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DEVELOPMENT OF FAST SPHEROIDIZING ANNEALING MODES AND MODELING OF THE INTENSIFICATION PROCESS OF CEMENTITE SPHEROIDIZATION OF LOW-CARBON STEELS

The object of research is the process of cementite spheroidization of 20Г2Р low-carbon steel during heat treatment, in particular spheroidizing annealing.

Special attention in conducting research is paid to the influence of the initial structural state of the steel, temperature regimes and heating methods on the formation of the microstructure of the workpiece.

Traditional methods of spheroidizing annealing are characterized by a significant duration of the regime, which reaches more than 10 hours and, in connection with this, energy costs, which limits the efficiency of the technological process. This is especially true for low-carbon steels with a relatively weak thermodynamic stimulus for spheroidization.

The research problem is the need to reduce the duration of spheroidizing annealing of steel and reduce energy costs while ensuring a uniform distribution of cementite globules in the ferrite matrix.

The scientific novelty of the obtained results lies in the development of high-speed regimes of spheroidizing annealing of 20Г2Р steel using the initial ferritic-bainite structure and non-isothermal holding with increasing temperature, in contrast to known studies based on long isothermal holdings. It is shown that the total duration of spheroidizing annealing of low-carbon steels significantly depends on the initial structural state of the workpiece. It is established that the transition from ferritic-pearlitic to ferritic-bainite initial structural state provides a reduction in the duration of cementite spheroidization from 1500–1800 s to 200–450 s.

The features of the intensification of spheroidizing annealing of low-carbon steels have been studied and the influence of changes in the values of thermodynamic and kinetic factors during structural transformation has been established. The effectiveness of using non-isothermal holding with increasing temperature in a certain temperature range and optimization of spheroidizing treatment parameters has been proven.

The practical significance of the results obtained lies in the implementation of the developed high-speed modes of spheroidizing annealing of 20Г2Р low-carbon steel for the production of coiled strip and wire with a diameter of 6.0–20.0 mm. The obtained structural states of the blanks provide the necessary set of properties for the subsequent manufacture of metal products by cold drawing, in particular products of complex configuration. The proposed approaches are fully suitable and meet the requirements for technological and mechanical properties of blanks for the manufacture of metal products by cold drawing.

Keywords: *spheroidization, thermodynamics, kinetics, structural transformations, non-isothermal holding, microstructure, process modeling.*

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1. Introduction

The complex of technological properties of heterophase alloys is largely determined by the structural state, in this case, the morphology of the microstructure, which is provided by heat treatment. In this case, the size, shape and number of excess phase particles (EPP) per unit volume of the matrix can have a decisive impact on the technological and operational properties of the alloy [1]. From the point of view of thermodynamics, the equilibrium form of EPP is usually their spherical shape or a shape close to spherical, since the value of the specific area of the interphase boundaries is minimal [2].

The production practice of using heterophase alloys shows that the requirements for the EPP shape and its thermodynamic stability can be different. In some cases, for example, during cold drawing of steels, the EPP non-equilibrium form will be favorable for the corresponding properties of the heterophase alloy. Therefore, it is this EPP form that should be made the most thermodynamically stable and the speed of the process of obtaining the granular pearlite structure should be slowed down as much as possible.

In other cases, the spherical shape of the EPP is optimal. For example, in the case of cold heading, the necessary technological plasticity is provided by the EPP spherical morphology. Therefore, in this case, it is necessary to stimulate the spheroidization process and accelerate it as much as possible under the condition of appropriate processing. Therefore, steel billets intended for the production of metal products by cold heading are subjected to spheroidizing annealing, which is carried out in furnaces with a long duration of the regime and is characterized by significant energy consumption [3].

A reduction in the duration of spheroidizing annealing using furnace heating was achieved by using a heat treatment scheme with partial phase recrystallization, i.e. by special preparation of the workpiece structure [2, 4]. The specified preparation of the structure for annealing was carried out either by accelerated cooling of austenite (reducing the austenite decomposition temperature) or by thermal deformation.

Promising for the intensification of the spheroidizing annealing process is the use of electric contact or induction heating, i. e. heating with an "internal" coolant [3, 5]. The specified methods of heat treatment allow:

- to implement heat treatment in automated flow lines;
- to significantly reduce oxidation and practically eliminate decarburization of steel;
- to significantly reduce the duration of spheroidizing annealing [5, 6].

The use of an internal coolant is used in flow line-type units only to intensify the heating of the metal to the appropriate temperatures. However, the temperature regimes that ensure the actual cementite spheroidization in steel are carried out in furnaces.

