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DETERMINING RATIONAL COMPLEX MODIFYING AND ALLOYING ADDITIVES TO IMPROVE THE MECHANICAL CHARACTERISTICS OF GRAY CAST IRON

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The object of this study is the mechanical properties and parameters of the cast iron microstructure. The task to solve was to ensure high mechanical properties of cast iron for mechanical engineering part. To this end, a working hypothesis was put forward, which assumed the possibility of increasing mechanical properties by selecting complex additives based on modifiers and alloying ferroalloys.

The effect of 4 groups of additives was investigated: group 1 – ferrochrome (FeCr025) and silicocalcium (SiCa-30), group 2 – ferrotitanium (FTi35) and ferroboral (FeB6), group 3 – ferrotitanium (FTi35) and ferrochrome (FeCr025), group 4 – ferroboral (FeB6) and silicocalcium (SiCa-30). They were introduced into the liquid metal in different percentages in the amount of 3 % of the mass of liquid cast iron. The following mechanical characteristics were selected: flexural strength (σ, MPa), tensile strength (UTS, MPa), deflection arrow (f, mm), hardness (HB), and whitening.

It was determined that the strength characteristics of cast iron treated with ferroalloys of group 1 reach a maximum at about 40 % silicocalcium in the composition of the additive. The tensile strength of cast iron reaches about 320 MPa, the bending strength is about 710 MPa, the deflection arrow is 4.5 mm, and the hardness corresponds to the HB250 level. The fact of competition of hardness and other mechanical properties was established in the range of silicocalcium content in the modifier composition up to 40 %. Thus, it was established that it is the combination FeCr025+SiCa-30 with the ratio of components of 40:60, respectively, that is rational.

The revealed regularities of changes in the amount of carbides, the size of graphite, and the amount of ferrite when using different additives allow us to explain patterns in the formation of mechanical properties of cast irons. Owing to this, it becomes possible to identify the mechanism of formation of properties, ensuring purposeful regulation of the quality of cast iron.

The results could be used at iron foundries to produce castings for machine building

Keywords: mechanical characteristics of cast iron, modifiers of cast iron, alloying, microstructure of cast iron, graphitizing and carbide-forming elements

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1. Introduction

Obtaining a given grade of cast iron is a complex technological task whose solution involves taking into account a set of influencing factors: the composition of the charge, the metallurgical processes of melting, the composition of the liquid metal, the presence of a secondary melting unit in the technological chain, alloying and modification of the melt [1]. Therefore, it is extremely difficult to determine the moment of the appearance of a new brand of cast iron with sufficient accuracy, which as a result could lead to the formation of damaged castings. Because of this, the practice of bringing cast iron to a given grade involves the use of post-furnace processing operations, which aims to bring the melt to a given chemical composition and temperature by introducing ferroalloys, in particular modifiers. High-temperature ferroalloys and modifiers, when introduced into the furnace, often fall below the melting zone, which could reduce the productivity of the process and form significant material losses, which could be from 15 % to 25 %. Therefore, alloying and modifying elements are often introduced into the ladle before pouring. Due to the fact that alloying and modification processes affect the melt complex, it becomes possible to change the physical and mechanical properties of cast iron within wide limits. The results of research into these issues enable practitioners to determine rational combinations of alloying and modifying elements built according to the principle of balancing graphitizing and carbide-forming effects, for purposeful regulation of structure formation processes in the process of cast iron crystallization. In addition, it makes it possible to solve the practical task of choosing the most effective and economically justified methods for processing the melt, because, as noted in works [2, 3], the properties and structure of cast iron are influenced by alternative factors – both the type of modifier and modes of modification, and the chemical composition base alloy. As it follows from those studies, it is possible to minimize the cost of expensive modifiers by maintaining the appropriate optimal ratios of carbon and silicon in the melt and adding alloying elements in minimum quantities to improve mechanical properties [4]. Such ratios could be calculated on the basis of regression equations relating the chemical composition of cast iron with the selected type of modifier and modes of modification and alloying with the mechanical properties of the alloy.

That is, the main ideas of complex alloying and modification imply the use of combinations of individual chemical elements to regulate influence on primary and secondary crystallization, countermeasures and actions on graphitization, formation of solutions with ferrite and austenite and, through this, increasing the efficiency of alloy processing. Combinations of elements substantiated by relevant scientific research find practical implementation in the form of complex ligatures, which significantly change the mechanical properties of cast iron, are cheaper and easily assimilated, and also make it possible to obtain several grades of cast iron on the basis of one charge by the method of processing liquid metal in a ladle.

All this allows us to argue about the relevance of research aimed at designing rational complex additives for the processing of liquid cast iron and technological regimes of alloying and modification.

2. Literature review and problem statement

The formation of properties of cast iron is mainly considered through the study of the following factors: melting and the selection of its modes, which ensure qualitative regulation of the chemical composition, the selection of types of modifiers and modes of modification, the selection of rational combinations of graphitizing and carbide-forming elements, and the optimization of alloying complexes.

Work [5] reports the results of studies on the effect of induction melting followed by treatment with a double additive (iron powder + inoculant), which promotes both the formation of austenite and graphite, and has a positive effect on the structure of gray cast iron. However, the presented concept of the three-stage model of graphite nucleation does not contain analytical dependences for controlling the processes of structure formation. In addition, it should be noted that the formation of the structure and, as a result, the mechanical properties of induction melting cast iron depends on the temperature regimes of melting, which could be low- and high-temperature. Deviation from them could lead to a change in the directions of physical-chemical processes in the “melt - slag - lining” system, which affects the formation of the chemical composition, and therefore requires control and adjustment. Thus, the system for diagnosing the temperature regime of induction melting proposed in [6] implies slag control and determination of possible deviations in the melting regimes based on the obtained results. The latter lead to obtaining a chemical composition that does not correspond to the given one. However, continuous control over slag is difficult to implement in practice.

