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Article

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THE CHOICE OF RATIONAL ADJUSTMENT OF THE CHEMICAL COMPOSITION OF IRON MELTED IN AN ELECTRIC ARC FURNACE ON THE BASIS OF TECHNOLOGICAL AUDIT OF SERIAL FILMS

The object of research in the work is cast iron of the SCh20 grade according to GOST 1412-85 (DSTU EN 1561, EN-GJL-200), which is melted in an electric arc furnace. In this work, the parameters of serial smeltings of cast iron used for machine-building castings were determined, which were used to select the content of elements of the chemical composition.

The existing problem is that the impossibility of taking into account many factors influencing the formation of the chemical composition of cast iron during smelting leads to deviations of the chemical composition from the requirements regulated by the technical conditions. The main reason for this is the uncontrollability of the chemical composition of the charge materials and the difficulty of accurately determining the soot of the elements during the smelting process. This can lead to the formation of a shortage of cast iron, or to excessive costs for smelting, associated with the need for additional technological operations and the use of additional materials to eliminate detected deviations of the composition from the requirements.

The procedure of technological audit of serial smeltings is proposed, the feature of which is a comprehensive assessment of the actual indicators of smelting. They include: mathematical expectations of the content of the elements of the chemical composition, estimates of their dispersions, root mean square deviations, systematic errors, scattering fields and deviations of the lower and upper limits of the content of each element from the lower and upper limits required by the technical conditions. The results of such an audit are the possibility of calculating corrective combinations of charge materials and ferroalloys, which eliminate inaccuracies in the calculation of the charge and the determination of the heat of the elements during the smelting process.

As a result of the audit of a sample of 31 serial smelters, it was established that the average content of the elements C, Mn, Si, Cr exceeds the average required by technical conditions. These deviations are: +0.04 % C, +0.06 % Mn, +0.038 % Si, +0.06 % Cr. To compensate for these deviations, the following combination of charge materials and ferroalloys, which are introduced into the melt before delivering the cast iron to the casting area, is proposed: 44 kg of steel scrap +88 kg of recycled iron.

The presented study will be useful for machine-building enterprises that have foundries in their structure, where iron is melted for the production of castings.

Keywords: *electric arc smelting, chemical composition of cast iron, technological audit, serial smelting, charge materials, ferroalloys.*

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1. Introduction

The advantages of electric arc furnaces, associated with the possibility of remelting a charge of any quality and almost any size, stimulate their use not only for the smelting of steel of various grades, but also for the smelting of cast iron. At the same time, manufacturers of modern electric arc furnaces are trying to incorporate into their designs technical solutions that reduce unfavorable operational factors, such as the flicker effect, increased power consumption, phase misalignment during the smelting process, noise and environmental indicators. In addition, modern concepts for the structure of electric arc furnaces are based on the maximum possible use of automation, which is justified, since this reduces the influence of operator experience on the quality of the alloy.

However, the realities of our time indicate that it is necessary to rationally use the available capabilities and resources. The equipment of the smelting sections of foundries is no exception, many of which are equipped with obsolete and physically worn out electric arc furnaces that continue to be used. The deterioration of these funds does not eliminate the need to smelt high-quality alloys, therefore, in relation to the functioning of such furnaces, it is important to search for their reserves and improve the smelting processes, based on the available capabilities. Therefore, great efforts are spent on finding ways to rationally control smelting processes [1, 2], in particular, considering electric arc furnaces as energy-technological controlled complexes [3, 4]. The correct choice of smelting modes should ensure the possibility of obtaining the desired chemical composition of the alloy, which is formed under the influence of temperature, alloying and modification. The chemical composition, in turn, together with physical and chemical processes at the crystallization stage, forms the microstructure and, thereby, determines the mechanical properties. In relation to cast iron, these processes are especially important, since the formation of a microstructure is possible not only along a stable, but also through a metastable path. Thus, issues of the formation of properties, as the final stage of all physical and chemical transformations, require modeling, regardless of the brand of cast iron. In support of this, studies can be cited concerning the smelting of cast iron with flake graphite [5, 6], malleable cast iron [7], aluminum cast iron [8, 9], special wear-resistant and alloy cast iron [10, 11]. All these works are limited to the chemical compositions for which studies were carried out and properties and structure were evaluated. Such a limitation is justified, since the industrial conditions of specific industries for which such research is carried out require the solution of specific practical problems. This conclusion can be generalized to many other works that are not mentioned here, but it is important to understand that control of the chemical composition of the arc melt is the factor that ultimately determines the mechanical or special properties of the alloy.