Therefore, the problem of improving the methods of spheroidizing annealing of low-carbon steels requires the identification and use of new directions for intensification of cementite spheroidization. The directions of intensification should be based on achieving a new structural state of the workpiece before annealing. In addition, the result of research in the areas of intensification should be the development of new modes of high-speed spheroidizing processing.

It is known [5] that the electrothermal method of processing metal products is characterized by a high heating rate due to the influence of electromagnetic induction (induction heating) or electrical resistance (electrical contact heating). In the works [3, 5, 6], the possibility of obtaining intensification of the spheroidizing annealing process using electrothermal treatment with preliminary preparation of a regulated structure of the workpiece is shown. In the indicated works, the "technological contribution" of electrothermal treatment to the intensification of the process is shown based on the application of the effect of an intensive growing process of nucleation of new grains [7]. The indicated effect is realized due to a local increase in temperature in microregions near the ferrite/cementite interface, i. e. precisely where the diffusion rate of components is crucial for the structural transformation under consideration.

The indicated works do not take into account the influence of the thermodynamic factor in the process of cementite spheroidization on the duration of heat treatment of steels. Also, the issues of analytical studies of the increase in the rate of cementite spheroidization under the regime of non-isothermal holding with increasing temperature are not considered. In addition, the modeling processes to explain the fact of the increase in the rate of spheroidization during local temperature increase were not considered at all.

To determine the directions of intensification of the spheroidization process, it is necessary to take into account the features of spheroidizing annealing of low-carbon steels. For pre-eutectoid and eutectoid steels on the isothermal diagram of the structural state above the point Ac1 there is almost no region of stable existence of the carbide phase. In these steels, under traditional annealing regimes, there is a very narrow temperature interval upon heating to which the required number of carbides of granular morphology of the required size is formed and retained for some time. Due to the small volume fraction of cementite, the thermodynamic stimulus of the spheroidization process is of relatively small importance.

The next feature of spheroidizing annealing of low-carbon steels is ensuring a uniform distribution of cementite globules in the ferrite matrix. The unevenness of the structure of the workpiece during cold-setting will lead to the localization of deformation and the possible formation of ductile cracks due to the high loading rate and the complex stress state of the metal. Therefore, an important stage in determining the direction of intensification of cementite spheroidization in low-carbon steels is the preparation of the structural state of the steel workpiece preceding annealing. At this stage, the requirements for the structure of these steels after annealing regarding the distribution of cementite globules in the ferrite matrix must be taken into account.

The feature of the intensification of the process of spheroidizing annealing of low-carbon steels necessitates the consideration of the temperature regimes that ensure the actual cementite spheroidization. The used temperature ranges of the spheroidization regime should take into account the peculiarities of changes in the values of thermodynamic and kinetic factors in the process of development of structural transformations. Therefore, studying the influence of the initial structural state taking into account changes in the values of thermodynamic and kinetic factors in the process of development of structural transformations will allow for a significant increase in the efficiency of heat treatment of low-carbon steels.

Thus, the growing requirements for the quality of the workpiece, which is intended for further cold deformation, in particular, for its plasticity and structural uniformity, actualize the need to improve the processes of forming the microstructure of steel during heat treatment. Taking this into account, it can be noted that the development of methods for intensifying the cementite spheroidization and optimizing the temperature regimes of heat treatment appear as important tasks of modern materials science.

The object of research is the process of cementite spheroidization in low-carbon steels during heat treatment, in particular spheroidizing annealing.

The aim of research is to develop steel structure formation regimes based on a combination of thermodynamic and kinetic factors that determine the rate of cementite spheroidization, as well as modeling the processes of intensification of spheroidizing annealing of low-carbon steels.

To achieve the above aim, it is necessary to perform the following objectives:

1. Conduct microstructural studies of samples and investigate the influence of spheroidizing annealing regimes with different initial structural states on the final structure of 20Г2Р steel.
2. Develop parameters of the high-speed regime of spheroidizing annealing of 20Г2Р steel.
3. Based on computer modeling, investigate the influence of thermodynamic and kinetic factors of intensification of cementite spheroidization on the speed and efficiency of structural transformations during spheroidizing annealing of steel.

2. Materials and Methods

As a material for conducting research to study the processes of structure formation, samples from an industrial batch of wire rod with a diameter of 6.5 mm made of low-carbon steel grade 20Г2Р were used. The chemical composition of the steel, given in Table 1, corresponds to the standard DSTU 3684-98 [8].

