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MODELING THE MICROSTRUCTURE EVOLUTION DURING THE COMBINED PROCESS OF DRAWING WITH CRYOGENIC COOLING

MODELIRANJE RAZVOJA MIKROSTRUKTURE MED KOMBINIRANIM PROCESOM VLEČENJA IN KRIOGENEGA OHLAJANJA

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In this study, finite-element modeling of the microstructure evolution of the combined drawing process with cryogenic cooling by JMAK and Cellular Automata methods was carried out. The use of different methods is due to the fundamental difference in the results obtained—in the JMAK method, it is possible to obtain only grain size data, but this is calculated for the entire workpiece volume. In the Cellular Automata method, the calculation is performed only at predefined points, but in this case the user receives information about the size and shape of the grains. An analysis of the initial microstructure of 25 μm showed that the most optimal option is a reduced drawing speed and the absence of intermediate heating—in both considered blanks, a grain size of 0.5 μm approximately was obtained on the surface. At the same time, variants with an increased deformation rate also have fairly good grain-grinding results up to 0.7 μm. At the same time, it was found that the use of intermediate heating to ambient temperature in the proposed thermomechanical processing scheme will lead to a higher grain size gradient along the wire section.

Keywords: modeling, microstructure evolution. drawing. cryogenic cooling.

V članku avtorji opisujejo modeliranje razvoja mikrostrukture med kombiniranim procesom vlečenja in kriogenega ohlajanja z dvema metodama; metodo na osnovi končnih elementov JMAK in metodo celičnih avtomatov (CA; angl.: Cellular Automata). Uporaba dveh različnih metod daje že v temeljih polnoma drugačne rezultate. Z JMAK metodo lahko dobimo samo podatke o velikosti zrn, toda izračunavanje poteka po celotni delovni prostornini preiskovanca. Pri uporabi metode celičnih avtomatov pa izračun poteka samo v okviru izbrane delovne prostornine. Izračun s CA metodo poteka torej samo na vnaprej določenih točkah, toda uporabnik dobi informacijo o velikosti in obliki kristalnih zrn. Analiza z začetno 25 μm mikrostrukturo nerjavnega jekla tipa AISI 316 je pokazala, da je optimalna najmanša izbrana hitrost vlečenja brez dodatnega vmesnega ogrevanja. V dveh analiziranih primerih so avtorji dobili na površini velikost kristalnih zrn približno 0,5 μm. Istočasno variranje s povečevanjem hitrosti deformacije so dobili ravno tako dokaj dobre vrednosti do 0,7 μm. Rezultati analiz so pokazali, da uporaba vmesnega ogrevanja do sobne temperature v predlagani termomehanski procesni shemi vodi do večjih kristalnih zrn vzdolž preseka vlečene žice.

Ključne besede: modeliranje, razvoj mikrostrukture, vlečenje, kriogeno ohlajanje

1 INTRODUCTION

The production of long-length, deformed, semi-finished products, such as bars, profiles, and wire, is a key task of modern metallurgy. These materials are widely used in various industries, from mechanical engineering and construction to electronics and aviation.[1–3]

Modern wire production is facing serious challenges due to outdated technologies. The equipment used is characterized by a high energy consumption and a low productivity, which negatively affects the profitability of production and the competitiveness of companies in the global market.

Of particular relevance is the production of wire from austenitic corrosion-resistant steels, the demand for which is steadily growing. These steels, which make up about 80% of the global corrosion-resistant steel market, are characterized by unique properties that make them indispensable in a wide range of industries.[4,5]

A key feature of austenitic corrosion-resistant steels, such as AISI-316 steel, is their purely austenitic structure after quenching. During plastic deformation, a γ-α transformation occurs, i.e., austenite (γ-phase) turns into martensite (α-phase). The higher the concentration of martensite, the lower the deformation temperature and the higher the degree of deformation. However, it is important to understand that even with intense deformation, some austenite may not turn into martensite.[6]

To obtain a wire with high strength properties made of AISI-316 steel and its analogues, deformation in the range of 90–92 % is recommended. This degree of com-

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pression makes it possible to achieve an optimal balance of strength and ductility. At the same time, no more than 75% martensite is formed in the wire structure, which provides high strength, but retains the necessary plasticity for further processing.