If we consider the factor of influence on the properties of cast iron of its chemical composition, which is formed directly by the melting modes, it is important to take into account the specificity of induction melting – conducting the process on a constant residual melt in the furnace. Batch dispensing of the melt and the presence of a permanent melt residue could make it difficult to accurately ensure the chemical composition. This leads to the need to have accurate kinetic equations that take into account the factors of change in the mass of the melt as a reaction system [7]. However, the cited work is theoretical in nature and does not contain clear solutions regarding induction melting.

The results of work [8] confirm the significance of factors of carbon content, chemical composition, and solidification rate in terms of influence on microstructural morphology in lamellar graphite and fluctuations in material properties. The presented model covers a wide range of carbon content, which solidifies at different cooling rates, characteristic of both thin-walled and thick-walled castings of complex shape. This allowed the authors to conclude that the dominant parameter that could be used to determine the ultimate tensile strength is the characteristic distance between pearlite grains. However, the study is actually limited to one characteristic of cast iron and does not contain the necessary data on the influence of post-furnace processing.

It should also be noted that induction melting is very sensitive to the quality of the charge, so the lack of a guarantee of the quality of the charge materials could complicate the task of qualitative regulation of the chemical composition of cast iron. In order to find effective control over induction melting under conditions of such uncertainty, a method was proposed in [9] that allows for the synthesis of optimal control both at the melting stage and at the stage of thermo-time treatment. However, the work does not consider the actual formation of the structure and properties of cast iron.

The effect of modification on the microstructure and fatigue behavior of castings made of high-quality cast iron (EN GJS 700-2) is determined in [10]. It has been shown that the chosen mode of modification has a strong influence on the microstructure of the alloy, as well as the fatigue resistance of heavy castings made of high-quality cast iron. However, the emphasis on determining the zones of initiation and propagation of cracks limits the results of the study.

The complex effect of graphitizing and carbide-forming elements on the tensile strength was studied in [11]; however, the results are limited by the carbon equivalent in the range (4.214–4.372) % and the carbon content in the range (3.425–3.563) %, provided that the specified the ratio of chromium and copper, which are used for alloying in a minimum amount. The optimization of the corresponding composition according to the criterion of the maximum strength limit is covered in work [12], and according to the criterion of conformity to hardness – in [13]. However, the results of exposure to carbon equivalent and carbon in cast iron alloyed with minimal amounts of chromium and copper are limited to ranges of carbon equivalent and carbon content of (4.2–4.4) % and (3.42–3.57) %, respectively.

In [14], the influence of a number of alloying elements on the mechanical properties and microstructure of compacted graphite cast iron (CGI) is considered. The intermediate properties between gray and ductile iron typical of CGI have been shown to provide unique properties for manufacturing automotive and other engineering applications. The formation of these properties occurs under the action of alloying elements during the subsequent heat treatment. But the results are descriptive in nature and do not contain specific dependences that could be used for purposeful management of properties. It is obvious that such management could be considered a necessary element of general management of the quality of cast iron castings [15].

Work [16] reports the results of a study on the effect of modifying low-chromium pre-eutectic cast iron (about 1 % chromium) with carbothermic ferroboron and ferrosilicobarium in the amount of 0.08 % and 0.05 % of the mass of the liquid metal, respectively, as well as with a complex boron-barium ferroalloy in the amount of 0.14 % of the mass of liquid metal. The studies showed that as a result of such processing, there is grinding and uniform distribution of carbides, as well as the transformation of the morphology of carbides from dendritic to compact granular form. At the same time, the pearlite colonies in the modified cast iron are characterized by a higher degree of dispersion than in the control sample. A conclusion was drawn about the positive effect of such structural transformations on the improvement of mechanical properties; however, the results are limited by the selected types of additives and processing modes.

In work [17] it is noted that the strengthening of the alloy is carried out due to a solid solution containing silicon and aluminum. In particular, it was determined that when replacing Si with Al, the standard properties of gray cast irons are significantly increased, reaching a strength of 466 MPa at a moderate hardness (250 HB). At the same time, the tensile strength increases with the Al content, reaching a maximum of about 3 % Al, after which it decreases. The influence of these elements was also studied in works [18, 19], in which the optimal combinations of Al–Si in cast iron were determined, providing the maximum tensile strength limits of 245–334 MPa [18] and the optimal combinations of Mn–Al depending on the carbon content, which could provide a tensile strength of about 300 MPa [19]. However, it is important to note that aluminum cast iron has a limited scope of application; in particular, it is used for casting parts of internal combustion engines.

Work [20] proved the possibility of reducing the content of Cr, which is introduced into cast iron to increase its strength as part of the alloying complex Cr:Ni. It is statistically proven that the Cr:Ni ratio could be shifted towards lower values of Cr – from Cr:Ni=2.2:1 to Cr:Ni=1.76:1 in existing casting manufacturing technology. But the work does not emphasize the influence of other factors, which could be significant considering the composition of cast iron discussed in the work.