Table 1

Chemical composition of 20Г2Р steel

Mass fraction of main elements, % by mass										
C	Si	Mn	Al	Ti	S	P	Cr	Cu	B	N
0.20	0.26	1.20	0.04	0.04	0.011	0.026	0.20	0.04	0.003	0.0095

Metallographic analysis was performed on an optical microscope NEOPHOT 21 (Carl Zeiss Jena, Germany). Light microscopy used magnification in the range of 100–500 times. Phase transformations after heat treatment of samples were studied by differential thermal analysis (DTA) [9]. DTA is used to study the processes of structure formation taking into account the specific chemical composition of steel. In modern conditions, this method is an effective tool for developing new modes of spheroidizing annealing of 20Г2Р steel. The study of the microstructure of the samples was carried out by analogy with the works [10, 11] with sections made using the standard method.

The temperature of the samples was controlled using a pyrometer "Mikron M90-0" (Micron Instruments, Inc, USA). Temperature registration by DTA was carried out by a potentiometer KSP-4 (PJSC "Lvivprilad", Ukraine). The temperature difference by DTA was recorded by a two-coordinate self-recorder PDP-4-002 with a digital ADC module ("ASTMA-PRYLAD", Ukraine).

To model the process of cementite spheroidization intensification, the Python programming language [12] was used as a universal tool for numerical calculations and computer modeling of physical and metallurgical processes.

The NumPy library played a key role in the implementation of computational procedures, which provided effective work with multidimensional arrays and high-performance mathematical calculations. It was used to form model variables (for example, spheroidization rate, annealing temperature), and to calculate functional dependencies describing the evolution of thermodynamic and kinetic factors in the process of cementite spheroidization. Thus, NumPy served as a basic tool for generating and processing numerical data.

For graphical interpretation of the results, the Matplotlib library was used, in particular its pyplot (PLT) module. It provided the construction of dependence curves, the design of coordinate axes, the addition of legends, a grid and other visualization elements.

Thus, the NumPy library performed the function of the computational core of the model, while the Matplotlib library provided its graphical representation. The combined use of these libraries allowed not only to study the complex physical processes of cementite spheroidization, but also to give them an intuitive form for further analysis.

3. Results and Discussion

3.1. Research of the microstructure of samples and the influence of spheroidizing annealing modes on the final structure of 20Г2Р steel

The type of structure of the blanks is determined by constructing thermokinetic diagrams of the decomposition of supercooled austenite at certain cooling rates [9, 10]. The research results of the kinetics of the decomposition of deformed austenite allow to obtain the quantitative content of structural components and determine the parameters of the optimal heat treatment modes.

Analysis of the constructed thermokinetic diagrams allowed to identify the following transformation regions: ferritic, pearlitic, bainite, martensitic. In the process of cooling samples at rates of 0.3–120°C/s, the decomposition of austenite occurs according to different mechanisms: in the temperature range of 660–580°C, pearlite with a ferrite component is formed, at temperatures of 400–550°C, the formation of structures of an intermediate type – bainite occurs. Three types of the initial structure were distinguished (Fig. 1).

For a well-founded choice of a rational heat treatment regime, experimental studies were conducted to study the possibility of obtaining the required set of properties (as well as the structure) during high-speed annealing of the studied metal with different initial structures. The research of control samples was carried out according to a scheme that involves partial phase recrystallization during heating of the steel during annealing in the intercritical temperature range, which ensures incomplete dissolution of the structural components (bainite or pearlite) [13, 14]. This allows during further subcritical holding either to intensify the spheroidization processes (by coagulation of carbide particles that have not yet dissolved [15]), or to cause the preferential separation of spherical carbides on the finished substrates – clusters.

The main principle schemes of spheroidizing annealing of a 20Г2Р steel roll provided for the following operations:

- heating to different temperatures in the intercritical interval;
- isothermal holding of different durations for partial or complete dissolution of the second phase;
- regulated cooling to the subcritical temperature interval and isothermal holding of different durations.

Fig. 2 shows the principle schemes of high-speed spheroidizing annealing with the corresponding results of microstructural studies.

The critical points of 20Г2Р steel of the specified chemical composition correspond to the temperatures: $Ac_1 = 720$°C; $Ac_3 = 855$°C [10, 11].

Based on experimental studies, data were obtained on the parameters of each specified mode (Fig. 2) of spheroidizing annealing of 20Г2Р steel. The duration of isothermal holding in combination with the corresponding values of subcritical temperature intervals were determined for each mode with the corresponding initial structural state based on the fact of obtaining granular pearlite of not less than 80% in the final structure.