The use of high compression during deformation of medium and small cross-sections of wire is impractical, since drawing, as a method of deformation, always leads to a significant decrease in the diameter of the wire.[7–9]

In this paper, a new wire-deformation technology based on cryogenic cooling is proposed. Its essence is as follows: the wire, passing through the die, is subjected to cold processing based on the use of low temperatures. The developed technology will allow us to refine the microstructure and obtain the martensitic component in the wire.

Modeling occupies a central place in modern science and technology. It allows us to explore complex physical phenomena, predict their behavior and, importantly, develop new technologies or improve existing ones.[10–12]

Computer models are used to develop and optimize the technology of cryogenically cooled wire deformation. The models allow us to study the influence of various process parameters on the structure and properties of the wire (temperature, deformation rate, wire diameter), as well as optimize the technological process.

Modeling plays a special role in materials science. The study of the microstructure of materials, their properties, as well as the processes of their deformation and processing, is the subject of numerous studies, which are often impossible to carry out without the use of computer modeling.

In the world of materials science, where subtle changes in the structure of a material can radically affect its properties, the Deform system acts as a powerful tool for modeling microstructure. Deform provides two key methods for investigating microstructural changes occurring during deformation and heat treatment processes: the classical Johnson-Mehl-Avrami-Kolmogorov (JMAK) method and the discrete-lattice method implemented using the Cellular Automata algorithm.

The JMAK method is a classic approach to microstructure modeling. It relies on the simple but effective assumption that the average grain size varies depending on the initial size, material properties, and processing conditions such as temperature, strain, strain rate, and time. This method, in fact, "averages" information about the microstructure, without taking into account its heterogeneity. Also, JMAK does not take into account the influence of grain shape on the kinetics of its development. Two materials with the same average grain size but different grain shapes will behave differently during heat treatment. The JMAK method is not able to take this important detail into account, making it less accurate when modeling real processes.

To solve the problem related to the shape of the grain, the method of discrete lattices based on the algorithm of cellular automata was introduced in the Deform system. This method, unlike JMAK, presents the microstructure in a more "realistic" way, clearly showing individual grains and their boundaries. Such detailed visualization makes it possible to take into account local changes in geometry that can affect the development of the microstructure. Due to the explicit representation of grains, the discrete-lattice method allows for more accurate data on recrystallization and grain growth.

When modeling using the discrete-lattice method, the key factor is the choice of rules for interaction between neighboring lattice cells representing grains. It is these rules that determine the accuracy of modeling and its ability to reflect the real processes occurring in the material.

The discrete lattice method can be used to simulate changes in the microstructure of the wire at each stage of thermomechanical processing. It allows you to take into account the influence of deformation, temperature, time and other parameters on the size, shape and orientation of the grains.

With the help of modeling, it is possible to optimize the developed process of thermomechanical processing of wire, selecting the most appropriate parameters of deformation, temperature and time to obtain the desired properties of the material. This can increase the strength, ductility and other important properties of the wire.

The novelty of this article is the modeling by JMAK and discrete-lattice methods of the microstructure evolution during a new combined drawing process with cryogenic cooling.

2 EXPERIMENTAL PART

To use this method it is necessary to initially calculate 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 AISI-316 steel. This grain size in this steel can be obtained after quenching at 1050 °C, holding at this temperature for 30 min and cooling in water.

For correct modeling, you need 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 (**Figure 1**). 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 [13,14], 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.