In [21], when comparing the effect of two types of FeSi75 and FeSi65CaBaSr2 modifiers on the microstructure of cast iron, a procedure for sequentially bringing the data of serial melts to uniform conditions, which are determined by the closeness of the chemical composition of the melt, is proposed. For the implementation of this procedure, it was determined that the compared modifiers have the same effect on the size of graphite, but the use of FeSi65CaBaSr2 in combination with an alloying complex (0.27 % Cr+ +0.083 % Ni+0.048 % Ti+0.155 % Cu+0.018 % V) makes it possible to obtain an average microstructure in the amount of pearlite of 96 %. The issue of complex processing of the modification melt with vanadium alloying is considered in [22], in which the effect on the mechanical properties of two types of modifiers – FeSi75 and FeSi40V7 – is investigated. The results indicate that the introduction of vanadium into cast iron as part of the FeSi40V7 modifier leads to a decrease in the strength limit by 4 %, but to an increase in hardness by 2 %. Therefore, the use of vanadium in the composition of FeSi40V7 within the limits of the final content in cast iron at the level of 0.04–0.078 % could be expedient only if it is necessary to increase the hardness of cast iron. However, the results of works [21, 22] are limited by the ranges of element content and selected types of modifiers.

The problem of the impossibility of taking into account many factors influencing the formation of the chemical composition of cast iron during melting, which leads to deviations of the chemical composition from the requirements regulated by technical conditions, was investigated in [23]. The paper proposes a procedure for the technological audit of serial melts, the feature of which is a comprehensive assessment of actual melting indicators, based on the results of which it becomes possible to calculate corrective combinations of ferroalloys. However, the proposed solutions relate only to individual elements of the chemical composition and do not cover the formation of mechanical properties. In this aspect, it is important to note that some properties of cast iron, or even the content of elements of the chemical composition, are competing, which is due to the processes that occur in the melt during crystallization. Solving such a problem is possible on the basis of mathematical modeling for each process parameter and search for optimal technological modes based on a multi-alternative description of the final state, which is determined by alloy quality indicators [24].

Based on our review of the literature, one can conclude that the challenging issue is the validity of the choice of modifiers and alloying additives to ensure the given requirements for the quality of cast iron. At the same time, as a rule, the influence of individual modifiers and ferroalloys on the properties of cast iron is investigated. It is also important to note the selectivity in matters of determining the priority criteria for assessing the quality of cast iron and the difficulty of identifying patterns in the formation of mechanical properties in connection with microstructure parameters. This provides the basis for conducting a study aimed at determining the possibilities for using complex compositions of modifiers and alloying ferroalloys on the mechanical properties of cast iron, as the main criteria of cast iron quality, and determining the possible influence on their formation of microstructure parameters.

3. The aim and objectives of the study

The purpose of our study is to reveal patterns of influence exerted by complex additives based on combinations of modifiers and alloying ferroalloys on the characteristics of cast iron. This will make it possible to improve the quality of cast iron for mechanical engineering parts.

To achieve the goal, the following tasks were set:

– to determine the influence of selected combinations of modifiers and alloying ferroalloys on the mechanical characteristics of cast iron;

– to compare the characteristics of the action of complex additives on mechanical properties;

– to establish the dependence of characteristics of the microstructure of cast iron on the selected complex additive.

4. The study materials and methods

The object of our research is the characteristics of cast iron – mechanical properties and microstructure parameters.

The research hypothesis assumes that by selecting complex additives based on modifiers and alloying ferroalloys, it is possible to adjust the properties of cast iron, ensuring an increase in mechanical characteristics.

It was assumed that the mechanical properties are random variables with the law of normal distribution.

The following simplifications were adopted: the problem of determining the effect of complex additives on the characteristics of cast iron was considered in a one-dimensional statement.

To assess the alloying and modifying effect of various additives, the change in the structure and properties of cast iron when they were introduced into the charge and into the liquid metal was compared. Laboratory smelting of cast iron was carried out using a charge consisting of 70–85 % cast iron and 30–15 % steel scrap. Cast iron was smelted in an induction furnace. The chemical composition of basic cast irons is given in Table 1.

The influence of alloying components on the structure and hardness of cast iron, depending on its cooling rate, was determined on cylindrical samples with a diameter of 15 mm to 120 mm and a length of 220 mm, which were poured into soil molds. In some cases, more massive samples were cast to check the effectiveness of complex alloying at reduced cooling rates of cast iron, which corresponded to real conditions. The choice of dimensions of the casting model was carried out in such a way that the time of its cooling until the end of the pearlite transformation was the same as during cooling under actual conditions. In addition to the above, standard samples with a diameter of 30 mm were cast in some melts for mechanical studies. Alloying and modifying additives in a grinding form were introduced to the bottom of the casting ladle before the release of liquid metal from the furnace. Under these conditions, the assimilation of alloying additives was 90–97 %, and that of modifiers was 50–60 %, respectively. The scheme of smelting and their processing is shown in Fig. 1.

The microstructure of cast iron was determined by the method of quantitative metallography at magnifications of 100 and 500. The amount of solid structural components or ferrite was determined in 30–50 fields of view of each micro section by overlaying a grid with a square side of 5 mm and was calculated using the following formula:

$$C=[(\Sigma n_C \cdot i)/N \cdot i] \cdot 100, \qquad (1)$$

where C is the average content of cementite (or ferrite) in cast iron, %; Σn_C is the number of cells in the field of view of the micro section, which is occupied by cementite (or ferrite); N is the total number of grid cells; i is the number of positions.

The microhardness of the structural components was determined using a microhardness tester PMT-3 (Ukraine) at a stress of 20 and 50 g. Based on the results of 40–60 measurements, partial microhardness distribution curves were constructed.

