allows refining the initial grain more than 3 times on the workpiece surface, from 25 µm to 8 µm. At the same time, workpiece deformation with a diameter of 30 mm to 23 mm at ambient temperature gives a twofold refinement of the initial grain, from 25 µm to 12 µm. The processing of the central area of the workpiece in all considered models is insignificant; it reaches only a 35%-reduction under the most optimal conditions.

Key words: steel, drawing, radial-shear broaching, severe plastic deformation, bar.

У статті наведено результати моделювання методом скінченних елементів еволюції мікроструктури під час реалізації комбінованої технології радіально-зсувного протягання з подальшим витягуванням методами JMAK та клітинних автоматів. Аналіза даних показала, що результати

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моделювання мають високий ступінь збіжности між собою; тому можна рекомендувати використовувати будь-який з цих методів для одержання інформації про розмір зерен. Деформація заготівки діяметром від 30 мм до 20 мм за температури навколишнього середовища є найбільш ефективним методом, оскільки дає змогу подрібнити вихідне зерно на поверхні заготівки більш ніж у 3 рази — з 25 мкм до 8 мкм. У той же час, деформація заготівки діяметром від 30 мм до 23 мм за температури навколишнього середовища дає дворазове подрібнення вихідного зерна — з 25 мкм до 12 мкм. Оброблення центральної зони заготівки у всіх розглянутих моделях є незначним і сягає лише 35%-зменшення за найоптимальніших умов.

Ключові слова: криця, волочіння, радіяльно-зсувне протягання, інтенсивна пластична деформація, дротик арматурного заліза.

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1. INTRODUCTION

Wire is an indispensable material in a wide variety of industries. It is used in the form of finished products such as steel ropes, nets (welded and woven), nails, screws, as well as semi-finished products for the production of machine parts, wire and cable products and many other components. The key process in wire production is drawing, in which the workpiece is stretched along its longitudinal axis. During drawing, deformation occurs mainly in one direction, which makes this process quasi-monotonic.

However, modern technologies tend to go beyond traditional processing methods in order to obtain materials with improved properties. One of the most interesting areas is the creation of materials with a sub-, micro- and nanocrystalline structure. These materials have increased strength, wear resistance, corrosion resistance and other advantages [1–7].

To obtain a sub-, micro- and nanocrystalline structure in metals, it is necessary to use high-intensity deformation and the non-monotonic nature of the process. Non-monotonic deformation implies a change in the direction of deformation in each subsequent pass. For example, if the angle between the deformation directions in two consecutive passes is 90° or 180°, this will be considered a non-monotonic deformation.

Existing methods of severe plastic deformation (SPD), such as high-pressure torsion, equal-channel angular pressing, extrusion and impact treatment, have their limitations [8–14]. For example, they do not allow the creation of products with the necessary shapes and dimensions for practical use, especially for long products such as rods and wire.

To date, one of the most promising methods of forming an ultrafine-grained structure in long products is radial-shear rolling (RSR). RSR can be considered as a special case of screw rolling, but with significantly higher feed angles. This method combines deformations of shape change and torsion shear. However, the presence of torsion of the workpiece limits the use of RSR for processing long products.

The traditional method of producing long products, such as RSR, is widely used in metallurgy. However, the use of planetary crates required for this method makes it impractical for wire production. That is why a radial-shear broaching, as a new method of producing round wire, was developed and investigated [15].

Radial-shear broaching is an innovative process that allows obtaining wire by broaching without twisting, which eliminates the risk of defects and improves the quality of the final product. The method is based on the application of a forward pulling force to the wire rod (the starting wire) and the rotation of the roller lug.

In this work, it was proposed to combine radial-shear broaching with traditional drawing. In order to study the mechanism of radial-shear broaching and drawing and to optimize the process, modelling was carried out in Deform software package. Radial-shear broaching is a promising method for producing rods, which promises to improve product quality, reduce costs and increase productivity. Further research in this direction promises to further improve the process and open up new opportunities for the development of the wire industry.

2. EXPERIMENTAL

When developing a new deformation technology, along with studying the stress–strain state and energy–force parameters, an important task is to study the microstructure evolution. This knowledge provides a visual representation of the material processing effectiveness on the investigated technology. In recent years, in addition to experimental studies, an approach to studying the microstructure evolution by the finite element method has been actively developing. At the same time, the most commonly used methods for predicting microstructure are mathematical models that take into account dynamic and static recrystallization. The ultimate goal of such studies is data on the size and shape of metal grains after mechanical or thermal processing.