To simulate the microstructure evolution by the Cellular Automata method, a ready-made calculated model with fields of metal flow, temperature, velocities, stresses and deformations is used. The initial grain size is used as

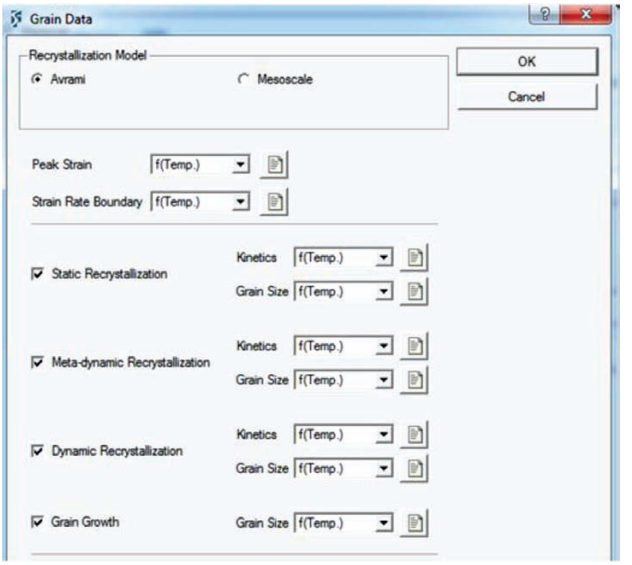

Figure 1: Entering the JMAK model parameters

the initial data for the calculation in this algorithm. Besides that, several coefficients of the model should be introduced, the values of which depend on the nature of the material being processed. These coefficients for steel are shown below:

ρ_i = 0,01 - dislocation density;
ε – strain-rate calibration constant;
r_0 = 7087 - recovery constant;
Q = 266616 - activation energy;
K = 6030 – coefficient depends on the material;
h_0 = 0,75 - hardening constant;
m = 0,2 - sensitivity to hardening.

Taking into account the revealed differences in grain sizes after all the stages of thermomechanical processing when calculated by the JMAK method, it was decided to study the microstructure evolution by Cellular Automata method at two points (on the surface and in the center).

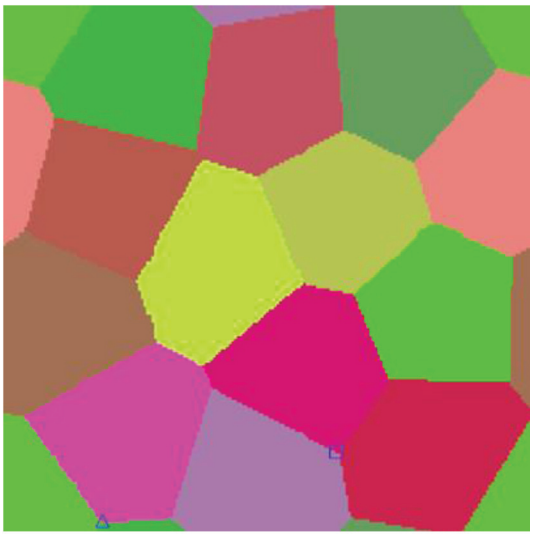

Figure 2: Initial microstructure

The value of 25 μm was taken as the initial grain size. To display the structure during the calculation, the parameters of the window were set to (100 × 100) μm (**Figure 2**).

3 RESULTS

3.1 Modeling by JMAK method

Figure 3 shows the results of the step-by-step structure evolution along the workpiece section for the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece. After the first stage of drawing, the initial grain size is reduced to 15 μm. After the second stage of cryogenic cooling, the grain size decreases