The conducted studies have established that, other things being equal (electrical contact heating), the duration of the cementite spheroidization process is reduced from 1800 s to 1300–1500 s and 450–600 s, respectively, upon transition from ferrite-pearlite (Fig. 2, *a*) to ferrite-pearlite-bainite (Fig. 2, *b*) and to ferrite-bainite (Fig. 2, *c*) structure. At the same time, according to the results of microstructural studies, it is possible to see that the most uniform distribution of cementite grains was obtained on samples with the initial ferrite-bainite structure (Fig. 2, *c*).

The conducted microstructural studies of 20Г2Р steel have shown the decisive influence of the initial structural state on the final morphology of cementite after spheroidizing annealing. Comparative evaluation of the results of studies on structure formation showed that preliminary preparation of the workpiece structure ensures a uniform distribution of cementite globules in the ferrite matrix. This contributes to increasing the plasticity of the metal, therefore, the further direction of research should be the development of rational regimes of spheroidizing annealing of low-carbon steels.

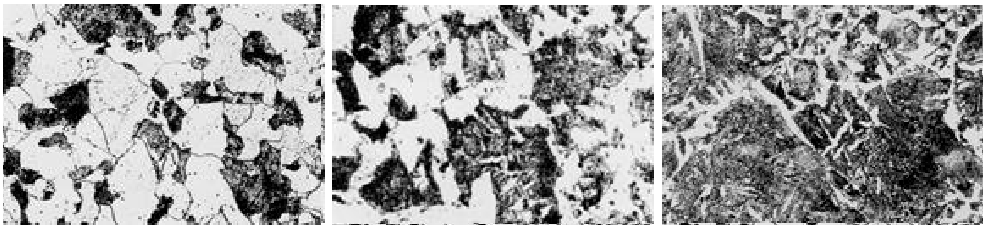

a *b* *c*

Fig. 1. Microstructure of samples of 20Г2Р steel with the initial structure, ×500: *a* – ferritic-pearlitic; *b* – ferritic-pearlitic-bainite; *c* – ferritic-bainite

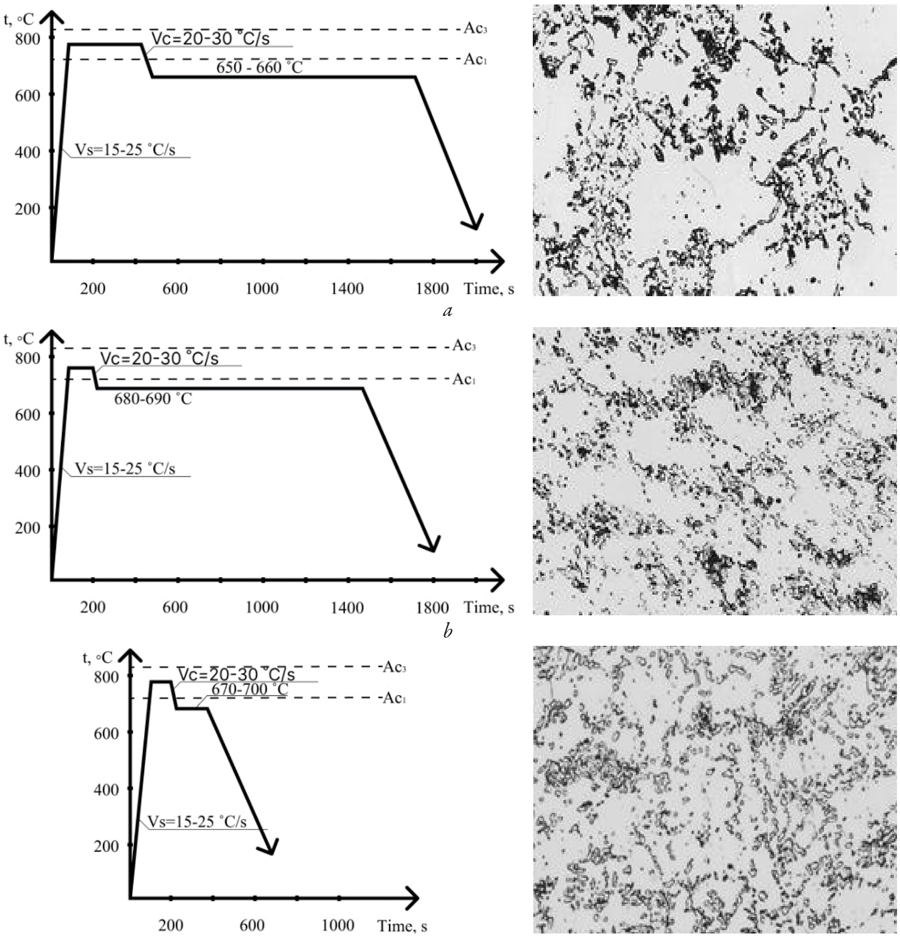


Fig. 2. Schematic diagrams of the modes of spheroidizing annealing of 20Г2Р steel with the corresponding microstructure after heat treatment according to the initial structure, ×500: *a* – ferritic-pearlitic; *b* – ferritic-pearlitic-bainite; *c* – ferritic-bainite