There are two methods of microstructure modelling in the Deform system. The first method is the Johnson–Mehl–Avrami–Kolmogorov (or JMAK) method. The main disadvantage of the JMAK method is the fact that it does not take into account the different shape of the grain. At the same time, its advantage is that during the calculation it is possible to obtain data on the grain size at any point of the workpiece. The second method of microstructure modelling in Deform is the discrete lattice method, implemented using the cellular automata algorithm, which was implemented to eliminate the disadvantages of the JMAK method. This model, which explicitly represents grains and grain boundaries visually, is more sensitive to local geometry changes. The main disadvantage of the cellular automata method is that it cannot provide data for the entire volume of the workpiece, since the calculation mechanism allows evaluating the microstructure only at predefined points of the workpiece. Its advantage is that during the calculation it is possible to obtain data on the shape and size of the grains.

To use the JMAK method, it is necessary to calculate initially a model with microstructure calculation parameters. By default, the model assumes a uniform distribution of the initial grain size over the entire area or volume of the workpiece. The value of 25 μm was adopted as the initial grain size of steel 10.

For correct modelling, it is necessary to enter the parameters of grain evolution for the JMAK method. They include data on static, dynamic and meta-dynamic recrystallization, as well as on the kinetics of new grain growth. The essence of entering this data is to enter certain constants of the model, depending on the properties of the material and the type of processing process. All of them are considered in detail in Ref. [16], which presents a large number of values of these coefficients for various grades of steels and alloys, depending on the types of deformation and thermal treatments.

When using the JMAK method, three types of recrystallizations are calculated. Dynamic recrystallization (DRX) starts after reaching a critical degree of deformation, due to dynamic return, the process of nucleation of new grains is added, which also undergo riveting during deformation, which can lead to the formation of new grains inside them. The basic JMAK equations describing dynamic recrystallization for steel 10 are presented below: kinetic exponent (Avrami index) responsible for the rate of embryo formation,

$$k_{\mathrm{d}} = 0.029\dot{\varepsilon}^{-0.04}\exp(-16550/RT); \qquad (1)$$

critical value of the strain intensity,

$$k_{\mathrm{KP}} = 1.97\dot{\varepsilon}^{0.06}\exp(23590/RT); \qquad (2)$$

strain intensity at 50% recrystallization,

$$k_{0.5} = 71\dot{\varepsilon}^{0.124}\exp(51300/RT); \qquad (3)$$

the size of dynamically recrystallized grains [μm],

$$d_{\mathrm{DRX}} = 0.3\dot{\varepsilon}^{-0.123}\exp(50900/RT); \qquad (4)$$

here, $\dot{\varepsilon}$ is strain rate [s^{-1}], $R = 8.31$ J/(mole·K) is universal gas constant, T is material temperature [K].

The process of metadynamic recrystallization (MRX) begins after the deformation process stops when its critical degree is reached. In fact, the MRX process consists in the growth of grains (embryos) that appeared as a result of dynamic recrystallization. The basic JMAK equations describing the metadynamic recrystallization for steel 10 are presented below: an empirically determined constant,

$$k_{\mathrm{m}} = 0.237\,; \tag{5}$$

the time, at which 50% of the metadynamically recrystallized grains are formed in the structure,

$$t_{0.5} = 1.12 \cdot 10^{-9} d_0 \dot{\varepsilon}^{-0.8} \exp(230000 / RT)\,; \tag{6}$$

the size of metadynamically recrystallized grains [μm],

$$d_{\mathrm{MRX}} = 1.57 d_0^{0.99} \dot{\varepsilon}^{-0.033} \exp(-5115 / RT)\,. \tag{7}$$