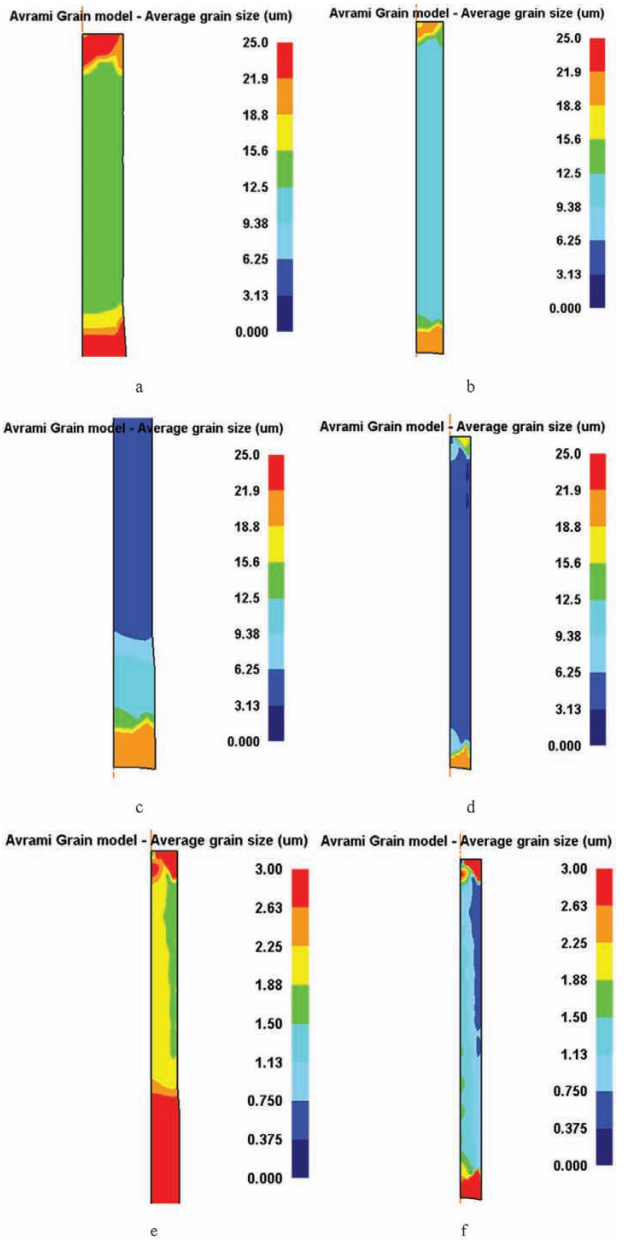

Figure 3: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece

Table 1. Summary results of JMAK microstructure modeling, μm

#	Workpiece	500 mm/s without heating	500 mm/s with heating	1000 mm/s without heating	1000 mm/s with heating
Center	9 mm	1.2	2.2	1.3	2.5
Surface	9 mm	0.6	1.3	0.8	1.5
Center	6 mm	1.0	2.1	1.1	2.3
Surface	6 mm	0.5	1.1	0.7	1.2

to 11 μm approximately. After the third stage of drawing, the grain size decreases to 6 μm approximately. The fourth stage of cryogenic cooling reduces the grain size to 3.7 μm approximately.

Further consideration of the microstructure using the initial scale is not possible, since in this case all possible grain-size changes will be in one color block. Therefore, starting from the fifth stage, a local scale was made with a reduced range of grain size.

After the fifth stage of drawing, the grain size decreases to 2.2 μm in the axial zone of the workpiece and to 1.8 μm in the surface zone. After the sixth stage of cryogenic cooling, the grain size decreases to 0.6 μm on the surface and to 1.2 μm in the workpiece center. After analyzing other models, the results of microstructure changes after all the stages of thermomechanical processing are summarized in **Table 1**.

It can be concluded that both wire sizes are being intensively processed according to the proposed route technology of thermomechanical processing. At the same time, there is a distinct difference in the results with the presence or absence of intermediate heating. Here, the final grain size differs by about 2 times, in the presence of intermediate heating, the final grain size reaches 1.0–1.2 μm, whereas the absence of heating allows the initial grain to be refined to 0.5–0.7 μm. An increase in temperature only slightly reduces the intensity of grain refinement, so this factor cannot be decisive for choosing the kinematic conditions of the process.

