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A STUDY THE RELATIONSHIP BETWEEN COMPOSITION, STRUCTURE AND PROPERTIES OF DUCTILE IRON IN CONTINUOUS CASTING

Introduction

The horizontal continuous casting is very productive and economic method and has a lot of advantages in comparison with traditional casting methods: few operations, no waste, stable dimensions of the billet, better operation service characteristics and personal work conditions. All these factors force to be find possibilities to wider implementation of the method. Continuous casting with high cooling rates and directional crystallization of liquid cast iron causes the dense macro- and microstructure of castings and high mechanical properties [1].

Continuous casting has its peculiarities, which, first of all predetermine cast iron microstructure and properties. It is well known that the quality and properties of cast products are strongly related to the microstructure developed during solidification. Therefore, it is important to investigate the effect of different technological factors on the microstructure of metal in order to regulate properties of ingots. The key to an increase in productivity remains often in the control of all operational parameters. Simulation is convenient and accurate method to understand and analyze the importance of each casting parameter [2].

Nodular graphite cast iron is considered as one of the most versatile materials nowadays. Nodular graphite cast iron or also known as ductile iron is a special variety of cast iron having carbon content more than 3% and has graphite present in compact, spherical shapes. These compact spheroids hamper the continuity of the matrix much less than graphite flakes which results in higher strength and toughness with a structure that resembles gray cast iron, thus imparting superior mechanical properties much higher than all other cast irons and which can be compared to steels [3]. This unique property enables ductile irons to be used for numerous industrial applications. The matrix structure of ductile iron can be ferritic, pearlitic, ferritic-pearlitic, martensitic, austenitic or bainitic. Ferritic, pearlitic, ferritic-pearlitic ductile irons are normally produced and usually used in the as-cast condition.

Most favorable for ingots is ferritic structure. But low yield strength and high ductility makes it difficult to be used in certain applications. Thus if some carbon is left intentionally in cementite form, property gets enhanced. Such type of ductile iron is referred as pearlitic ductile iron. If the rate of cooling is very high then the matrix will get converted into martensite. Due to its ductile nature it has limited applications. Thus the matrix may vary from a soft ductile ferritic structure through a hard and higher strength pearlitic structure to an austentic structure [4].

One of the main parameters, which determine the structure of cast iron ingots, is the chemical composition.

Silicon in the ductile iron matrix provides the ferritic matrix with the pearlitic structure. Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon reach surface layer, which inhibits the oxidation. Si is used to promote ferrite and to strengthen ferrite.

Manganese is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent. As Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilize cementite (Fe_3C). But the problem here is the embrittlement caused by it, so the limiting range would be 0,3–1,0%.

Chromium prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere.

But as it is a strong carbide former so not required in carbide free structure.

Phosphorus is kept intentionally very low, as it is not required because it causes cold shortness and so the property of ductile iron will be ruined. But the addition of sulphur is done for better machinability, but it is kept around 0,009% and maximum 0,015%. As the larger additions of sulphur may cause the hot (red) shortness.

Computer technology allows now to predict the development of structure by using different mathematical models for castings. In this work conducted computer simulations of the assessment of structure and properties of ductile iron on the basis of presentation structure of cast iron as composite material. In this approach the individual structural components and phases have their own physical and mechanical properties and structure of ductile iron is represented as a composition of its individual component parts.

Experimental

Were investigated continuous casting ingots produced in the workshop of Public corporation «Gomel foundry «TSENTROLIT».

To obtain mathematical relationships used the method of experimental design and regression analysis. Was studied the effect of chemical composition of ductile iron on structural components of metal matrix. Also the influence of structural components on technological properties of ductile iron was studied.

In the first experiment as independent variables were used the following chemical elements of ductile iron: C, Cr, Si, Mn, Mg, S, P, as well as reduced wall thickness of ingots R ($R = S/P$, where S is a cross-sectional area of a ingot, mm^2; P – girth, mm). Was investigated two output parameters: the number of of ferrite F in structure of metal matrix and number of structurally free cementite Ce. Since in ingots prevailed ferritic-pearlitic structure with the amount of floor space in 100%, knowing the content of ferrite and cementite were determined number of of pearlite in the matrix of ductile iron from the formula: P = 100 – (F + Ce), %.

In the second series of experiments as independent variables accepted structural components of metal matrix: ferrite F, perlite P, cementite Ce. As dependent parameters were selected technological properties of cast iron: tensile strength σ, elongation δ and hardness HB.