Static recrystallization (SRX) occurs, if the critical degree is not reached as a result of plastic deformation, but the accumulated internal energy due to the temperature of the metal is sufficient for the formation of new grain nuclei. This temperature value is a reference value (A_{c1} critical point), for steel 10 it is equal to 742°C. The basic JMAK equations describing static recrystallization for steel 10 are presented below: degree indicator,

$$k_{\mathrm{m}} = 0.31\,; \tag{8}$$

the time, at which 50% of statically recrystallized grains are formed in the structure,

$$t_{0.5} = 1.14 \cdot 10^{-13} \varepsilon^{-3.8} \dot{\varepsilon}^{-0.41} \exp(252000 / RT)\,; \tag{9}$$

the size of statically recrystallized grains [μm],

$$d_{\mathrm{SRX}} = 0.5 d_0^{0.67} \dot{\varepsilon}^{-0.67}\,. \tag{10}$$

To simulate the microstructure evolution using the Cellular Automata method, it is necessary to use pre-calculated models with fields of all parameters (stress, strain, flow velocity, *etc*.). To be able to compare with the results of the JMAK model, two points were considered in each model, when calculating cellular automata,—in the workpiece centre and at a distance of 0.5 mm on the surface in the contact area metal with rolls, which allows to estimate the maximum level of metal

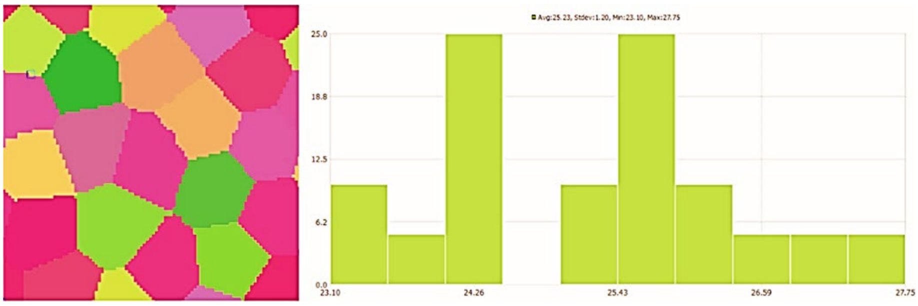

Fig. 1. Initial microstructure.

processing.

In addition, it was decided to calculate the microstructure at the designated points in two directions (transverse and longitudinal), since this method provides a visual picture of the grains, and it is possible to assess not only changes in their size, but also their shape. For the calculation of all models, the construction of a window with dimensions of 100×100 μm was used. The initial structure with an average grain size of 25 μm is shown in Fig. 1.

3. RESULTS AND DISCUSSION

Figure 2 shows the patterns of the microstructure evolution in the cross section of the workpiece after all stages of deformation for all

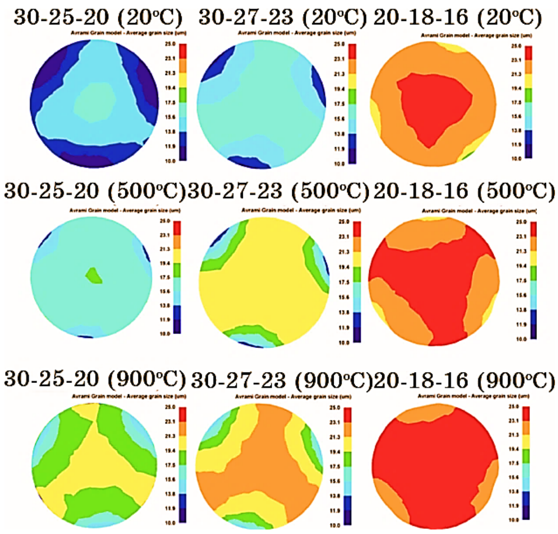

Fig. 2. Average grain size over the workpiece section.

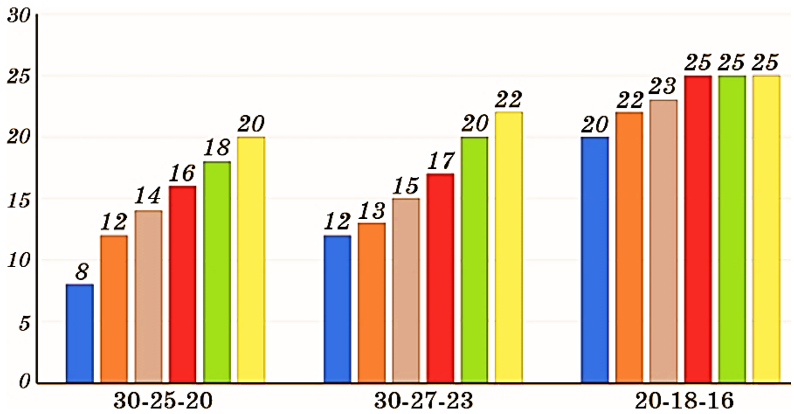

Fig. 3. Summary chart of average size values by the JMAK method.

models that were considered earlier in the study of the stress-strain state. For ease of comparison, all results have the same scale range.