2.2 Modeling by Cellular Automata method

Figures 4–9 show the results of modeling the microstructure using Cellular Automata for all stages of the drawing process from 9 mm to 7 mm at 500 mm/s without heating the workpiece.

Comparing the microstructure at each stage between the surface and axial zones, it is possible to note the characteristic elongation of the grains on the surface of the wire after each stage of drawing. After cryogenic cooling and further refinement of the grains, this elongation is reduced due to the formation of new grains without directional metal flow. After calculating all the other

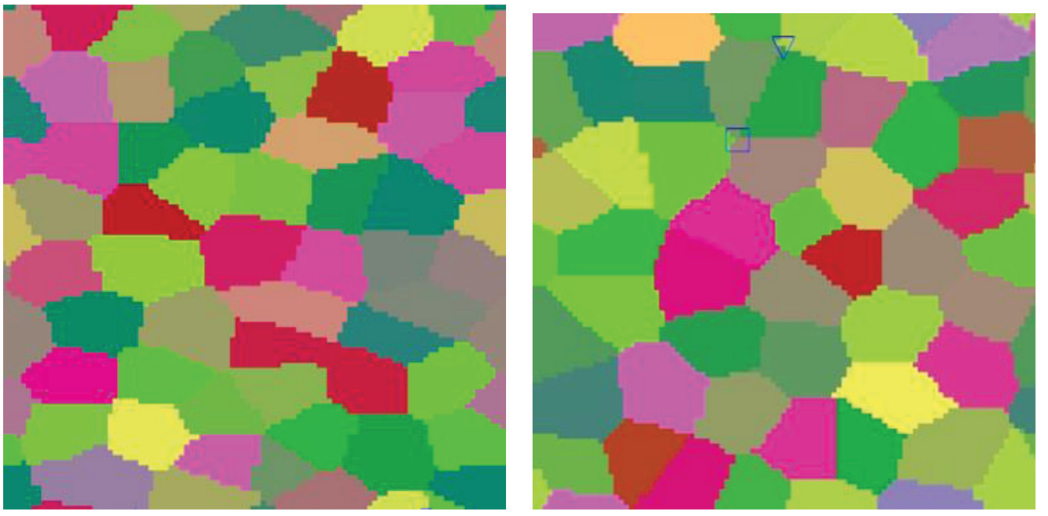

Figure 4: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the first stage of drawing: a – surface, b – center

Table 2: Summary results of microstructure modeling by Cellular Automata method, μm

#	Workpiece	500 mm/s without heating	500 mm/s with heating	1000 mm/s without heating	1000 mm/s with heating
Center	9 mm	0.9	2.0	1.1	2.2
Surface	9 mm	0.6	1.2	0.7	1.4
Center	6 mm	0.9	1.9	1.0	2.2
Surface	6 mm	0.5	1.0	0.7	1.1

