Table 3. Distribution of twisting moments by layers			
Technique	Residual twisting by layers, rev/6m		Difference in layers, revolutions
	1+6+12	1+6	
With fine twisting of all internal and external lay wires	–0.75	–0.5	0.25
Without fine twisting of internal lay wires	–0.5	+1.5	2
Note: for "Z" lay the sign "+" means spiral unwinding (increase in $D_{res.}$); "–" means spiral winding and N increase (see Figures 1 and 2).			

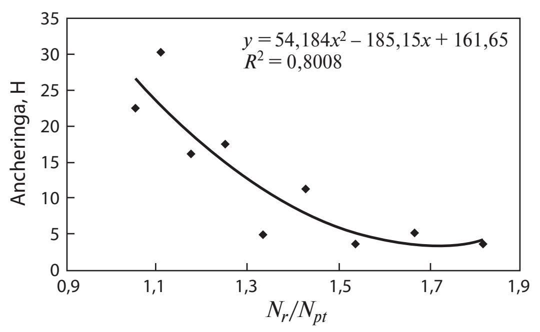

Fig. 5. Dependency of central wire anchorage force on ratio of rotational speed of machine's laying rotor (N_r) to rotation velocity of wire pre-twister (N_{pt})

Based on the above mentioned information, the following conclusions can be made:

1. It is possible to use various technological methods to control migration tendency of steel cord central layers in the course of steel cord production.

2. The main reason for reduction of central structures anchorage is weakening of external lay wires under the effect of compressive stresses in wire.

3. Squeezing moment of elastic come-back on steel cord central structures from external lay wires can be produced through obtainment of optimum difference in tensions and residual torques with the use of fine twisting in rotary unwinding.

This problem is of particular actual importance for the manufacture of steel cord out of wire with strength level 3800–4200 MPa.

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On new mathematics methods in the analysis of microstructures of eutectoid colonies in pearlitic steels

The paper describes an algorithm for the mathematical description of microstructures of pearlitic steels. The purpose of this work is the development of a method for mathematical description of the microstructures in pearlitic steels for their quantification. It is proves the fact that the mathematical models of microstructures, developed using the frequency distribution of eutectoid colonies in pearlitic steels depending on interlamellar distances, allow estimating the degree of heterogeneity of a microstructure. It is known that microstructures of pearlitic steels, obtained under non-equilibrium conditions, consist of eutectoid colonies formed after decomposition of austenite and incoherently distributed in the plane of the section. At the same time, in different parts of microstructure, the sizes of interlamellar distances of "ferrite-cementite" system can differ by several times. In these circumstances, establishment of relationships between the characteristics of microstructure and steel properties is virtually impossible, if using the traditional approaches based on qualitative analysis of microstructure. Simple averaging of microstructure parameters equalizes structural features of eutectoid colonies and the study of relationship between the properties of steel and its *microstructure parameters becomes even more complicated. At the same time, today's computer-based image processing techniques open up new possibilities for analyzing the relationship "structure-properties".*

Key words: *microstructure, pearlitic steels, mathematical methods, eutectoid colonies, ferrite, cementite, austenite, mechanical properties, qualitative analysis.*

Analysis of the published data on treatment of alloy microstructure shows that the term "mathematical model of microstructure" is not a generally accepted one. This is due to the fact that microstructures of alloys in metallurgy and metal physics are still treated via traditional methods. That is, they are used to estimate the intergranular grains, size and shape of the phases. Moreover, this information tends to be qualitative. Magazine pages often demonstrate non-equilibrium microstructures containing grains with several times difference in size. And at the same time, the authors try to explain alloy properties by variations of the grain structure without providing the calculations of the uncertainty in determining the area of the grain.

It is well known that "the image of microstructure" contains much more information than the one traditionally used by metallurgists in their researches. Therefore, the main problem in the use of modern methods of treatment of the microstructure is to replace "image of microstructure" with a set of quantitative parameters.