The object of research in this work is cast iron grade SCh20 according to GOST 1412-85 (DSTU EN 1561, EN-GJL-200), smelted in an electric arc furnace. *The purpose of the study* is to determine the qualitative and quantitative composition of corrective additives in cast iron, eliminating systematic errors in charge calculation, based on a technological audit of serial smeltings.

2. Materials and Methods

Serial smelting was carried out in the iron foundry, where castings for automobile and road equipment are made from SCh20 cast iron in accordance with GOST 1412-85 (DSTU EN 1561, EN-GJL-200).

Smelting and bringing the temperature of cast iron to 1400–1450 °C was carried out in an electric arc furnace DChM-10 with a transformer power of 2250 kVA at voltages of the low side of the transformer 150, 125, 105 V with deviations of ±5 %. The electrode movement control system provided a stroke of 1200 mm at a speed of 1.65 m/min. The specific electricity consumption for heating cast iron was 105 kWh/t when heated from 1400 to 1550 °C.

The chemical composition is adjusted by introducing a charge and ferroalloys:

- to increase the content of Si, Mn, Cr, ferroalloys were introduced: ferrosilicon FeSi25, ferromanganese FeMn70, ferrochrome FeCr100;
- to reduce the content of Si, Mn, Cr, steel scrap and pig iron DSTU 3133-95 (GOST 805-95) were introduced [12].

The adjustment was carried out to bring the chemical composition to the specified technical specifications for cast iron: C=3.2–3.6 %, Si=2.2–2.5 %, Mn=0.6–0.8 %, Cr=0.1–0.3 %, S no more than 0.12 %, P no more 0.2 %. Data on the chemical composition were recorded in the charge log.

When the sulfur content was exceeded, a desulfurization operation was carried out with soda ash and limestone.

The temperature of the melt released from the electric furnace is controlled by a spectral ratio pyrometer installed in the furnace control panel room.

To assess the correspondence of actual smelting parameters in terms of chemical composition to the specified ones, data from 31 serial meltings (N=31) were obtained, on the basis of which the following characteristics of cast iron were determined, taken as quality indicators:

- mathematical expectations of the content of carbon, silicon, manganese, chromium, %, $M(X)$;
- estimates of dispersions of carbon, silicon, manganese, chromium content, $s^2(X)$;
- standard deviations of the content of carbon, silicon, manganese, chromium, %, $s(X)$;
- systematic errors in estimating the content of carbon, silicon, manganese, chromium, %, ΔX;
- dispersion fields of carbon, silicon, manganese, chromium content, δX.

Calculations were performed using the formulas:

$$M(X)=\frac{\sum_{i=1}^{N} X_i}{N}, \quad (1)$$

$$s^2(X)=\frac{1}{N-1}\sqrt{\sum_{i=1}^{N}\left(X_i-M(X)\right)^2}, \quad (2)$$

$$s(X)=\sqrt{\frac{\sum_{i=1}^{N}\left(X_i-M(X)\right)^2}{N-1}}, \quad (3)$$

$$\Delta X=M(X)-X_{ts}, \quad (4)$$

$$\delta X=(X_{\min}-X_{\min\ ts};\ X_{\max}-X_{\max\ ts}), \quad (5)$$

where X_{ts} – the average content of a chemical element in accordance with the technical specifications; $X_{\min\ ts}$, $X_{\max\ ts}$ – minimum and maximum values of element content in accordance with technical specifications; $X_{\min}$, $X_{\max}$ – the lower and upper values of the content of an element of chemical composition in a series of smeltings, which was determined by constructing histograms in the range from $M(X)-3s(X)$ to $M(X)+3s(X)$.

To assess the compliance of the actual smelting parameters in terms of chemical composition with the required ones, the statistical hypothesis about the equality of the mathematical expectation to a given value was tested. The content of the chemical composition for each element, specified by the technical conditions, was chosen as such a value:

$$H:\ M(X)=X_{ts}. \quad (6)$$

The hypothesis was considered rejected if the following condition was met:

$$t=\frac{\left(M(X)-X_{ts}\right)}{s(X)/\sqrt{N}}>t_{cv}, \quad (7)$$

where t_{cv} – the critical value of the Student distribution.