The hardness of the cast iron was measured every 3–10 mm along the diameter of the micro section, which was cut at a distance of 60 mm from the bottom of the sample during pouring.

Thus, in this work, the following characteristics of cast iron were studied: bending strength (σ, MPa), ultimate tensile strength (UTS, MPa), deflection arrow (f, mm), hardness (HB), and whitening.

As additive components, ferrochrome, ferrotitanium, ferroboral, and silicon calcium were used [25, 26]. They were introduced into the liquid metal in different percentages in the amount of 3 % of the mass of liquid cast iron in given proportions. 4 groups were considered: group 1 – ferrochrome (FeCr025) and silicocalcium (SiCa-30), group 2 – ferrotitanium (FTi35) and ferroboral (FeB6), group 3 – ferrotitanium (FTi35) and ferrochrome (FeCr025), group 4 – ferroboral (FeB6) and silicocalcium (SiCa-30). The chemical composition of additives is given in Table 2.

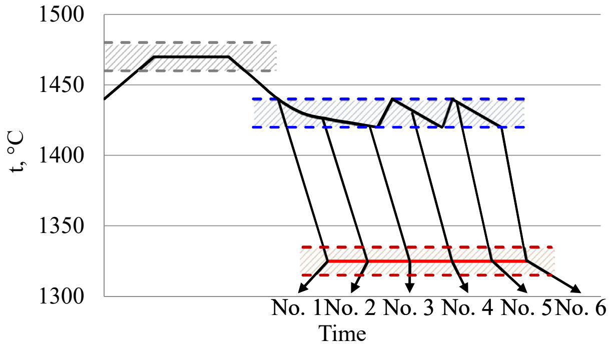


Fig. 1. Methodology of experimental melting with fractional alloying of cast iron: ▨ – temperature of overheating; ▨ – temperature of introduction of additives; ▨ – pouring temperature

Table 1

Chemical composition of experimental cast irons

No. of entry	Content of chemical elements, %							Degree of eutecticity, S_e
	C	Si	Mn	Cr	Cu	P	S	
1	2.97	1.35	0.52	0.08	0.05	0.10	0.03	0.78
2	3.11	1.64	0.43	0.09	0.04	0.09	0.03	0.84
3	3.32	2.07	0.46	0.07	0.05	0.10	0.03	0.93

Table 2

Chemical composition of ligatures

Additive ID	Concentration of chemical elements, %									
	Fe	C	Si	Cr	Cu	Al	S	P	Ca	Ti	B
FeCr025	remaining	0.25	2.0	62.0	–	–	0.02	0.03–0.05	–	–	–
FTi35	remaining	0.20	5.0	–	2.0	8.0	0.04	0.04	–	36.0	–
SiCa-30	remaining	0.50	50.0	–	–	2.0	–	0.01	30.0	–	–
FeB6	remaining	–	10.0	–	–	10.0	0.04	–	–	–	6.5

5. Results of research on the influence of complex additives on the characteristics of cast iron

5. 1. Determining dependences of the mechanical characteristics of cast iron on the use of complex additives

Dependences of the mechanical characteristics of cast iron on the volume of components in a complex additive by group are shown in Fig. 2–4.

From Fig. 2–4, one can see that the nature of all dependences corresponds to the polynomial form with the presence of an extremum, with the exception of the UTS dependences for groups 1, 3, and HB for group 1, which is determined from the following formula:

$$\frac{\partial y_i}{\partial x_j}=0,\quad y_i \to \max, \tag{1}$$

where x_i is the content of the component in the complex additive, y_j is the j-th mechanical characteristic of cast iron.