Cast iron was melted in the standard line frequency induction furnace of capacity the 3 tons. The iron charge contained steel scrap, cast iron returns, ferrosilicon (FeSi45), scrap copper. The average chemical composition of cast irons aimed at 3,0–3,8% C, 1,9–2,8% Si, 0,5–0,9% Mn, 0,20% Cr. The industrial continuous casting machine A-126 was used. The capacity of the not heated metal receiver of the machine was 1,8 tons. The cylindrical and rectangular specimens were cast by continuous casting.

A microstructure analysis was made by optical microscopy. The graphite lake type, form, and size were defined by procedure described in the Russian Standard «Castings of cast iron with different forms of graphite. Methods for determining the structure» (GOST 3443-87).

The microstructures observed were identified from the corresponding reference diagrams included in this standard.

The tensile test and elongation were been determined on the machined test pieces prepared from samples cut from the continuously cast ingots in accordance with Russian Standard «Metals. Test methods for tension» (GOST 1497-84).

The hardness was been determined as Brinell hardness from the samples cut from a casting, according to standard «Metals. The method of measuring Brinell hardness» (GOST 27208-87).

T a b l e 1. **Experimental design, chemical composition – metal structure**

Factors	C,%	Si,%	Mn,%	Cr,%	S,%	P,%	Mg,%	R, mm
Middle level	3,4	2,5	0,7	0,15	0,0055	0,0725	0,05	40
High level	3,8	3,0	0,9	0,2	0,01	0,09	0,06	70
Low level	3,0	2,0	0,5	0,1	0,001	0,055	0,04	10
Factor's code	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8

T a b l e 2. **Experimental design, metal structure - technological properties**

Factors	F,%	P,%	Ce,%
Middle level	50	50	10
High level	100	100	20
Low level	0	0	0
Factor's code	X_1	X_2	X_3

Results and discussion

Results of experiments were collected and analyzed. To evaluate results of experiments were applied statistical methods, and use the software STATISTICA 7.0. Selection of a suitable model was carried out by sorting and selecting the best according to certain criteria.

For the dependent variable $F(Y_1)$ was chosen power dependence from input parameters.

$$Y_1 = B_0 X_1^{B_1} X_2^{B_2} X_3^{B_3} X_4^{B_4} X_5^{B_5} X_6^{B_6} X_7^{B_7} X_8^{B_8}. \quad (1)$$

Then has been audited the significance of regression coefficients. To do this, the null hypothesis is nominated that coefficients are statistically insignificant different from zero. For testing the hypothesis is using t-test. Further empirical value of t-test should be compared with the table. If $t_{exp} > t_{tabl}$, then the null hypothesis should be rejected. Consequently coefficient was significantly different from zero and should be retained in regression model. If $t_{exp} \leq t_{tabl}$, the null hypothesis is accepted, the corresponding regression coefficient is assumed to be insignificant and excluded from regression model. After insignificant factors were discarded from regression model, the model is recalculated.

Thus, consistently performing significance tests of regression coefficients and making appropriate correction eventually received model containing only significant regression coefficients:

$$Y_1 = 0{,}019 X_1^{3{,}042} X_2^{1{,}746} X_3^{-2{,}114} X_4^{-0{,}196} X_8^{0{,}239}. \quad (2)$$

Regression results for the dependence are shown in tables 3, 4.

Table 3. **Regression statistics**

Index	Value
Multiple *R*	0,922
R-squared	0,850
Normalized *R*-squared	0,840
Standard error	0,389
Observations	80

Table 4. **Variance analysis**

Variables	Coefficients	Standard error	*t*-statistics	*P*-level
Y-intersection	–3,962	0,560	–7,079	6,99E–10
Variable X_1	3,042	0,379	8,023	1,17E–11
Variable X_2	1,746	0,207	8,422	2,06E–12
Variable X_3	–2,114	0,133	–15,892	1,46E–25
Variable X_4	–0,196	0,097	–2,025	4,65E–02
Variable X_8	0,239	0,048	4,953	4,47E–06

	df	*SS*	*MS*	*F*
Regression	5	63,285	12,657	83,735
Residue	74	11,185	0,151	–
Total	79	74,470	–	–

For the resulting regression equation was carried out verification of its adequacy. This checkperformed with Fisher's exact test, the numerical value which is compared with the tabulated critical value. If $F_{exp} \leq F_{tabl}$, there is no reason to reject the null hypothesis. If $F_{exp} > F_{tabl}$, then the hypothesis about the lack ofa linear relation is rejected. Since $F_{exp} = 83{,}735$ and $F_{tabl} = 3{,}204$ hence the constructed model is adequate.

