SELECTION OF OPTIMAL Al–Si COMBINATIONS IN CAST IRON FOR CASTINGS FOR ENGINEERING PURPOSES

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Abstract

In this work, the optimal combinations of Al–Si in cast iron for cast parts for machine-building purposes were determined with the aim of subsequent selection of rational modes of modification and alloying, and the possibility of their implementation under industrial smelting conditions was checked.

The graphical dependence $Si = f(Al)$ is obtained, which is a set of optimal combinations of the content of Al and Si in cast iron, providing the maximum ultimate tensile strength UTS $\approx$ 245...334 MPa.

The technological audit of the results of serial industrial smelting included the analysis of actual indicators, the calculation of sample distribution functions (mathematical expectation and dispersion) of the Al and Si content in the alloy, as well as the UTS value. The correspondence of the indicators of the content of Al and Si and the value of σ to the optimal values was assessed by testing the statistical hypotheses: H: $M(Al) = Al_{opt}$, $M(Si) = Si_{opt}$, $M(\sigma_B) = \sigma_{Bopt}$. On the basis of the obtained results of the assessment of statistical characteristics and verification of hypotheses, it was established that at the chosen significance level $\alpha = 0.05$, the technological process of smelting satisfies the requirements of optimality in terms of the Si content, but in terms of the Al content, the technological process does not meet the requirements of optimality.

The proposed procedure for choosing the optimal combinations of Al and Si makes it possible to choose the amount of correcting additives depending on the actual indicators of the chemical composition during the smelting process. To do this, it is necessary to assess the closeness of the actual composition to the optimal curve $Si = f(Al)$ and choose the one that most satisfies the criteria of rationality. The latter can be the cost of ferroalloys, through which Al and Si are introduced.

Keywords: cast iron, inoculation, alloying, optimal Al–Si combinations, industrial smelting, tensile strength.

1. Introduction

Improving the performance characteristics of machine parts made of cast iron is possible by searching for optimal technological solutions for its smelting. Among such solutions is the combination of modification and alloying [1]. The introduction of modifying elements predetermines the course of the graphitization process during crystallization, which can lead to a decrease in mechanical properties. This decrease can be compensated by the introduction of alloying elements [2, 3]. The high price of ferroalloys, with which alloying elements are added, necessitates their use in the minimum required amount. This should be such an amount that provides the required compensation for the loss of properties. Combining the operations of modification and alloying requires the development of rational technological solutions that can be obtained after the regularities of the formation of properties under the influence of modifiers and alloying elements are revealed. This paradigm of property formation is reflected in many publications. This can be confirmed by a brief analysis of such publications. They describe different priorities in the choice of factors influencing the formation of properties. For example, in [4], the effect of microstructural inhomogeneities on the strength of cast iron: graphite, casting defects, the structure of a metal matrix was investigated. The works [5, 6] describe the effect of modifiers on the morphology of graphite, microstructure of the alloy, and the mechanical properties formed by the structure of the alloy. The effect on tensile strength of carbon content, chemical composition and solidification rate is described in [7]. The effect of carbon and carbon equivalent on ultimate strength and hardness was studied in [8–10], and the effect of sulfur content on the properties of synthetic cast iron is described in [11]. All these studies can be attributed to the category of works devoted to obtaining and analyzing models of the «composition – property» type in a clear formulation. A number of works consider similar issues, but in an unclear formulation [12–14], arguing this by the presence of uncertainty in the assessment of variables describing the formation of the structure and properties of the alloy.

Also important are not only the out-of-furnace treatment processes, but also the technologies of iron smelting, which form the chemical composition of the alloy [15]. Depending on the chemical composition of the alloy, the best of the alternative options [16] of impact on the melt is selected, which ensures its optimal characteristics. It is important to note that the choice of such actions leads to a change in the course of physicochemical processes in the melt. This is expressed in a change in the rates and activation energy of reactions of interaction of elements of the chemical composition with each other and with the reaction products. This is explained by the formation of carbides in the microstructure and is caused precisely by the influence of alloying elements, since it is they that cause a change in the activation energies of the ongoing processes [17]. That is why, when using V, Cr, W, etc. as alloying elements, which actively contribute to the development of carbide formation processes, either alloying elements promoting graphitization, for example, Ni, Cu, or ferroalloys containing Si are introduced. The choice is dictated not only by economic considerations, but also by the requirements for cast parts. For example, for machine-building castings it can be tightness [18–20], strength with minimum weight and size characteristics [21, 22]. The latter is especially important for parts of internal combustion engines (ICEs), in which aluminum cast irons can be used, which are characterized by high specific work of destruction due to their high strength and deformation of destruction [22].