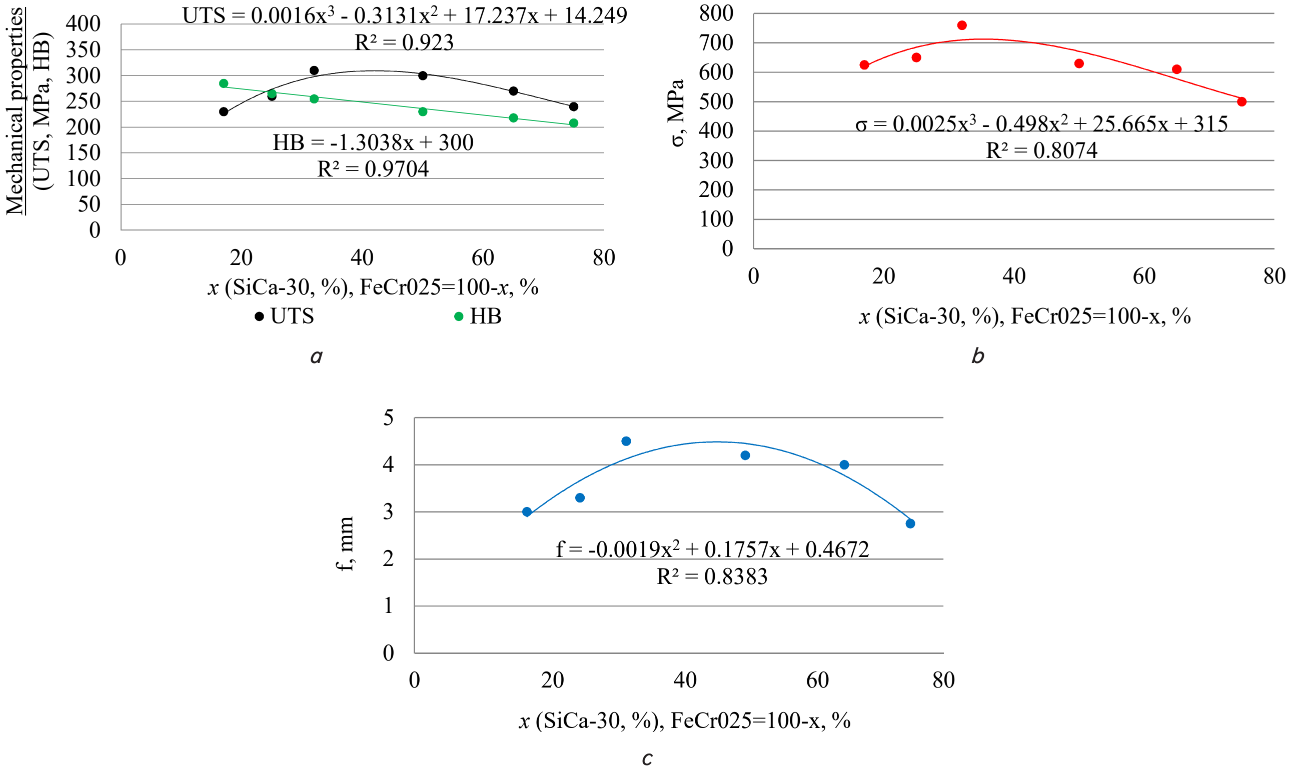


Fig. 2. Mechanical characteristics of cast iron when modified with a mixture of silicocalcium and ferrochrome (SiCa-30+FeCr025): *a* — UTS, HB; *b* — σ; *c* — f

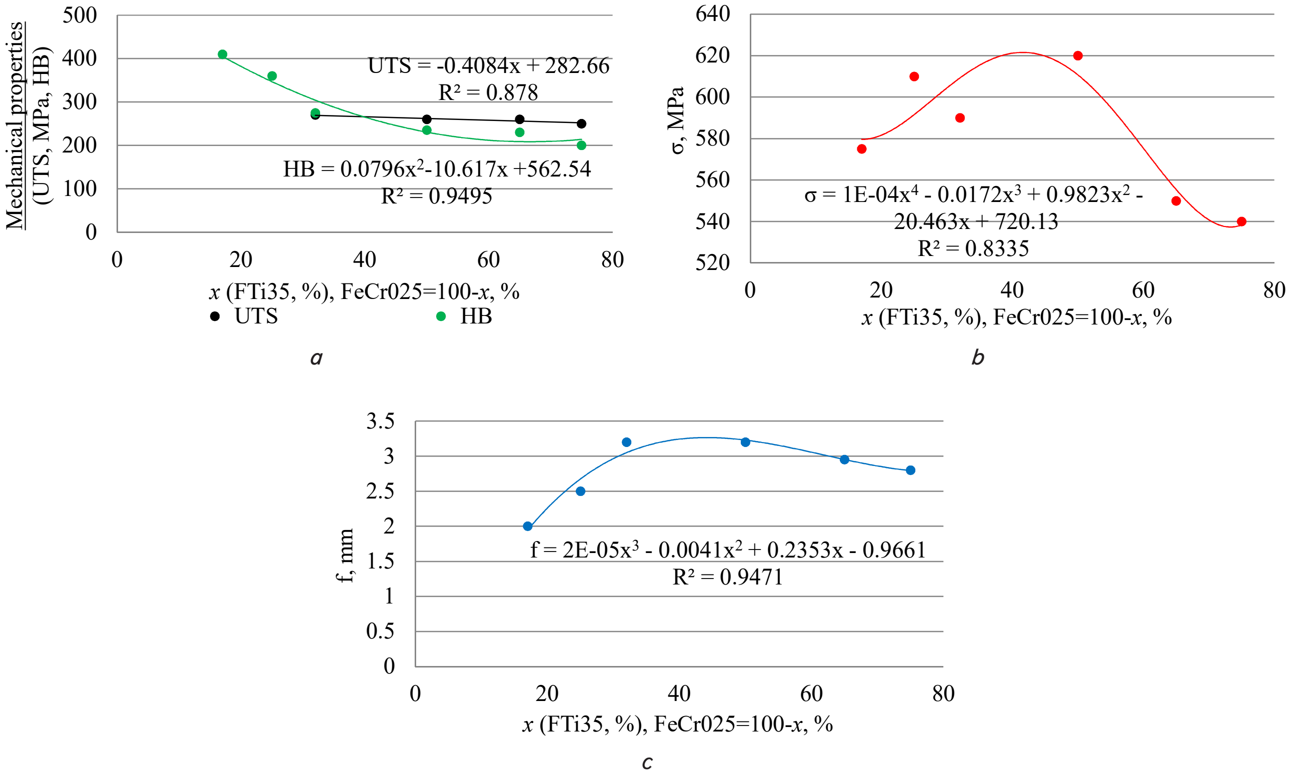
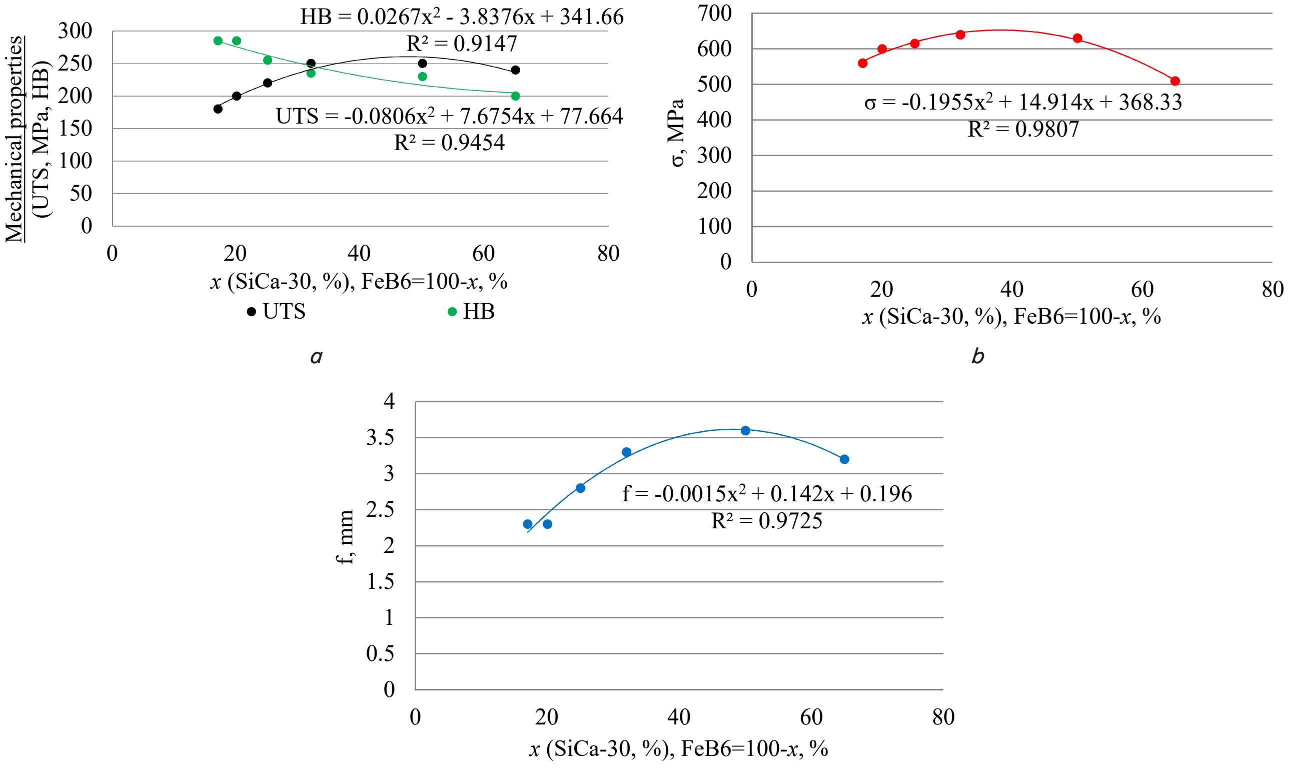