The ability to use regression equations to predict the value of the response was assessedby analysis of performance of the model. The model may be workable if the modelcoefficient of determination $R^2 \geq 0{,}75$. Since the constructed regresionnoy model $R^2 = 0{,}840$, the model is working.

Final relation: number of ferrite - chemical composition:

$$F = 0{,}019 \mathrm{C}^{3{,}042} \mathrm{Si}^{1{,}746} \mathrm{Mn}^{-2{,}114} \mathrm{Cr}^{-0{,}196} R^{0{,}239}. \quad (3)$$

Coefficients corresponding to each independent variable in the equation may not fully reflectthe impact of chemical elements on number of ferrite in ingots, because their content has a very large spread and the content of elements an order different.

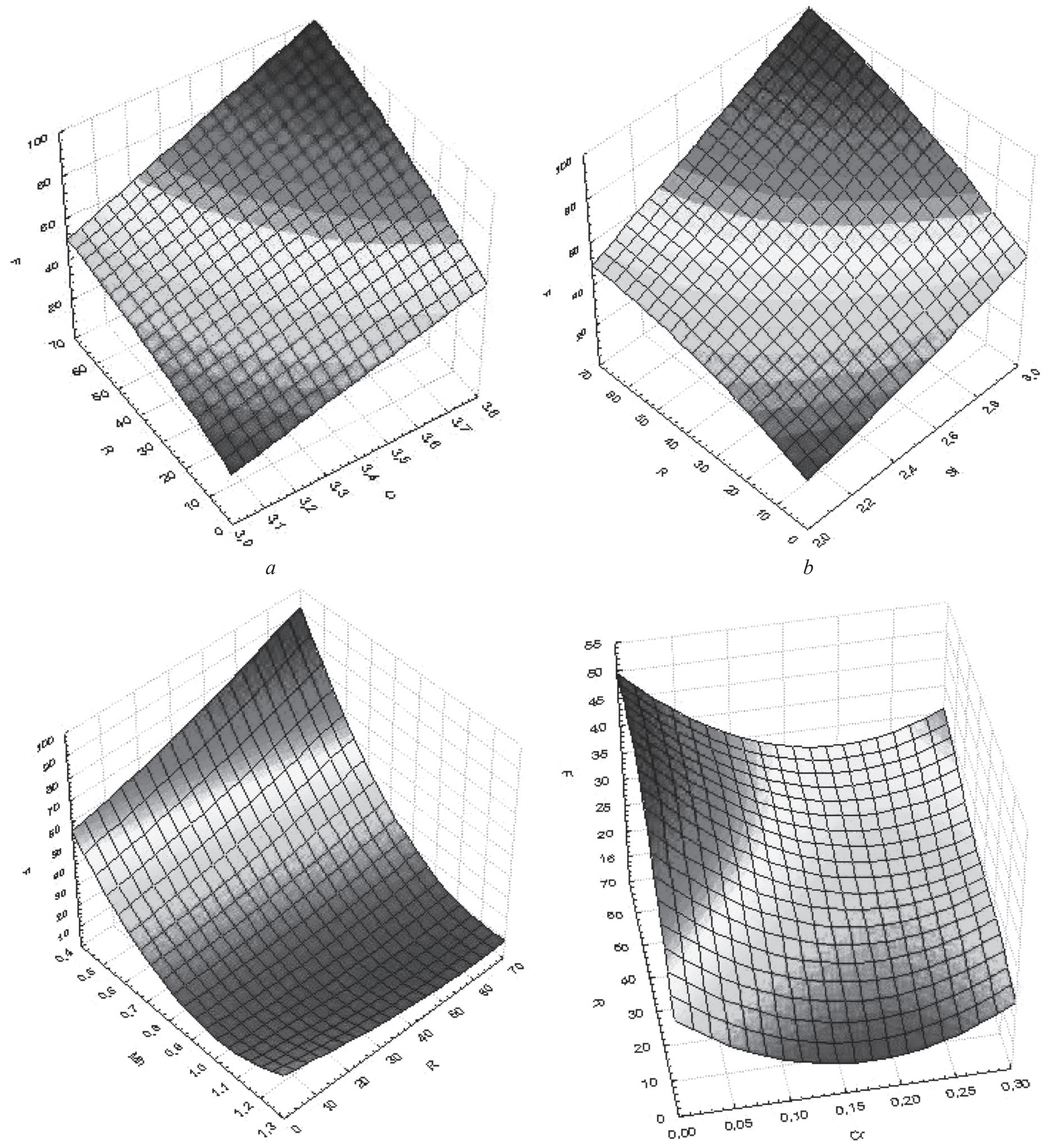
To determine the amount of ferrite in structure of ingot is enough to substitute in the equation chemical composition of cast iron. For further evaluate the effect of individual chemical elements on metal structure examine graphical dependence.