In this study, the optimal combinations of Al–Si in cast iron for internal combustion engine parts were determined with the aim of subsequent selection of rational modes of inoculation and alloying, and the possibility of their implementation in industrial smelting was checked. Based on this, it becomes possible to choose such combinations of Al–Si, depending on the actual smelting performance, which provide maximum ultimate strength. At the same time, the presence of many alternatives providing equally optimal results according to this criterion makes it possible to select a combination of ferroalloys for reasons of minimum costs.

2. Materials and Methods

The research was carried out within the framework of the PC Technology Center research topic «Technology audit and identification of production reserves». Retrospective data from a series of industrial smelting were selected as the initial ones [23]. As an object of research, let's use the tensile strength model described in [22, 23]:

$$y = 17 + 13.7x_1 - 4.5x_2 - 4x_1^2 - 1.6x_2^2 - x_1x_2, \tag{1}$$

where x_1 – the Al content in the alloy, x_2 – the Si content in the alloy, y – the ultimate tensile strength UTS, kg/mm^2.

Model (1) is presented in the space of normalized input variables x_i in the dimensionless range [–1; +1]. The ranges of variation were: Al=1...2 %, Si=0.5...1.5 %.

The standardization of these serial industrial smelting was carried out according to the formula:

$$x_i = \frac{2x_i^* - \left(x_{i\max}^* + x_{i\min}^*\right)}{x_{i\max}^* - x_{i\min}^*}, \ i = 1,..,N, \ j = 1,..,n, \ x_{i\max}^* = \max_j x_{ji}^*, \ x_{i\min}^* = \min_j x_{ji}^*, \tag{2}$$

where the * symbol denotes the natural value of the input variables.

To analyze the response surface described by model (1), Hurl ridge analysis was used. For this, a parametric representation of model (1) was performed according to the procedure described in [9, 10].

The optimal values of the input variables in a normalized form, providing the maximum UTS value, were determined by solving equation (3):

$$\mathbf{x}_{opt}(\lambda) = \begin{pmatrix} \lambda - 4 & -0.5 \\ -0.5 & \lambda - 1.6 \end{pmatrix}^{-1} \begin{pmatrix} 6.85 \\ -2.25 \end{pmatrix}, \tag{3}$$

where $\mathbf{x}_{opt}(\lambda)$ – the matrix of optimal values of the input variables, λ – the Lagrange multiplier, which acts as a parameter in the parametric description of model (1).

The output values at such values of the input variables were calculated from equation (4):

$$y_{opt}(\lambda) = 17 + 2(6.85 \ -2.25)\mathbf{x}_{opt} + \mathbf{x}_{opt}^T \begin{pmatrix} -4 & -0.5 \\ -0.5 & -1.6 \end{pmatrix} \mathbf{x}_{opt}, \tag{4}$$

where $y_{opt}(\lambda)$ – the optimal UTS values.

The data of serial industrial smelting were processed by the methods of mathematical statistics to determine the sample distribution functions (mathematical expectation and variance) of the Al and Si content in the alloy, as well as the UTS value.