Let's consider the definition of a mathematical model. Mathematical model is a mental representation and the material implemented system that, displaying or making an object of research, is able to replace it so that its examination provides new information about the object [1–9]. Modeling as a research method is based on the substitution of a certain object (sample) into other one similar (model). In this case we are talking about replacing the image of microstructure into the mathematical model, which reflects the basic properties of the image of the phase components. As the main property of the mathematical model of microstructure, this paper selects interlamellar distance of eutectoid colonies.

Thus, the essence of the proposed approach lies in the fact that the image of the microstructure is replaced by a mathematical model (functional dependency), which represents properties of the studied microstructure. Such property in this case is the interlamellar distance of spatially distributed eutectoid colonies of pearlite — "ferrite-cementite". To develop a mathematical description of microstructures, the following structural and logic processing model for microstructures, shown in **Fig. 1**, is proposed.

As it can be seen from this figure, in the first phase for the microstructure, the dependence of the number of elements of eutectoid colony on the size of interlamellar distance $N(d_{il})$ can be found. In the next step the parameters of the mathematical model as a function of $N(d_{il})$, which characterize the main features of alterations in the eutectic colonies along the micro-section, are introduced.

Fig. 2 shows an enlarged processing algorithm of image of pearlitic steel microstructure used to develop a mathematical model. Algorithm for computer processing of the microstructure consists of the following stages: image binarization with the selected threshold; recognition of lines in the image; calculation of the