By analyzing the dependence shown on fig. 1, we can say that with increasing content of C there is increase in the amount of ferrite. With increasing the proportion of Mn in ductile iron, ferrite amount is reduced. The maximum content of ferrite in metal matrix is observed as a rule with a minimum content of Mn, because it reduces the thermodynamic activity of C and thus increases the pearlite in ingots. Dependence shown on fig. 1, *b*, captures the growth of ferrite component of a matrix of ductile iron with increasing content of Si. In contrast to Si, chromium increases the pearlite in iron. Wall thickness – generalized criterion of thermokinetic factors. With its increasing rate of cooling of ingot is reduced, which leads to an increase in the interval corresponding to eutectoid temperature and consequently to increase ferrite in the metal matrix.

For the dependent variable Ce (Y_2) was chosen linear dependence from input parameters.

$$Y_2 = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_4 + B_5 X_5 + B_6 X_6 + B_7 X_7 + B_8 X_8. \quad (4)$$

Further test was conducted by the significance of estimated coefficients in the regression equation. After discarding insignificant factors from the regression model coefficients were recalculated.



a *b* *c* *d*

Fig. 1. Dependence of the effect by the number ferrite in structure of ductile iron ingots: *a* – C and *R*; *b* – Si and *R*; *c* – Mn and *R*; *d* – Cr and *R*

As a result, received the following regression model:

$$Y_2 = 0,07 + 1,596X_1 + 0,832X_2 + 4,061X_3 - 44,736X_6 - 0,062X_8. \quad (5)$$

Regression results for the dependence are shown in tables 5 and 6.

Table 5. **Regression statistics**

Index	Value
Multiple *R*	0,916
R-squared	0,839
Normalized *R*-squared	0,828
Standard error	1,008
Observations	80

Table 6. **Variance analysis**

Variables	Coefficients	Standard error	*t*-statistics	*P*-level
Y-intersection	0,070	1,318	0,053	9,58E–01
Variable X_1	1,596	0,297	5,369	8,77E–07
Variable X_2	0,833	0,225	3,694	4,20E–04
Variable X_3	4,061	0,564	7,204	4,08E–10
Variable X_6	–44,736	6,431	–6,956	1,19E–09
Variable X_8	–0,062	0,004	–15,607	4,12E–25

	df	*SS*	*MS*	*F*
Regression	5	391,259	78,252	76,974
Residue	74	75,229	1,017	–
Total	79	466,488	–	–