3.2. Development of parameters of the high-speed regime of spheroidizing annealing

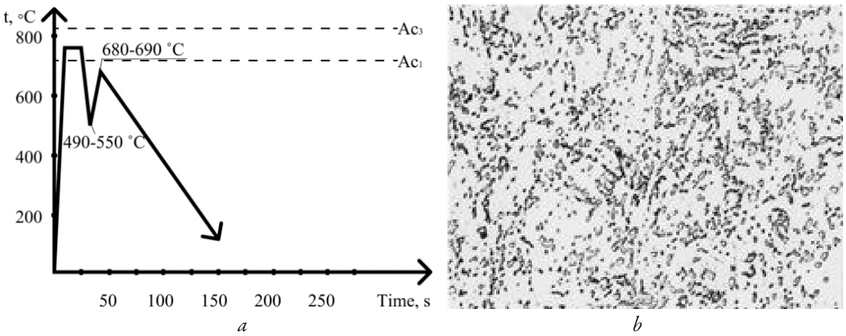
The results obtained on reducing the annealing duration were used as the basis for the development of a fundamentally new regime of annealing of a roll from 20Г2Р steel with an initial ferrite-bainite structure. The following parameters of the spheroidizing treatment regimes were established:

- heating at a rate of 15–25°C/s to a temperature of 720–780°C;
- holding at a temperature of 690°C for 20 s;
- cooling at a rate of 13–22°C/s (the optimal value is 20–30°C/s) to a temperature of 490–550°C (the optimal value is 510–530°C);
- temperature increase at a rate of 0.3–0.5°C/s of 680–690°C;
- cooling at an arbitrary rate to room temperature.

The schematic diagram of high-speed spheroidizing annealing is presented in Fig. 3 with the corresponding microstructure.

The results of experimental studies using the specified mode indicate a significant reduction in the time of spheroidizing annealing (the total processing duration was 40–50 s). The results of metallographic studies indicate the formation of globular cementite with a dispersed carbide phase.

Experiments performed using the developed schemes with the parameters of the high-speed mode of spheroidizing annealing of 20Г2Р steel confirmed the possibility of significantly reducing the duration of the process while maintaining the necessary technological properties. The difference between the proposed spheroidization modes is the use of electrothermal methods of heating the metal (induction and electrocontact). Further research is aimed at determining the main factors of intensification using computer modeling of the cementite spheroidization process.



a *b*

Fig. 3. Schematic diagram of the high-speed mode of spheroidizing annealing of 20Г2Р steel with the corresponding microstructure, ×500: *a* – mode diagram; *b* – sample microstructure

3.3. Computer modeling of the spheroidizing annealing process of steel

To substantiate the thermodynamic effect of accelerating the spheroidization process, the ratio was chosen to determine the speed of the heat treatment process [1], in this case, the spheroidization process

$$V_s = A \cdot \nu \cdot \frac{\Delta G_{TCF}}{\Delta X} \cdot TF \cdot \exp\left(-\frac{\Delta G_{ac}^{D}}{RT}\right), \tag{1}$$

where A – a constant that depends on the type of structural transformation; ν – the frequency factor, s^{-1}; $\Delta G_{TCF}/\Delta X$ – the free energy gradient between the corresponding structural components, J/(mol · m); ΔG_{ac}^{D} – the diffusion activation energy of the component that determines the process speed, J/mol; ΔG_{TCF} – the thermodynamic driving force of the structural transformation; R – the universal gas constant, J/(mol · K); T – the absolute temperature of the process, K; TF – the thermodynamic factor.

The analytical ratio of the kinetic factor *KF* is described as follows

$$KF = \nu \cdot \exp\left(-\frac{\Delta G_{ac}^{D}}{RT}\right) \cdot \frac{\Delta G_{TCF}}{\Delta X}. \tag{2}$$