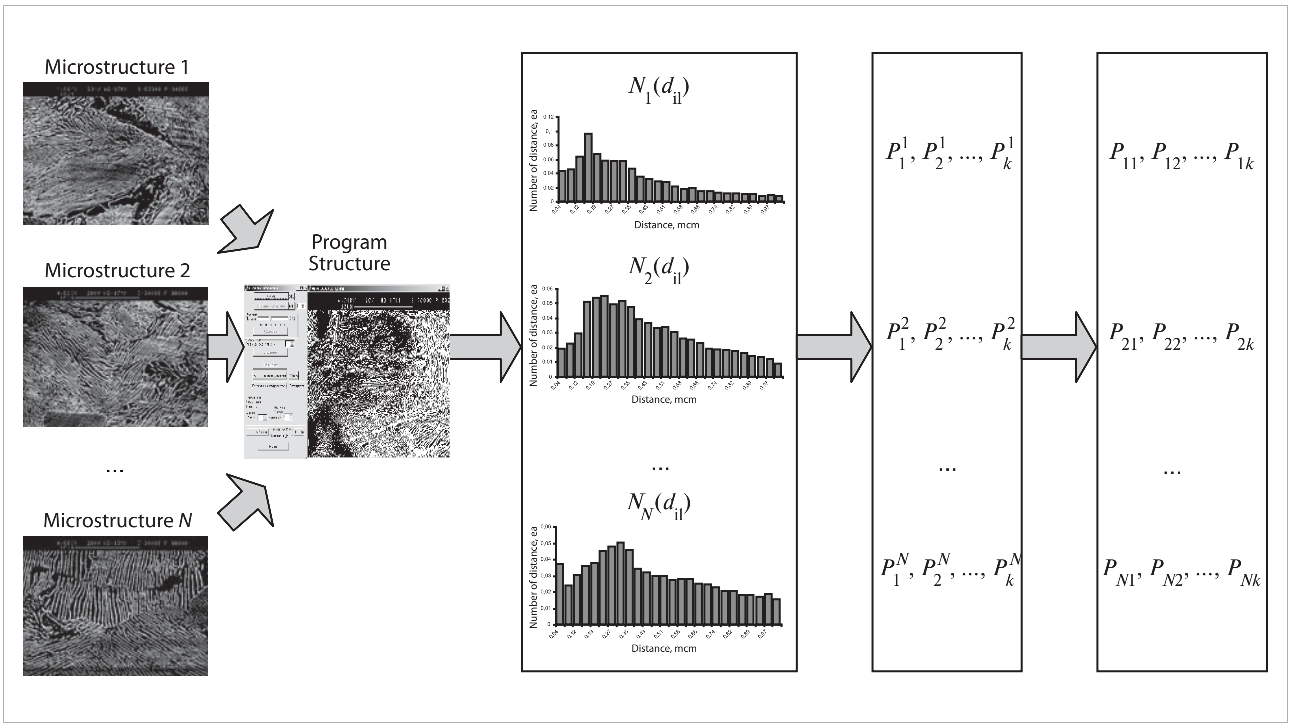

Fig. 1. Stages of developing mathematical model to describe pearlitic steel microstructure

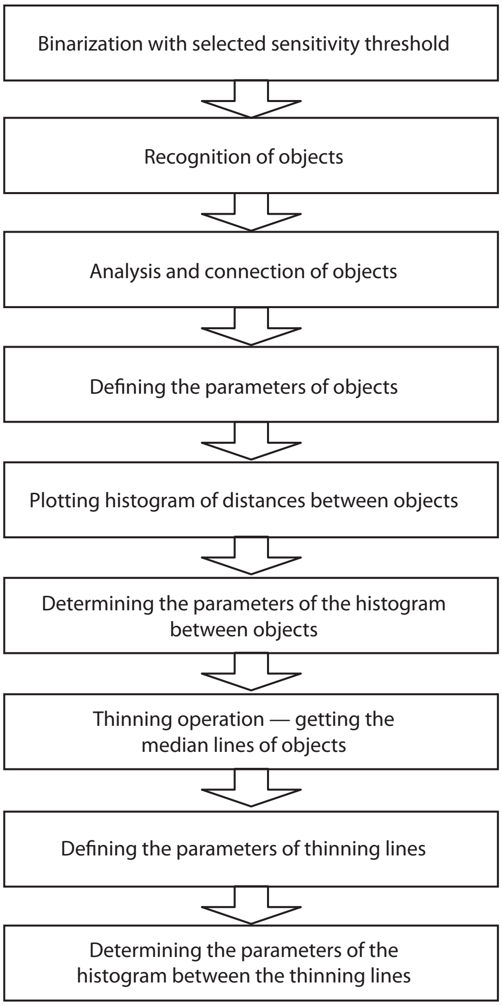

Fig. 2. Algorithm for computer processing of the microstructure in order to obtain its mathematical model

number of perpendicular lines between pearlite lines; drawing a histogram for distribution of interlamellar distances for the structure as a whole; thinning operation of recognized lines of the image, calculation of the perpendicular lines between the thinning lines; development of a mathematical model as a histogram for distribution of interlamellar distances between thinning lines throughout the microstructure.

In order to generate such mathematical model, microstructures of pearlitic steel wire rod obtained at Byelorussian Steel Works have been used. **Fig. 3** shows microstructures, taken from different parts of the sample and corresponding to one heat of steel grade 80.

For each of these microstructures functional dependencies of the form $N = F(d_{il})$, which are constructed in **Fig. 4** have been calculated using the algorithm shown in Fig. 2. To investigate stability of the mathematical model of the pearlitic steel microstruc-