Fig. 3. Mechanical characteristics of cast iron when modified with a mixture of ferrochrome and ferrotitanium (FeCr025+FTi35): *a* — UTS, HB; *b* — σ, *c* — f



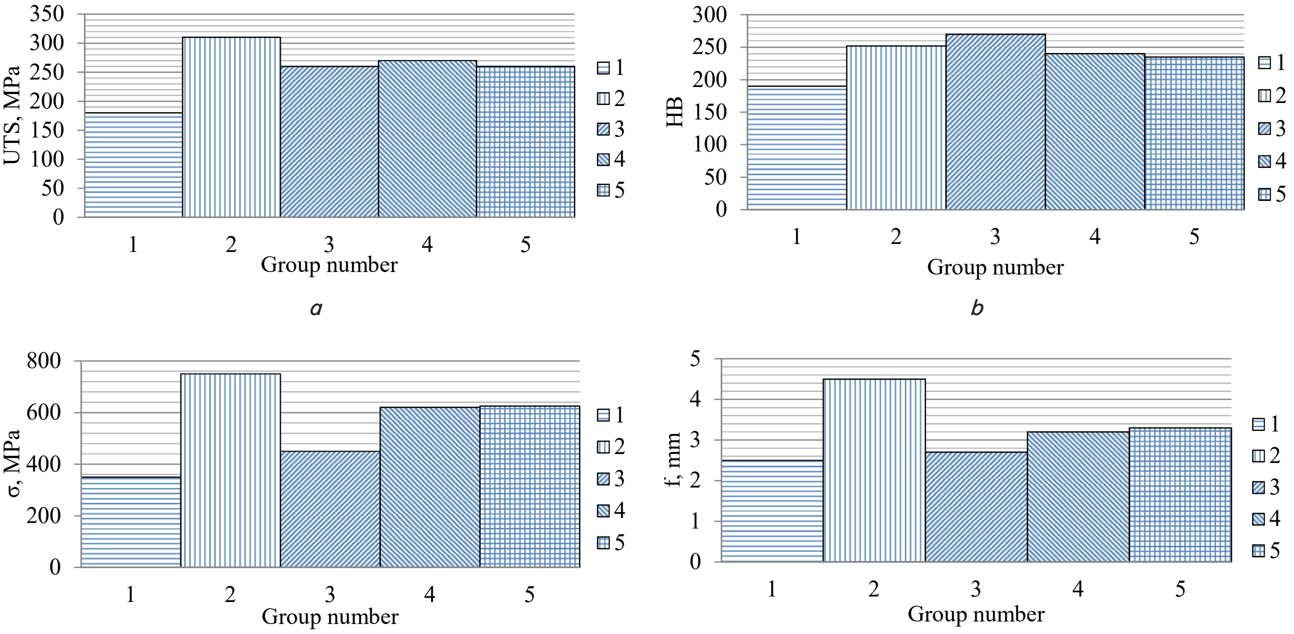
a *b* *c*

Fig. 4. Mechanical characteristics of cast iron when modified with a mixture of silicocalcium and ferroboral (SiCa-30+FeB6): *a* – UTS, HB; *b* – σ; *c* – f

It is important to note that extremes for all characteristics except HB are maxima in the range of values of the input variable of 30–60 %. For HB dependences, there are no extrema, and the minimum is observed at the upper limit of the value of the input variable for all groups.