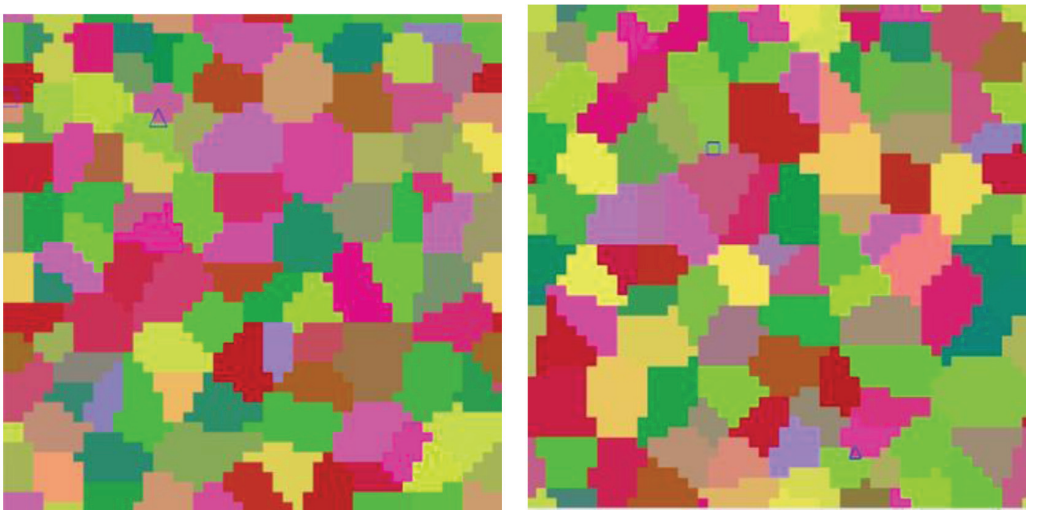

Figure 5: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the second stage of cryogenic cooling: a – surface, b – center

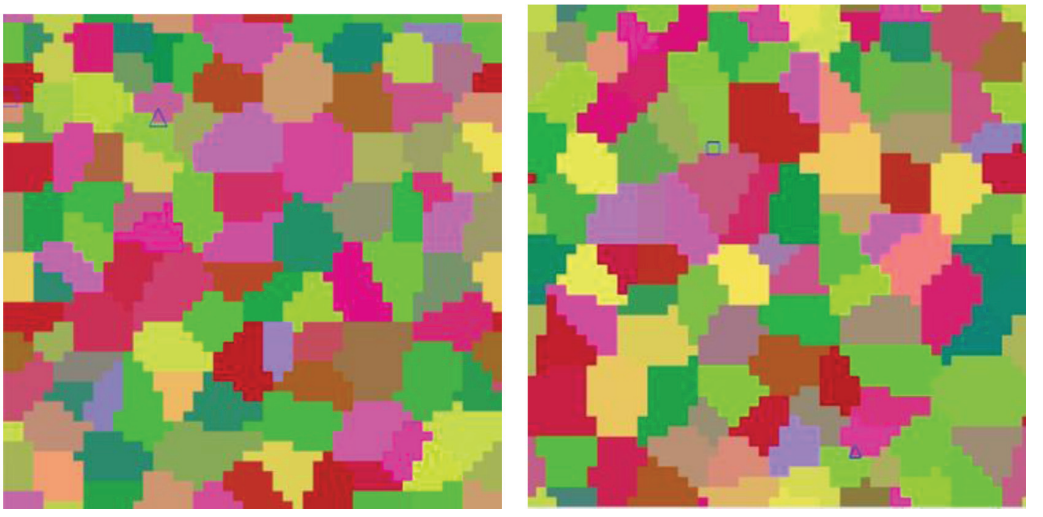

Figure 6: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the third stage of drawing: a – surface, b – center