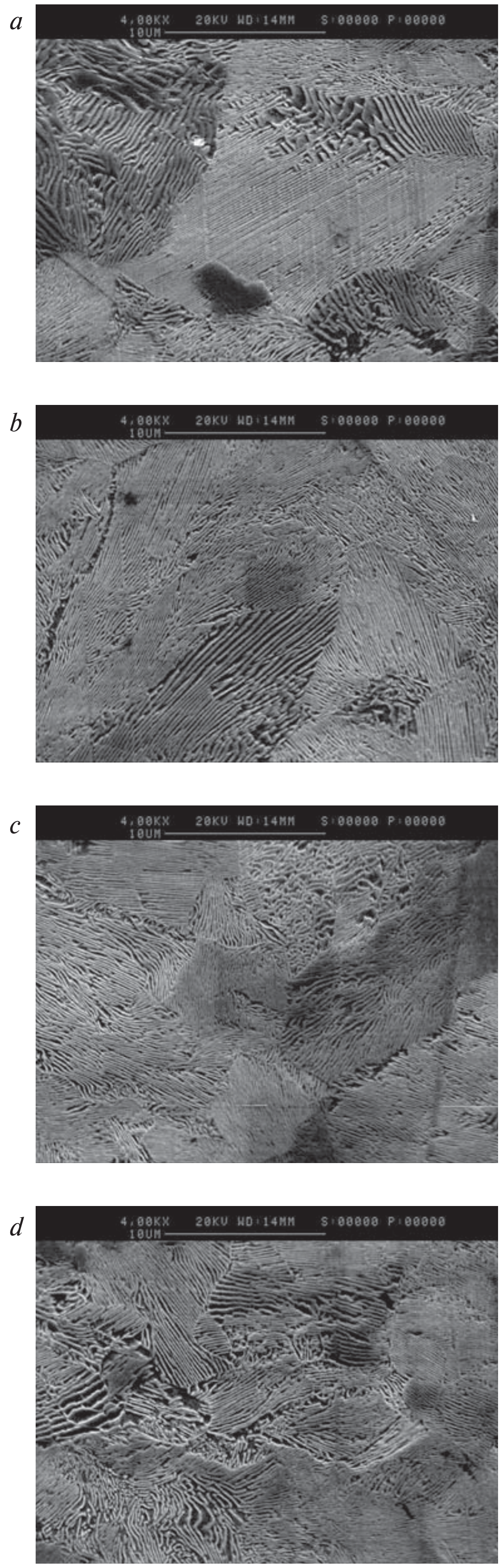

Fig. 3. Photographs of microstructures (*a*–*d*) for melting 1 of sample 4

ture, the confidence interval for four micrographs (**Fig. 5**) has been calculated. As the figure shows, the scatter of characteristics of eutectoid colony interlamellar distances is structured in the range, which does not exceed 3.5%. This indicates satisfactory mathematical description of the microstructure and the possibility of its use for practical purposes.

Results obtained in the present study can be used to address specific applied problems. In the industrial production at Byelorussian Steel Works, in the process of drawing bead wire was made from wire rods. And one of the defects of this wire is a defect of compacting crack type, which manifests itself in the emergence of a break in the form of a spiral or a step. In the process of production of wire rod, pearlite steel microstructure is investigated and interlamellar distance is determined. And at the same time, microstructures of wire rod, which is used to get a bead wire, is indistinguishable at the qualitative level. Therefore, using the wire rod with virtually the same microstructure it is possible to obtain bead wire, which might has or has not a defect of compacting crack type. In this case, the question arises: whether the microstructure of wire rod, used to make the wire, is homogeneous and in what extent?

Mathematical modeling methods, developed in the present paper, allow us to solve problems of this kind. To illustrate this problem at Byelorussian Steel Works, sampling of microstructures from two versions of wire rods, has been carried out; these wire rods are later used to produce bead wire. The first version of wire rod (conventionally denoted as wire rod A) inherits microstructure in which later manufactured bead wire does not manifest a defect of the compacting crack type. The second group of wire rod (conventionally denoted as wire rod B) inherits the microstructure of pearlitic steel which, after manufacturing bead wire using such raw material, forms a defect of the compacting crack type.

Analysis of the compacting crack defect on the basis of the traditional microstructural analysis showed that microstructures of the wire rod samples, with the defect of compacting crack type occurred and not occurred, are virtually indistinguishable, and that there are no visible changes in microstructure. However, computer analysis, conducted with the aim of processing images of type A and B wire rod microstructures, generating and not generating compacting crack defect, showed that the mathematical models of these microstructures are different. Therefore, microstructures of wire rod, generating and not generating compacting crack defect, may be divided into two classes. The first class includes wire rod microstructures resulting in a compacting crack, the second class includes wire rod microstructures, which do not lead to a compacting crack.