The correspondence of the indicators of the content of Al and Si and the UTS to the optimal values was assessed by testing statistical hypotheses:

$$H: M(\text{Al}) = \text{Al}_{opt}, \ M(\text{Si}) = \text{Si}_{opt}, \ M(\sigma_B) = \sigma_{Bopt}. \tag{5}$$

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

$$t = \frac{\left(M(x) - x_{opt}\right)\sqrt{n}}{s(x)} > t_{cv}, \tag{6}$$

where $M(\text{Al})$, $M(\text{Si})$, $M(\text{UTS})$ – the mathematical expectation of the Al and Si content and the UTS value, respectively, x – the values of Al, Si, UTS in natural form, x_{opt} – the optimal value of Al, Si, UTS in natural form, $s(x)$ – the standard deviation of Al, Si, UTS in natural form, t_{cv} – the critical value of the Student's distribution, n – the sample size. Sample functions $M(x)$ and $s(x)$ were calculated by formulas (7), (8), respectively:

$$M(x) = \frac{\sum_{i=1}^{n} x_i}{n}, \tag{7}$$

$$s(x) = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - M(x)\right)^2}{n-1}}. \tag{8}$$

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To determine the range of rational values of the correcting additives (nAl+mSi), the procedure for searching for control under the conditions of a multi-alternative description of the final state was used [16].

Fig. 1–3 show the results of serial smelting, which are the initial data for the study, presented in the form of circular diagrams.
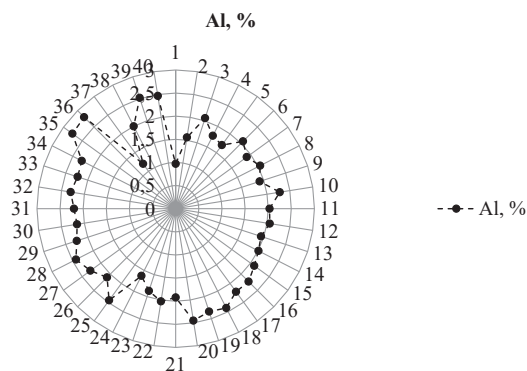
Al, %

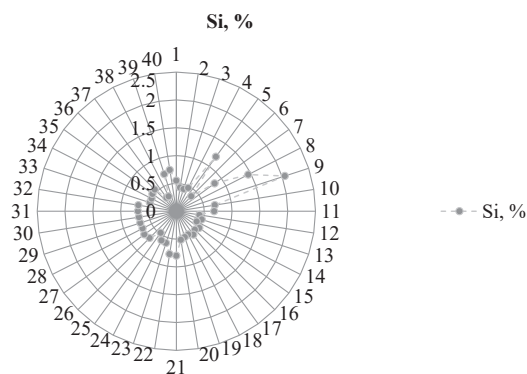**Fig. 1.** Diagram of distribution of Al content in serial smelting

Si, %

Fig. 2. Diagram of Si content distribution in serial smelting
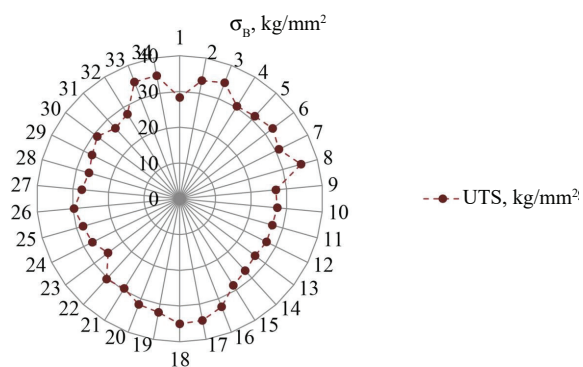
σ_B, kg/mm²

Fig. 3. Diagram of the distribution of the UTS content in serial smelting

3. Results and discussion

It is found that the optimal values of the input variables in normalized form:

$$\mathbf{x}_{opt}(\lambda) = \begin{pmatrix} x_{1opt} \\ x_{2opt} \end{pmatrix},$$

which ensure the maximum UTS value, are in the domain of definition $-1.5 < \lambda < \infty$.

Table 1 shows the optimal UTS values and the corresponding values of the input variables in kind.