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3. Results and Discussion

Fig. 1–6 show the results of serial smeltings based on the content of chemical composition elements, and Table 1 – results of statistical analysis of the obtained data.

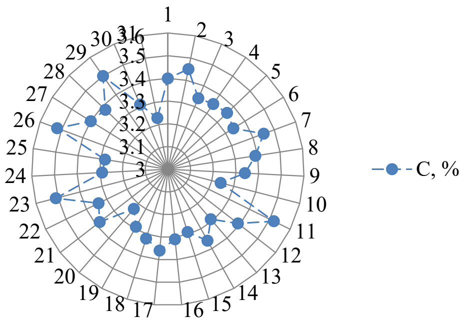

Fig. 1. Carbon content in cast iron

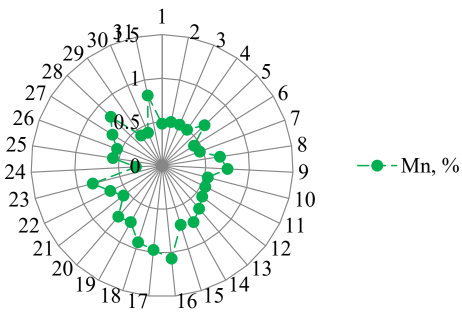

Fig. 2. Manganese content in cast iron

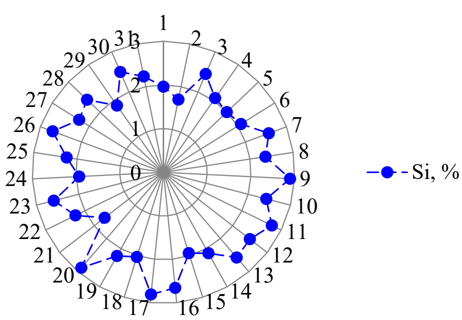

Fig. 3. Silicon content in cast iron

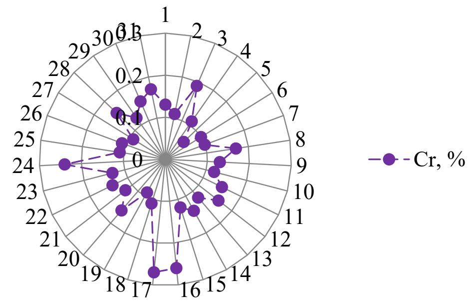

Fig. 4. Chromium content in cast iron

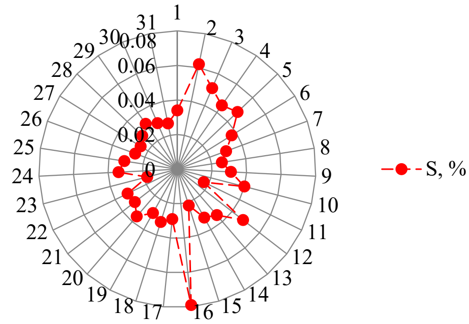

Fig. 5. Sulfur content in cast iron

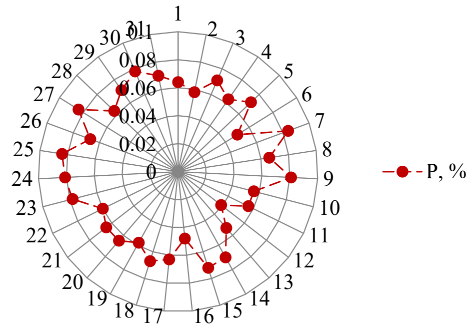

Fig. 6. Phosphorus content in cast iron

Fig. 7–12 show distribution histograms of the content of chemical elements in cast iron.

Table 2 shows the results of calculations to test hypothesis (6).