For each of the selected microstructures of wire rod attributed to contingent classes A or B, frequency distributions on the basis of interlamellar distances have been calculated. **Fig. 6** shows the mathematical models (frequency distributions depending on interlamellar distances) for microstructures of wire rod class A, which does not lead to the formation of compacting crack defect. **Fig. 7** displays the mathematical models (frequency distributions depending on interlamellar distances) for microstructures of wire rod class B, which lead to the formation of compacting crack defect.

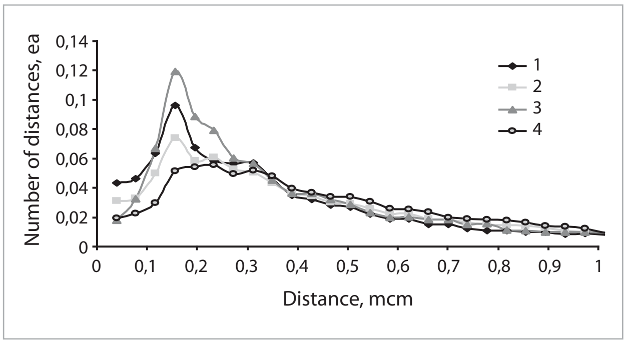

Fig. 4. Frequency distribution of eutectoid colonies share through the interlamellar distance for microstructure (1–4) of sample 4 in heat 1 from Byelorussian Steel Works

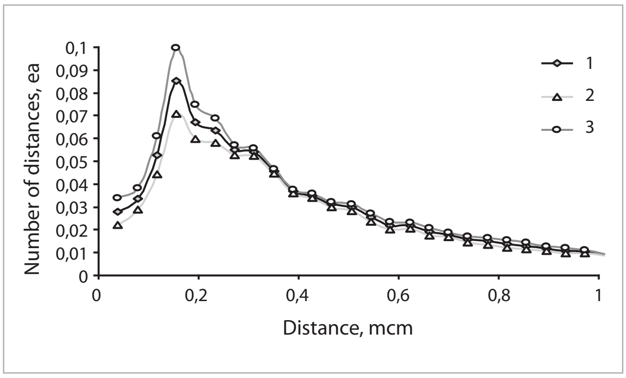

Fig. 5. Frequency distribution of eutectoid colonies share through the interlamellar distance for microstructure (1–3) of sample 4 in heat 1 from Byelorussian Steel Works:
1 — average value of eutectoid colonies characteristics, calculated from the microstructures (fig. 3, *a—d*); 2 — lower value of eutectoid colonies share in the microstructure; 3 — upper value of eutectoid colonies share in the microstructure

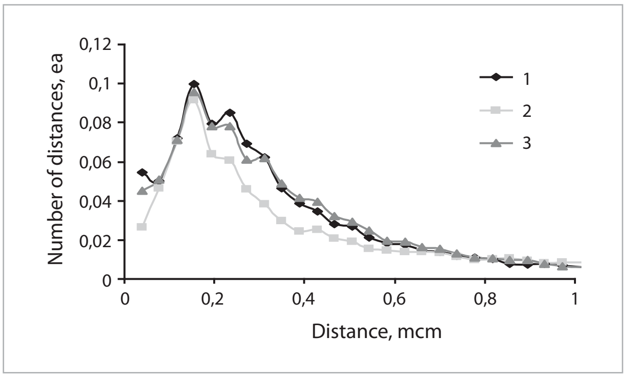

Fig. 6. Frequency distribution of eutectoid colonies share according to interlamellar distance for the three microstructures (1–3) of wire rod inheriting the microstructure not resulting in the formation of compacting crack defect in bead wire