Thermodynamic factor is calculated by the formula

$$TF = \left[1 - \exp\left(-\frac{\Delta G_{TCF}}{RT}\right)\right]. \tag{3}$$

The equation for determining the thermodynamic driving force, according to work [1], is written as follows

$$\Delta G_{TCF} = \overline{r_s^2} \cdot N_o \cdot \bar{\gamma}_o \cdot \left(4\pi \cdot \frac{N_s}{N_o} \cdot \frac{\gamma_s}{\bar{\gamma}_o} - a_f^o \cdot \frac{\overline{r_o^2}}{\overline{r_s^2}}\right), \tag{4}$$

where $\bar{r}_s$ – average particle size after spheroidization, m; N_o – initial number of particles per unit volume, m^{-3}; $\bar{\gamma}_o$ – average specific surface energy of the initial unequal-axis particles, J/m^2; *Ns* – number of particles per unit volume after spheroidization, m^{-3}; γ_s – specific surface energy of spherical particles, J/m^2; a_f^o – EPP shape coefficient, which is determined by equating the volume of unequal-axis EPP to the volume of spherical shape EPP; $\bar{r}_o$ – average initial aggregate particle size, m.

Thus, the main features of the cementite spheroidization process in low-carbon steels were considered based on the analysis of the *TF* influence on the process speed taking into account the relationship (4). Firstly, the lower speed of the spheroidization process in low-carbon steels compared to high-carbon steels due to the reduction of the thermodynamic stimulus of the process – the *TF* value in equation (1). For example [2], the volume fraction of cementite in steel grade 20 is four times less than in steel grade У8. This means that with the same size of cementite particles, the area of the interfacial surface in steel 20 will be smaller – in equation (4) the values of $\bar{r}_o$ and N_o. However, the specified area in low-carbon steels can be significantly increased by dispersing cementite particles. This is ensured by the preparation of the initial structural state by the decomposition of supercooled austenite at lower temperatures – by the decomposition of austenite in the bainite transformation interval.

Secondly, the change in *TF* values with increasing temperature and duration of isothermal holding can be realized by using spheroidizing annealing in the non-isothermal holding mode with increasing temperature with an appropriate heating rate. It is important to emphasize that the *TF* value is a hereditary function of temperature and holding time at a given temperature. As is known, the *KF* value is an increasing function of temperature. The corresponding calculations according to formula (1) and the results of analytical studies of the joint influence of *TF* and *KF* on the rate of cementite spheroidization are presented in Fig. 4.

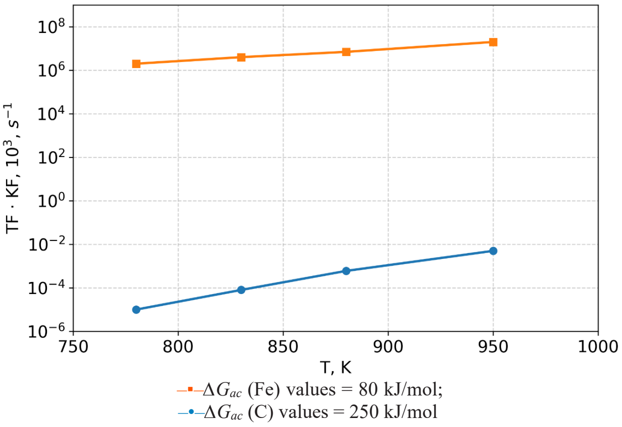


Fig. 4. Graph of the joint influence of thermodynamic and kinetic factors on temperature in the process of cementite spheroidization

Analysis of the calculations shows that the increase in the kinetic factor more than compensates for the decrease in the thermodynamic factor, as a result of which the spheroidization rate increases. This conclusion is confirmed by the significant reduction in the duration of metal processing fixed by the experiment (Fig. 2, 3).

To study the complex intensification of spheroidizing annealing of steel, the kinetic equation of the structural transformation process was considered in the general form

$$V_S = A \cdot KF \cdot TF. \tag{5}$$

Furthermore, analytical relations (2) and (3) were analyzed to determine the values of *KF* (2) and *TF* (3). The graphical interpretation of these relations is given in Fig. 5.

Based on the analysis of changes in the indicated ratios of *TF* and *KF* values, presented in graphical form, the following definitions were formulated:

1) the thermodynamic equilibrium point is the intersection point of the *TF* and *KF* curves;

2) active spheroidization interval: *TF* > *KF*;

3) passive spheroidization interval: *TF* < *KF*.

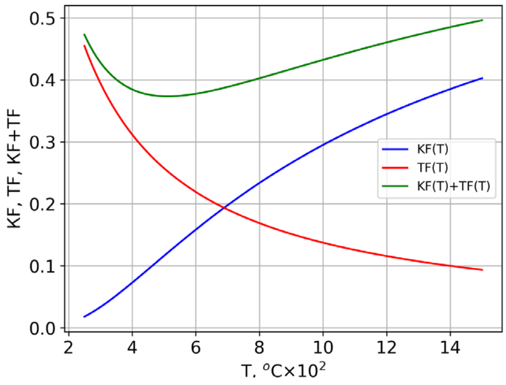


Fig. 5. Graphical interpretation of changes in the values of thermodynamic and kinetic factors in the process of complex cementite spheroidization

In the zone of active spheroidization, the change in *TF* has a certain effect on the speed of the process. It is here that non-isothermal holding is most effectively implemented, since the increase in temperature compensates for the decrease in *TF* due to the increase in *KF*. This provides a complex effect of intensification of cementite spheroidization.