The following conclusions can be drawn from the results obtained:
1) the intensity of grain refinement is significantly influenced by both the level of compression in direct dependence and an increase in temperature in inverse dependence;
2) the most intensive refinement of the initial grain size is observed in the model 30-25-20 at 20°C, which is a consequence of the maximum single and total compressions, as well as the minimum temperature of the workpiece; also in other models, this temperature is the most preferable;
3) the model 20-18-16 is the least effective in terms of grain refinement at all temperatures, even in the absence of heating of the workpiece, the central zone of the workpiece almost does not receive any significant grain grinding;
4) in all models at 900°C, there is a sharp decrease in the intensity of grain refinement, which is associated with the launch of the static recrystallization process at 742°C.

Figure 3 shows a summary diagram of the values of the average grain size on the surface and in the centre of all the models considered.

From the data obtained, it can be said that the deformation of the workpiece according to the 30-25-20 scheme at ambient temperature allows the initial grain to be refined more than 3 times on the workpiece surface, where the maximum metal processing is usually accumulated during RSR.

At the same time, using the 30-27-23 scheme at ambient temperature gives a twofold refinement of the initial grain. The processing of the central area of the workpiece in all the considered models is weakly pronounced, reaching a 35%-reduction in the most optimal conditions.

Figures 4–6 show the results of the calculation of the microstruc-

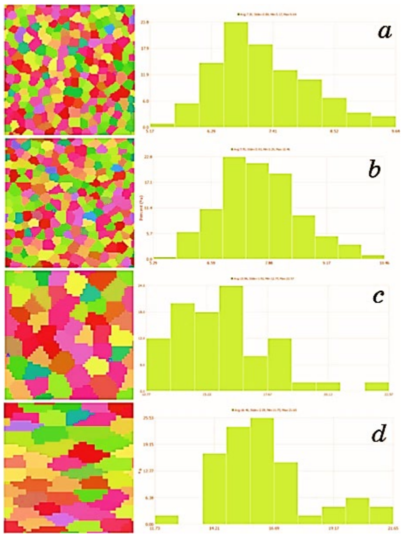

Fig. 4. Microstructure of the model 30-25-20 at 20°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

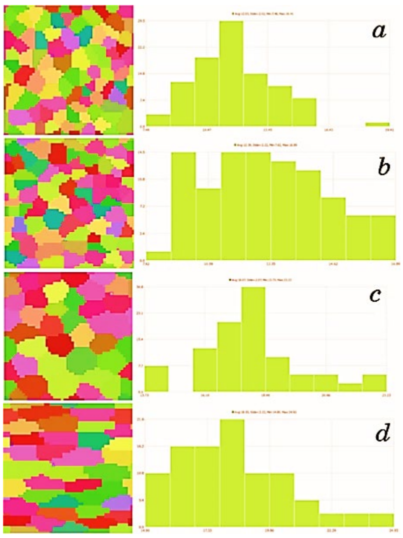

Fig. 5. Microstructure of the model 30-25-20 at 500°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

ture by the cellular automata method for models 30-25-20 at three temperatures.

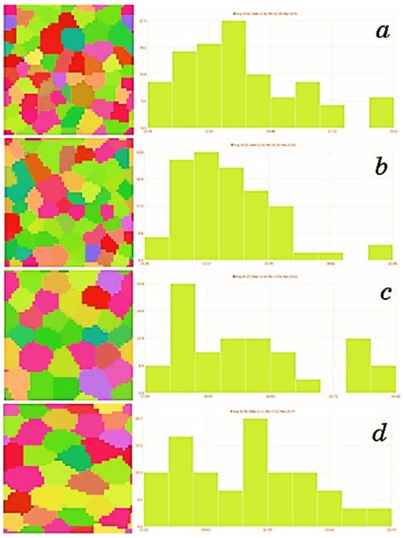

Fig. 6. Microstructure of the model 30-25-20 at 900°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

TABLE 1. Average grain size in models 30-25-20 [μm].