Table 1

Results of statistical analysis of the chemical composition of cast iron

Characteristics	Chemical composition, %					
	C	Mn	Si	Cr	S	P
$M(X)$	3.36	0.6390323	2.311935	0.14	0.03471	0.066355
$s^2(X)$	0.006381	0.0312157	0.114336	0.00228	0.000159	0.000125
$s(X)$	0.079879	0.1766797	0.338136	0.0477493	0.012599	0.011161
X_{min}	3.28	0.46	1.97	0.09	0.022	0.044
X_{max}	3.52	1.17	2.99	0.28	0.073	0.089
ΔX	+0.04	+0.060968	+0.03806	+0.06	Norm	Norm
$X_{min}–X_{min\ ts}$	+0.08	–0.14	–0.23	–0.01	–	–
$X_{max}–X_{max\ ts}$	–0.08	+0.37	+0.39	–0.02	–	–

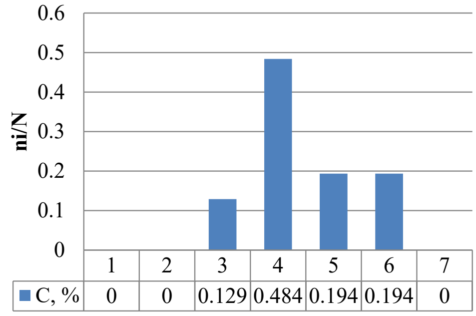

Fig. 7. Distribution of carbon content in cast iron

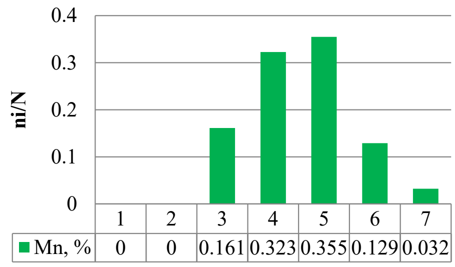

Fig. 8. Distribution of manganese content in cast iron

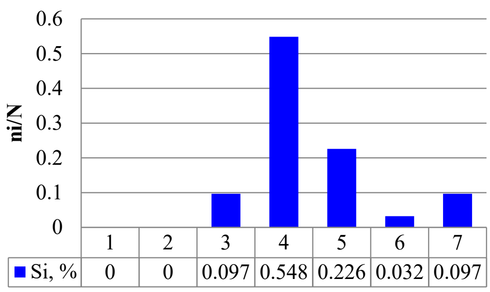

Fig. 9. Distribution of silicon content in cast iron

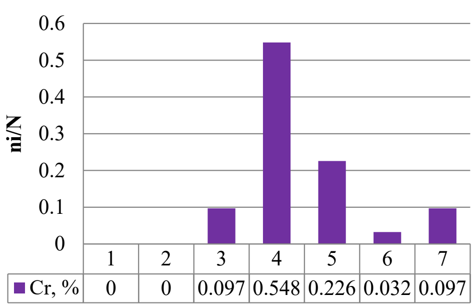

Fig. 10. Distribution of chromium content in cast iron

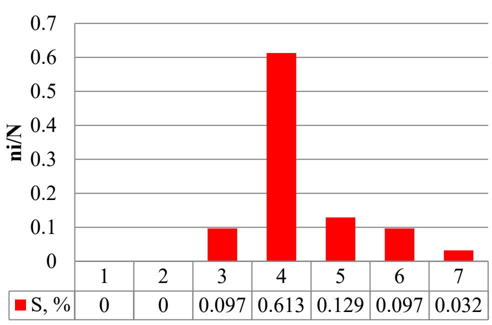

Fig. 11. Distribution of sulfur content in cast iron

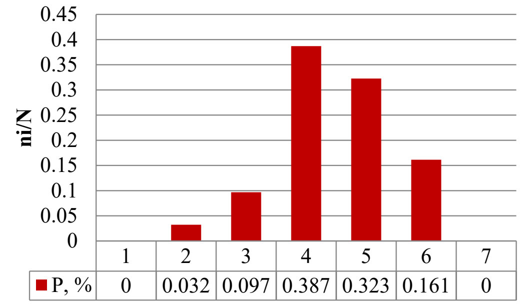

Fig. 12. Distribution of phosphorus content in cast iron

Table 2

Calculation parameters for testing the hypothesis

Parameters	Parameter values for the content of elements of chemical composition, %			
	C	Mn	Si	Cr
$M(X)-X_{ts}$	0.04	0.060968	0.03806	0.06
P	0.95	0.95	0.95	0.95
t_{cv}	2.042	2.042	2.042	2.042
t	2.788	1.921	0.627	6.996

From the data in Table 2 it can be seen that the hypothesis that the actual average content is equal to the given one is satisfied only for Mn and Si. However, this result is ensured by a large field of deviations in the series of smeltings under study. The use of measures that help reduce the field of deviations without adjusting the composition of these elements, aimed at eliminating systematic errors, will lead to rejection of the hypothesis. This, in turn, can lead to the formation of defects in the Mn and Si content in cast iron.