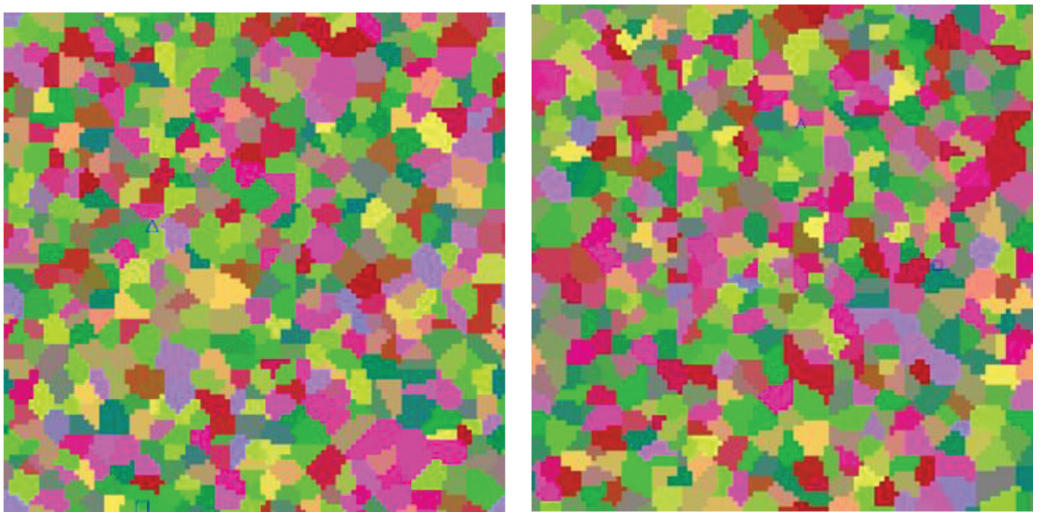

Figure 7: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the second stage of cryogenic cooling: a – surface, b – center

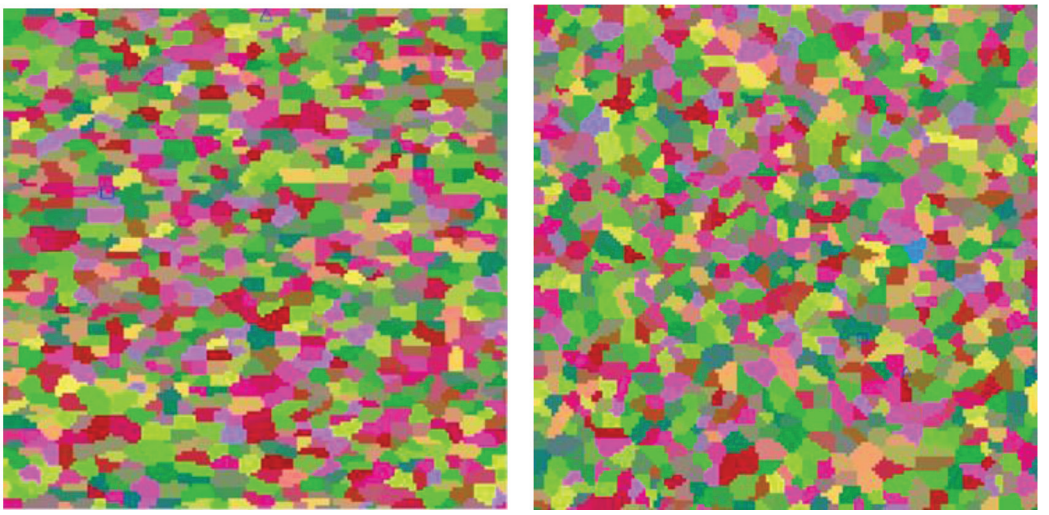

Figure 8: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the fifth stage of drawing: a – surface, b – center