Temperature	Direction	Surface		Centre	
		CA	JMAK	CA	JMAK
20°C	Transverse	7.3	8	15.96	16
	Longitudinal	7.7		16.46	
500°C	Transverse	12.03	12	18.07	18
	Longitudinal	12.39		18.55	
900°C	Transverse	14	14	20.27	20
	Longitudinal	14.33		20.95	

With analysing the data obtained, it can be noted that the calculation results by cellular automata have high convergence with the results in the JMAK model, especially in the transverse direction. In the longitudinal direction, sufficient uniformity of the grain shape remains on the surface, whereas in the central region there is an intense elongation of the grains due to the action of tensile forces during drawing and laminar flow according to the RSR scheme. At a temperature of 900°C, the intensity of grain elongation decreases due to the activation of the static recrystallization mechanism, which leads to the formation of new grains.

Table 1 shows comparative data on the average grain size for both microstructure calculation methods.

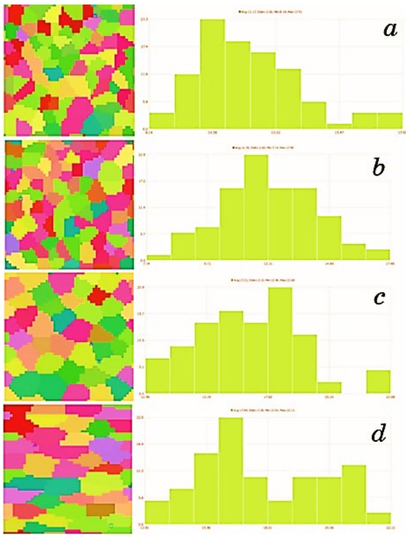

Fig. 7. Microstructure of the model 30-27-23 at 20°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

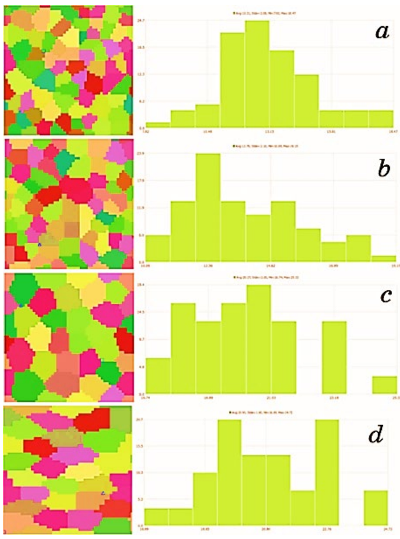

Fig. 8. Microstructure of the model 30-27-23 at 500°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

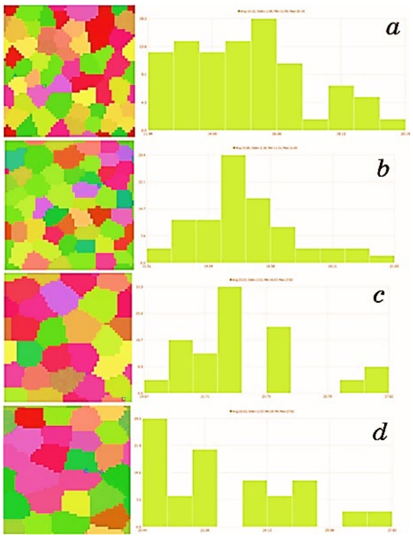

Fig. 9. Microstructure of the model 30-27-23 at 900°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

TABLE 2. Average grain size in models 30-27-23 [μm].

Temperature	Direction	Surface		Centre	
		CA	JMAK	CA	JMAK
20°C	Transverse	12.17	12	17.21	17
	Longitudinal	12.39		17.84	
500°C	Transverse	13.21	13	20.27	20
	Longitudinal	13.79		20.95	
900°C	Transverse	15.22	15	23.03	22
	Longitudinal	15.8		23.03	

Figures 7–9 show the results of calculating the microstructure for models 30-27-23 at three temperatures.

As in the case of models 30-25-20, the analysis of the results of models 30-27-23 reveals a high convergence of the results of the calculation of the microstructure with the results of the JMAK method—both on the surface and in the centre (see Table 2). There is also an elongation of the grains in the longitudinal direction in the central area of the workpiece; on the surface, the grains have a more equiaxed shape due to the turbulent flow pattern of the metal due to the constructive arrangement of the rolls of the RSR mill.