In order for hypothesis (6) to be fulfilled for C and Cr, it is necessary to eliminate the systematic error (+0.04 % for C and +0.06 % for Cr) with the existing deviation fields. However, from Table 1 shows that the requirements of the technical specifications for C are met. This is evidenced by the combination of «+» signs in the calculated values of the lower ($X_{\min}-X_{\min\ ts}$) and upper ($X_{\max}-X_{\max\ ts}$) limits of deviations of the maximum C contents from the requirements of the technical specifications. However, such requirements are not met for the remaining elements – only the upper limit for Cr is maintained and the lower limit is close to being maintained (a combination of the signs «–» and «–») – Table 1. The technical requirements for the permissible limits of Mn and Si content are not met.

The reasons for deviations in the content of elements from the required ones can be either the amount of element waste that was incorrectly included in the calculation of the charge, or the composition of the charge that is not fully controlled. Based on the fact that these factors cannot be eliminated, it is necessary to adjust the chemical composition before dispensing the melt for pouring molds, the size of which is selected depending on the identified systematic error.

Based on the results obtained (Table 1 and Table 2), to bring the composition of cast iron to the specified level, it is necessary to reduce the content of all elements: carbon by an average of 0.04 %, manganese by 0.07 %, silicon by 0.038 %, chromium by 0.06 %. To do this, based on corrective standards [13], the following combinations of charge and ferroalloys (per 1 ton of liquid cast iron) can be introduced into the furnace: 44 kg steel scrap +88 kg pig iron.

This combination is one of the possible ones, but the best choice can be made based on cost minimization using linear programming methods [6]. It should be noted that the use of this combination will lead to the introduction of additional amounts of Si and Mn, which can increase their content in cast iron, shifting the average value upward. However, it is also possible that this will lead to a change in the lower and upper boundaries of the dispersion field and may be a factor in reducing the consumption of FeSi25 and FeMn70 for smelting, but this issue requires additional verification.

Thus, the proposed procedure for selecting a rational corrective additive includes a technological audit of the serial smelting process to assess the chemical composition of cast iron and the calculation of a rational, and, in the long term, optimal option for corrective additives. The rational option ensures the elimination of systematic error when calculating the charge; the optimal option is the selection of the best corrective combination that eliminates the systematic error while minimizing the cost of the selected combination.

However, it should be noted that eliminating bias is not the only goal. It is also necessary to develop measures, the use of which in the technological process will reduce the dispersion field of the content of elements of the chemical composition. This development may be the subject of further research.

4. Conclusions

A technological audit of serial smeltings to assess the chemical composition of cast iron can establish the actual indicators of electric arc smelting, which must be selected: mathematical expectations of the content of elements of the chemical composition, estimates of their dispersions and standard deviations, systematic errors and dispersion fields. Comparison of the obtained data with the requirements of the technical specifications allows to determine the composition and quantity of corrective combinations, including charge materials and ferroalloys.

Based on serial smelting of cast iron in an electric arc furnace under industrial conditions, it was established that there are systematic errors in the elements of the chemical composition C, Mn, Si, Cr. In particular, the average content of these elements exceeds the average required by technical specifications. These deviations are: +0.04 % C, +0.06 % Mn, +0.038 % Si, +0.06 % Cr. To compensate for these deviations, the following combination of charge materials and ferroalloys introduced into the melt before the cast iron is delivered to the pouring area can be used: 44 kg steel scrap +88 kg pig iron.

To meet the requirements of technical specifications for the content of each element of the chemical composition, it is necessary not only to introduce corrective combinations that eliminate systematic errors in the calculation of the charge, but also to take measures to reduce the dispersion field of the content of each element. The effectiveness of such joint actions can be assessed at the stage of statistical testing of the hypothesis about the equality of mathematical expectations of the content of elements of the chemical composition required by technical conditions.

Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

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