As shown by the results of computer modeling, the speed of cementite spheroidization is determined by the complex influence of thermodynamic and kinetic factors. Local temperature increase in the interphase regions activates diffusion processes and accelerates the formation of spherical morphology of carbides. This justifies the feasibility of using modes with non-isothermal holding and new schemes of high-speed heat treatment to intensify the cementite spheroidization of low-carbon steels. In the future, the use of computer modeling methods will allow to determine the influence of temperature-time parameters of spheroidizing annealing modes on the rate of heat treatment of low-carbon steels.

3.4. Discussion

Analysis of the curves in the process of spheroidization (Fig. 5) shows that the kinetic factor $KF(T)$ – blue curve, increases in the process of spheroidization. The increase in the kinetic factor is due to the fact that the rate of nucleation of pearlite centers is accelerated and the interfacial surface increases in the process of transformation. At the same time, the influence of the thermodynamic factor $TF(T)$ – red curve, decreases. The thermodynamic factor loses its contribution over time: the system (body) tends to reduce the free energy (grain growth), approaching the state corresponding to the minimum energy of the grain boundaries. But grain growth is not the only way to reduce the free energy of the system. Another way is to change the shape of the crystals of the second phase, that is, the transformation of lamellar and second-form carbide crystals into spherical, which has a smaller value in the ratio of surface to volume of the crystal. On the other hand, $KF(T) + TF(T)$ – the green curve, shows a synergistic effect: initially the value is high due to thermodynamics, but later it stabilizes, because kinetics takes on the main role. This happens because the surface and the free energy associated with it decreases during the transition of the non-equilibrium form of crystals of the excess phase to the isomeric one, in particular during the process of spheroidization of carbides.

According to the conducted comprehensive study of the influence of interrelated factors, it is advisable to note the following. At the beginning of the spheroidization process, the thermodynamics of the process has a significant impact on the system, although the thermodynamic driving force (the difference in free energies) linearly or smoothly decreases with increasing temperature, the kinetic factor (diffusion coefficient) increases exponentially (according to the Arrhenius law). This means that even with a smaller "desire" of the system to transition to a stable state, the rate of "transportation" of atoms increases so much that the total process time is reduced. That is, increasing the temperature to the subcritical region significantly accelerates the spheroidization process.

Therefore, when combining factors, an optimal temperature range is created:

- at low temperatures, the thermodynamic stimulus has large values (plates are very unstable), but the kinetics of the process almost does not occur. Diffusion in this case is too slow;
- at high temperatures (heating in the subcritical interval to Ac_1), the thermodynamic stimulus is minimal, but the kinetics are maximally active. Atoms move quickly, which allows to reduce the duration of the spheroidization process.

Thus, the intensification of cementite spheroidization occurs due to the transition from thermodynamic control (at the beginning) to kinetic control (later). This is visible on the total curve (Fig. 5): first it is determined by thermodynamics, and then by kinetics. This means that to accelerate the process at the beginning of spheroidization, it is important to create a strong thermodynamic stimulus. In the future, kinetics uses this increased solubility.

The process of cementite spheroidization in steels is a complex thermodynamically determined process of morphological adaptation, the speed of which is completely determined by the kinetic parameters of diffusion, where temperature acts as the main regulator of the balance between the energy stimulus and the rate of mass transfer.

According to the created model (1), a stage of complex modeling of the high-speed process of cementite spheroidization was performed, an illustration of which is given in Fig. 6.

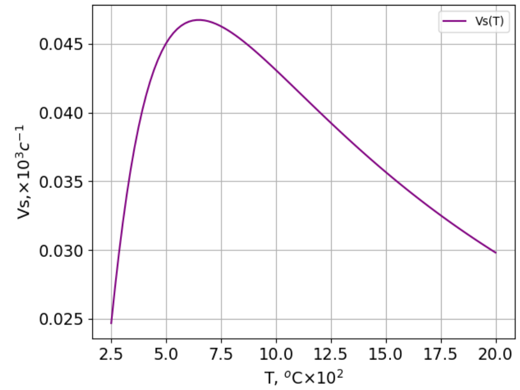


Fig. 6. Intensification schedule of cementite spheroidization

Analysis of Fig. 6 shows that the speed of the cementite spheroidization process (interaction of kinetic and thermodynamic factors) depends on the heating temperature of the sample.