Table 1

Content in the alloy of Al and Si, providing a UTS maximum

Al, %	Si, %	UTS calculation, kg/mm^2
2.34	0.49	33.4
2.27	0.58	32.6
2.21	0.65	31.7
2.14	0.7	30.9
2.08	0.74	30.0
2.03	0.78	29.2
1.98	0.8	28.4
1.94	0.83	27.6
1.9	0.84	26.9
1.87	0.86	26.2
1.84	0.87	25.6
1.81	0.89	25.0
1.78	0.9	24.5

Fig. 4 shows the line of optimal combinations of input variables, represented in the form Si = f(Al) according to the data in **Table 1**.

Fig. 5, 6 show the distribution histograms of the Al and Si content in serial smelting, and in **Table 2** the values of the sample functions – the mathematical expectation $M(x)$, the variance $D(x)$, the standard deviation $s(x)$.
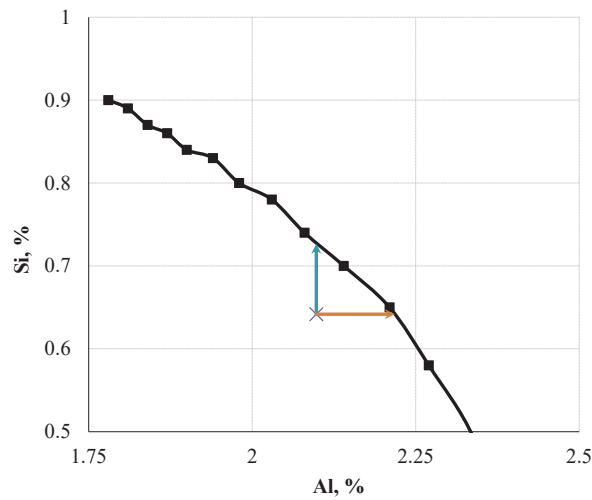

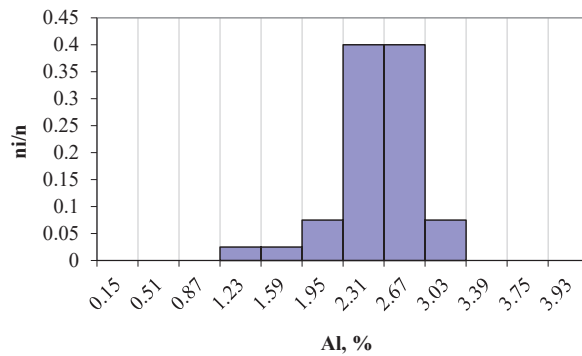**Fig. 4.** Line of optimal combinations of input variables

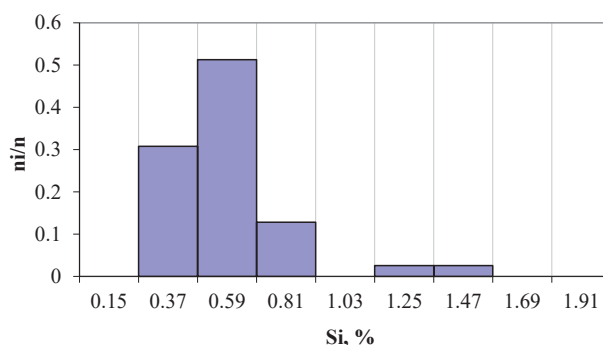**Fig. 5.** Histogram of distribution of Al content in serial smelting

Fig. 6. Histogram of the distribution of Si content in serial smelting

Table 2

Sample function values

M(x), %		D(x)		s(x), %	
Al	Si	Al	Si	Al	Si
2.098	0.642	0.1295	0.1	0.36	0.316

Fig. 7 shows the histograms of the distribution of the UTS value, according to the data of serial smelting and calculations according to (1). The initial data for constructing the histogram are given in **Table 3**.
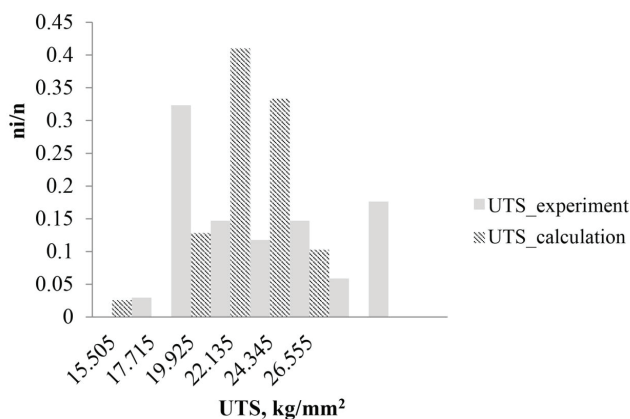