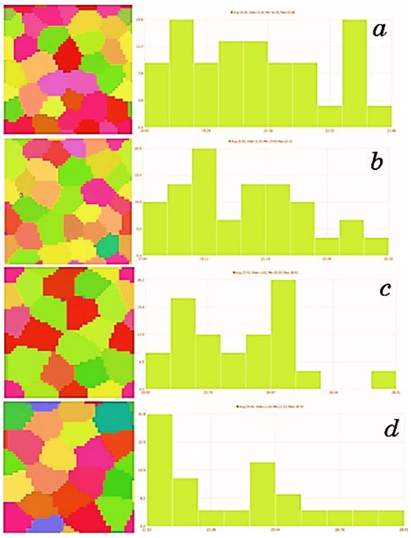

Fig. 10. Microstructure of the model 20-18-16 at 20°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

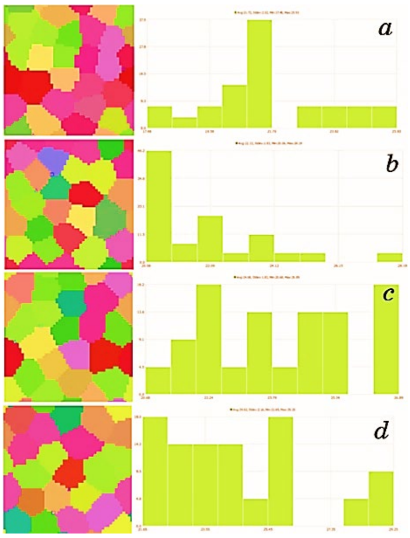

Fig. 11. Microstructure of the model 20-18-16 at 500°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

Figures 10–12 show the results of calculating the microstructure for models 20-18-16 at three temperatures.

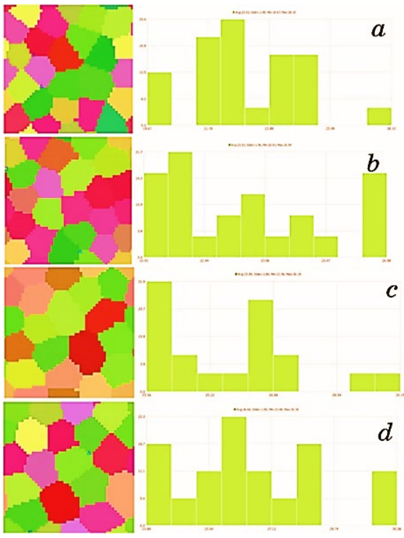

Fig. 12. Microstructure of the model 20-18-16 at 900°C: surface, transverse direction (*a*), surface, longitudinal direction (*b*), centre, transverse direction (*c*), centre, longitudinal direction (*d*).

TABLE 3. Average grain size in models 20-18-16 [μm].

Temperature	Direction	Surface		Centre	
		CA	JMAK	CA	JMAK
20°C	Transverse	19.95	20	23.53	25
	Longitudinal	20.6		24.06	
500°C	Transverse	21.72	22	24.06	25
	Longitudinal	22.13		24.62	
900°C	Transverse	23.03	23	25.89	25
	Longitudinal	23.53		26.6	

When analysing the results of models 20-18-16, a high convergence of the results of calculating the microstructure with the results of the JMAK method was revealed both on the surface and in the centre (see Table 3).

There is practically no effect of grain elongation in the longitudinal direction, since the central layers in these models receive extremely insignificant grain refinement. The surface layers are also poorly worked out. The main reason for this effect is a sharp decrease in single compressions, as well as the use of a workpiece with a reduced diameter. As a result, the deformation zone in the rolls is formed in the rectilinear region of the rolls, which sharply reduces the angle of twisting of the surface layers; in this case, it is advisable to talk not about radial-shear rolling, but about conventional screw rolling.

4. CONCLUSION

In this article, the influence of the combined technology of radial-shear broaching and subsequent drawing on the microstructure evolution of rods was studied by two modelling methods—JMAK and cellular automata ones. The analysis of the results showed that the simulation results have a very high degree of convergence among themselves, so it can be recommended to use any of these methods to obtain information about the grain size. If it is necessary to obtain data on grain shape changes, then, cellular automata will be a suitable method in this case. In this case, it will be possible to track the change in the shape of the grains in different directions. From the obtained microstructure modelling data, it can be said that deformation of the workpiece according to the 30-25-20 scheme at ambient temperature is the most effective method, since it allows refinement the initial grain more than 3 times on the workpiece surface. At the same time, using the 30-27-23 scheme at ambient temperature gives a twofold refinement of the initial grain. The processing of the central area of the workpiece in all the considered models is weakly pronounced, reaching a 35%-reduction in the most optimal conditions.

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