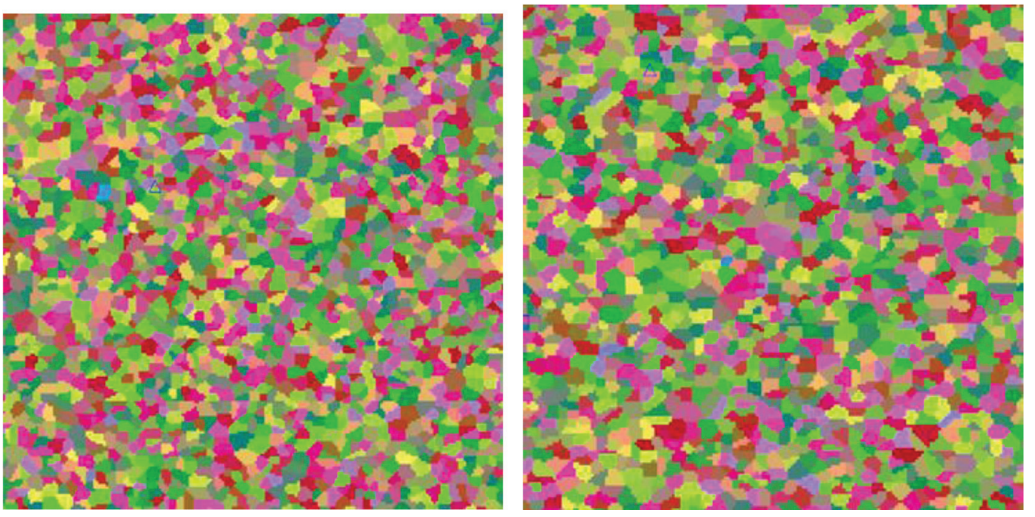

Figure 9: Microstructure in the drawing model from 9 mm to 7 mm at 500 mm/s without heating the workpiece after the sixth stage of cryogenic cooling: a – surface, b – center

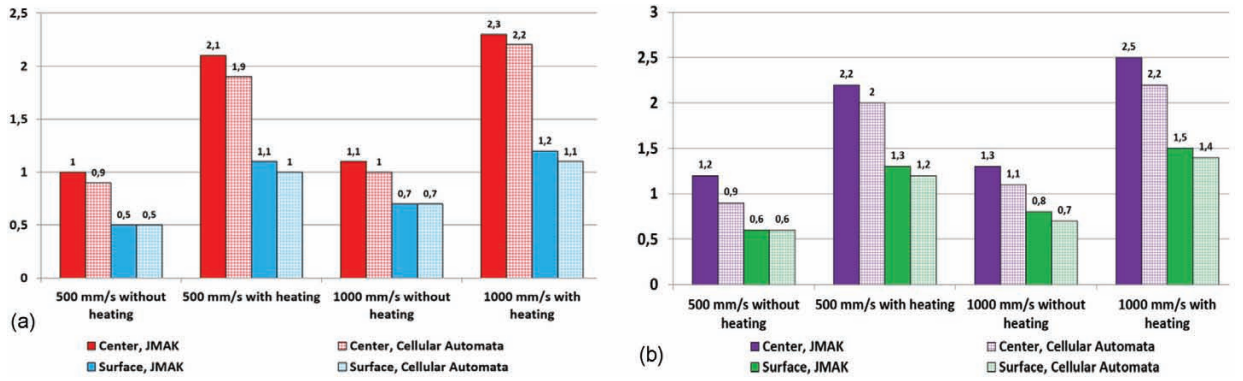

Figure 10: Summary diagrams of the final grain size: a – for workpiece of 6 mm; b – for workpiece of 9 mm

models, all the final results of the microstructure evolution were summarized in **Table 2**.

Comparing the results of the microstructure changes obtained by both methods, it is necessary to note their high convergence in all the models considered. **Figure 10** shows summary diagrams of the final grain size for both billet thicknesses. It can be seen that the results arranged in pairs have almost the same values

4 DISCUSSION

At the same time, the following patterns are clearly visible:

1) in all the considered cases, the grain-size values in the Cellular Automata models are lower than in the JMAK models. This is due to the fact that in addition to the grain size, this method also calculates their shape. During the drawing process, there is some elongation of the grains in the longitudinal direction, which affects the results of measuring the average size.

2) The difference in grain size between the surface and the axial zone is most strongly observed in models with intermediate heating of the workpiece. This is due to the fact that after heating, the entire section of the workpiece has the same temperature and subsequent short-term cooling in liquid nitrogen does not contribute to uniform cooling of the wire section. In models without heating, this difference is much lower.

5 CONCLUSIONS

In this research, finite-element modeling of the microstructure evolution of the combined drawing process with cryogenic cooling by JMAK and Cellular Automata methods was carried out. Analysis of the data on the microstructure evolution allows us to conclude that the most optimal option is a reduced drawing speed and the absence of intermediate heating. At the same time, variants with an increased deformation rate also have fairly good grain-grinding results. At the same time, a significant effect of intermediate heating on the uniformity of refinement of the microstructure was revealed. The inclusion of intermediate heating stages to room temperature in the proposed thermomechanical processing scheme will result in a higher grain-size gradient along the wire section.

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