During cementite spheroidization in the subcritical temperature range, the following processes occur simultaneously:

- division of large plates into several subplates by dissolving individual cementite sections;
- diffusion of carbon along interphase, intergrain and subgrain boundaries in a solid solution;
- release of cementite on favorable areas of the surface of carbide particles that are being transformed;
- removal of iron atoms (self-diffusion) from the growth front of carbide particles and filling with them the volumes that are vacated by carbide particles.

The listed processes are associated with the diffusion of carbon and iron atoms. Therefore, the thermodynamic factor is compensated by the influence of the kinetic factor and under their combined influence, the diffusion of atoms is accelerated and the rate of cementite spheroidization is further accelerated.

Cementite spheroidization plates occurs in two stages: the division of carbide plates into parts (subplates) and the actual spheroidization of the subplates. Both stages occur simultaneously, and as long as the plate shape is preserved, it is impossible to divide them into separate processes. After the completion of the first stage (the thermodynamic factor decreases), the second stage of spheroidization (an increase in the kinetic factor) develops further, and the process of coagulation of carbide particles begins (the factors are compensated) Fig. 6. Therefore, the intensification of the process is achieved in the zone of maximum spheroidization speed V_S – spheroidizing annealing (after non-isothermal holding with increasing temperature) in the zone of subcritical temperatures. This graph directly reflects such dynamics – the transition from thermodynamic to kinetic control, which is key to optimizing the cementite spheroidization in low-carbon steels.

The practical significance of the research results lies in a significant reduction in the duration of spheroidizing annealing, which makes it possible to synchronize technological operations in production lines for metal products.

The limitations for the use of research are the need for additional consideration of high-speed methods of heat treatment in production lines and the development of equipment for heating and cooling the processed metal at appropriate speeds.

Further research should be directed towards modeling spheroidizing annealing modes with the determination of the degree of influence of temperature-time parameters on the speed of the cementite spheroidization process.

4. Conclusions

1. Microstructural analysis of samples and research of the influence of different initial structural states on the rate of cementite spheroidization of 20Г2Р steel were carried out. It was established that the modes of spheroidizing annealing of low-carbon steel with different initial states affect its final structure. It was shown that the duration of the cementite spheroidization is reduced from 1500–1800 s to 200–450 s with the transition from ferrite-pearlite to ferrite-bainite structure, respectively. This allows to significantly reduce the total duration of spheroidizing annealing of steel and reduce the energy intensity of the heat treatment process.

2. Based on the experimental analysis of the cementite spheroidization, a new annealing mode for 20Г2Р low-carbon steel with an initial ferrite-bainite structure is proposed. The following parameters of the spheroidizing annealing regime were set:
- heating at a rate of 15–25°C/s to a temperature of 720–780°C;
- holding at a temperature of 690°C for 20 s;
- cooling at a rate of 13–22°C/s to a temperature of 490–550°C;
- increasing the temperature to 680–690°C at a rate of 0.3–0.5°C/s;
- cooling at an arbitrary rate to room temperature.

The metallographic studies conducted indicate the formation of globular cementite with a dispersed carbide phase. A uniform distribution of cementite globules in a ferrite matrix was obtained in the final structure. The results obtained provide an increase in the mechanical properties of steel for cold heading with the possibility of manufacturing products of complex configuration.

3. Based on analytical studies of the process of intensification of cementite spheroidization, a complex influence of thermodynamic and kinetic factors on the course of structural transformations has been established. Computer modeling of the speed parameters of the cementite spheroidization process has been performed. It has been shown that the intensification of the process is achieved in the region of maximum spheroidization speeds under conditions of non-isothermal holding with increasing temperature. It has been established that the key condition for optimizing cementite spheroidization in low-carbon steels is the transition from thermodynamic to kinetic control of the dynamics of structural transformations.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or other, that could influence the research and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted paper.

Authors' contributions

Hennadii Shvachych: Conceptualization, Methodology, Writing – original draft, Writing – review and editing; ***Mariia Sobolenko***: Conceptualization, Methodology, Investigation, Writing – original draft; Writing – review and editing; ***Valeriy Ivashchenko***: Conceptualization, Writing – original draft; ***Tamara Manko***: Conceptualization, Verification, Writing – review and editing; ***Borys Moroz***: Conceptualization, Writing – original drafting; ***Leonid Meshcheriakov***: Conceptualization, Formal analysis, Investigation, Resources.

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