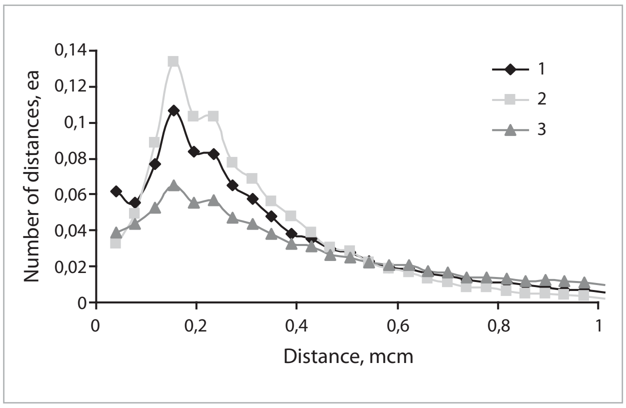

Fig. 7. Distribution of eutectoid colonies share according to interlamellar distance for the three microstructures (1, 2, 3) of wire rod inheriting the microstructure resulting in the formation of compacting crack defect in bead wire

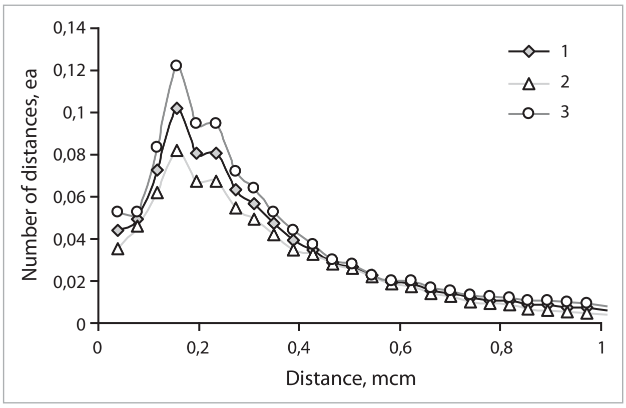

Fig. 9. Calculated curve for distribution with confidence interval of eutectoid colonies share according to interlamellar distance for three microstructures of wire rod inheriting microstructure resulting in the formation of "compacting crack" defect in bead wire:
1 — averaged distribution; 2 — low limit of the distribution confidence interval; 3 — high limit of the distribution confidence interval

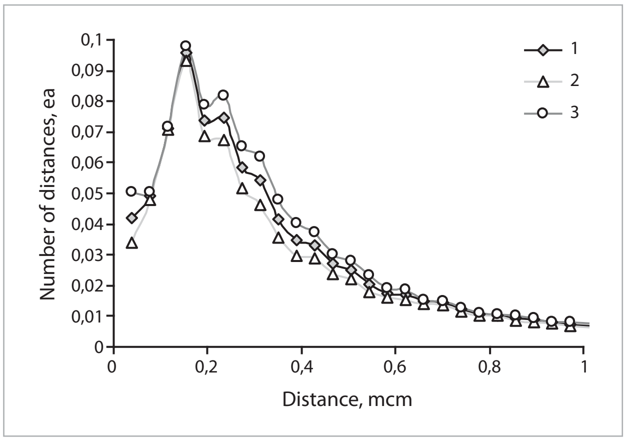

Fig. 8. Calculated curve for distribution with confidence interval of eutectoid colonies share according to interlamellar distance for the three microstructures of wire rod inheriting the microstructure not resulting in the formation of compacting crack defect in bead wire:
1 — averaged distribution; 2 — low limit of the distribution confidence interval; 3 — high limit of the distribution confidence interval

In order to conduct a comparative analysis of microstructures, the next stage included calculation for microstructures (Fig. 6, 7) of mean frequency distributions depending on interlamellar distances on the basis of three frequency curves. **Fig. 8** and **9** show averaged mathematical models of microstructures with the calculated confidence intervals for wire rod, leading and not leading to compacting crack defect. By comparing the calculated confidence intervals, one can conclude that microstructure of wire rod, which leads to compacting crack defect, has greater spread of frequency characteristics for eutectoid colonies on the basis of interlamellar distances than the wire rod, which does not lead to compacting crack defect. These results may reflect the fact that wire rod of class A inherited microstructure which does not result in a compacting crack defect, has more uniform distribution in terms of the interlamellar distances of eutectoid colonies in steel, than wire rod of class B, which leads to a compacting crack defect.