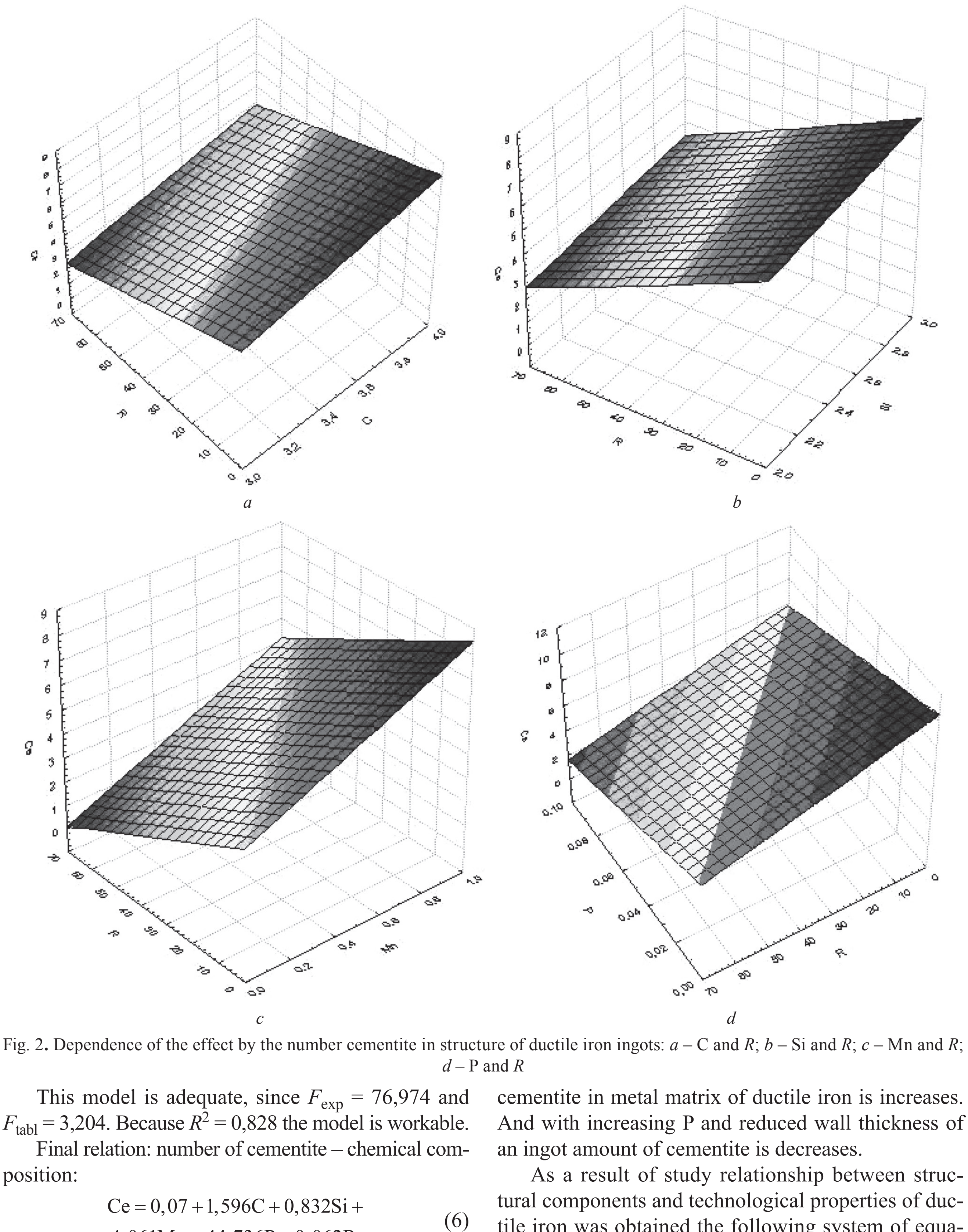


Fig. 2. Dependence of the effect by the number cementite in structure of ductile iron ingots: *a* – C and *R*; *b* – Si and *R*; *c* – Mn and *R*; *d* – P and *R*

This model is adequate, since F_{exp} = 76,974 and F_{tabl} = 3,204. Because R^2 = 0,828 the model is workable.

Final relation: number of cementite – chemical composition:

$$\begin{gathered} \mathrm{Ce} = 0,07 + 1,596\mathrm{C} + 0,832\mathrm{Si} + \\ 4,061\mathrm{Mn} - 44,736\mathrm{P} - 0,062\mathrm{R}. \end{gathered} \qquad (6)$$

In the fig. 2 shows the dependence number of cementite on the contents of chemical elements and reduced thickness of ingots.

Analyzing the graphs, we can conclude that with increasing content of C, Si and Mn, the amount of of cementite in metal matrix of ductile iron is increases. And with increasing P and reduced wall thickness of an ingot amount of cementite is decreases.

As a result of study relationship between structural components and technological properties of ductile iron was obtained the following system of equations:

$$\begin{gathered} \delta = 7,0337 + 0,0013F^2 - 0,00035P^2 + \\ 0,0211\mathrm{Ce}^2 - 0,459\mathrm{Ce} \end{gathered} \qquad (7)$$

($t_{exp} > t_{tabl}$ for the regression coefficients; F_{exp} (199,632) $> F_{tabl}$; R^2 = 0,979);

$$HB = 541{,}667 - 4{,}016F - 3{,}317P^2 - 0{,}126Ce^2 \quad (8)$$

($t_{exp} > t_{tabl}$ for the regression coefficients; F_{exp} (39,426) $> F_{tabl}$; $R^2 = 0{,}871$);

$$\sigma = 28{,}980 + 0{,}038F^2 - 5{,}465P + 0{,}167Ce^2 \quad (9)$$

($t_{exp} > t_{tabl}$ for the regression coefficients; F_{exp} (100,248) $> F_{tabl}$; $R^2 = 0{,}946$).

Conclusions

The developed empirical relationships have practical significance and used for determine the structural composition of iron on known data of express-analysis and for optimization technical process of obtaining castings of ductile iron at Public corporation «Gomel foundry «TSENTROLIT».

The obtained dependences allow:

- to predict obtaining of metal structures and technological properties of cast iron ingots received by continuous casting;
- for previously defined structures and properties of ingots to recommend chemical composition.

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