5. 2. Results of comparative characteristics of the action of complex additives

The results of comparative characteristics of mechanical properties for the use of complex additives for all groups are shown in Fig. 5.



a *b*

c *d*

Fig. 5. Comparative characteristics of the action of complex additives of groups 1–4 on the mechanical properties of cast iron: 1 – starting cast iron; 2 – group 1; 3 – group 2; 4 – group 3; 5 – group 4

It should be noted that UTS_{max} σ_{max}, f_{max} is achieved using a group 1 complex additive, and HB_{min} is achieved using a group 4 complex additive.

5. 3. Dependence of characteristics of the microstructure of cast iron on the selected complex additive

The results of determining the characteristics of the microstructure of cast iron are shown in Fig. 6–9.

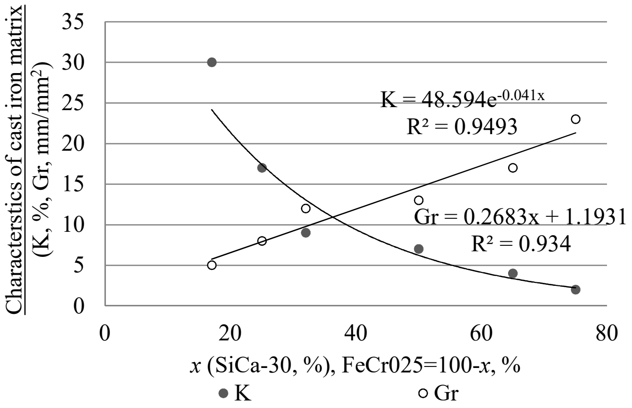


Fig. 6. Characteristics of the microstructure of cast iron when modified with a mixture of silicocalcium and ferrochrome (SiCa-30+FeCr025)

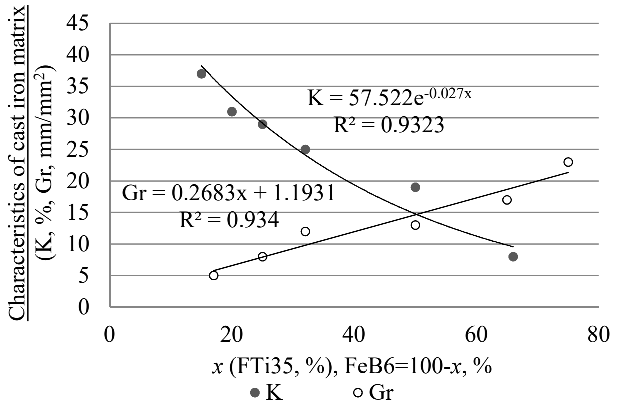


Fig. 7. Characteristics of the microstructure of cast iron when modified with a mixture of ferrotitanium and ferroboral (FTi35+FeB6)

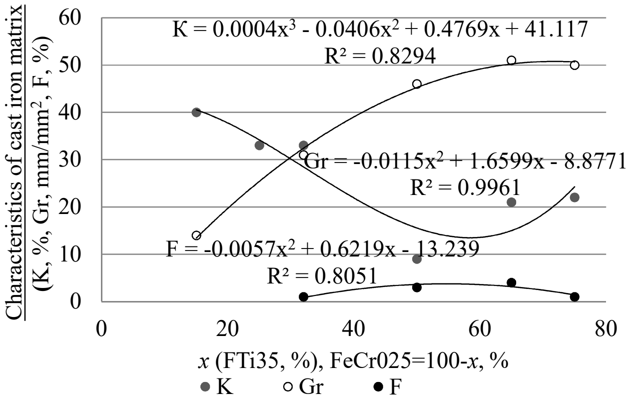


Fig. 8. Characteristics of the microstructure of cast iron when modified with a mixture of ferrotitanium and ferrochromium (FTi35+FeCr025)

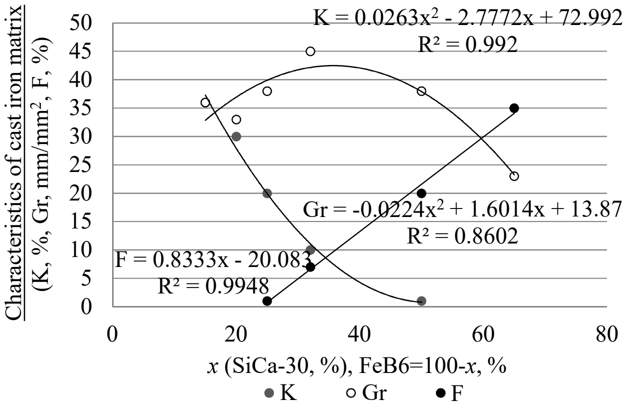


Fig. 9. Characteristics of the microstructure of cast iron when modified with a mixture of silicocalcium and ferroboral (SiCa-30+FeB6)

In Fig. 6–9, the following designations are adopted: K – the amount of carbides in the structure of cast iron, **%**, Gr – the size of graphite, mm/mm², F– the amount of ferrite in the structure of cast iron (α-Fe).