As seen from the distributions shown, the comparative analysis of the frequency distributions of eutectoid colonies allows evaluating the degree of inhomogeneity of steel microstructures.

Thus, presented mathematical approach to the study of microstructures of steels can be used in solving the applied problems of metal science — in identifying the quantitative particularities in variations of the characteristics of the microstructure, which is has theoretical and practical importance for the steel making industry.

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Prediction of dendritic micro-heterogeneity of cast steel: review of models and computer-aided analysis of problems (Part 1. Models based on thermal-physical parameters)

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The paper reviews the publications concerning dependence of dendrite arm spacings of iron-based industrial alloys from the conditions of solidification. It was noted that the used thermal parameters which characterize the conditions of dendrite formation — the rate of solidification, the temperature gradient and the cooling rate — quite often are determined with significant experimental errors, are estimated on the basis of approximate relationships and often mutually correlated. It was established that the published empirical power-type models of dendrite arm spacing for carbon and low-alloy steels are characterized by a lot of the types of the parameters- predictors and by scatters of their values, do not consider the effect of the alloys composition and slightly suitable for prediction of the dendritic structure. For objective assessment of uncertainties arising from the use of insufficiently large data sets and simplified method of estimation for model parameters the procedures of statistical analysis of the models adequacy for their correction and/or rejection were proposed.

The comparison of results of computer modeling for a steel slabs (250 mm thickness) with 0.006, 0.06 and 0.6% C are used for analysis the evolution during solidification of the rate of crystallization and the temperature gradient under various intensity of heat extraction and natural convection of the melt. It was deduced that a radical increase in the accuracy of the analysis of the conditions of formation of the dendritic structure is provided using a developed computer model of the non-equilibrium solidification of ingots and castings on the base the thermal properties of alloys, determined by means of thermodynamic modeling, with obligatory taking into account the intense convective heat transfer in the melt.

Key words: *carbon and low-alloy steel, dendritic structure, dendrite arm spacing, empirical power-type models, computer modeling, non-equilibrium crystallization.*

Setting of the problem. Multiple publications devoted to investigation of dendrite microstructure of iron-base industrial alloys [1–22 et al.], including recent review papers [11, 19, 20], contain large data about values of primary λ_1 and secondary λ_2 dendrite arm spacings as well as their relationships depending on different metallurgical and technological factors. Such attention to parameters of structural micro-heterogeneity of steel is caused by their substantial effect of forming defects of cast metal (such as dendrite segregation, gas and/or shrinkage porosity, hot cracks etc.) and by corresponding mechanical properties of deformed metal. The stream of publications describing this theme, started in 1960-ies and continuing at present time, is caused evidently not only by its importance, but also (last but not least) by exclusive complication of the observed appearances occurring during crystallization of multicomponent industrial alloys, in combination with difficulty of experimental works at increased temperatures. As a result, the analysis of the processes of dendritic crystallization does not allow yet to reveal the causes of some of the observed contradictions and to get substantiated answer on the key theoretical and practical questions in the field of quality forming of cast metal.

Confident technological forecast of dendritic microstructure in the steel with preset composition, as well as synthesis of alloys with required structure need high-quality mathematical models in combination with reliably established scientific regulations, describing comparative effect of steel components on the values of λ_1 and λ_2; this information is now rather approximate and is characterized by apparent contradiction. Local heterogeneity of dendritic structure plays an important role in forming the quality of cast metal and had not any adequate quantitative description until today. It is important to have adequate calculated relationships in