Fig. 7. Histograms of the distribution of the UTS value, according to serial smelting and calculations according to (1)

Based on the data in **Table 3**, it is possible to establish the average composition of the alloy for Al and Si in serial smelting and its location relative to the optimal curve Si=f(Al) (**Fig. 4**). This measure of proximity makes it possible to assess the extent to which the actual technological process meets the requirements for maintaining the optimal alloy composition.

For example, **Table 4** shows the results of testing the corresponding hypothesis at a confidence level of $P=0.95$, if the composition Al=2.21 %, Si=0.65 % is chosen as the optimal one. This point is located on the line of optimal combinations Si=f(Al) (**Fig. 4**).

It follows from **Table 4** that for the chosen significance level $\alpha=0.05$, it is possible to say that the technological process meets the requirements of optimality, at least for the Si content. If to set the significance level $\alpha=0.1$, then it can be seen that the technological process does not meet the requirements of optimality in terms of Al content, since in this case $t=1.97>t_{cv}=1.69$.

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Table 3

Initial data for constructing a histogram of UTS distribution obtained in serial smelting and by calculation

UTS experiment, kg/mm²	UTS calculation, kg/mm²
28.3	23
33.6	25.7
34.8	25.2
30.4	25.4
31.2	18.9
32.6	25.5
31.0	22
35.3	15.4
27.0	21.9
27.4	23.1
26.9	25.2
27.1	25.1
26.4	25.4
27.2	24.3
28.5	24.1
32.4	23.8
34.6	23.2
35.0	23.4
32.3	22.5
31.7	22.4
29.5	22.3
30.4	24.2
25.1	24.5
27.3	22.9
28.1	22.9
29.7	21.8
27.5	21.3
26.4	22.2
27.4	22.7
28.9	22.4
26.7	21.9
27.8	23.9
35	23.7
35	20
–	19.5
–	25.8
–	26.3
–	20.4
–	20.3

Table 4

Results of testing hypotheses H: $M(\text{Al}) = \text{Al}_{opt}$, $M(\text{Si}) = \text{Si}_{opt}$, $M(\text{UTS}) = \sigma_{Bopt}$

Al			Si			UTS		
n	t	t_{cv}	n	t	t_{cv}	n	t	t_{cv}
40	1.97	2.02	40	0.16	2.02	34	3.176	2.03

At a significance level of $\alpha = 0.05$, the technological process does not satisfy the requirements for optimality in relation to UTS, therefore, it is necessary to adjust the chemical composition by introducing a correcting additive nAl+mSi. The principle of choosing a correcting additive value is shown in **Fig. 4**, where the coordinate corresponding to the mathematical expectation of the Al and Si content in serial smelting is marked and the vectors show possible alternative ways to achieve their optimal values. It can be seen that there are many such paths and the choice of the most rational of them should be based on the cost of the combination of ferroalloys, by means of which the correcting additive is introduced into the melt.

4. Conclusions

The graphical dependence Si=f(Al) is obtained, which is a set of optimal combinations of the content of Al and Si in cast iron, providing the maximum ultimate tensile strength UTS $\approx$ 245...334 MPa. The technological audit of the results of serial smelting made it possible to establish that at the chosen significance level $\alpha = 0.05$, the smelting process meets the requirements of optimality in terms of the Si content, but in terms of Al content, the technological process does not meet the requirements of optimality. The proposed procedure for choosing the optimal combinations of Al and Si makes it possible to choose the amount of correcting additives depending on the actual indicators of the chemical composition during the melting process. To do this, it is necessary to assess the closeness of the actual composition to the optimal curve Si=f(Al) and choose the one that most satisfies the criteria of rationality. The latter can be the cost of ferroalloys, through which Al and Si are introduced.

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