As could be seen from Fig. 6, 7, the change in the amount of carbides is described by an exponential dependence for groups 1 and 2, but it has a more complex character in the case of the introduction of additives of groups 3 and 4 into the melt (Fig. 8, 9). These are polynomial dependences with the presence of an extremum in the form of a minimum. The change in graphite size in the case of the introduction of additives of groups 1 and 2 has a linear character, but in the case of the introduction of additives of groups 3 and 4 it takes on a polynomial character with the presence of a maximum. Also worth paying attention is the uncertainty in the change in the amount of ferrite when introducing additives of groups 3 and 4, which is manifested in the different nature of the dependence.

6. Discussion of results based on the influence of complex additives on the characteristics of cast iron

The strength characteristics of cast iron treated with group 1 additives reach a theoretical maximum of about 320 MPa with about 40 % silicocalcium in the modifier composition (Fig. 2). With this amount of silicocalcium, the bending strength limit of cast iron reaches a maximum of about 710 MPa, the deflection arrow is 4.5 mm, and the hardness corresponds to the HB250 level. That is, hardness and other mechanical properties are competitive in the range of silicocalcium content in the modifier up to 40 %. This could be explained by the characteristics of the microstructure, because, as could be seen from Fig. 6, the amount of carbides decreases. With a silicocalcium content of more than 40 %, the increase in graphite size leads to a drop in mechanical characteristics. The change in microstructure due to the introduction of additives of group 2 is similar to the character determined for group 1 (Fig. 7), which may indicate the expectation of dependences of mechanical properties on the amount of ferrotitanium in the additive, similar to those observed when additives of group 1 are introduced.

An increase in the plastic properties of cast iron treated with ferroalloys of group 3 is observed with a decrease in hardness and ultimate tensile strength limit (Fig. 3). The minimum hardness corresponds to the amount in the composition of the ferrotitanium additive of about 60 %, which could be explained by the decrease in the amount of carbides to the minimum and the increase in the amount of ferrite to the maximum (Fig. 8).

The maximum limit of ultimate tensile strength and bending arrow when introducing additives of group 4 is reached with an amount of silicocalcium in the modifier composition of about 50 %, but with this amount of modifier in the composition of the additive, the value of the limit of bending strength is not maximum. It is observed for the amount of silicocalcium in the modifier composition of about 40 % (Fig. 4). The explanation of this fact requires additional research, which could be based on the detection of the influence of the microstructure on the formation of mechanical properties. As could be seen from Fig. 9, the patterns of changes in microstructure characteristics show a complex nature, which is especially evident in the behavior of the amount of ferrite.

As evidenced by the comparative data (Fig. 5), the most expedient from the point of view of ensuring increased strength limit values is the use of additives of group 1, while the amount of modifier in the composition of the additive should be about 40 %.

In contrast to works aimed at identifying the influence of alloying and modifying additives to improve mechanical properties, for example [2–4, 18–20], our solutions are based on the use of complex additives. It was owing to such solutions that it became possible to improve the set of characteristics of cast iron, some of which are competing with each other.

The research is limited by the chemical composition of the base iron and the used modes of melting and addition. Therefore, when using the results in practice, such regimes should be taken into account.

Our study could be advanced in the future towards quantitative and qualitative determination of the influence of the microstructure of cast iron on the investigated mechanical properties. This would make it possible to reveal mechanisms behind the formation of properties, which is important for the practical purposeful regulation of the structure formation processes and might contribute to improving the quality of cast iron.

7. Conclusions

1. It has been determined that the strength characteristics of cast iron treated with ferroalloys of group 1 depend on the ratio of components and the maximum is observed at about 40 % silicocalcium in the modifier composition. The ultimate tensile strength of cast iron reaches about 320 MPa, the bending strength reaches a maximum of about 710 MPa, the deflection arrow is 4.5 mm, and the hardness corresponds to the HB250 level. Hardness and other mechanical properties are competitive in the range of silicocalcium content in the modifier up to 40 %.

The change in microstructure after the addition of group 2 additives is similar to the character determined for group 1, which may indicate a similar type of dependence of mechanical properties on the amount of ferrotitanium in the additive.

An increase in the plastic properties of cast iron when adding group 3 additives is accompanied by a decrease in hardness and ultimate tensile strength. The minimum hardness is about HB200 and accounts for about 60 % of the ferrotitanium additive.

The maximum ultimate tensile strength limit (about 260 MPa) and bending radius (about 3.6 mm) with the introduction of additives of group 4 are achieved with an amount of silicocalcium in the modifier composition of about 50 %, but with this amount of modifier in the additive composition, the value of the bending strength limit value is not maximum. In this case, the maximum shifts to the area where the amount of silicocalcium in the modifier composition decreases to 40 %, which provides a theoretical value for the bending strength limit of about 650 MPa.

2. By comparing the mechanical characteristics of cast iron based on the selected optimal compositions of additives for all groups, it was found that compositions from components of group 1 provide the best properties.

3. We have determined that the change in the amount of carbides is described by an exponential dependence when using additives of groups 1 and 2 but has a polynomial character in the case of the introduction of additives of groups 3 and 4 into the melt. The change in the size of graphite in the case of the introduction of additives of groups 1 and 2 has a linear character, but in case of introduction of additives of groups 3 and 4, it takes a polynomial character with the presence of a maximum. Uncertainty in the change in the amount of ferrite when introducing additives of groups 3 and 4 was revealed, which is manifested in a different nature of the dependence: for group 3, this dependence is polynomial, for group 4, it is linear increasing.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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